HTS CABLE--STATUS, CHALLENGE and OPPORTUNITY

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Implementing Agreement for a Cooperative Programme for Assessing the Impacts of High-Temperature Superconductivity on the Electric Power Sector

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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 infra-structure (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)

[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.

III. THE DEVELOPMENT OF ELECTRICAL CABLE

III.1 Purpose and Scope

This chapter sketches the history (and prehistory) of electrical cable. In fact, many of the technical challenges faced by today's HTS cable RD&D were also faced by past effort, which yielded today's network. Thus, this chapter broaches technical issues to which subsequent chapters will return.

Technical issues describe only one aspect of applications. Consideration of what is necessary to realize the promise of HTS power cable can be informed by an appreciation of the incentives that attracted talent, money, and political support to enable the creation of today's technology and infrastructure. Those incentives and the roles of governments and the private sector are also sketched in the following pages.

Today's technology and the networks that embody it are the result of effort and ingenuity of many people, located all over the world, during the past two hundred years.

III.2 Why Electrical Conductors First Attracted General Interest

Electrical conductors were first developed to satisfy two needs: protection from lightning and communication that is instantaneous and always available. In fact, the profession we know as electrical engineering began as telegraphy. Further advances and investment were required to enable conductor to guide power, as well as information.

III.3 State-of-the-Art (in 1800) Communications Technology and the Infancy of Its Rival

At the beginning of the 1800s, many scientists were trying to communicate by sending electricity through wires.[10] The conventional technology at that time was the "Chappé telegraph," a system of semaphores mounted on towers, each manned by one or more persons with a telescope and the means to alter the positions of the semaphore's arms.

[10] Indeed, in the 1700s, B. Franklin had proposed transmitting sparks across the Schuylkill River for the entertainment of his friends. On 29 April 1747, he wrote to P. Collins, of London, "Chagrined a little that have hitherto been able to produce nothing in this way of use to mankind; and the hot weather coming on, when electrical experiments are not so agreeable, it is proposed to put an end to them this season, somewhat humorously, in a party of pleasure on the banks of the Schuylkill. Spirits, at the same time, are to be fired by a spark sent from side to side through the river, without any other conductor than the water; an experiment which we some time since performed to the amazement of many. …" In 1774 in Geneve, Switzerland, G. Lesage constructed a telegraph consisting of 24 wires, each terminating on a pith ball.

That technology had been developed in France[11] in 1794 and was soon adopted in England, where sequences of towers were erected, putting Channel ports (indirectly) in sight of inland cities to enable rapid transmission of news of Napoleon's much-feared invasion.[12] Because inclement weather and the darkness of night impede vision, people sought an alternative, including an electrical alternative.

By 1800, the discoveries of L. Galvani and A. Volta had provided batteries, and thus, a ready source of "electrical motive force." This enabled the electrolysis of water. (H. Davy developed electrochemistry, winning potassium from potash in 1806.) Some considered electrochemical telegraph receivers—the products of electrolysis constituting the received signal.

Davy did not limit his investigations to communication. By 1810, he showed that electricity could produce light; specifically, Davy made an arc lamp employing carbon electrodes. The efforts of many persons yielded improved batteries and improved electrodes. Arc lights came to be used for public illumination, lighthouses, and theatres. Despite the improvements that made them feasible, battery-powered arc lights were neither convenient nor congenial in many settings.

Discoveries by H. C. Oersted (1819), J.M. Ampere (1820), and Davy's young assistant, M. Faraday (1821), provided the basis for converting shaft power to electric power and electric power to shaft power; thus began the infancy of today's generators and motors. The magnetization of iron was discovered and brought to use by J. Henry's practice of wrapping wire with silk and then winding many turns around iron (1826), thereby making electromagnets of useful strength. Thus the relay was made possible, and arguments about the possibility of overcoming the resistance in wire to send electricity over long distances were mooted. Telegraphs were demonstrated in St. Petersburg (1832) and in Göttingen (1833). By 1837, C.A. Steinheil built and operated the first commercial telegraph lines in and around Munich. Most important, Steinheil understood the vital fact that the earth conducts electricity and so he halved the need for wire by grounding its ends.

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[11] The first sequence of towers connected Paris and Lille, 230 km (144 miles) apart. "…transmission could be fairly rapid. For example, over the 760 km (475 mile) line with its 120 towers from Paris to Toulon, it is said that operators could transmit a message in ten to twelve minutes," according to R.S. Kirby, S. Withington, A.B. Darling, F.G. Kilgour, Engineering in History, Dover (New York, 1990), page 336.

[12] In 1826, F. Ronalds was able to build a telegraph using one wire, pith balls and two synchronous wheels. To Ronalds' invitation to consider his device, the British government replied "…telegraphs of any kind are now wholly unnecessary…." The Congress of Vienna had concluded eleven years earlier.

III.4 Why the Telegraph Was Widely Adopted

A happy synergy soon became apparent. Around the world, railroads were being built.[13] Co-location eased the cost of telegraph line construction and maintenance. On the demand side, "The telegraph system of dispatching revolutionized railroading. Trains that might have taken four days to travel a given distance before the telegraph were covering the same distance in a single day after the telegraph was used for dispatching," because precautions against collisions on one track railroads could be taken in a timely way. [14]

The electromagnet was put to use in what became the standard telegraph key and S. Morse's invention of his famous code showed that information could be transmitted using little bandwidth. On March 3, 1843, the last night of the U.S. Congressional session, a $30,000 appropriation was added[15] to the budget to fund a 60-km telegraph line connecting Washington D.C., and Baltimore. In 1844, Morse ran his wires underground; he soon found this led to difficulty, and so he ran his wires overhead, as had already been done elsewhere in the world. One account states that the first overhead lines were built near Calcutta.[16]

By 1850, the telegraph was no longer a curiosity. More and more lines were being constructed. Iron wires, separated from their supporting poles by glass insulators, appeared.

What drove the innovators' enthusiasm? According to one study, the vision of the "obliteration of time and space".[17]

Besides this vision, what prompted the sizeable investment and subsequent use of the new technology? Such massive investment should not be passed over in silence. Two speculations are offered here. First, the speed and scale of rail transport increased the wish for fast communication, in the service of commerce. Second, the desire to maintain

[13] G. Stephenson's Manchester and Liverpool Railroad began operating profitably in 1829, according to J.S. Gordon, A Thread across the Ocean, Walker & Co (New York, 2002), page 5.

[14] H.I. Sharlin, The Making of the Electrical Age, Abelard-Schuman (London, 1963), page 22.

[15] Morse first testified to the U.S. Congress' Commerce Committee in 1838.

[16] The construction, in 1839, is attributed to W. O'Shaughnessy, to whom an earlier underwater line, at the Hugli River, is also attributed. For more detail on early projects, and related information, see V.T. Coates and B. Finn, A Retrospective Technology Assessment: Submarine telegraphy-the Transatlantic cable of 1866, San Francisco Press, Inc. (San Francisco, 1979) ISBN 0-911302-39-5.

[17] V.T. Coates and B. Finn, A Retrospective Technology Assessment: Submarine telegraphy-the Transatlantic cable of 1866, San Francisco Press, Inc., (San Francisco, 1979) ISBN 0-911302-39-5.

a single polity across great distance motivated large-scale efforts. For instance, transcontinental rail and telegraph projects to link the Atlantic and Pacific were vigorously pursued in both the U.S. and Canada.[18,19,20] And development of submarine cable enabled the feasibility and then led to the desire for rapid communication between London and the rest of the British Empire, a point to which we return below.[21]

The first speculation -- that rail enables speedy, massive, long-distance transport and thus increases the demand for fast communication over the same distance -- bears upon Europe, too. The mid-nineteenth century may have been the first time one could travel from Constantinople to Scotland as quickly as had been possible under the reign of Marcus Aurelius. The speed of steam locomotives compensated for the lack of political unity and stability. And, much more freight could be moved by steam than by horse.

The second speculation -- the desire for a single polity over great distances driving the wish for fast communication -- might be tested by studying the Russian expansion to the east, the English domination of the Indian subcontinent[22], and various nineteenth-century European visions of East Africa, including a "Cape to Cairo" railroad.

While these two needs may explain the initial willingness to construct and use telegraphy, once it was demonstrated, other needs increased its use and necessitated the concomitant training of telegraphers (the name "electrical engineer" was not adopted until the 1870s). Among other stimulants was the realization that telegraphy could alert police to crime[23] and firemen to fires,[24] and that telegraphy could improve the effectiveness of armies, all long-standing wants or needs.[25]

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[18] What is now Canada became a single political entity in 1867.

[19] The author suspects, though he does not know, that telegraphs were built from Russia to Siberia for the same reason—to enable both commercial and governmental communication—in support of transcontinental expansion. *A fortiori*, he surmises that the Trans-Siberian Railroad was built to enable both commercial and military transport.

[20] In this connection, the "wire services", the Associated Press (1848) and Reuters (1850) were formed to enable newspapers to share the cost of telegraph services.

[21] In addition to financial capital and property rights, the British and US governments employed their navies to assist deployment of submarine cable.

[22] In 1863-64, a British group connected India with the Persian Gulf and thence back to London.

[23] In 1844, the English public's attention was arrested by news that a murderer, who had fled by train from Slough, was apprehended by the London police with help of a telegram that preceded his arrival.

[24] A telegraph system, using overhead lines, for Boston's firemen was installed in 1851. Other cities adopted such systems in the following years.

[25] The Crimean War (1853-1856) was the first in which officials in capital cities could communicate with the commander of the expedition. The American Civil War, 1861-1865, was the first in which soldiers could instantaneously communicate with each other over thousands of kilometers. Sharlin, citing Dupuy & Dupuy Military Heritage of America, McGraw-Hill (New York, 1956) writes that U.S. Grant said "the

At the same time, technical attention turned to constructing telegraphs that could simultaneously receive and transmit, so-called duplex and multiplex telegraphy. Here the driver was narrowly economic; more bandwidth was wanted from the same investment. Reliable systems were deployed by the mid-1870s.[26] These depended on the invention of the condenser (capacitor). Soon thereafter, telephony was shown to be practical. That technical advance involved the transmitter and receiver. However, telephony did stress engineers' ability to effectively use wires, a topic to which we will return when the work of O. Heaviside and M. Pupin is recalled.

III.5 Underwater Wire, or "Cable": Insulation, Adoption and the Partial Understanding of Signal Propagation

This report's concern with electrical transmission and distribution leads us to a different technical issue. As was mentioned, Morse failed in his attempt to lay useful underground wires. This was not simply a matter of novelty, to be overcome by practice. Nor was this failure inconsequential, because overhead lines could not span lakes or even some rivers. Part of the difficulty was insulation.

Soon after a Singapore surgeon recommended gutta-percha (made from the sap of certain Malayan trees) for splints, Wilhelm Siemens of London sent some gutta-percha to Werner Siemens[27] who recognized it to be an excellent electrical insulator that could function underwater. Indeed, in 1847, he developed a machine that extruded gutta-percha insulation over copper wire.[28] T. Willoughby's Gutta-Percha Company became the leading English supplier.

In 1848, a submarine cable was successfully installed under the Hudson River, where it connected New York and Jersey City. The next year, a cable was installed under Kiel Harbor. In 1851, an insulated cable armored by iron wires was successfully installed under the English Channel, connecting Calais and Dover. Three years later, Italy, Sardinia and Corsica were connected. In 1854, Britain and France cooperated by laying a

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telegraph connected each division, each corps, each army, and …my headquarters." Others appreciated the possibility. For example, Ernst Werner von Siemens began his career as telegrapher for the Prussian army.

[26] For a review of telegraphy until 1880, including social-economic considerations, see Y. Nakagawa, "The Development of Early Practical Electromagnetic Telegraphs and the Mechanization of Skilled Operation" Historia Scientarium (1984) vol. 27, pages 77-89.

[27] Ernst Werner von Siemens had three brothers. Each was a leader in either the electric or iron and steel industries.

[28] T. Coates and B. Finn, A Retrospective Technology Assessment: Submarine Telegraphy-the Transatlantic cable of 1866, San Francisco Press, Inc., (San Francisco, 1979) ISBN 0-911302-39-5. p.35

telegraph cable (570 km, 356 miles) under the Black Sea connecting the Crimean War zone to Bulgaria (Balaklava to Varna) and from there to Paris and London.[29,30]

Seven years earlier, iron-hulled steam ships had begun to carry mail and freight across the Atlantic. The "Atlantic Ferry" had begun, and now a gigantic engineering challenge was seriously contemplated. Was transoceanic telegraphy possible?

C.W. Field and his associates began to raise money for a transatlantic cable.[31] The first installation was unsuccessfully attempted in 1858.[32,33] Subsequent unsuccessful attempts were made until 1866, when the goal was achieved.[34,35] A transatlantic submarine cable

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[29] A little earlier, the Russian government had hired W. Siemens and J.G. Halske to run a telegraph line from St. Petersburg to the Crimea.

[30] At that time, two weeks were required to get a message from London to Canada, two months to India and three months to New Zealand. The Suez Canal was completed later, in 1865.

[31] While it was Field's initiative and associates who began the project, repeated failures and the realization of what it would take prompted Field to solicit "the deep pockets" in England. It was English money that paid for the 1866 cable; American money had been lost beneath the Atlantic. Nor was cash enough. The British Navy and the American Navy, each contributed ships, sailors and oceanographic expertise.

[32] W. Thomson (later made Lord Kelvin of Largs by Queen Victoria because of his work on the transatlantic cable) described the first cable as follows: "In the year 1857 as much iron as would make a cube of 20 feet side was drawn into wire long enough to extend from the earth to the moon, and bind several times around each globe. This wire was made into 126 lengths of 2,500 miles, and spun into 18 strands of 7 wires each. A single strand of 7 copper wires of the same length, weighing in all 110 grains per foot, was three times coated with gutta-percha, to an entire outer thickness of .4 of an inch; and this was "served" outside with 240 tons of tarred yarn, and then laid over with the 18 strands of iron wire in long, contiguous spirals and passed through a bath of melted pitch." as cited on page 141 of T.C. Mendenhall, A Century of Electricity, Houghton, Mifflin and Company (Boston & New York, 1887, 1890)

[33] This cable functioned briefly. "On August 27, the British Government, realizing that the Indian Mutiny was nearly over, had used the cable to countermand orders for two regiments to board ship in Halifax, Nova Scotia and sail for India. By carrying those new orders, the cable saved £50,000 – £60,000, more than one seventh of the total investment that now lay useless beneath the Atlantic. With such potential to save money, there could be no doubt that the desire of the British government to have a functioning Atlantic Cable had only been whetted." according to J.S. Gordon, A Thread Across the Ocean, Walker & Co (New York, 2002) page 141.

[34] Though it might be supposed that the transatlantic cable had no competition, in fact, it did. In the mid-1850s, P. Collins began advocating an overhead line from California to British Columbia to the Yukon to Russian America (Alaska), across the Bering Straights and then down to the Amur Valley where it would connect to Russian overhead lines. An overhead line connecting the Atlantic and Pacific was completed in 1861 but the outbreak of the American Civil War delayed further activity until 1864 when the US Congress (with the support of Pres. A. Lincoln and Sec. W. Seward) adopted legislation to support the California to Amur Valley line. Construction began in 1866 but petered out soon after the transatlantic cable succeeded, according to T. Coates and B. Finn, A Retrospective Technology Assessment: Submarine Telegraphy-the Transatlantic cable of 1866, San Francisco Press, Inc., (San Francisco, 1979) ISBN 0-911302-39-5. p.51-52.

[35] It certainly helped to enlist the interest of I.K. Brunel who designed the Great Eastern, the largest ship in the world, to carry the cable and to provide general engineering judgment, not always accepted, on how to manage the project. Thus did the project benefit from wholly non-electrical engineering.

was put in continuous service.[36] In 1869, the British Indian Submarine Telegraph Co. laid a cable from Suez to Bombay, providing a secure connection between London and India.[37] By 1871, the connection was extended via Singapore to Australia.

The concomitant risk was not the private sector's alone. The UK government guaranteed rates of return, granted monopoly rights and offered other financial support to deploy the technology.[38,39] As already noted, the U.S. federal government had funded Morse's demonstration and was prepared to assist the planned telegraph line from California to Amur Valley in Manchuria. Other lines were also assisted by federal and state governments.

Technical success had not been thought inevitable. Too much energy would be dissipated by the wire's resistance when what we now call the "charging current" passed through it. The capacitance[40] of the cable—the cable is a conductor (metal) separated from another conductor (salt water) by an insulator—would make the cable useless. The receiver would see a signal that was both weakened and much distorted; in particular, an abrupt dot or dash would be received as a gradually rising and falling signal. It was said that the rate of information transmission would have to be much reduced to distinguish one diffuse signal from another. These issues got W. Thomson's attention, and he advanced the understanding of both.[41] Thomson assumed the submarine cable could be

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[36] In the following years, additional cables were laid between Europe and North America. In 1903, the Pacific Coast of Canada (i.e., British Columbia) was connected to Australia by telegraph cable. In the same year, another cable, connecting San Francisco and the Philippines began operation. That cable was extended to China and Japan in 1906. By 1918, 290,000 miles of submarine cable were in use and 46 cable steamers plied the oceans, repairing and maintaining same. The investment was $300,000,000 (1918), according to T.C. Martin and S.L. Coles, The Story of Electricity, M.M. Marcy (New York, 1919) page 40.

[37] The "Indian Mutiny" of 1857-58 stimulated an unsuccessful 1859-60 attempt to communicate with India by laying a cable under the Red Sea. In 1870, the Siemens brothers (Werner and Wilhelm, who had changed his name to William, after moving to England) built an overland line connecting London, Berlin, Odessa, Teheran and Calcutta, according to S.P. Bordeau, Volts to Hertz, Burgess Co (Minneapolis, 1982).

[38] See T. Coates and B. Finn, A Retrospective Technology Assessment: Submarine Telegraphy-the Transatlantic cable of 1866, San Francisco Press, Inc., (San Francisco, 1979) ISBN 0-911302-39-5. p.47-62 and to H.I. Sharlin, The Making of the Electrical Age, Abelard-Schuman (London, 1963) p. 7-32.

[39] While overhead lines for transcontinental telegraphy were important to the governments of both the US and Canada, trans-oceanic cable was vital to the government of the British Empire.

[40] "In early 1854, Faraday showed experimentally that a submarine cable formed of copper wire covered by gutta-percha 'may be assimilated exactly to an immense Leyden battery; the glass of the jars represents the gutta-percha; the internal coating is the surface of the copper wire' while the outer coating corresponds to the sea water." according to E.T. Whittaker, A History of the Theories of the Aether and Electricity, Volume 1 , Thomas Nelson & sons (London, 1910), revised, enlarged and republished by Harper (New York, 1951) page 228.

[41] G.G. Stokes corresponded with Thomson about the feasibility of submarine telegraphy. Thomson is usually remembered correctly as a great scientist. He was also keenly interested in what today would be called electrical engineering.

treated as an RC circuit and presented an analysis of such circuits to clarify the situation.[42] Later, he devised suitably sensitive receivers, the first being a galvanometer with attached mirror.

III.6 Understanding and Using Transmission Line Inductance, as well as Capacitance

Today's electrical engineer would recognize that Thomson did not take into account the cable's inductance. Nor did his description of the cable involve a wave equation. The basis for the modern theory of electricity and magnetism was first published in 1864 by J.C. Maxwell, who subsequently elaborated it in his encyclopedic treatise.[43] Nonetheless, Maxwell's work was not immediately understood.[44] The men who recast Maxwell into the form now taught were H. Hertz and O. Heaviside.[45,46] In particular, it is to Heaviside

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[42] Thomson considered the cable to be many parallel capacitors having plates connected to a common battery and switch. This line of thought led him to the equation $\partial_z^2 V[t,z] = CR\partial_t V[t,z]$ where C and R are the capacitance per unit length and resistance per unit length, respectively. Today, one recognizes the absence of cable's inductance and knows the equation is faulty. Nonetheless, when the input is provided by a battery and controlled by an on-off switch, the output is in error only for short times. After some time, the incorrectly omitted transients die away and a particular solution usefully approximates the solution of the correct equation.

[43] In addition to his great scientific insight, Maxwell had a more subtle understanding of technical progress than many others. His Preface to his Treatise (1873) includes the following passage, "The important applications of electromagnetism to telegraphy have also reacted on pure science by giving a commercial value to accurate electrical measurements, and by affording to electricians the use of apparatus on a scale which greatly transcends that of any ordinary laboratory. The consequences of this demand for electrical knowledge, and of these experimental opportunities for acquiring it, have been already very great, both in stimulating the energies of advanced electricians, and in diffusing among practical men a degree of accurate knowledge which is likely to conduce to the general scientific progress of the whole engineering profession." In fact, while old books devote much attention to boundary value problems involving dielectrics, the only well studied dielectric was gutta-percha.

[44] "Many a man has thrown himself with zeal into the study of Maxwell's work and, even when he has not stumbled upon unusual mathematical difficulties, has nevertheless been compelled to abandon the hope of forming for himself an altogether consistent conception of Maxwell's ideas. I have fared no better." H.Hertz, in the introduction to Electric Waves, Being Researches on the Propagation of Electric Action with Finite Velocity Through Space, originally *Einleitende Übersicht*, *Untersuchungen über die Ausbreitung der elektrischen Kraft* and "There are many lovers of science… to whom Maxwell's theory is nevertheless a book with seven seals." H. Hertz, "On the Relations between Light and Electricity", 20 September 1889, 62nd Conference of German Scientists and Physicians held in Heidleberg, Germany. For English translations see, J.F. Mulligan (editor), Heinrich Rudolph Hertz (1857-1894), Garland Publishing (New York & London, 1994). ISBN 0-8153-1288-1. An extraordinary student recalled, "It was as though scales fell from my eyes when I read Hertz' great paper… Here Maxwell's Equations, purified by Heaviside and Hertz, were made axioms and starting points for the theory." A. Sommerfeld, Electrodynamics, (trans. E.G. Ramberg) Academic Press (New York, 1952), p.2.

[45] Others include G. Fitzgerald, J. Larmor, O. Lodge, H.A. Lorentz and S.H. Poynting.

[46] Heaviside entered the workforce as an operator of submarine telegraph cable near Newcastle upon Tyne, soon quit to study J.C. Maxwell's Treatise, and finished his career as an engineer, physicist and mathematician, a mix that was not congenial to most of his contemporaries who regarded him as "other".

that today's electrical engineer owes the correct mathematical formulation of transmission lines and, with it, the idea of reactive compensation.[47,48,49] Later, in 1892, C.P. Steinmetz initiated what has become the standard practice of using complex numbers when analyzing AC circuits.

[47] Correct analysis of a transmission line, with a lossless insulator, yields $\partial_z^{\,2}V[t,z] = LC\partial_t^{\,2}V[t,z] + CR\partial_t V[t,z]$. Heaviside derived this equation and a more elaborate one, including losses, understood their significance and suggested ways to add inductance to cables in order to reduce distortion, a practice that was first successfully implemented in submarine cables during the 1920s, after work by M. Pupin. Thomson "got by" without the inductance term because he was looking at "almost direct current". Heaviside's treatment is necessary for alternating current, the situation that became central to power engineering. It is even more important to telephony where higher frequencies (e.g., 10^3 Hz) are required to convey the range in the human voice.

[48] O. Heaviside, Electromagnetic Theory, Dover (New York, 1950)

[49] Informative descriptions of work by Heaviside and his colleagues include: J. Buchwald, From Maxwell to Microphysics, Aspects of Electromagnetic Theory in the Last Quarter of the Nineteenth Century, The University of Chicago Press, (Chicago & London, 1985), I. Yavetz, From Obscurity to Enigma, The Work of Oliver Heaviside, 1872-1889, Birkhäuser (Basel, 1995) and O. Lee, Oliver Heaviside, IEE (London, 1950).

III.7 From Telegraph Line to Power Line

As valuable as the solutions to communications problems were, new problems arose when power, not information, was to be transmitted. Batteries were and are an unappealing source of power, but power was wanted for indoor illumination after the incandescent light was found to be preferable to gas, itself much preferable to arc-lighting indoors.

T.A. Edison realized that by combining generation with transmission and distribution, he could make illumination possible for a mass-market.[50,51] Every home and office would be connected to a single power grid. Further more, shaft power need no longer be available only to those near rivers or those with enough land and fuel to run steam engines. In addition, by the end of the nineteenth century, electrochemical industry had developed. Aluminum, magnesium, steel and hydrochloric acid were each valued for its contribution to the economy at large, and electrolytically refined copper was itself wanted because it is a better conductor than iron.

Edison envisioned a single grid that would supply electric power for illumination, electrometallurgy, electrochemistry, and motors[52]. Transmission and distribution cable would enable all this power to be generated far from where it would be consumed.[53] The focus shifted from the energy required to move a telegraph key or a telephone microphone to the energy needed to light cities, drive trains, recover elements from their ores, and manufacture millions of machines.

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[50] In 1879, the California Electric Company built a central station to power arc-lights. They were also installed in Cleveland during the same year. In 1882, Holborn Viaduct, a central generating station, was built in London to serve 3,000 incandescent lights. However, those with a financial interest in gas lighting prevailed upon the British government and so the Electric Lighting Act of 1882 forbade the construction of large generating stations, impeding the British adoption of electric lighting. Similar interests were at work in New York; however, a surprise, electrically illuminated banquet at Menlo Park, N.J., provided the occasion for persuading New York City's politicians to support the new technology, according to T.P. Hughes, "*The Electrification of America: The System Builders*", Technology and Culture 1979 vol. 20, pages 124-161

[51] J. Swann, an English inventor of the incandescent light, offered it to the English aristocracy who could certainly afford it but formed no significant market for it. Swann himself was an ingenious chemist who had already improved photography.

[52] At the end of the nineteenth century, urban transport (trains and trolleys) was the most anticipated application of electric motors. (The conventional technology was horses; their impact on the urban environment, and the sanitation required to mitigate same, had people's attention.) Another issue stimulated the adoption of electric locomotives. The health and safety of persons operating trains pulled through long tunnels by coal-fired, steam locomotives was endangered. After adoption, other advantages (e.g., regenerative braking in mountains, higher utilization factor because refueling and re-watering became unnecessary) became apparent.

[53] Until the 1930s, most electric power generation was from hydroelectric plants.

The wish for more power could be satisfied by providing more current. However, it was well known that conductor resistance would entail losses (i.e., I^2R losses) and that electrical resistance could be reduced by using more conductor. Unfortunately, conductor was and is expensive.[54] W. Thomson had devoted his attention to the optimal amount of conductor for submarine telegraph lines and concluded that the answer should be found by equating the marginal reduction in operating cost from ohmic losses to the increase in interest paid on the marginal capital invested to purchase the conductor.

Although Thomson's observation remains pertinent, today one would add another consideration, the value of reliability. In fact, many utilities connect two transmitting circuits to the same source to enable service despite a fault in one. And distribution systems often serve a large, important load with two "feeder" lines, each connected to a separate generator and each operating at half its capacity, to increase reliability despite the increase in capital costs. This "extra" conductor certainly reduces ohmic losses. Nonetheless, it is not the avoided cost of losses that governs the investment, but rather the desire for reliability.

The cost of copper concerned Edison when he contemplated his intended competition with gas light. He realized that low-resistance lamps drawing high currents would require so much copper that the needed investment would be unprofitable. Thus did Edison begin his "mission-directed research" to find and mass-produce high-resistance lamp filaments.[55] Once he had these in hand, Edison supplied modest currents at high voltage (i.e., 110 V) and then halved the remaining need for copper by using the ground as the return, just as Steinheil had done fifty years earlier.[56]

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[54] Despite its high resistance, iron wire was preferred for overhead telegraph lines for three reasons: (a) iron is stronger than copper, (b) commercial specifications for iron were much more reliable than for copper and (c) there was concern that copper wire, left on poles in broad day light, would be stolen, if not by day then by night. Theft remains appealing to some. Twenty years ago when copper prices rose, a great deal of conductor, initially within the equipment of New York City's subways, vanished.

[55] T.P. Hughes, "*The Electrification of America: The System Builders,*" Technology and Culture 1979, vol. 20, pages 124-161

[56] The goal of reducing conductor also stimulated more or less simultaneous (1882-1885) patent applications by T. Edison (US), J. Hopkinson (UK), and W. Siemens (Germany) for "DC three wire" systems.

III.8 Transmission and Distribution via Alternating Current and Three-Phase Circuits

Another technical approach to reducing investment in conductor was possible. Unlike Edison, E.L. Gaulard and J.D. Gibbs developed an alternating current system.[57] It was first demonstrated in Paris; the inventors sold the patent rights for the U.S. to George Westinghouse.[58] His chief engineer, William Stanley, improved transformers, and in 1886, the firm installed an AC system in Great Barrington, Massachusetts and then Buffalo, New York. In 1891, long distance AC transmission was demonstrated by a 77% efficient, 77-kW, 30-kV, 160-km line from Lauffen to Frankfurt. That line's performance helped persuade the investors planning the Niagara Falls hydroelectric station to generate AC.[59]

For a time, AC and DC systems competed, and then they were combined. AC (133.3 Hz) was used for "long distance" transmission at 1-2 kV. Power was transformed and rectified at a substation with subsequent distribution to lighting circuits. This hybrid did not last. A reliable AC (25 Hz and 60 Hz) motor became available in the 1890s. It was soon realized that incandescent lights flickered at 25 Hz and that the problem vanished at 50 and 60 Hz. For a while, 25 Hz continued to be used for motors in the U.S. and 16.5 Hz in Europe. Motor loads increased but the vibrations concomitant with power, delivered from single-phase 16.5 Hz and 25 Hz systems, were not wanted. The engineering solution was "three-phase power" produced by three-phase generators for three-phase motors, thus three-phase circuits. Many persons contributed, among whom N. Tesla is best remembered both for his technical advances and for finally winning the patent rights.

By 1910, the power sector had settled on the configuration of transmission and distribution that has been gradually improved and extended ever since: three-phase, AC (50 or 60 Hz) generated at 10-20 kV, transmitted at high voltage and distributed at successively lower voltages for use at what is now low voltage (e.g., 120V, 230V, 600V).

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[57] The following suggests the difference between what was "cutting edge" and what was generally appreciated. "In 1882, their [Gibbs and Gaulard] patent claim [for an AC transformer] was refused on the grounds that turning low voltage into high voltage "made something out of nothing", according to E.T. Canby, A History of Electricity, Hawthorne (New York, 1963) page 72.

[58] "The system did not operate satisfactorily. [It] had the primaries of the transformers in series in the line, and as the number of lamps connected to each transformer, the voltage in the line was affected. The difficulty was removed when three Hungarian inventors, K. Zipernowsky, M. Deri, and O. Blathy, devised the parallel connection for transformers." according to H.I. Sharlin, The Making of the Electrical Age, Abelard-Schuman (London, 1963) pages 192-193.

[59] This despite a telegram from W. Thomson, "Trust you avoid the gigantic mistake of adoption of alternating current." Sharlin citing E.D. Adams, Niagara Power: History of the Niagara Falls Power Company, 1886-1918, Niagara Falls, New York: privately printed for the Niagara Falls Power Company, 1927, vol.1 page 76-80.

Overhead lines were used wherever possible to take advantage of the free cooling and free insulation provided by the atmosphere.[60] Underground cable was increasingly desired in cities, where the juxtaposition of overhead lines and tall buildings presented a fire hazard and where the sky had become veiled by wire.[61]

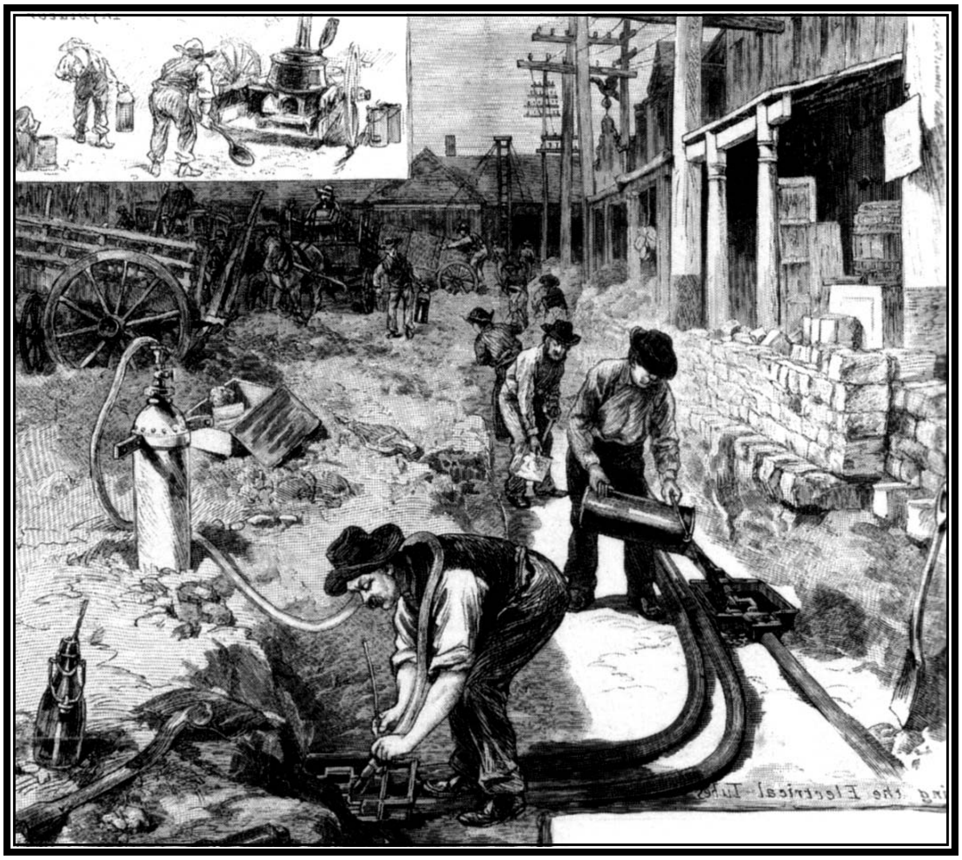

Figure III.8

Edison prided himself on safely burying his cable (DC, 300 V max) under the streets of Manhattan, an arduous task, as illustrated in this print from the contemporary Harpers Weekly.[62] Then as now, the cost of cable in the ground is much more than the cost of cable delivered to the site.

[60] Electric railroads that had originally used DC avoided the losses by adopting AC in the overhead lines (13 kV) and putting rectifiers within electric locomotives, according to E.T. Canby, A History of Electricity, Hawthorne (New York, 1963).

[61] Related aesthetics drove most elevated electric trains underground, though not until the 1950s.

[62] The writer is grateful to R. Schainker, EPRI, for this illustration.

III.9 Diffusion and Adoption of Electrotechnology

The diffusion and adoption of electrical technology was not limited to the western hemisphere. As already noted, Suez and Bombay were connected in 1869. That same year, the first Japanese telegraph line connected the Yokohama lighthouse with its port authority; a public line was also opened and a school for operators was established, all this within a year of the end of the Tokugawa Shogunate and the beginning of the Meiji Restoration. Nor was this telegraph line an isolated curiosity. In 1873, upon leaving the Indian Telegraph Company, W.E. Ayrton arrived in Japan to become the first Professor of Natural Philosophy and Telegraphy at the Imperial School of Engineering, holding that chair until 1878, when he returned to Great Britain. The Imperial School of Engineering was the first to establish an electrical engineering department; its first graduate was sent to Scotland where he worked under W. Thomson before returning home. The Tokyo Electric Power Company started in 1890. In the following year, the *Electrical Friend*, a Japanese journal of electrical engineering, began publication.[63]

Nor was Japan alone in northern Asia. Electric lights were being supplied to Seoul in 1901. And, as already mentioned, by 1906, transpacific cables linked North America with Australia, the Philippines, China, and Japan.

[63] For a history of electrical engineering in Japan, see volume 19 (edited by S. Nojima) of Nihon kagaku gijutsushi taikei, Daiichi Hoki Shuppan Kabushiki Kaisha (Tokyo, 1964-1972). Other sources include K. Imazu, "The Beginning of Electrical Engineers in Japan", Japanese Studies in the History of Science, no. 17, 1978, and Y. Takahashi, "Institutional Formation of Electrical Engineering in Japan" in F. Cardot (editor), 1880-1980, Un Siècle d'Électricité Dans Le Monde, Association pour l'Histoire de l'Électricité en France (Paris, 1987)

III.10 Copper, Iron, Electrical Copper and Aluminum

The preceding sections recall the diverse insights needed for transmission and distribution, the diverse people who conceived them and inspired others to implement them, as well as the visions that stimulated others to invest their time, money, or both in supporting this enterprise. Here, we give attention to the materials that were used.

As was already noted, Henry fabricated electromagnets of useful strength by departing from his contemporaries' practice of varnishing the magnetic core and then wrapping a few turns of bare iron wire about it. Instead, Henry put his wire in its own silk sleeve and then proceeded to wrap many tightly packed turns around the iron core.[64] That practical insight enabled the fabrication of useful electromagnets.

Unfortunately, silk or cotton could not serve, by themselves, when the conductor had to be separated from water, as it must if laid in the ground — thus, the importance of the discovery, mentioned earlier, that gutta-percha is both an electrical insulator and impervious to water, accompanied by the invention of a machine to extrude gutta-percha insulation over copper wire.[65]

However, water is everywhere, even in the air. The iron wire suspended from telegraph poles was subject to rust. Nonetheless, after 1846, iron was the preferred conductor for three reasons: (a) strength, (b) cost, and (c) the erratic quality of commercially available copper.

The last reason may seem odd. Copper has been an article of commerce for at least 10,000 years, since it supplanted stone in certain applications. Indeed, copper working/metallurgy began in Egypt at least 6,000 years ago. Later (the "bronze age"), alloys of copper and tin were found preferable. After iron was found to be easier to work with, brass (copper and zinc) was still widely used for decoration—in fact, brass was used in Europe until the beginning of the modern era (until the price of gold fell in Europe, a result of the Spanish importing of gold from the South American mines it had seized). Even then, the use of copper alloys declined without disappearing. Copper wire lingered; it was still used in inexpensive jewelry and as "bell-wire," where its ductility and corrosion resistance were relevant.[66,67]

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[64] Henry's "iron in silk" process was earlier employed by milliners.

[65] B.J. Hunt, "Insulation for an Empire: Gutta-Percha and the Development of Electrical Measurement in Victorian Britain" appearing in F.A.J.L. James (editor), From Semaphores to Short Waves: Proceedings of a Conference on the Technology and Impact of Early Telecommunications, Royal Society for the Encouragement of the Arts, Manufactures and Commerce (London, 1996).

[66] Within the same house, persons signaled each other by pulling one of several copper wires. Each ran over various pulleys until terminating on the clapper of a particular bell.

When electrical telegraphy began, water from copper mines had recently found application as a bath in which to cure wood intended for ship's hulls. Wood, so cured, was inhospitable to barnacles and other marine life that would otherwise accumulate, slowing the ship. For the same reason, hulls were often covered with copper sheets.

Indeed, it is on ships that copper electrical conductor was first put to use. In 1777, T. Cavallo wrote, "In order to guard edifices or ships from being damaged from lightning…it was judiciously proposed by Dr. Franklin to raise a metallic conductor. Copper would do much better than iron; it being a more perfect conductor." However, adoption and improvement were neither uniform nor swift. In his 1842 *Lectures on Electricity*, W. Sturgeon wrote, "Marine lightning conductors are simply chains of copper, formed of links similar to those of the surveying chain. But the lightning has frequently struck ships before the chains could be got up; fixed conductors have been proposed and some are on trial with the [British] Navy."[68]

One might suppose that it was no great step from lightning rod to telegraph line. Indeed, early telegraph lines were made from copper. However, copper was soon abandoned. This may surprise the technical reader, particularly because G.S. Ohm had published his work in 1826.[69] In retrospect, we realize that no one knew that copper's electrical resistance is sensitive to small amounts of impurities. That lack of appreciation is easy to understand; no one could measure those small impurities. All that was known was that the electrical resistance of "copper" was variable, too variable, and that its mechanical properties were much inferior to iron's. Thus, the last overhead copper telegraph line was dismantled in 1846.

Poor mechanical properties did not disqualify copper from use in submarine cable. However, the variability in copper's electrical performance got the attention of those trying to make submarine cables. W. Smith, the owner of the Gutta-Percha Co., which insulated the copper that was delivered to him for an 1850 submarine cable, later wrote, "To its electrical condition and quality no attention was given, for the simple reason that

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[67] By the 1780s, some had discovered that copper could be plated with silver and silver plate was much demanded by families that could not afford pure silver. Indeed, some workers found that the electrical conducting power of silver and silver plated copper is very good. Nonetheless, "copper in silver" was not adopted as electrical conductor because of its cost.

[68] A unique presentation of the history of copper wire is that by B.C. Blake-Coleman, Copper Wire and Electrical Conductors-The Shaping of a Technology, Harwood Academic Publishers (Chur, Switzerland, 1992)

[69] Ohm's work was derided by some contemporaries and ignored by most. Significant, favorable recognition began in 1849, five years before Ohm died.

all copper wire was credited with the possession of equal value in these respects".[70] Thomson took an interest in this, too, and found that different wire suppliers, working from the same specs, supplied wire that differed in resistance by a factor of two.[71] In 1858, Thomson retained a chemist, A.W. Hoffman, to investigate the matter. Hoffman did conclude that chemical impurities caused the variability, but no one could identify or measure them. "The problems were great and the incentives few. The orders for copper wire in its role as a conductor could be lucrative, but made only sporadic appearances in the shape of orders for submarine cables, and there was little call elsewhere."[72] Besides these difficulties, another was in play: there was no common standard for electrical resistance until the late 1860s.[73]

The technical advance that made copper a practical electric conductor came in the 1870s, and it came from electro-technology itself. Electrical copper was refined to suitable purity and consistency by electrolysis.[74] Though it became available, copper remained expensive enough to move Edison to search for high-resistance filaments (and thus, low-current systems), as described earlier.

The demand for copper grew for other reasons: (a) realization that iron wire's self-inductance was greater than copper's and that this difference was not always helpful, (b) the use of copper coils in generators and motors, and (c) the adoption of telephony and its need for good electrical conductor. Both copper wire drawing and copper refining via electrolysis improved and grew. Complaints about the unpredictable quality of commercial copper wire died out in the 1890s. Leading manufacturers were located in England. On the continent, the leading firms included Eisen Industrie zu Munden und

[70] W. Smith, Rise and Extension of Submarine Telegraphy, J.S.Virtue & Co., 1991, pages 1-2 cited in B.C. Blake-Coleman, Copper Wire and Electrical Conductors-The Shaping of a Technology, Harwood Academic Publishers (Chur, Switzerland, 1992) p.156. See the same source for a detailed history of copper.

[71] "In measuring the resistances of wires manufactured for submarine telegraphs, I was surprised to find differences between specimens so great as must materially effect their value in electrical operations for which they are designed." W. Thomson, "On the Electrical Conductivity of Commercial Copper", Proceedings of the Royal Society, vol. VIII (1858) page 550-555 as cited in B.C. Blake-Coleman, Copper Wire and Electrical Conductors-The Shaping of a Technology, Harwood Academic Publishers (Chur, Switzerland, 1992) p.159.

[72] B.C. Blake-Coleman, Copper Wire and Electrical Conductors-The Shaping of a Technology, Harwood Academic Publishers (Chur, Switzerland, 1992) p.167.

[73] B.J. Hunt, "The Ohm is Where the Art Is: British Telegraph Engineers and the Development of Electrical Standards", Osiris, vol.9 (1994) pages 48-63.

[74] A copper cathode is put in an acid bath through which current flows. The previously dissolved copper deposits on the anode where the result is more than 99.9% pure.

Schwerte, Felton and Guilleaume, and Westfalische Union. Two U.S. wire makers, Washburn and Moen and John Roebling's Sons Co., were also technical leaders.[75]

When enough people were operating electrical systems that were not telegraphic, what we now call electrical engineering adopted that name.

At the same time (1886), C. Hall and P. Héroult each developed an electrolytic way to reduce alumina to aluminum.[76] A new generation of electrical conductors became available, and a new use for electric power was created. By the end of the First World War, aluminum had become a commodity metal — just in time for the great surge in electrification around the world. Today's overhead transmission lines are aluminum conductor wound around a steel cable, abbreviated ACRS. Steel bears the tension required to balance the line's weight, as well as the weight of ice and the force of the wind, while aluminum conducts the current.[77]

Electro-technology provided a motive and the means for both copper and aluminum production.

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[75] The business began, in the 1840s, by making hemp rope and then some of the first wire rope and then a variety of wire products. Thus did J.A. Roebling contemplate suspension bridges and then promote, design and begin to build the Brooklyn Bridge, a project that was completed by his sons.

[76] Al_2O_3 is dissolved in cryolite and then deposited on the anode when current flows through the solution.

[77] "Compound wire"—copper electroplated on iron wire—become available in the mid-1880s but its cost deterred widespread adoption. When comparing copper and aluminum, one finds that for equal resistance, aluminum weighs less and so the cost per mile for poles or towers supporting aluminum conductor is less than for copper.

III.11 Underground Power Cable after the 1880s

Although gutta-percha enabled the waterproof electrical insulation of telegraph lines, gutta-percha could not handle "high" temperatures. This was something to be considered when designing a telegraph cable, but it was hardly a "show-stopper."

When large currents were desired through inexpensive conductor, the problem became important. The cost of conductor can be reduced by using less of it, (that is by using a smaller-diameter wire). Unhappily, as the diameter decreases, the electrical resistance increases, more electrical energy is dissipated and the wire's temperature rises. Temperature must be considered when designing overhead lines; the metal conductor sags. This is a mechanical issue, not an electrical problem; air remains a good electrical insulator.

However, this is not the case when gutta-percha or its modern successors are used as the insulators. They are damaged by high temperatures. This damage is cumulative, and the net result is shortened lifetime for the cable. Since underground and underwater cable is much more awkward to repair or replace than overhead lines, great importance attaches to long life, in particular to avoiding overheating. Thus, the desire for underground power transmission and distribution stimulated the wish for insulators that could take the heat.

In the 1880s, underground cable for lighting was installed in New York, by Edison, and in London, by S.Z. de Ferranti. "The cables were rigid, consisting of copper rods insulated with a jute wrapping. Reliability was reasonable and most problems arose from the large number of joints or splices necessary in a rigid system in which the conductor could not be coiled on a reel.

In a subsequent scheme, Ferranti decided on a new form of insulation — paper impregnated with Ozokerite wax (a by-product from the manufacture of candles). In this cable the modern paper-taped version was born. The Ferranti 10-kV cable consisted of two concentric tubes (conductors) insulated from each other by the impregnated paper. The conductors were brazed copper tubes, of 20.7 mm and 49.5 mm in diameter. To satisfy the communication authorities, Ferranti was forced to cover the outer tube (sheath) with further layers of paper and the cable was then installed in an iron pipe.[78]

[78] Substantial anxiety about safety was raised by the unprecedented voltage, 10 kV, that Ferranti planned to use. To remove the basis for this concern, Ferranti included an outer conductor that was grounded. To prove his system's safety, "…one of Ferranti's assistants held a cold chisel, another drove it through the live 10,000 volt cable. The chisel short-circuited the main, and the fuse cut the supply." according to T.P. Hughes, Networks of Power, Electrification in Western Society, 1880-1930, Johns Hopkins Press (Baltimore and London, 1983) p.244.

The route length was 7.5 miles, and four cables were laid, involving over 7000 joints. Over the service life of 42 years, relatively few joint failures occurred and the cable was only superseded because of a need for higher current in the circuit.

Ferranti's rigid conductor was supplanted by flexible stranded conductor cable, and by 1898 the insulation maximum stress was 2.1 kV/mm (single-phase cable). Many insulation materials were investigated and used, including paper, cotton, gutta-percha, vulcanized bitumen, and rubber. 11-kV rubber vulcanized cables were installed in Buffalo (N.Y.) in 1897, and 25 kV cables in St. Paul and Minneapolis in 1900. Paper impregnated with oil using vacuum drying and hot-oil impregnation was available for 10-kV single-phase circuits in 1895.

In the early days in the U.S., cables were often laid in ducts because of legislation that allowed only one authority to open up trenches in a city. Electrical utilities hired a passage through the duct ways provided. In this environment, single-core rubber insulated cables were used because of their greater flexibility compared with the paper—oil type, and this influence remains today in the great usage of single-core elastomeric insulation in the USA compared with paper—oil cables in Britain, which are direct-buried in trenches.

At these lower voltages, oil-impregnated (mass impregnated) paper-insulated cables (solid type) were used, often with the three conductors contained in a single sheath. The three conductors were stranded and insulated separately and then laid up spirally together. The space between and around the insulated conductors was packed with paper or jute to form a circular surface which was then further wrapped with insulation. This is called the 'belted' type of cable; it may have steel-wire armoring over the sheath because only small induced eddy currents are produced in the armoring wires, whereas with single-conductor cables severe loss and increased impedance would result. With the three-core cable, high electric stresses are set up tangentially to the paper insulation surfaces, in which direction the insulation strength is weakest. To overcome this, each core is wrapped with a conducting layer of metallized paper which converts the cable electrically into three single-core cables with the electric stress completely in the radial direction. This form of construction was originated by M. Hochstadter and is known as the 'H' type. As system voltages increased above 33 kV, the solid-type paper-oil cable became prone to break down because of the voids (small pockets of air or gas) formed in the insulation when constituent parts of the cable expanded and contracted to different extents with the heat evolved on load cycles. The stress across these voids is high and local discharges occur,

III.12 Cooling Underground Cable with Oil

As always, there is a tension between the designers' wish to save money by using less conductor and the need to prevent the electrical insulation from being damaged by too high temperatures. Two strategies present themselves. Each, and both, has been pursued. First, the wanted power can be guided with higher voltage differences between the conductors and less current within them. Second, the heat can be transferred from the conductor to a fluid that carries away that heat.

In 1926, L. Emanueli, working in Italy, implemented both. He introduced the self-contained Low-Pressure Oil-Filled (LPOF) cable, which is still used. The central conductor is a tube having a hollow core which is filled with insulating oil (e.g., dodecyl benzene), maintained under modest pressure by reservoirs feeding the cable along the route. The oil infiltrates the dielectric where it reduces the likelihood of voids and assists in conducting heat. As the conductor warms so does the oil, which is driven from cable into the reservoirs, and vice versa. The self-contained LPOF cable is completely finished and sealed at the factory and is transported containing oil under a pressure of about one atmosphere.

"In Europe the low-pressure oil-filled (LPOF) system is widely used mainly in the form of three separate, self-contained cables. Occasionally, at 132 kV and below, three insulated cores in one sheath are used. These cables are buried in trenches, which are refilled around the cables with special [good thermal conductivity, even when dry] backfill and the trench refilled with local soil. The maximum voltage at which LPOF cables are in use is 500 kV. In high-capacity installations water cooling is incorporated to increase the current rating."[79] Figure III.12.1 shows a three-quarter view of a cross-section of one phase of a 345 kV self contained fluid filled cable. Note the central channel in which the oil resides. This cable shown is intended for submarine use and so its exterior is well armored.

[79] B.M. Weedy, Underground Transmission of Electric Power, John Wiley & Sons (Chichester, 1980) p. 7.

Figure III.12.1
One Phase of a 345 kV, Self-Contained Fluid (Oil) Filled Cable
The cooling fluid (oil) resides in the central channel within the copper conductor.

According to B.M. Weedy, “In the USA the paper/oil insulated cores are installed in a rigid pipe containing the insulating oil, and the conductor oil-duct is not required. The difficulties in the USA of keeping a trench open for a time sufficient for the direct burial of the self-contained (LPOF) cable have led to the use of the pipe-type oil-filled cable, in which the three paper-tape insulated cores are pulled into a previously buried pipe via manholes at intervals along the route. After core installation the pipe is filled with insulating oil which is maintained under a pressure of 1.38 MN/m (200 psi). This is known as the High-Pressure Oil-Filled pipe-type cable (HPOF) and is widely used in the USA and elsewhere. Figure III.12.2 shows a cross-section of one such cable.

Figure III.12.2
345 kV, 760 MW Cable of the High Pressure Fluid (Oil) Filled Pipe Design

The pipe is generally provided in 20 m (60 feet) lengths which are welded together on site using backing rings. During installation, extreme care is taken to prevent moisture entering the pipe, and at the end of a day's operations the pipe is sealed and filled with a dry gas. The reels containing the insulated conductors are hermetically sealed when shipped from the factory. The installation of the pipe-type cable must take place on a dry day and the splicing operations call for precision and cleanliness. Strict temperature and humidity limits are observed. … In the USA the pipe-type cable has virtually superseded the self-contained oil-filled type. The first 345 kV pipe-type cable was installed in New York City in 1964, being 24 km in length. An advantage of the HPOF cable is the longer lengths of insulated cores that can be placed on a reel (e.g., at 138 kV typically 800 to 1000 m, and at 345 kV, 600 m)."[80]

The designer of such cables must consider the heat transfer from the dielectric, through the oil to the pipe wall. Their temperature differences drive natural convection. To enable more current to alternate in the same conductor, forced convection may be employed.[81]

III.13 The Distinction Between Transmission and Distribution

As ever bigger central station generators were installed throughout the world, the distinction between transmission and distribution became important. It is the same distinction one makes between highways and streets: the former facilitates high-volume traffic between population centers, and the latter enables arrival at the destination and departure from the origin. A connected system of highways corresponds to the transmission grid, while the progressively smaller roads and streets that connect highway entrances and exits with origins and destinations correspond to the distribution system. This analogy is not metaphorical; indeed it can be made quantitative. One asks how many lines must be severed to isolate a given point in the grid from all the generators. If the answer is one then that point is served by the distribution system. If the answer is many, the point is served by the transmission system. Obviously, the intermediate cases can be quantified. Large end-users often served by two "feeder" cables to increase the reliability of their supply.

Transmission systems are usually made from high-voltage, overhead lines (except when the route traverses water), while distribution systems use progressively lower voltages, often underground in densely populated areas. Though exact numbers vary with region,

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[80] B.M. Weedy, Underground Transmission of Electric Power, John Wiley & Sons (Chichester, 1980) p. .

[81] D.P. Johnsen and J.M. Gburek, "*Dialysis on a Grand Scale*", Transmission & Distribution World (April 2003).

today roughly half the power sector's capital is invested in generation and half in transmission and distribution.[82]

III.14 Extruded Dielectric Cables

As already stated, electrical insulation was made from paper, saturated with insulating oil. The oil was meant to fill whatever pores might be in the paper and thus reduce the number of local inhomogeneities, each of which might be the site of unusually large electric fields and thus ionization. Low average electric fields (i.e., low voltages) raise less concern.

The wish to eliminate the fluid and the desire for low losses in the dielectric stimulated adoption, in the 1950s, of polyethylene, first fabricated in the '30s, as the dielectric for distribution cables. Successful effort, particularly in France and Japan, to extend the use of polyethylene and other synthetic polymers to higher voltages has been underway since. Recently, extruded cross-linked polyethylene (XLPE) cables have been designed for operation at 500 kV.[83]

Beside eliminating the oil, sometimes messy, the solid dielectrics offer greater breakdown strength. Expressed in other words, solid dielectric can be thinner than paper-oil.[84]

III.15 Today's Practice

This sketch of cable's history can be brought up to date by recalling a few other innovations made available since World War II.

The choice between overhead and underground installation has been widened to include the possibility of "a bit above or a bit under the ground." These cables are Compressed Gas Insulated Line (CGIL), have been deployed where utilities already own right-of-way or, most commonly, in utility switchyards/substations where there is no concern about a vehicle colliding with a cable.

The cost of underground distribution, within residential neighborhoods (e.g., 13 kV), has declined to where it might be only 50% more than overhead distribution.

[82] For a history of this development, see T.P. Hughes, Networks of Power, Electrification in Western Society, 1880-1930, Johns Hopkins Press (Baltimore and London, 1983).

[83] E. Peschke, R. Schroth, and R. Olshausen, "Extension of XLPE cables to 500 kV based on progress in technology," JICABLE, Versailles, France, 1995 pages 6-10.

[84] D.G. Fink and H. Wayne Beaty, Standard Handbook for Electrical Engineers, 14th edition, McGraw-Hill (London, Milan and elsewhere, 2000) ISBN#0-07-020975-8 pages 14-114.

Finally, the use of submarine (power) cable has increased. Long cables are usually DC, for a reason that was first discussed when the transatlantic telegraph cable was considered. The capacitance of submarine and underground cable is so high that the no-load, alternating current required to charge the capacitor, which is the cable, can take up a significant fraction of the cable's rated current, leaving too little room to convey power without overheating. Thus, submarine AC cable requires so much conductor that the cost of an AC-DC converter at either end of a DC cable looks more appealing.

DC power is also considered in long, high-voltage overhead lines because voltage differences have grown to the point where air is no longer such a good insulator; corona losses matter. Thus, overhead, high-voltage DC lines are being employed in some circumstances (for example, the line from Siberia to Russia, the Pacific intertie, and others). The potential relevance for HTS comes from the possibility that future effort might reduce the cost of AC-DC converters to a point where a well-situated DC superconducting cable could compete with a longer AC conventional cable. Of course, the DC HTS cable would also have to compete with a DC conventional cable.

The transmission and distribution (T&D) system has many other components besides cable. Any proposed change in cable technology will be judged by the change's compatibility with the rest of the T&D network. Thus we mention three innovations made during the past 50 years. The first was linear algebraic formulation of network behavior[85] and the second was digital computation. Together, they enable today's power engineers to simulate and anticipate power flows throughout the network.[86] Before cable with unusual electrical characteristics (e.g., very low impedance) is adopted, utilities should be expected to ask for results of simulations of the new cable's effect on their system. The other innovation is the use of solid-state electronics to switch impedances in and out of the grid at a rapid rate. Such technology is known as Flexible AC Transmission (FACTS) because it enables the user to steer power flows.[87] FACTS requires large investment but the technology has been deployed in some places and its

[85] For example, G. Kron, "*Analyze tensorielle appliquee a l'Art de l'Ingenieu*"r.Bulletin de l'Association des Ingenieurs Electriciens sortis de l'lnstitut Electrotechnique Montefiore, no. 9 (September 1936), no. 10 (October 1936), no. 1 (January 1937), no. 2 (February 1937), 56 pp. and Kron, Gabriel, Tensor Analysis of Networks, John Wiley & Sons (New York, 1939). S. Austen Stigant, Matrix and Tensor Analysis in Electrical Network Theory, MacDonald (London, 1964) p.130.

[86] However, this is not done in "real time". Addressing North Americans, two commentators wrote, "Computers, sensors and computational ability have transformed every major industry in the Western World except the electric power industry." C.W. Gellings and K.E. Yeager, *Transforming the Electric Infrastructure*, Physics Today, AIP, December, 2004 pages 45-51.

[87] See IEEE http://ieeexplore.ieee.org/xpl/RecentCon.jsp?puNumber=6136 and N.G. Hingorani, L. Gyugyi, Understanding FACTS : Concepts and Technology of Flexible AC Transmission Systems, Wiley-IEEE Press (December, 1999) ISBN: 0-7803-3455-8. Both ABB and Siemens offer equipment for FACTS.

increasing use is expected by the power sector. It is likely that some will ask if investment in FACTS enhances the benefits of investing in new cable (e.g., HTS cable) or not. The answer is likely to depend on the specific system under consideration and potential investors are likely to want to consider results of system simulations.

III.16 Two Proposed Innovations that Were Not Adopted

After post-war reconstruction, prosperity was achieved in western Europe, Japan and North America. In the late 1960s, many in the power sector anticipated continued growth at the preceding post-war rates. Nuclear-powered generators were built for profit and it was expected that they would provide less expensive energy, as their power ratings grew. By the mid-1970s, concern about the environment was part of public policy. One such concern was the availability of cooling water. Large "nuclear energy parks" located on the shores of very large lakes or the sea were discussed by some. Since large cities are often similarly situated, interest grew in technology for high-power transmission that would not require much right-of-way.

Some advocated transmission guided by liquid sodium conductor.[88] This was not widely adopted, perhaps because it was novel and perhaps because liquid sodium burns when exposed to air.[89]

Others considered superconducting cables incorporating niobium, "niobium three tin" (Nb_3Sn), or niobium titanium alloy, NbTi, and cooled by liquid helium.[90] Feasibility studies were done and several cable demonstration projects were begun[91,92,93], most

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[88] P. Graneau, Underground Power Transmission: The Science, Technology and Economics of High Voltage Cables, John Wiley & Sons, (New York, 1979) # ASIN: 0471057576

[89] The sodium fills a polyethylene tube that serves as its dielectric. Some 50 circuits were installed in the US at voltages up to 34.5kV before manufacture stopped, according to B.M. Weedy, Underground Transmission of Electric Power, John Wiley & Sons (Chichester, 1980) p. 142.

[90] Immediately after he discovered superconductivity in 1911, K. Onnes suggested that very strong electromagnets could be made from superconductors. However, it was not until 1961 that Nb_3Sn, the first potentially useful material, was identified (J.E. Kunzler, E. Beuhler, F.S.L. Hsu, and J.H. Wernick, Superconductivity in Nb_3Sn at High Current Density in a Magnetic Field of 88 kgauss, *Phys. Rev. Letters* 1 Feb.1961, pages 89-91). Almost immediately thereafter, an alloy of niobium, NbTi, was found to also have promising electrical and magnetic properties and to be ductile. The latter property made NbTi easy to form into practical conductor. The process was made commercial during the next ten years, and the result satisfied the demand from doctors for magnets to be used in Magnetic Resonance Imaging (MRI) machines, from physicists for magnets in accelerators and detectors, and from chemists for magnets in their nuclear magnetic resonance (NMR) instruments. These markets supported several businesses that became expert in conductor fabrication.

[91] G. Bogner, "Large Scale Applications of Superconductivity," appearing in S. Foner and B.B. Schwartz, Superconductor Applications: Squids and Machines, Plenum Press (New York & London, 1977), ISBN 0-306-35721-6.

notably one (using Nb film) in Austria[94,95] and one in the U.S. at Brookhaven National Laboratory.[96]

In due course, these LTS cable projects were abandoned[97], for reasons whose relative importance varied with location: (a) after 1973, electricity consumption grew at a lower rate than before, (b) nuclear plants proved to be less profitable than had been anticipated, and (c) Nb_3Sn and NbTi cables appeared to offer an economic advantage over conventional cable only when many gigawatts had to be sent through one cable (because of the cost of liquid helium cooling). The first two items reduced the urgency for ultra high power transmission through existing right-of-way. The third item boxed LTS cable into meeting a need that was no longer urgent. Finally, a fourth consideration became apparent to those who were involved: "Do we want all the eggs in one basket?" The answer was no. Utilities did not think it prudent to put a high fraction of a load center's power through one corridor; they and their customers prize reliability.

The cost of cooling high temperature superconductors is much less than the cost of cooling Nb_3Sn or NbTi. That reduction raises the possibility that HTS can be used in cable that breaks even with conventional cable (which incorporates aluminum or copper) at modest power levels. This greatly increases the size of the potential market for HTS cable and so unlike LTS, HTS need not be restricted to those situations in which "all the eggs are in one basket".

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[92] G. Bogner, "Reviews of Large Superconducting Machines," appearing in S. Foner and B.B. Schwartz, Superconductor Materials Science: Metallurgy, Fabrication and Applications, Plenum Press (New York & London, 1981), ISBN 0-306-40750-7.

[93] E.B. Forsyth, *The High-Voltage Design of Superconducting Power Transmission Systems*, IEEE Insulation Magazine, volume 6, number 4, (July/August 1990) pages 6-16.

[94] P. Klaudy, "In Arnstein war das erste supraleitende Kabel der Welte erfolgreich in Betrieb," Energie, vol.32, 1980, pages 138-145.

[95] P. Klaudy and F. Gerhold, "Practical Conclusions from Field Trials of a Superconducting Cable," IEEE Trans. Magnetics, Vol. Mag-19, 1983, pages 656-661.

[96] E.B. Forsyth and R.A. Thomas, "Performance Summary of the Brookhaven Superconducting Power Transmission Systems," Cryogenics, Vol. 26, 1986, pages 599-614.

[97] Abandoned, but not inconsequential - the Austrian cable project stimulated activity that initiated the group, now within Nexans-Hannover, that offers the only commercial, flexible cryostat. These cryostats define the state-of-the-art for cryostats used in today's demonstrations of HTS cable.

III.17 The Past as Prologue

III.17.1 Past Goals

Each reader may see the history of cable as evidence for his or her own speculations. The author thinks several aspects are pertinent to the topic of this report.

First, consider the goals that motivated cable development. They included:

a) the private citizen's wish for instantaneous, always available, long distance communication;
b) the politico-military and commercial wish for trans-oceanic communication;
c) the desire for illumination better than gaslight;
d) the desire for transportation without the environmental, safety, and health effects associated with either horsepower or coal combustion;
e) the wish to separate the use of shaft-power from the place where it is generated; and
f) the wish to provide clean power to persons within densely populated cities.

III.17.2 Past Institutions

Past goals moved exceptionally persistent and talented people to develop the technology and induced both business and government, particularly the military, to make resources available for the effort. That effort was not organized into small businesses. Institutionalized, mission-directed research was successfully conducted.[98] The intellectual focus was not disciplinary. Mission-directed research, development, and demonstration focused light from any source on the task at hand.[99]

III.17.3 Past Technical Achievements

We recall the technical achievements yielded by past effort and resources. They include the items summarized below.

III.17.3.1 Conductor

More than 100 years elapsed between T. Cavallo's suggestion that ships' lightning rods be fashioned from copper and S. Elmore's discovery of how to refine copper to the point

[98] Edison's organization at Menlo Park provides one example. Indeed, Edison's organizational success induced the U.S. government to ask him for advice on forming the U.S. Naval Research Laboratory. (Contrary to Edison's advice, NRL was located in Washington, DC and put under military control.)

[99] This metaphor might be extended by noting that disciplinary research includes both supernovas that illuminate many worlds and other stellar objects that are rarely or never seen.

where it could be commercially made with suitable purity, reliability, and price to become the default conductor. Almost immediately, another useful conductor, aluminum, appeared and was put to use.

III.17.3.2 Electrical Insulator

Underwater and underground cable was enabled by W. Siemens' realization that gutta-percha, first drawn to attention for use in splints, was both electrically insulating and waterproof, and by Siemens' invention of a machine that extruded the insulation on the conductor. During the past fifty years, very-high-voltage cable has been made practical by the unrelated creation of synthetic polymers (e.g., nylon and then polyethylene) and their subsequent, mission-directed development.

III.17.3.3 Heat Transfer

The design of economical cable required a balance between money invested in the conductor (the more conductor, the less dissipation and the lower the temperature) and the lifetime of the electrical insulator (the higher the temperature, the shorter the lifetime). The balance was struck with the help of dielectric oil, whose use was initiated by L. Emanueli in 1926. Indeed, cable that depends on natural convection may be uprated by switching to forced convection, if a return path is available or can be constructed.

III.17.3.4 The Changing Synthesis

The balance between conductor, electrical insulator, and heat transfer was changed by the development of insulators (e.g., cross-linked polyethylene, XLPE) that can function at higher temperatures (i.e., 130°C or 403 K) than past insulators. This opened the possibility of eliminating the cooling fluid and/or using less conductor. However, success was only achieved during the past 20 years, when it was learned how to manufacture insulator without voids and other defects that make the dielectric vulnerable to sudden breakdown (i.e., the sudden, unexpected, and unwanted change from insulator to conductor).

III.17.3.5 Theory as a Reliable Guide to Practice

Though some important pioneers of electro-technology did not think of their efforts in terms of today's rigid division between theory and practice, we may look back and say that the electrical theory that has proved useful to today's power-cable engineer was begun in the 1840s by W. Thomson and reached its completion around 1900, with the work of G. Mie, C.P. Steinmetz and A. Sommerfeld.

Subsequent theoretical and computational advances concerned the network more than its cable component. Engineers learned to anticipate power flows (e.g., by the use of digital computers) and to control load flow with protection schemes and most recently by switching (e.g., the use of semiconductors as fast switches, flexible AC transmission).

III.17.4 Foreseeable Challenges to Superconducting Transmission and Distribution

The future use of ceramic superconductors requires successful synthesis of responses to three technical challenges: conductor, electrical insulator (dielectric), and heat transfer (usually called cryogenics because the operating temperature of today's ceramic superconductors is below 120 K). However, new issues will also arise because ceramic superconductors must be integrated in an already existing network. That network operates at approximately ambient temperature and almost everywhere with alternating current.

As far as practical, superconducting transmission and distribution must be electrically connected but thermally isolated from the rest of the network.

And, insofar as possible, superconducting transmission and distribution must conduct alternating current with very little dissipation to avoid costly refrigeration.

Also, either intentionally or unintentionally, the temperature of superconducting transmission and distribution equipment will rise from operating temperature (roughly 70 K) to ambient temperature (roughly 298 K), after which it must return to operating temperature.[100] The new conductors must be robust enough to be wound into cable and to tolerate electromechanical forces. In short, the cable must be built to accommodate stress, strain and fatigue.

Institutions with the resources and persistence to bring forth new commercially attractive technology are also required.

Finally, new benefits concomitant with new characteristics of superconducting transmission and distribution deserve attention. To date, two benefits have been widely anticipated and discussed—energy conservation and capacity expansion via increased power density. These do not exhaust the potential benefits of the materials. Their non-linear resistance and their ability (or lack of same) to handle brief overloads may each deserve the attention of the power sector. Each bears upon system behavior during and after transient events. The materials also raise the possibility of constructing cables

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[100] M. Ickikawa, M. Kanegami, T. Okamoto, S. Akita, M. Yagi, A. Kimura, *Thermomechanical Characteristics of 500m High-Tc Superconducting Cable*, presented at the Applied Superconductivity Conference, October 3-8, 2004, Jacksonville, Florida

having unusually low impedance. That would affect current and power flow elsewhere in the system. The potential benefits and risks deserve careful, timely attention. In the past, advances in transportation stimulated the development of communications cable and then power cable. Today, advances in communications have proceeded without stimulating changes in power T&D. This may not continue for two reasons:

(a) reliable communications need reliable power which is increasingly wanted from the grid, not an autonomous power source for telephone lines and
(b) right-of-way is valuable in urban areas and so designing communications cable and power cable in ways that allow them to share infra-structure may be economically desirable.

Indeed, research and development to use the grid as an information carrier is now underway. The compatibility of HTS cable with recent effort to use the grid for communicating information merits attention.

IV. THE ELECTRICAL ASPECTS OF POWER CABLE

IV.1 Purpose

Though the electrical grid is ubiquitous, it is not widely understood. Here we introduce several topics: alternatives to the grid, the choice between overhead lines and underground cable, three-phase power, and the designs of HTS cable. Each bears on the use of cable and the design of cable. Power engineers' familiarity with three-phase AC separates them from other persons interested in HTS. Our introduction is intended for R&D managers and scientists. Certain conventions are explained and allusion is made to a few trigonometric relations. Power engineers will find this familiar. Not widely appreciated is the possibility of lower than usual inductance in a cold dielectric HTS cable. That possibility is introduced in Section IV.6.2.4. Once the point is made, calculations of inductance and capacitance are omitted because they are standard and because we touch a related matter in Section XII.1.4. Most of the material is presented in natural, not mathematical language. For those who prefer the latter, citations to the literature are given.

IV.2 Orientation

Just as rails guide trains along their tracks, power lines guide electric power. More precisely, the electrical currents within the lines' conductors guide the power. Just as trains move through the air, the electric power flows through the electrical insulators (e.g. air) between (and around) the conductors.

Just as rails must be held in place by ties and mounted on gravel to protect their support from erosion, electrical conductors require support and protection from the environment.

The analogy is not complete because, unlike trains which can use one rail (but with two flanges), electric power must be guided by at least two conductors that differ in voltage.

IV.3 Overhead Lines

IV.3.1 Their Design and Attractiveness

In most situations, overhead power lines are less expensive than underground cable. Air provides electrical insulation and cooling, without cost. Of course, towers must be built to maintain the spacing between the conductors and support their conductors' weight, the weight of ice, and the force of the wind. The towers must also ensure that the conductors' do not come too close to each other or to the ground, despite the wind and the expansion concomitant with increasing temperature. The result would be sparks or worse; current would flow to unwanted places and power would be misguided, rather than flow to its intended destination.

Of course, the mechanical support to balance gravity and sustain the wind must be paid for. Aluminum is used as conductor to minimize the lines' weight. To increase the distance between towers, the aluminum is wrapped around strong steel wire; it bears the tension needed to balance gravity and wind.[101]

IV.3.2 Overhead Lines, Not Always Feasible and Desirable

However, overhead lines are not always feasible and not always desirable. They have vanished from most cities for three reasons: (a) a fire hazard results when conductors come too close to buildings, (b) the needed "clearance space" could be more profitably used for another purpose (e.g., a building might be placed there), and (c) people don't like them to veil the sky.

The first and second reasons deserve elaboration. Whether in the city or not, the overhead conductors require space between each other and between each and the earth or any structure connected to it. The greater the voltage difference between the lines, the greater the distance required by air to insulate them from each other. The minimum tolerable distance can be seen by looking at the insulating spacers which suspend the conductors from their supporting towers. More space between wires is required to allow for wind blown change in position. More space is also required between the wires and trees or other structures, lest one fall on the line.

[101] It has been suggested that steel be replaced by carbon fiber where utilities want more power through the same overhead corridor. The carbon fiber is lighter and stronger than steel and the carbon fiber sags less at the high temperatures concomitant with high currents and thus high power. "…But the companies that own transmission lines have been slow to adopt the new technology. John K. Chan, the project manager for overhead Transmission cable at EPRI, said there were several reasons. One is that conventional steel-core cable lasts "forever," while no one is certain how long the newer materials will last." New York Times, 4 March 2004. Utilities may also be concerned about the projected lifetime and reliability of HTS cable.

In addition to trees, overhead lines are vulnerable to lightening, animals, and automobiles. In some places, earthquakes, hurricanes, ice, and tornadoes must also be considered.

Finally, towers are not always feasible. When one wants to guide power from one side of a body of water to the other, one often finds it impractical to construct towers anchored underwater. Even when it is practical, it is not always desirable. The towers may interfere with shipping.

IV.4 The Conventional Alternatives to Overhead Electric Power Lines (Railroad, Gas Pipelines, and Electrical Cable)

Alternatives to overhead lines are considered in two different situations: (a) electric power is wanted far from the mine or well-head and (b) electric power is wanted in congested areas or areas having particular hazards.

In the first situation, overhead power lines compete with natural gas pipelines and coal carrying railroads or ships. (Some envision hydrogen pipelines which would be part of a future "hydrogen economy". The contemplated power flows are very large.) In recent years, relatively small gas-turbine generators have been constructed near load centers in some nations, while large coal or nuclear power plants have not been built. The comparison is "gas pipeline and gas turbine" vs. "coal or nuclear and electrical transmission". One sees how electrical generating capacity can increase while electrical transmission capacity need not. Gas transmission or "ton-miles of coal" does increase.

The second situation often arises when one wants to expand the capacity of an existing electrical network to serve present and projected electrical end-users. While it is straightforward to use electrical power to decompose water, then transport hydrogen and finally burn it to generate electricity, few are likely to invest as long as their alternative is the construction of electric T&D. Beside being placed overhead, it can be placed near the ground, (e.g. one meter above it) resting on concrete blocks, underground, or underwater.

However, power lines are rarely placed near the ground because they would impede transportation and because they would be vulnerable to some of the same events (automobile collisions) as overhead lines. Near-the-ground power lines are built only where they can be isolated from the general public. Such locations include utility switchyards and utility right-of-way with restricted access. Because the conductor is near the ground, air is not an effective electrical insulator. In fact, a great deal of engineering must be done to provide the needed electrical insulation. Today's technology uses contained, compressed SF_6. The technology is referred to as "Compressed Gas Insulated Lines", CGIL, or CGI cable.

The most widely adopted alternative to overhead lines in crowded areas is underground cable.

IV. 5 Underground Cable

Cable is placed underground to keep it out of harms' way and to protect the public. Access is restricted to employees of electric utilities.

As with "near ground cable", engineering is required to provide electrical insulation for underground cable. That location raises two new issues: (a) size, and (b) cooling. Excavation is expensive--the less required the better. Thus one wants to guide the needed power with cable that requires little excavation. That desire favors copper conductor in underground cable. One ohm of copper takes up less space than one ohm of aluminum. (As noted earlier, one ohm of aluminum weighs less than one ohm of copper and so aluminum is favored overhead.)

Underground, cooling is no longer free. Heat is not easily transferred from the electrical conductor to the earth. Unlike the situation in air, there is no free convective heat transport underground. Heat transfer is the biggest issue when considering underground cable.

To understand underground cable and the potential benefits of incorporating superconductor in it, one must consider at least four engineering topics:

(a) electrical current
(b) electrical conductor
(c) electrical insulation
(d) heat transfer.

To avoid overlooking them, we also cite

5) terminations
6) splices
7) protection from the environment.

IV.6 Electric Current in the Electrical Conductor

The electric current in the underground cable or overhead lines guides the electric power to follow the line. Either DC or AC may be used, though the overwhelming choice is "three-phase AC". As elaborated below, it differs from "single phase AC" which is used within commercial and residential buildings.

IV.6.1 Direct Current

Current that always flows in the same direction is called Direct Current or DC. While the direction stays the same, the magnitude of the current varies—it can be thought of as the sum of constant and a ripple.

Direct current is often used in "long" cable and "long" cable is often sited underwater. The bottom of the English Channel, Long Island Sound and Japan's Straights of Ichi-Ichi are each traversed by DC cable.

"Long" is related to geographic distance but not defined by it. An overhead line and underground cable could each traverse 100 km, but the overhead line is likely to be "electrically short" while the underground cable will certainly be "electrically long". (This difference reflects the difference between the capacitance of overhead line and underground cable.)

IV.6.2 Alternating Current

IV.6.2.1 AC Ubiquitous

All of today's electrical grids use alternating current for the technical and economic reasons given in Chapter III. Only unusual circumstances, most often the need for long submarine cable, has justified the additional cost (both capital and operating) of converting from AC to DC and then inverting back to AC. As discussed in Chapter XI, these circumstances are more likely in the future than they have been in the past. Nonetheless, most power transmission and distribution is and will be guided by three phase AC.

IV.6.2.2 Three Phase AC—The Reason

The power that is guided by alternating current in two conductors, arrives at its destination in pulses, not a steady flow. If the frequency at which the current alternates is 50 Hz or 60 Hz, the power pulses at 100 Hz or 120 Hz. This is fine for lights but not good for rotating machines. They might vibrate with undesirable effects. The standard solution is to power rotating machines with three pairs of conductors. Current alternates in each pair but not at the some time. Instead, each pair delivers power a bit before or a bit after another pair. Thus three-phase power arrives relatively smoothly. Beside this smoothing, there is another consequence. The three pairs of conductors need not be physically distinct. They can share one common conductor. Moreover, when the loads on each two conductor circuit are the same, the current in the shared physical conductor is zero. Thus, the shared conductor need only be sized to accommodate the sometime imbalance of loads. Instead of six conductors for three pairs, only four conductors are needed and the fourth can be smaller than the other three.

IV.6.2.3 Three Phase AC—Current and Voltage

Current alternates in each of the three conductors but, at any instant, the current differs from conductor to conductor. For example, there are instants when no current flows in one of the conductors and when current flows in each of the other two, but in opposite directions. A common convention is to name each of the phases “a”, “b”, or “c” (or “r”,”s”, or “t”) and the desired state of affairs is to have the currents at any place varying as shown:

$$I_a = ISin\left[2\pi f\left(t - t_0\right) - \varphi_L\right]$$
$$I_b = ISin\left[2\pi f\left(t - t_0\right) - \varphi_L + \frac{2\pi}{3}\right]$$
$$I_c = ISin\left[2\pi f\left(t - t_0\right) - \varphi_L + \frac{4\pi}{3}\right]$$

A consequence of these same, desired operating conditions is that no current flows in the neutral.

$$I_{neutral} = I_a + I_b + I_c = 0$$

The angle, φ_L was introduced above. When it is positive, current is said to "lag" voltage and when the angle is negative, current is said to "lead" voltage, of which more below.

While current guides power, another quantity is also necessary. Each of the conductors must have charge, or saying the same thing in another way, there must be a voltage difference between the phases and between each phase and the neutral (and ground).[102] The following expresses the desired voltage difference between each phase and the neutral. [103]

$$V_{a-n} = V_{\max} Sin\left[2\pi f\left(t - t_0\right)\right]$$
$$V_{b-n} = V_{\max} Sin\left[2\pi f\left(t - t_0\right) - \frac{2\pi}{3}\right]$$
$$V_{c-n} = V_{\max} Sin\left[2\pi f\left(t - t_0\right) - \frac{4\pi}{3}\right]$$

(At first glance, these formulae look like the ones for current. However, they should not be identical because the maximum voltage difference need not be simultaneous with maximum current flows. That is why the angle φ_L was introduced in the current equations. It specifies the lead or lag between current and voltage alternation. The following section returns to this point.)

A consequence of these same desired operating conditions is that the voltage difference between the phases (e.g., between "*a*" and "*b*") is as shown next.

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[102] flux of power $\equiv P = \int dA \cdot \left(E \times H\right) \sim D^2\left(\frac{\Delta V}{D}\right) \times \left(\frac{I}{D}\right)$

[103] Electrical engineers sometimes call this difference the voltage difference across a leg of a "wye" or "star " connection. The difference between phases is the voltage difference across a leg of a "delta" connection. As shown subsequently, $V_{p-p'} = \sqrt{3} V_{p-n}$.

$$V_{b-a} = V_{b-n} - V_{a-n} = V_{\max}\left(Sin\left[2\pi f\left(t-t_0\right)-\frac{2\pi}{3}\right] - Sin\left[2\pi f\left(t-t_0\right)\right]\right)$$

$$V_{b-a} = V_{b-n} - V_{a-n} = -V_{\max}\left(2Sin\left[-\frac{2\pi}{2\times 3}\right]Cos\left[\frac{+4\pi f\left(t-t_0\right)-\frac{2\pi}{3}}{2}\right]\right)$$

$$= V_{\max}\frac{\sqrt{3}}{2}2Cos\left[2\pi f\left(t-t_0\right)-\frac{\pi}{3}\right]$$

$$V_{b-a} = \sqrt{3}V_{\max}Cos\left[2\pi f\left(t-t_0\right)-\frac{\pi}{3}\right]$$

There is a possibility for confusion and frustration when discussing the "cable's voltage". Power engineers use that phrase to mean the root mean square of the phase to phase voltage difference which, in the notation of the equations, is

$$\text{"voltage of cable"} = \underbrace{V_{rms}}_{\text{phase to phase}} = \sqrt{3}\underbrace{V_{rms}}_{\text{phase to neutral}} = \frac{\sqrt{3}}{\sqrt{2}}\underbrace{V_{max}}_{\text{phase to neutral}}$$

The phase to phase voltage difference determines combinations of spacing and electrical insulation needed between the conductors. For a given electrically insulating material (the "dielectric"), higher voltage requires more space. The minimum diameter of a high voltage cable depends on the dielectric not the conductor or superconductor.

The neutral is grounded, that is to say the neutral is connected to the earth by a very low resistance conductor. Electrical engineers include the neutral in a cable (or overhead line) so that there is a low resistance conductor available, in the unwanted case that the three phases carry unequal currents ("unbalanced current"). Because the neutral conducts current only to the degree that the phases are unbalanced, the designer can choose to put less conductor in the neutral than in each of the phases.[104,105]

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[104] For more on three phase power, as it bears upon cable see E. Guile and W. Paterson, Electrical Power Systems, (2nd edition, SI metric units) Pregamon Press (Oxford, 1977) ISBN 0-08 021730-1 (vol.1)

[105] When the currents or voltages are unbalanced, the situation can be described in terms of two (counter-rotating) balanced currents or voltages (named "positive sequence" and "negative sequence") and a single common current or voltage (named "zero sequence"). Engineers call this the method of Symmetrical Components.

IV.6.2.4 AC—The RMS Current and its Relevance within SuperConducting Cable

The preceding section mentioned power engineers' practice of describing the AC voltage between phases by the value of its root mean square during one cycle. The same practice is followed when describing the current alternating within each phase; the current is specified by its root mean square. In this way, the formula for dissipation within each metal conductor, I_{rms}^2 R, is the same as the formula for DC dissipation, I^2 R.

A cable designer will bear in mind two numbers. First, the maximum steady state current should be related the cross-sectional area of the copper conductor by choosing a current density of 1 A/mm^2 and second, the skin depth of copper is roughly 3 mm. Of course, the designer will also consider the geometry of the copper (e.g., packing fraction), as well as other factors.

The practice of identifying the rms value of AC current with a DC current of equal numerical value is so firmly established, that it may be helpful to recall that its basis is Ohm's Law, a law that does not describe HTS. This point is elaborated below.

Persons working to develop practical HTS tape describe its current carrying capacity, in the plane of the tape, by a generalization of Ohm's Law that is shown below.

$$\mathbf{E} \approx e_0 \left| J / J_c \right|^n \hat{\mathbf{J}} \quad \text{and} \quad e_0 \equiv 10^{-4}\, V/m$$

Both n and J_c depend on magnetic field and temperature. For all materials, the rate of dissipation per volume is $\mathbf{E} \cdot \mathbf{J}$ and so, the rate of dissipation within the HTS is

$$\dot{\mathrm{Q}} \approx e_0 J_c \iiint_{HTS} d^3x \left| J \big/ J_c \right|^{n+1} = \left(e_0 J_c \right) \left| I \big/ I_c \right|^{n+1} \iiint_{HTS} d^3x$$

$$\dot{\mathrm{Q}} \approx \left(e_0 \frac{I_c}{width_{HTS}} \right) \left| I \big/ I_c \right|^{n+1} \left(length_{HTS} \times width_{HTS} \right)$$

The critical current, I_c, is determined by measuring with DC. Consistent with the above, if a tape's critical current is 100 A and 100 A of DC flows through that tape, its rate of dissipation would be 0.01 W/m (i.e., 10^{-4} V/m × 100 A).

Now, consider the rate of dissipation when current alternates, as a sinusoid having frequency *f*, within the HTS. During some of the cycle the current will be less than its rms value and during other parts the current will be greater. In order to build cable, one needs to know the average rate of dissipation.

$$\frac{\langle \dot{Q} \rangle}{e_0 I_c \times length_{HTS}} = f \int_0^{f^{-1}} dt \left| I[t] / I_c \right|^{n+1} = \left| \sqrt{2}\, I_{rms} / I_c \right|^{n+1} f \int_0^{f^{-1}} dt \left| Sin[2\pi f t] \right|^{n+1}$$

If the conductor where "ohmic" then n=1 and because the average over the square of the sine is 1/2, the average rate of dissipation would be equal to the usual expression, $(I_{rms}/I_c)^2$. The is not so for the HTS conductor now under development. Its index, *n*, is greater than one. Different conductors have different indices. Qualitatively speaking, the Bi-2212 that is contemplated for fault current limiters has the smallest index, the Bi-2223 now used in demonstration cables has a larger index, and the REBaCuO that would be used in "second generation or coated" conductor has the greatest, perhaps reaching *n*=28. Thus we give the average value for all indices, *n*, of potential interest. The average over the sinusoid depends on *n*, as shown.

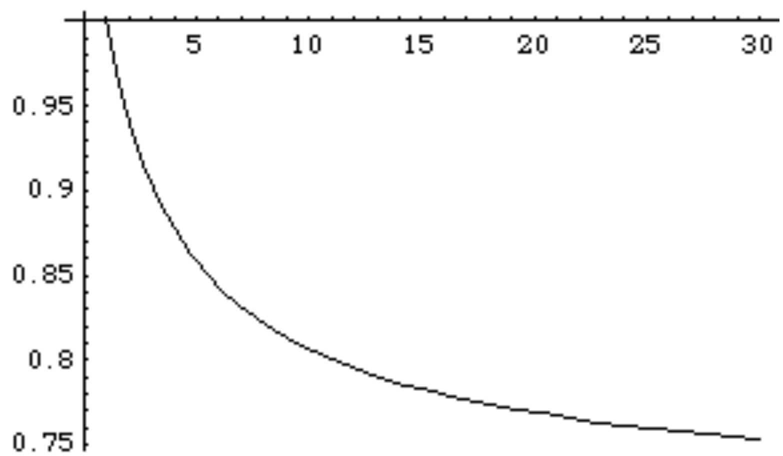
$$f \int_0^{f^{-1}} dt \left| Sin[2\pi f t] \right|^{n+1} = \frac{2}{\pi} \int_0^{\pi/4} d\theta \left| Sin[\theta] \right|^{n+1} = \frac{1}{\sqrt{\pi}} \frac{\Gamma\left[\frac{n+2}{2}\right]}{\Gamma\left[\frac{n+3}{2}\right]}$$

One sees that the dissipation depends on the index, *n*, as well as on the ratio of the rms current to the DC critical current, as shown below.

$$\frac{\langle \dot{Q} \rangle}{e_0 I_c \times length_{HTS}} = c[n] \left| I_{rms} / I_c \right|^{n+1} \quad \text{and} \quad c[n] \equiv \left(\sqrt{2}\right)^{n+1} \times \frac{1}{\sqrt{\pi}} \frac{\Gamma\left[\frac{n+2}{2}\right]}{\Gamma\left[\frac{n+3}{2}\right]}$$

The net result is that when current alternates in the HTS the dissipation is greater than the DC dissipation and the effective critical current (defined by the cooling capacity of the refrigeration) should be reduced. The reduction depends on the index, *n*. Figure IV.6.2.4 shows the critical current should be reduced as *n* increases, in order to maintain the same rate of dissipation.

Figure IV.6.2.4



We will return to this point when discussing cryogenics in Chapter V and the cost of cable in Chapter VII.

IV.6.2.5 Three-Phase AC—A Consequence For Cable, HTS & Ordinary

Overhead power lines are electrically insulated from each other by air. It has the same electrical properties in all directions (isotropic). The situation is otherwise within cable. The electrical insulation is made from paper or newer laminates. Many HTS cable projects use polypropylene laminated paper (PPLP). Taped insulation is not isotropic. It is most likely to break down when the electric field is tangent to the tape surface. If cable consisted of only its three phase conductors and its dielectric, then the phase to phase voltage differences described above would imply a perpetually rotating pattern of electrical forces that would include sizable components parallel to various tapes. Cable makers avoid this by surrounding each phase' dielectric tape with a "semi-conducting screen". This semi-conductor is not the material from which transistors or chips are made. The semi-conducting screen of the power engineer is often carbon and some times metal. It is a good enough conductor to serve as the neutral or be at ground voltage. Each screen guaranties that the electric fields are radial and so they "see the strongest" side of the dielectric tape.

In conventional cable, the screen affects the electric field but not the magnetic field because the screen does not carry (much) current. Expressing the same thing in another way, the presence of the screen makes the phase' capacitance like that of coaxial cable but it does not affect the cable's inductance to nearly the same degree. The phase' magnetic field is not confined and the change in the phase' current is the source of changing magnetic fields out of the cable. These changing fields induce currents in the cable's armor and in other conductors external to the cable. Those currents dissipate energy and interfere with other equipment.

Within "warm dielectric" cable, the HTS conductor is surrounded by its cryostat and then by its ambient temperature dielectric which itself is surrounded by a conventional screen that is grounded. There is no cryogenic problem because the grounded screen does not create a heat leak.

On the other hand, a choice can be made when designing "cold dielectric" HTS cable. One might try to put the screen outside of the cryostat or one can put the screen within the cryostat. If the latter, the grounding the screen contributes to the heat leak.

The usually taken alternative is to make a cable with superconducting screen, indeed one with the same current capacity as the central phase. The three phase cable becomes three (electrically) separate coaxial cables. Each has its own "go" and "return". Each confines both the electric and magnetic field to the dielectric between its superconductors. (See Section IV.9 where HTS cables are described.) By confining the fields, one avoids ohmic dissipation in cold metal and thus one reduces the heat load. (See Chapter V and Chapter VII for the importance of this.) Another consequence is that the inductance (and surge impedance) of the coaxial cable is much less than the inductance of a conventional cable.[106] Section XII.1.4 elaborates this topic.

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[106] Recall that the surge impedance $\equiv Z_s = \sqrt{\frac{L}{C}}$

IV.6.2.6 A Potential Benefit of Low Impedance Co-Axial Cold Dielectric Cable

It has been suggested that this reduced impedance might benefit the network.[107,108] More specifically, low impedance might draw large currents and so reduce the current and thus reduce the temperature in otherwise overloaded conventional cable in the network. It has also been suggested that shifting the phase, by placing a Phase Angle Regulator (e.g., a 1-1 transformer wound, so that each output coil is driven by more than one input coil and so that their relative contribution can be varied) at either of the low impedance cable's terminations, would allow the operator to affect current flows elsewhere in the network. These suggestions raise the prospect of benefits that might be substantial. At this time, no system studies have been done to evaluate the suggested benefits or consider related contingencies (e.g., loss of the PAR). The cost of a Phase Angle Regulator is roughly 1.25 times the cost of a transformer with the same MVA rating (e.g., 10 $/kW for modest power and declining to perhaps 5 $/kW for 800 MVA).[109,110] Such systems studies deserve to be carried out. They may substantiate a benefit that is not widely appreciated within the utility community.

IV.7 Power Guided by Currents but not Wholly Determined by Them

IV.7.1 Current and Voltage Difference, both Necessary for Power

As noted, cable's purpose is to guide power. The amount of power is determined by the product of the current in the conductors and the voltage difference between the conductors. That voltage is itself the product of the force of attraction between the net (opposite) charges, one kind on each conductor, and the distance between them. The

[107] M.J. McCarthy, *Very Low Impedance (VLI) Superconductor Cables*, presented at the Applied Superconductivity Conference, October 3-8, 2004, Jacksonville, Florida.

[108] T. Lynch, J. Schwartz, *Economic, Environmental and Energy Risk Benefit Assessment of Superconducting Technologies Configured in the Florida Grid 2004*, presented at the Applied Superconductivity Conference, October 3-8, 2004, Jacksonville, Florida.

[109] private communication, 12 October 2004, with B. Kerhli.

[110] For a preliminary suggestion for an alternative device, not a study of the effect of the device, see T. Baldwin, M. Steurer, Y. Liu, *A Novel Method of Controlling the Effective Impedance of a VLI Cable*, presented at the Applied Superconductivity Conference, October 3-8, 2004, Jacksonville, Florida

opposite charges attract; the electrical insulation, also known as "the dielectric", prevents them from moving toward each other and then "canceling out". The two materials and purposes, conductor and insulator, are each necessary for power flow.

IV.7.2 Real Power, Reactive Power, and Phase Difference

The power engineer's vocabulary reminds its users how to calculate. Unfortunately, the same vocabulary does not always suggest its meaning. Here, we give the meaning behind the names of this subsection.

As stated before, a combination of alternating current and alternating voltage difference is used in the grid. When the current is largest and the voltage difference is largest simultaneously, then pulses of power flow in only one direction. This is not always the case. Electric power, like sound, can echo back instead of being absorbed at its destination. When this happens, power flows in two directions at the same time. The echoes do not reach the customer; instead the echo power dissipates in the grid. Of course, echoes are physically necessary. When a customer turns off his or her electric equipment, the power that reaches it simply echoes back into the grid. To avoid the build up of reverberations, one turns down the generator. In general, one wants the power to be emitted from the generator and absorbed by the customer. However, echoes or reflections do occur. In fact, whenever the alternating current and alternating voltage do not have simultaneous maxima, they are accommodating such reflections. The degree to which they are not simultaneous is measured by the phase angle, φ. The time average power flow, which is the average power absorbed by the customer, is called "real power", and the power that is echoed or reflected is called "reactive power".

When both the current and the voltage difference alternate as sine waves, the power flow past a point is expressed symbolically as shown next.

power, P, flowing by a point at an instant, t

$$P[t] = V[t] \times I[t]$$

$$P[t] = (I_{\max} \sin[2\pi ft]) \times (V_{\max} \sin[2\pi f - \varphi_L])$$

$$P[t] = (I_{\max} \times \Delta V_{\max}) \frac{1}{2} \left(\underbrace{\cos[\varphi_L]}_{steady} - \underbrace{\cos[4\pi ft - \varphi_L]}_{\textit{fluctuates} \text{ with zero average}} \right)$$

average (over one cycle) of power, $\langle \mathrm{P} \rangle$, flowing by point is "real power"

$$\langle P \rangle = \left(\frac{I_{\max}}{\sqrt{2}} \times \frac{\Delta V_{\max}}{\sqrt{2}} \right) \cos[\varphi_L] = (I_{rms} \times \Delta V_{rms}) \cos[\varphi_L] \equiv \text{"real power"}$$

For three phase lines or cables, the power is three times larger than the power guided by one conductor and the neutral.

$$\langle P \rangle = 3 \times \underbrace{\Delta V_{rms}}_{\text{phase to neutral}} \times I_{rms} \times \cos[\varphi_L] = \sqrt{3} \times \underbrace{\Delta V_{rms}}_{\text{phase to phase}} \times I_{rms} \times \cos[\varphi_L]$$

IV.8 How Conventional Cables Fail

The foregoing does not describe how cables fail, though Section IV.6.2.5 alluded to it. Cables fail either because they are unintentionally damaged (e.g., during excavation of what was intended to be an adjacent site) or because their dielectric material is no longer a good electrical insulator. That degraded performance is the cumulative result of elevated temperature, most often caused by too much current alternating within the conductor. Most important, dielectric damage accumulates. Many separate overloads, each at a different time, can result in sudden, unpredicted failure. (See Chapter VI for more detail.) This is one aspect of the relation between T&D capacity and T&D reliability.

IV.9 Cable Incorporating Superconductor

Conventional cables incorporate copper or aluminum conductor. HTS cables use ceramic superconductors and copper. The different materials and different operating temperatures give each cable different features. The ceramic superconductor can be hundred times smaller than the metal it is intended to replace. Much less copper can be used in the shunt than is required in a conventional cable because copper's resistivity is much less at low temperature than at ambient temperature. Thus the cable can be lighter than usual. The cable can also have smaller diameter than usual because less material is contained within it. However, the cable cannot be so small as to allow the electric field to breakdown the dielectric. This is avoided by separating the conductors and by not allowing the inner conductor to be too small. The diminished outer diameter of HTS cable is most dramatic at lower voltages because at higher voltages (e.g., 138 kV and above) the dielectric accounts for a significant amount of the cross-sectional area. We also note that some of today's projects to demonstrate HTS do not plan to construct cables of the smallest possible diameter or to house their in pipes of smallest possible diameter. These projects' goal is to demonstrate technical feasibility and operational reliability. Minimization and other optimizations are for the future.

It is also important to note that, the cross-sectional area of a cable is not the only area that matters. Conventional cables cannot overheat without damage, thus conventional cable is spaced and nearby ground is prepared to facilitate heat transfer. The effective cross-sectional area of a conventional cable is much larger than the cross-section of the pipe. Superconducting cable differs. The cross-section of an HTS cable is just what it looks like and not bigger because the HTS cable is force-cooled from within. Passive cooling requires space. Forced cooling does not.[111]

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[111] Sometimes utilities will increase the capacity of an existing, passively cooled oil-filled cable by adding forced cooling. In practice, this possibility presupposes that the utility had the foresight to install a return pipe when the oil filled pipe cable was first installed. When it wishes to use the return pipe, the utility must also purchase and install an air-cooler (40C exit temperature) or chiller (20 C exit temperature), valves, pump, building to house same, as well as obtaining the land on which these will be situated. A rough estimate for installing a pumping plant, air cooler, refrigeration unit, relays, piping, land and housing for the equipment can be anywhere from 4 to 5 million dollars depending upon location and size of equipments. The experience of Chicago's utility, Commonwealth Edison, is that roughly a 15% increase is obtained with oil flows of 200 gallons per minute (roughly 800 liters per minute or 13.3 liters/second) in 8 inch (20 cm) pipe and an air-chiller from which the oil exits at 40C. If, instead, a chiller is used to lower the oil's temperature to 20 C, then capacity can be increased by 25%. ComEd's cables (138 kV and 345 kV) are of various lengths: 3.2 km, 6.4 km, and 9.6 km. (private communication, S. Nandi, 1 December 2004. Additional information concerning retrofitting forced cooling, see Power Delivery Consultants

In short, HTS cable promises to be much smaller and lighter than the conventional alternative.

The same characteristic—that only a small amount HTS is needed for large currents—can be used in another way. Voltage can be reduced and current increased when compared with conventional alternatives. In some jurisdictions, new medium voltage cable is more likely to be approved, and approved more swiftly, than high voltage cable.

Wherever, money and time can be saved by putting more power through the same infrastructure, HTS cable will offer a new and interesting possibility to the private sector.

On the following pages, we introduce the designs for HTS cable that are now being developed around the world.

(http://www.PDC-Engineering.com) or EPRI's recently revised and very expensive, Underground Systems Reference Book. For additional introduction, see J.A. Williams, *Pumping Power Underground*, Transmission & Distribution World (June 2002) and D.P. Johnsen and J.M. Gburek, *Dialysis on a Grand Scale*, Transmission & Distribution World (April 2003).

IV.9.1 Warm Dielectric

Figure IV.9.1
One Phase of a "Warm Dielectric" HTS Cable

As in all designs, the LN_2 channel and the HTS conductor are at operating temperature (e.g 70 K). In this design, they are surrounded by thermal insulation that is within the corrugated, hollow metal tube (that assembly is called the "cryostat"). Its purpose is to reduce heat transfer from ambient and thus reduce the amount of refrigeration necessary to maintain operating temperature. The cryostat is surrounded by electrical insulation (dielectric) that prevents current from flowing between high voltage and ground. This design takes its name, "warm dielectric" from the circumstance that the dielectric is at ambient temperature. The outermost layer (shown as black) protects the rest from mechanical damage and water.

This design's appeal comes from the fact that conventional, commercial dielectric of known reliability can be used. The novelty, perceived as technical risk by the power sector, inheres to only the HTS conductor, the LN_2 coolant and the cryostat.

IV.9.2 Cold Dielectric Coaxial

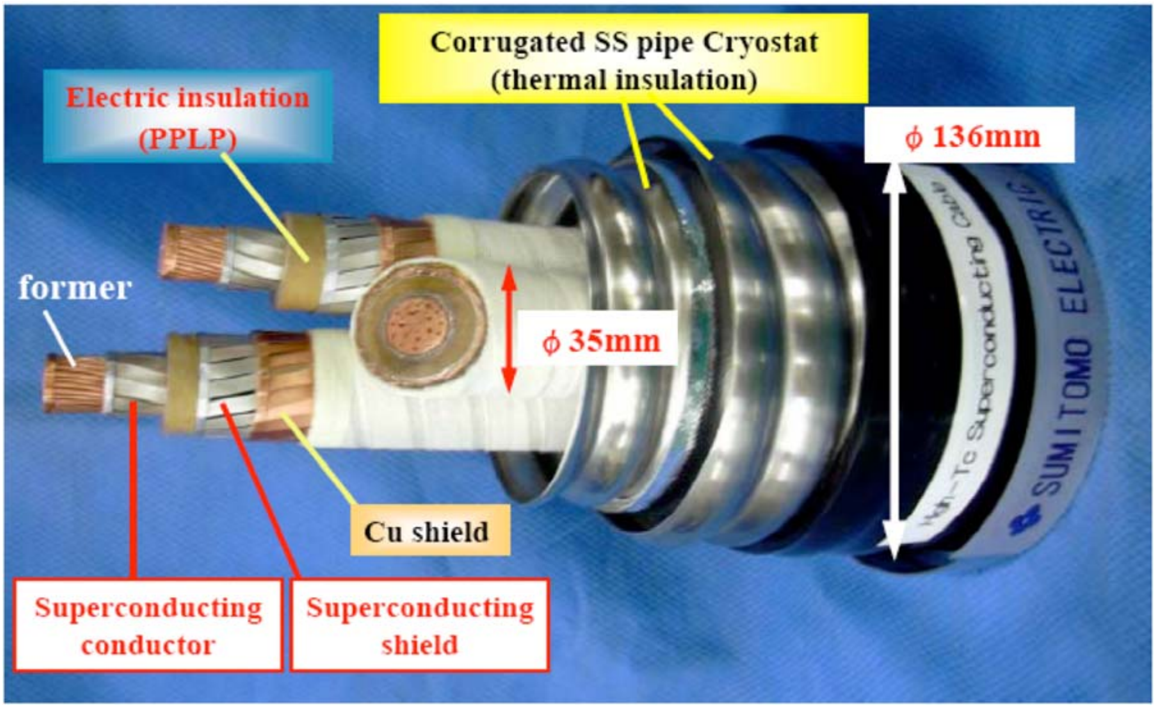

Figure IV.9.2.1
Cold Dielectric HTS Cable Having its Three Phases In One Cryostat

The LN_2 channel and the HTS conductor are at operating temperature (e.g 70 K). The three phases are separated from each other by the white tape. In this cable, each of the three phases is itself a coaxial cable, having an HTS "go conductor" and HTS "return conductor", also called "conductor" and "shield". They are separated by electrical insulation (dielectric) that is at operating temperature--thus the name "cold dielectric". The cable shown here incorporates polypropylene laminated paper (PPLP). The voltage difference between the three shields need not be as large as between each shield and its inner conductor.

Also evident in each phase are a central copper "former", on which the HTS tapes are wound, and a copper shield, external to the HTS shield. The former and the external shield are chosen to be good conductors so that they can provide a path for the occasional, brief fault current. Such currents can be very large, far exceeding the critical current of the HTS. And so, absent the alternative path provided by the cold metal conductor, the HTS would be damaged as the result of overheating. Copper is preferred to aluminum because aluminum's surface oxidizes to an insulator, Al_2O_3, while copper's does not and so the transfer of fault current from the HTS to the copper is expected to be easier.

The three phases are surrounded by LN_2. (Compare to Fig. III.12.2 showing a conventional High Pressure Fluid (Oil) Filled Pipe Type Cable).

To reduce heat transfer from ambient and thus reduce the amount of refrigeration necessary to maintain operating temperature, the coolant and phases are surrounded by thermal insulation that is within the corrugated, hollow metal tube (that assembly is called the "cryostat"). The outer most coating (shown in black) protects everything within it from mechanical damage and water.

This design's appeal comes from the three features: (a) all the conductor is within one cryostat and so less refrigeration is needed than for warm dielectric or for one phase per cryostat and (b) the coaxial design reduces AC losses when compared to other designs in which the alternating magnetic fields induce current and dissipation in cold metal and (c) there are no stray magnetic fields to interfere with other equipment. As stated in Section IV.6.2.5, the relatively low impedance of coaxial designs in conjunction with a Phase Angle Regulator may also offer a means of controlling current flow elsewhere. The potential benefit of this deserves more consideration than it has yet received.

The particular illustration shown above is of a cable being built by Sumitomo Electric Industries for demonstration in Albany, New York by a team led by Super-Power (a wholly owned subsidiary of IGC) and including BOC (cryogenics) and Niagara-Mohawk, part of National Grid US.[112],[113] 0.8 kA will alternate within the conductors and the difference in voltage across the dielectric will be 34 kV. As a result, the cable will guide 48 MW.

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[112] C.S. Weber, C.T. Reis, A. Dada, T. Masuda, J.R. Spadafore, *Overview of the Underground HTS 34.5kV HTS Power Cable Program in Albany, NY*, presented at the Applied Superconductivity Conference, October 3-8, 2004, Jacksonville, Florida.

[113] T. Masuda, H. Yumura, M. Watanabe, Y. Ashibe, H. Takigawa, C. Suzawa, S. Isojima, C. Weber, A. Dada, J.R. Spadafore, *Design and Experimental Results for Albany HTS Cable*, presented at the Applied Superconductivity Conference, October 3-8, 2004, Jacksonville,Florida.

Other "cold dielectric" cables differ from the one shown above by having each phase in its own cryostat. This choice is more likely as voltage difference increases and the outer diameter of the cable remains fixed. A larger voltage difference is accommodated by increasing the space between the conductors. This prevents the electric field from becoming large enough to "breakdown" the dielectric. (See Chapter VI.) Figure III.12.2. shows that roughly 3 cm of dielectric separate the phases of 345 kV cable from each other. As the voltage increases, the cable designer must leave more room for the dielectric and more room for the copper that stands by to handle the occasional, brief fault current.

Furukawa has built a 77kV, single-phase cable that is being tested by CRIEPI at its Yokosuka Laboratory, as part of Japan's Super-ACE project.[114] The cable is illustrated in Figure IV.9.2.2. Table IV.9.2 presents the cable's dimensions.

[114] S. Mukoyama, N. Ishii, M. Yagi, S. Tanaka, S. Maruyama, O. Sauou, M. Mimura, H. Kimura, *Manufacturing and Installation of the World's Longest 500m HTS Power Cable in the Super-ACE Project*, presented at the Applied Superconductivity Conference, October 3-8, 2004, Jacksonville, Florida.

Table IV.9.2
Dimensions of 77 kV Coaxial Cold Dielectric Cable
Built by Furukawa as Part of Japan's Super-ACE Project
and Being Tested at CRIEPI's Yokosuka Laboratory

Item	Configuration		O.D. (approx. mm)
Conductor	Former	SUS spiral tube Hollow Cu stranded Conductor ($250mm^2$)	28
	Superconductor	Ag sheathed Bi2223 ($0.25\ mm^t \times 4\ mm^w$)	30
Electrical insulation layer	Electrical Insulation (Insulation thickness: 8 mm)	Polypropylene laminated paper	48
Shielding layer	Superconducting shielding layer	Ag sheathed Bi2223 tape (0.25 mmt × 4 mmw)	58
Thermal insulation layer and tubes	Inner tube	SUS	92
	Vacuum thermal insulation	Evacuated multi-layer thermal insulation	—
	Outer tube	SUS	124
	Oversheath	PVC	133

Figure IV.9.2.2
One Phase of a 77kV kV Cold Dielectric HTS Cable Segment

Nexans is building a 138 kV, one phase per cryostat, cable for demonstration on Long Island by a team lead by American Superconductor and including Air Liquide (cryogenics) and the Long Island Power Authority.[115] That cable design is illustrated in Figure IV.9.2.3 without its outer protective layer. Compare the relative thickness of the insulation with that in the 34.5 kV and 77 kV cables, shown above.

Figure IV.9.2.3
One Phase of a 138 kV Cold Dielectric HTS Cable Segment

IV.9.2.3 Cold Dielectric Triaxial

As noted, each of the three phases, in the designs just discussed, have an HTS conductor and an HTS shield. This is not the only possibility. Ultera, a joint venture between Southwire and NKT, is developing a different design, known as triaxial. It is shown in Figure IV.9.2.3

[115] J.F. Maguire, F. Schmidt, F. Hamber, T.E. Welsh, *Development and Demonstration of a Long Length HTS Cable to Operate in the Long Island Power Authority Transmission Grid,*_presented at the Applied Superconductivity Conference, October 3-8, 2004, Jacksonville,Florida.

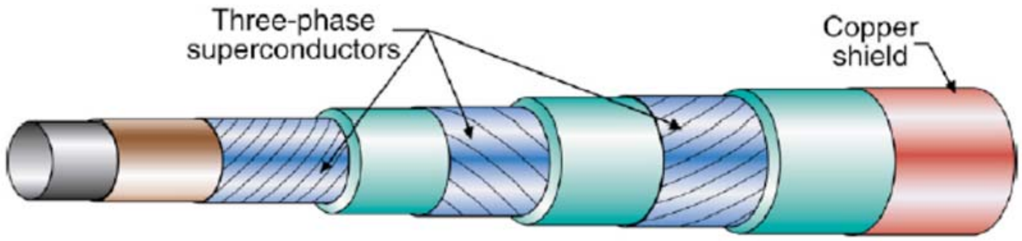

Figure IV.9.2.4
Electrical Components Cold Dielectric Cable of Triaxial Design

The central feature is three concentric conductors.[116,117,118] When the currents are equal, there is no current alternating in the copper shield. When the currents are unequal, a compensating current alternates in the copper shield. The triaxial design offers a way to use less HTS than designs with three HTS phases, each coaxial. The triaxial design promises to significantly reduce the cost of HTS cable. That is very important to potential customers and thus to adoption of HTS cable. (See Chapter VII for further discussion of costs.)

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[116] One feature of the triaxial design may raise a question in the minds of persons familiar with the electrical principles that bear upon power lines. The capacitance, inductance and surge impedance of the three different pairs of conductors cannot all be the same. Thus the cable is electrically "unbalanced". This is also true of overhead lines. There the conductors are transposed after a certain distance. The lack of balance in a triaxial cable is likely to become an issue only in cable longer than 10-20 km and thus not a steady-state problem in the near term applications. As described in Chapter V, cryogenic issues will likely be more urgent for cables of that length. One group is considering transients. M.A. Young, M.O. Pace, M.J. Gouge, J.A. Demko, R.C. Duckworth, J.W. Lue, *An Investigation of the Current Distribution in the Triaxial HTS Cable and its Operational Impacts on a Power System*, presented at the Applied Superconductivity Conference, October 3-8, 2004, Jacksonville, Florida.

[117] M. Sjöström, F. Grilli, B. Dutoit, *Modelling of a Three-Phase Concentric HTS-Cable*, presented at the Applied Superconductivity Conference, October 3-8, 2004, Jacksonville, Florida

[118] T. Hamajima, T. Yagai, M. Tsuda, N. Harada, *Current Distribution Analysis in Tri-Axial HTS Cable Considering Three Phases*, presented at the Applied Superconductivity Conference, October 3-8, 2004, Jacksonville, Florida

Ultera's team, including Praxair (cryogenics), Tech Center, and Oak Ridge National Laboratory is building a 200 m long, triaxial cable.[119,120,121] 3 kA will alternate within it and the voltage difference across the dielectric will be 13.2 kV. As a result, the cable will guide 69 MW. The team plans to demonstrate the triaxial cable at American Electric Power's Bixby substation near Columbus, Ohio, during 2006-2007.

The highest voltage HTS cable now being developed is 138 kV and the lowest is 13 kV. As shown in Chapter X, this range includes most cable. As also shown there, much more cable is devoted to low voltage than to high voltage.

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[119] Ultera states that, in its implementation of the triaxial design, Ultera will not have metal conductor in the central former.

[120] M.J. Gouge, J.A. Demko, R.C. Duckworth, J.W. Lue, D.T. Lindsay, P.W. Fisher, M.L. Roden, J.C. Tolbert, C. Traeholt, D. Willen, Tests of Triaxial HTS Cables, presented at the Applied Superconductivity Conference, October 3-8, 2004, Jacksonville, Florida.

[121] M.A. Young, M.O. Pace, M.J. Gouge, J.A. Demko, R.C. Duckworth, J.W. Lue, An Investigation of the Current Distribution in the Triaxial HTS Cable and its Operational Impacts on a Power System, presented at the Applied Superconductivity Conference, October 3-8, 2004, Jacksonville, Florida

V. CABLE CRYOGENICS

V.1 Purpose

When compared to all the other HTS equipment for the power sector, cable presents the biggest challenge to its cryogenic design and construction. The reason is simple; cable has the largest ratio of surface to volume. Below, we introduce the impediments that cryogenics must surmount. First the general issues are presented and then we describe relevant features of the coolant, the cryostat and the cryo-coolers. To achieve its full potential, HTS cable must accommodate the geography and topography of the places where utilities will want to use cable and so we indicate related goals that remain to be addressed.

Another report[122] complements this chapter and this chapter's appendix reviews some relevant aspects of fluid flow and the cryogenic properties of LN_2 and some metals.

V.2 Orientation

The HTS conductor within cable within must be kept at operating temperature (63 – 83 K) despite the appearance of heat from many sources. This section names the mechanisms and introduces the usual jargon.

The region to be maintained at operating temperature is called the cold region.

The standard strategy is to remove that heat from the cold region by transferring that heat to a moving fluid, typically LN_2.[123] That fluid is called the coolant. The heat is later removed from the coolant by refrigerators, which themselves contain fluids called refrigerants. The refrigerators exhaust the heat (and the energy they themselves dissipate) to the environment. The coolant leaves the refrigerator at lower temperature than it entered and is then re-circulated through the cable.

During normal operation, heat appears in the cold region for several reasons:

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[122] See Chapter VII of A.M. Wolsky, Cooling For Future Power Sector Equipment Incorporating Ceramic Superconductors prepared for and sponsored by the signatories of the International Energy Agency *Implementing Agreement for a Cooperative Programme for Assessing the Impacts of High-Temperature Superconductivity on the Electric Power Sector* (12 April 2002).

[123] One past cable project used liquid neon; see Section VIII.2.14.

a) Cable is electrically connected to the grid which operates at ambient temperature. This connection is conductive, though it need not be.[124] Thus, heat from the environment and heat generated within the terminations flows into the cold region through the metals in which the current alternates.

b) Heat passes from the environment (T = 300 K) through the thermal insulation into the region containing the conductor. The mechanisms for this heat transfer are conduction and radiation.

c) Electrical energy dissipates in the HTS when it carries alternating current. The mechanism is called "hysteresis", by analogy with the mechanical energy dissipated in rubber when it is repeatedly flexed (e.g., one reason cars need fuel is to flex their tires; their temperature rises as a result.)

d) Electrical energy dissipates in the cold metal (e.g., silver, copper stabilizer, stainless steel) when current is induced in the metal by alternating magnetic fields concomitant with alternating currents in the HTS. (Electrical energy also dissipates in the dielectric when its polarization alternates, but the quantity is small)

e) Mechanical energy dissipates in the LN_2 because it is viscous. It is common to allude to this dissipation by saying energy is lost due to pressure drop.

As discussed in Section IV.6.2.4, as long as the rms current is kept well below the DC critical current, resistive effects dissipate only a negligible amount of electrical energy within the conductor. Indeed, that negligible dissipation is the most widely publicized characteristic of superconducting materials. Nonetheless at each particular moment, the current in any single AC cable depends the demand and on the state of the network of which the cable is part. This dependence is most dramatic when a short circuit (also called a "fault") appears in the network and the cable's current varies suddenly and greatly. For example, a cable intended to handle at most 0.8 kA during routine operation may be called upon to handle 23 kA during a fault that lasts 38 cycles. The desire to survive faults influences the design of the conductor, the cable and the cable's cryogenics, as well as the choice of ancillary equipment (e.g., a fault current limiter).

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[124] In principle, the connection could be inductive, for example by making a "two temperature transformer"(i.e., a transformer having three cold windings and three ambient temperature windings. When the cable operates at lower voltage than the grid, a transformer would be needed anyway. A recent working paper presents thoughts on this topic; see F. Mumford, *Multi-Functional Transformer for HTS Applications,* kindly made available to the writer on 18 November 2004.

The immediate consequence is that there is a trade-off between the refrigeration needed to cope with the “index loss” discussed in Section IV.6.2.4 and the “extra” HTS tape that one puts in the cable to keep the rms operating current well below the DC critical current.

This same sensitivity for large *n* presents an as yet unexplored issue to the designer of a cable intended to accommodate a fault current that is more than 20-30 times larger than the maximum operating current. A balance must be struck between the cable’s capacity to handle sudden excess heat and the cost of that capacity. The designer will add copper shunt to avoid too much growth of current within the HTS. The amount of copper and its place remain to be sorted out when the conductor is REBaCuO. As stated in Section VII.2.3, some copper can be attached to the HTS film. Other copper could be included within the cable enabling it to act as a conventional cryogenic cable during a fault. At the time of this writing, these issues remain to be explored by tape developers and cable designers. Demonstrations now underway use Bi-2223which has a lower value of *n* than REBaCuO. First generation tape is more forgiving during a fault than today’s second generation tape.

V.3 Engineering Challenges

When considering how to design and construct the cable’s cryostat and refrigerator, further issues present themselves.[125]

1) Utilities expect cable to be delivered on drums and to snake the cable through bends in tunnels and ducts. This prompts the wish for a flexible cryostat. (See Figures V.5.1 and V.5.2.)

2) Utilities don’t have to pay much attention to the oil (dodecyl-benzene) within older conventional cables. Even so, utilities increasingly avoid such cable by purchasing cables incorporating synthetic polymer dielectrics. Thus, the HTS cable’s cryo-coolers should require infrequent, routine maintenance and the cryo-coolers should be robust and reliable.

3) The cold region’s voltage differs from the environment’s. Any design and construction must cope with the electric fields that act on the coolant, (e,g., LN_2), that travels from high voltage to low voltage. For this reason, designers of high voltage cable may prefer keeping the LN_2 exterior to the coaxial conductors. This preference may descend to medium voltage cable, as well.

[125] R.C. Lee, A. Dada, S.M. Ringo, *Cryogenic Refrigeration System for HTS Cables,* presented at the Applied Superconductivity Conference, October 3-8, 2004, Jacksonville, Florida.

4) While today's demonstration cables are less than 600m long, the market is likely to want distribution cables of at least one or two kilometers and transmission cables that are longer. The latter prompts the wish for cooling stations along the length of the cable. While today's cooling station can be located near the terminations and so be accessible, future cooling stations may be wanted for cable, along its length, including at some relatively remote and inaccessible locations (e.g., underwater).

5) The density of liquid nitrogen is roughly 840 kg/m^3. Correspondingly, the pressure exerted by a 100 m high column of LN_2 is 8 bars greater at the column's base than at its top.[126] In some places, the desired change in cable elevation may easily exceed 100 m.[127] The thermo-mechanical design and construction should be capable of handling flows driven by pressure and temperature gradients. Note that temperatures may be higher at the bottom of the LN_2 column than at the top[128] and that elevation changes cause pressure gradients.

V.4 The Coolant

Each of the recent HTS cable projects have used or plans to use liquid nitrogen, LN_2, as its coolant. A consequence is that the cable's operating temperature must be in the range 65-80 K.

A bit below 65 K, nitrogen freezes or turns into a mixture of solid and liquid. 63 K and 0.2 Bar are the temperature and pressure at which solid, liquid and vapor nitrogen are in thermal equilibrium. (This temperature and pressure is called the "triple point.") Some

[126] $\Delta P = \rho g \Delta z = 840\, kg / m^3 \times 9.8\, m/second^2\, \Delta z = 8.2\left(Bar / 100 m \right) \Delta z$

[127] A few examples suggest that changes in elevation are not uncommon in the world's major cities San Francisco's Twin Peaks are 285 meters above San Francisco Bay. Paris' Montmartre is 105 m above Pont de Grenelle. Even within Vatican City's tiny geographic area, the elevation changes by 55 m. More detail about two cities, New York and Hong Kong appears in Section V.7

[128] A simple case may suggest other complexity. The condition for mechanical stability in column of fluid is that the less dense material cannot be under the more dense material. After taking account of the dependence of density on temperature, one sees that the temperature cannot increase too fast with depth without making the column unstable against convection. "Too fast" means the column is stable against convection whenever the following inequality holds.

$$-\frac{dT}{dz} < g\left(\frac{\partial}{\partial T}\ln\left[\frac{1}{\rho\left[T,P\right]}\right]\right)\left(\frac{T}{c_p\left[T,P\right]}\right) = g\beta\left[T,P\right]\left(\frac{T}{c_p\left[T,P\right]}\right)$$

persons have discussed the possibility of depressing the freezing point of LN_2 by dissolving "anti-freeze", for example Krypton, in the LN_2. Lower operating temperature offers the possibility of more current in the superconductor. However, lowering operating temperature lowers the efficiency and raises the cost of refrigeration.

As its temperature rises above 77 K, the pressure needed to maintain nitrogen in its liquid state rises above ambient. As shown in Table V.4.1, at 80 K the needed pressure is 1.4 Bar, while at 105 K the pressure must be maintained at 11 Bar.

Cables must operate at above ambient pressure for two reasons, of which the second dominates: (a) to push the LN_2 through the cable, a pressure difference is needed and (b) to suppress bubble formation that would precipitate dielectric breakdown . As described in Chapter VI, the dielectric constant of nitrogen vapor differs from the dielectric constant of LN_2. The result is that the equilibrium electric field in the gas would be much greater than in the liquid and this difference is unstable against dielectric breakdown. Thus, bubbles should be avoided. This need, and the desire to keep the pressure below 10 Bar, defines the upper operating temperature.[129]

In the past, there was some concern about the possibility of LN_2 infiltrating the Bi-2223 tape. If this happened, the LN_2 would damage the tape when it vaporized in response to a combination of elevated temperature and decreased pressure, either inadvertent or planned (e.g., the equipment being allowed to come to ambient temperature). The effect is called "ballooning" or "blistering".

Recently, Sumitomo Electric Industries announced it has achieved "ballooning effect free" Bi-2223 tape as the result of heating its tape under high pressure.[130] Another tape maker, American Superconductor Inc, states its "…HTS Hermetic wire is designed to withstand high pressure liquid nitrogen and other cryogenic liquids that are often used in certain HTS applications such as power cables, transformers, and fault current limiters. By providing a hermetic seal to the cryogenic liquid AMSC's Hermetic wire increases the longevity of HTS power cables and other high pressure applications. Hermeticity: 10 atm LN_2 for 24 hrs." Effort to improve this specification to approximately 30 Bar is underway.

[129] Engineering practice in Japan and perhaps elsewhere requires more elaborate construction and precautions for systems operating above 10 Bar than below. At this time, the LIPA cable is planned have its LN_2 under 20 Bar at the pump exit and this pressure may decline to 3 Bar at the pump inlet, private communication with M. McCarthy, October 2004.

[130] private communication, dated 30 Aug. 04 from S. Akita.

There has been no public discussion of the ability of second generation tape, also known as coated conductor, to tolerate liquid nitrogen pressure. However, Super Power stated that Sumitomo wants it to deliver second generation tape that that can tolerate 10 Bar for 24 hours.[131]

[131] V. Selvamanickam, *Scale Up of Coated Conductor Technology at SuperPower*, presented to DOE Peer Review (July, 2004).

Table V.4.1
Nitrogen Gas-Liquid Saturation Temperature and Pressure

Temperature	Saturation Pressure
Kelvin	**Bar**
65	0.1742
66	0.2065
68	0.2852
70	0.3859
72	0.5126
74	0.6696
76	0.8614
78	1.093
80	1.369
82	1.694
84	2.074
86	2.515
88	3.022
90	3.600
92	4.256
94	4.995
96	5.824
98	6.748
100	7.775
102	8.910
104	10.16
106	11.53
108	13.03
110	14.67
112	16.45
114	18.36
116	20.47
118	22.72
120	25.15

As shown in Table V.4.2, the isothermal compressibility of LN_2 is rather small. (e.g. at 70 K and between 1 and 5 bar, it is 2.4×10^{-4} per Bar) and so for isothermal flows the coolant is incompressible. Some care may be warranted when LN_2 flows between different temperatures because its thermal expansion coefficient is not so small (e.g., at 5 bar and between 70 and 80 K it is 5.5×10^{-3} per Kelvin).

Table V.4.2
Mass Density (kg/m³) of LN_2
Depends on
Temperature and Pressure

Pressure / Temperature	70 K	80 K	90 K	100 K	110 K	120 K
30 Bar	843.8	801.1	753.8	701.5	638.0	541.1
20 Bar	841.8	798.4	750.1	695.8	627.5	79.5
10 Bar	839.8	795.6	746.1	689.6	37.0	
5 Bar	838.7	794.1	744.1	18.9		
1 Bar	837.9	4.4	3.8			

Source: N.B. Vargaftik, Y.K. Vinogradov, V.S. Yargin, Handbook of Physical Properties of Liquids and Gases, Pure Substances and Mixtures, 3rd Augmented and revised edition, Begell House Inc. (New York, Wallingford (UK), 1996) ISBN 1-56700-063-0 Green highlights indicate vapor phase.

Besides nitrogen's compressibility, freezing and boiling points, another property, viscosity, is relevant. LN_2 is viscous and so the flow's kinetic energy dissipates when adjacent layers of fluid move at different velocities. This is unavoidable because the fluid at the wall is at rest while the fluid must move in the cable's interior. The amount of dissipation depends on the flow, as does how one predicts the dissipation. (Some laminar flows can be analyzed. More than a century of work has enabled the parametrization of some turbulent flow.) As the coolant (e.g., LN_2) travels down the length of the cable, the coolant's pressure falls. That pressure drop is sensitive to the flow's Reynolds Number and the pipe's diameter and roughness. The pressure drop will depend on the particular cable design, though a relevant order of magnitude is 0.1 Bar/km.[132] The appendix to this chapter presents the relevant information and recalls the

[132] Engineering practice estimates the pressure gradient from the following formula

$$dP/dx = -f\,\frac{\rho v^2}{2D_{pipe}} = \frac{\eta^2}{\rho}\, f\left[N_{Re},\varepsilon\right]\frac{(N_{Re})^2}{2(D_{pipe})^3}$$

where D_{pipe} is the ratio of the wetted perimeter to π and f is the friction factor which depends on the Reynolds Number, N_{Re} and the pipe wall's roughness via ε. Various correlations have been published for f. See the appendix to this chapter for related information.

Note the pressure drop is not half the average gauge pressure in the system.

relevant ideas. It concludes with an illustration of how to use the properties of the flow to estimate the pumping power required by the LN_2 coolant.

V.5 Flexible Cryostats

V.5.1 Manufacturers and Market Size

As stated above, utilities expect cable to be delivered on drums and to be capable of snaking through bends and turns in tunnels and ducts. In principal, this might be achieved by making short straight sections of rigid cryostat and elbows. One would have to join the cryostats, put the cable inside them and then evacuate the cryostat. No one has followed this path to completion. In practice, cable groups want flexible cryostats.

Furukawa made a prototype, flexible cryostat for the HTS cable demonstrated at CRIEPI's Yokosuka Laboratory. This cryostat resulted from a special effort. Furukawa does not routinely offer them for sale or make them for itself.

Figure V.5.1
Furukawa Electric developed a prototype 300 m thermally insulated pipe for single core HTS power cable with vacuum layer between corrugated pipes in Super-ACE project. They could successfully evacuate vacuum layer from the end of pipe with conventional vacuum pump.

Nexans-Hannover is the only firm that offers flexible cryostats as an article of commerce. Their principal customers are industry (roughly 50%) which buys standard products and scientific facilities (roughly 50%) which often buys specialty items. The cryogenics group sells roughly 2-3 km/year of LN_2 transfer lines.[133]

[133] Some development and demonstration work has shown that LNG can be transferred from ship to ship in the North Sea and other work has shown that its flexible cryostats can be used to transfer LNG on the land.

Figure V.5.2
Nexans-Deutschland (Hannover) is now developing a 500m flexible cryostat for an HTS cable to be demonstrated by the Long Island Power Authority in the US.

V.5.2 Fabrication

When the cryostat is in use, its inner wall is at operating temperature. Of course, that wall is fabricated at ambient temperature. A sheet of stainless steel is rolled into a tube and welded down the seam, parallel to the tube's long axis. These welds are done in an inert atmosphere to reduce the chance of later leaks. Then, the stainless steel tube is corrugated. That provides the extra length along the tube's long axis; that extra length disappears when the material contracts, in response to its falling temperature. The weight of the cold inner wall is supported by plastic braids that are placed between the inner and warm outer wall. The braids are woven to minimize contact area and thus minimize heat conduction. Also between the walls are many sheets (e.g., 30 sheets) of aluminized mylar (MultiLayer Insulation, MLI). They are meant to reduce radiative heat transfer. Convective transfer is reduced by evacuating the space between the two walls, a typical pressure is10^{-8} Bar. It takes two weeks to pump down (sucking on each end) the volume when the tube is 100 m long. (In fact the pumping time increases exponentially with the length of the tube. This has limited the length of cryostats.). That length, 100 m, satisfies today's market. In fact, often shorter lengths are sold or rented. Those shorter lengths are cut from the 100 m lengths, routinely fabricated.

Many of the tools used are adapted from or designed in conjunction with the tools used to make metal tubes, in general, and electrical cable, in particular. This explains how Nexans can afford to serve today's very small market for flexible cryostat. However, it appears that these tools and their adaptation to fabricating flexible cryostats can only be used successfully by persons who have accumulated know-how from experience.

V.5.3 Performance

Cryostats are intended to limit heat transfer. Their performance depends on several factors:

a) surface area, a cryostat having a 100 mm diameter (314 mm circumference) would likely allow less heat transfer than a cryostat having a 150 mm diameter (471 mm circumference). Roughly speaking, today's cryostats are rated by heat transfer per surface area.

b) a straight section would likely allow less heat transfer than a curved section. The bend brings the inner cold wall closer to the warm outer wall, facilitating unwanted heat transfer.

Cryostats might also influence the electrical and mechanical energy dissipated within them and thus the heat that must be removed from the cryostat. One possibility is that electrical currents would be induced within the cold metal wall and there generate heat. This mechanism is reduced by reducing the alternating magnetic field in the cold wall. Co-axial and triaxial designs keep the field within the conductor and not the cryostat. The other possibility arises if and when the flowing coolant is adjacent to cold wall of the cryostat.

The last point deserves additional explanation. Nexans-Hannover states that the friction factor for its cold inner corrugated wall is 0.08 while a corresponding smooth pipe would have 0.015.[134] To compensate, Nexans uses a diameter that is 20% larger than it would be for smooth tubes. Indeed, Nexans is working on a "smoothing" insert to reduce dissipation. Such an insert might be made of a woven metal fabric such as one sees around cryogenics. It could cut the friction factor to half of what it would otherwise be. Nexans already does this to reduce noise from N_2 gas-lines and Nexans has used this woven fabric in Liquified Natural Gas (LNG) pipes when necessary. We return to heat transfer.

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[134] For illustrations and a bit more detail, see, K. Schippl, *Very Low Loss Cryogenic Envelope for Long HTS Cables*, paper presented to EUCAS (September, 2003) in Sorrento, Italy.

For straight sections, today's commercially available flexible cryostats, having diameter 150 mm, admit approximately 3 W/m.[135] The 100 mm cryostats admit approximately 2 W/m. Curved sections might admit twice as much heat transfer. The amount depends on the radius of the bend and the radius of the cryostat.

It is certainly possible to reduce this heat leak. Furukawa's demonstration (not commercially available) cryostat had a total heat load of 1 W/m in its straight section.

In fact, one commercial manufacturer thinks it feasible to reduce the heat transfer of commercial cryostats by a factor of two.

Another aspect of a cryostat's performance is the pressure that it can handle. The cold inner wall of Nexans' commercial flexible cryostats might be designed to burst at 150 Bar but present practice would operate them at not more than 20 Bar. This is sufficient for today's demonstration cables. The 500 m cable built by Furukawa and tested at CRIEPI's Yokosuka Lab is designed to up to 10 Bar.[136] Its termination normally operates at 7 Bar. Japanese engineering practice requires more elaborate safety systems above 10 Bar than below. The 600 m cable being built by Nexans for demonstration on Long Island (the "LIPA cable") will operate between 20 Bar (pump exist) and 3 Bar (pump inlet).[137] Of course, some potential cable routes (see Chapter XI) include changes in elevation that would cause substantial changes in pressure.[138] 20 Bar is the difference in pressure between the top and bottom of a 250 m column of LN_2.[139] Such changes can occur in some metropolitan areas.[140] Such changes also occur at some pumped hydro stations.[141] Changes in the cable's elevation must be accommodated by its cryogenics.

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[135] Some persons describe cryostat performance in terms of W/m^2. DL is the surface area of a cylinder of diameter D and length L. A meter long cylinder of 150 mm diameter has a surface area of 0.47 m^2 . Thus, a performance of 3 W/m is essentially 6 W/m^2. 5 W/m^2 was expected to be achieved in 2004 by Nexans-Hannover, according to K. Schippl, *Very Low Loss Envelope for Long HTS Cable*, paper presented to EUCAS meeting held in Sorrento, Italy (September, 2003).

[136] S. Mukoyama, M. Yagi, N. Ishii, M. Ickikawa, H. Suzuki, A. Kimura, *Sub-Cooled LN_2 Cooling System for the 500m Long HTS Power Cable*, presented at the Applied Superconductivity Conference, October 3-8, 2004, Jacksonville, Florida

[137]private communication, 11 October 2004, with M. McCarthy, AMSC.

[138] Some persons have proposed an intercontinental network of superconducting DC cables. See Chapter XI.

[140] In fact such changes occur in the center of some metropolitan areas, for example Hong Kong and San Francisco. Section V.7 describes both natural topography and man-made topography in two cities where future HTS cable might be desired.

One sees that two goals deserve attention. Flexible cryostats have to be long, as long the cables they enclose. Commercial cables are many kilometers long. Furukawa has made and demonstrated a prototype flexible cryostat that is 500 m. Nexans is at work on a 600 m cryostat. Such lengths require techniques to evacuate the cryostat from valves at intermediate points (e.g., 100 m apart). Flexible cryostats (and other aspects of cryogenic construction) must accommodate the pressure to suppress bubble formation in the terminations (which may be located on the earth's surface) and the increase in pressure due to changes in elevation--the greater the range of pressures, the more potential cable routes can be considered.

V.6 Cryo-Coolers

V.6.1 Today's Commercial Technology

Excellent cryocoolers are offered by several firms. For example, Aisin Seiki offers its model SC1501, which has a cooling capacity of 1 kW at 77K. The configuration of model SC1501 is reported to be similar to the one described below. Three units of the SC1501 machine were used for the TEPCO/Sumitomo HTS cable project.

As stated elsewhere, CRIEPI's Yokosuka Laboratory is testing where Furukawa's cable is 500m, single phase, 1 kA and 77 kV cable that was built by a team including Furukawa. The cooling capacity at the site is 6 kW at 77 K (some of this capacity is meant for back up) – 4 kW for the cable and 2 kW for the terminations. The needed shaftpower is 1.5x65 kW, a ratio of 16.25 to 1.

Stirling Cryogenics and Refrigeration BV offers its basic SPC-4 unit for approximately $150,000.[142] Stirling states that the machine can remove 2.8 kW from 66 K and 4.0 kW from 77 K. Some in the HTS community speak of cryocooler performance as a percent of the Carnot efficiency. The SPC-4 offers 22% at 66 K and 25% at 77 K.

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[141] Norway and Switzerland, as well as many other countries, have extensive pumped hydro. In some facilities, very large currents alternate in the connection between the generators and the step-up transformers. In some situations, HTS might be preferred for that connection, if it can handle the difference in elevation between the generator terminals and the step-up transformers.

[142] This is the cost for the basic liquefier. It does not include adaptations for 66 K use, nor for additional system components for the forced flow version. The balance of the system might add capital costs in the range $65,000–200,000.

Stirling also offers another configuration which enables forced cooling by nitrogen that is maintained as liquid, having temperature well below the boiling point. That configuration is appropriate for cryogenic cable. The forced flow configuration costs roughly $350,000 and removes 2.4 kW from 66K and 3.6 kW from 77 K.

Potential users will be concerned with reliability and maintenance. Stirling states that the mean time between maintenance MTBM is 6,000 hours and the downtime for maintenance is roughly 5 hours for HTS applications (18 hours for LN_2 separation from air). The maintenance often involves cleaning oil out of the regenerator; oil fouling reduces the capacity of the SPC-4.

V.6.2 Cryo-Coolers Now Under Development and Their Performance Goals

Electric utilities are likely to want cryo-coolers that are more reliable and less expensive than today's commercial units. Also desirable is a cryo-cooler that performs well when less than full output is wanted because current and thus current dependent losses are likely to vary during the day. Two firms are working to achieve these goals.

American Superconductor is working to develop a pulse-tube (also called acoustic) cryo-cooler that would be suitable for HTS. They plan to test it on non-critical service during their LIPA cable project.

A large firm, Praxair, and a small firm, QDrive, are working together to achieve the same goal. They hope to make large scale acoustic cryo-coolers. To date, they have tested a machine, model 2PX2-200-N, that can remove 200 W from 80 K with an input of 4.5 kW at 300 K. The model is driven by a motor, QDrive's model 2S241K, and acoustic coupling. Praxair expects it's cooler to have a 10 year life with no maintenance.

The Praxair-Qdrive team states it is developing a larger cryo-cooler (model 2S362K.1). Its performance goals are:

(e) remove 1 kW from 77 K using 21 kW input at 300 K
(f) draw power from one phase at 240 V or 480 V
(g) mass 590 kg
(h) lifetime: 10 years with no maintenance

Completion of this machine's development is scheduled December, 2005.

The Praxair-QDrive Team hopes to have a higher capacity machine, 1.5 kW from 65 K, by the end of 2006. The machine's mass is planned to be 750 kg. That hoped for model is numbered 2S241.2; it will use QDrive's model 2PX2-1500-N motor and acoustics.

(Other, smaller capacity machines are also under development. One has been delivered to Toshiba in Tokyo and another to the US Air Force.)

If successful, this machine will be an important advance in the state-of-the-art. One such machine might be required to remove the heat entering a future 1 km cable through its cryostat (e.g., 1.5 W/m). US DOE's stated goals are: 0.5 kg/W removed from 65 K and 40 $/W from 65 K. However, the actual development of this equipment has proceeded without funds from DOE. The Praxair-QDrive team's goals may reflect other considerations, for example the desires of LNG customers.

Figure V.6.2

The refrigeration required for future HTS equipment may benefit from the technology used to liquefy natural gas. The Praxair-QDrive team is developing an acoustic refrigerator, shown above, to condense natural gas. That development may contribute to refrigeration for LN_2 that is described in the text.

V.6.3 Total Heat Load

The heat that must be removed from a cable will vary with its design. Here we offer some order-of-magnitudes.

Table V.6.3
Order of Magnitude of Cable Heat Loads

Mechanism	Order of Magnitude (W at 77 K per m of cryostat)
heat transfer from ambient through the cryostat	1 –3 W/m
mechanical dissipation due to viscosity	< 0.01 W/m
electrical dissipation due to induced currents in cold metal	< 2 W/m
electrical dissipation due to hysteresis in HTS	$\leq \frac{2}{\sqrt{3}} 0.50 \;\; W/kA-m$

Note, some groups report better results for hysteresis in tape or ohmic losses in cold metal.

The most important conclusion is that cables that include three phases in one cryostat will require less refrigeration than cables that use a separate cryostat for each phase.

The feasibility of putting three phases in one cryostat depends on the maximum allowed outer diameter of the cryostat and the amount of electrical insulation required between the conductors. Higher voltages require more insulation. (The allowed outer diameter must be small enough to permit transport on a cable spool as well as fitting through the infra-structure's bends and straight sections.)

The above does not include the heat that must be removed from the terminations. That heat load has been larger than expected and not reported by many groups.[143] CRIEPI's

[143] Related discussion and references to publications by HTS groups appear on pages IV-7 through 11 of A.M. Wolsky, Cooling For Future Power Sector Equipment Incorporating Ceramic Superconductors ,

Yokosuka facility includes the capacity to remove 2 kW from the terminations for its single phase, 77 kV, 1 kA cable. This capacity includes redundancy, reflecting prudence appropriate to demonstrating a prototype.

The total heat load for a cable might be 4 W/m of cryostat or lower.

V.7 Examples of the Relevance of Accommodating Elevation Changes

As elaborated in Chapters X and XII of this report, HTS cable is likely to be more attractive than conventional alternatives in densely populated regions or in regions (e.g., under the English Channel where the Chunnel is 86 m below sea level) in which underground or underwater infrastructure has already been built. The small diameter of HTS cable would enable additional power to be sent through already built right-of-way. In this chapter, we noted that today's cryostats are operated below 20 Bar and one can imagine situations in which the design of fluid flow would have to account of instabilities against convection, as well as exceeding the practically desirable value of 10 Bar.

Those now developing cryogenics for cable might want to defer complications until the next demonstration is successfully built. Here we return to this topic, broached earlier, and explain why "defer" should not become "forget".

We do this by focusing on two regions of dense demand for electrical power (kW/km^2), New York City and Hong Kong. They are simply examples, meant to stimulate the reader to explore features of other regions that interest the reader. Both the natural topography and the man-made topography are relevant. (Some tall buildings contain 13 kV distribution cable.) We also draw attention to the some situations where elevation changes near the generator. These too are examples, meant only to stimulate the reader to consider others.

V.7.1 New York City

New York City is located on several islands and part of the mainland. Thus the city is divided by several waterways, each at sea level. The highest natural point on Manhattan Island is at 185th St. and Fort Washington Ave which is 87m above the water. Another

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prepared for and sponsored by the signatories of the International Energy Agency Implementing Agreement for a Cooperative Programme for Assessing the Impacts of High-Temperature Superconductivity on the Electric Power Sector (12 April 2002). Recent experience might be compared with a sometimes cited paper that estimated that the minimum heat leak through electrolytic tough pitch copper into 77 K would be 45 W/kA. See R. McFee, *Optimum Input Leads for Cryogenic Apparatus*, Review of Scientific Instruments, vol.30, no.2 (1958) page 98-102.

87 m height is nearby in the Bronx at 250th Street and Grosvenor Avenue. The two places are separated by the Harlem River, which is at sea level. (There are other places of comparable height in both Manhattan and the Bronx.) Because cable would be placed underground, its deepest point might be below sea level. If at least one of its terminations is above ground, some cable route's within and around New York City might include elevation changes comparable to 100 m. The New Jersey Palisades, on the opposite bank of the Hudson, rise 107-168 m above the water.

Were already existing infrastructure to be adapted to serve as cable right-of-way, greater changes in elevation would have to be considered. The Holland Tunnel and the Lincoln Tunnel, each passing under the Hudson River, are roughly 30 m below sea level. That is also the depth of the Queens MidTown Tunnel, under the East River. The maximum depth in New York's subway is 60m (at 191st Street). The depth of New York's new Deep Water Tunnel (Tunnel #3) varies between 80 m and 275 m. The lower deck of the George Washington Bridge is 65 m above the Hudson. The deck of the Verrazano-Narrows Bridge is a bit higher, 75 m.

V. 7.2 Hong Kong

Hong Kong is located on many islands and includes several jurisdictions. The heart of the city is on Hong Kong Island. Its highest natural point is the top of Victoria Peak, 556 m above the water.

Hong Kong's railroad tunnels are about 60 m deep and a system of underwater tunnels (HATS) is now under construction. They will transport sewage from several of the islands to one of them, Stone Cutters Island. These tunnels descend 250 m below the water.

V.7.3 Hydro-Electric Generators

The power sector depends on dams for seasonal and sometimes base-load power. The power sector also depends on pumped storage. This is particularly so in Canada, the US, Brazil, China, Russia, Norway, Japan, India, Sweden and France.

At some facilities, the generator terminals and the step-up transformers are located at different elevations. If more power were wanted at some of these facilities, one question would be whether or not there would be sufficient room for additional cable or overhead line, depending on the situation. This will vary from facility to facility. Here, we point out that some of the associated elevation changes are not small.

V.7.3.1 The Dinorwig Pumped Hydro Facility

Dinorwig is located in North Wales, within the UK. Most of the facility is within a mountain. The water falls from one reservoir, located 600 m above the turbines into another reservoir, somewhat below the turbines. Dinorwig has six generators, each rated at 288 MW and each has 18 kV across its terminals. Underground cables guide the electric power to and from the UK's National Grid.[144]

V.7.3.2 The Hoover Dam

The Hoover Dam stems the flow of the Colorado River in the southwestern part of the US. It can provide 2,000 MW, which is guided to the grid by overhead lines near the dam's top, 221 m above its turbines.

V.7.3.3 Three Gorges Dam

The Three Gorges Dam is being built on the Yangtze in China. It is intended to provide 18,000 MW from 26 generators, each 700 MW. The dam will be 181 m high.

V.8 Summary

Improved cryogenics are necessary to realizing the potential offered by HTS cable. Past and present public funding for cryogenics R&D has focused on topics (e.g., space, military sensors, LHe magnets) that do not bear upon applications that require high power and low cost. Now the principle technical challenges are to make

- cryo-coolers that are more reliable and less expensive than today's
- long lengths of flexible cryostat
- intermediate cooling stations
- design cryogenic systems that can cope with changes in elevation that cause the pressure to exceed 10-20 Bar.

The last would make it easier to use existing infrastructure as right-of-way for HTS cables. The avoided cost made possible by dual use infrastructure would be attractive to future investors.

[144] While Dinorwig's change in elevation is large;, it is not unique. A recently built facility in Iceland has a comparable change. In the US, TVA's Raccoon mountain pumped hydro facility has a change in elevation of roughly 305 m (exactly 990 ft.).

Appendix: Fluid Mechanics and Cryogenic Properties of Some Materials

V.A.1 Purpose

Several excellent texts[145],[146]and handbooks[147] are available to the cryogenics practioner. Most are engineers concerned with Liquified Natural Gas or technical physicists concerned with LHe cooling systems for accelerator magnets, MRI magnets and ITER. Effort to advance HTS cable may involve others who have not been or are not know specializing in this field.

This appendix is intended to aid those non-specialists who once studied the relevant principles but have not had recent occasion to think about them. It is a jog to memory, not a self-contained exposition. This sketch may be a convenience for those who, like the author, has not had the benefit of finding anything like it in the literature.

Fluid mechanical issues are important because they bear on the distance between future cables' cooling stations, on the ability to accommodate changes in future cables' elevations, as well as today's need to cool relatively short lengths of demonstration cable.

V.A.2 Conceptual Framework

First we recall the standard conceptual framework. LN_2 and other fluids are described by several kinds of quantities. At each place, *x*, and time, *t*, the fluid has a temperature, T, pressure, P, velocity, **v**, and mass density, ρ, and (equivalently) its reciprocal, the (mass) specific volume, *v*. The fluid's energy has three contributions: (a) from its motion, (b) from its location, and (c) from its internal state (given by temperature and pressure). The temperature and pressure determine the fluid's mass density and the fluid's (mass) specific internal energy. They in turn determine its (mass) specific entropy. (The latter might also depend on gradients of T and P.) The fluid's energy can change as the result of energy transfer through a surface surrounding it. Further, even if isolated, the fluid can dissipate its kinetic or potential energy and the result will be an increase in its internal energy.

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[145] R.F. Barron, Cryogenic Heat Transfer, Taylor & Francis (Philadelphia, 1999) ISBN 1-56032-551-8

[146] R.F. Barron, Cryogenic Systems (2nd edition), Oxford University Press (New York, 1985) ISBN 0-19-503567-4

[147] S.S. Kutateladze and V.M. Borishanskii, A Concise Encyclopedia of Heat Transfer,-original in Russian, translated to English by J.B. Arthur and published by Pergamon Press (Oxford, 1966)

Now we show how the above is stated precisely when the fluid is not too far from equilibrium (i.e., gradients of T and P enter at most linearly). It is universally assumed that this is more than sufficient for practical purposes. They involve approximations that are spelled out later.

V.A.2.1 Rates of Change

Before recalling the basic equations, one should describe to what they refer. They can describe the same mass within a moving volume of changing shape or the can refer to what occurs within a fixed volume of unchanging shape. In the former case, the equations resemble those for particles. In practice, the latter is more informative; then the equations must express fluxes though the surfaces that bound the unchanging region. These two different orientations are manifest in two different rates of change. One is that recorded by an observer moving at the same velocity as the fluid. His or her time derivative is denoted by Dt. The time derivative ∂_t, is the rate of change to an observer for whom the fluid has velocity, v. The relation between them is $D_t = \partial_t + \mathrm{v}\cdot\nabla$.

V.A.2.2 Basic Boundary Condition and Equations

One other observation: the velocity of a fluid at a wall is identical to the wall's velocity. Following are the basic equations and the notions to which they refer. We begin with the equations describing the motion of fluids. Then we turn to the temperature and pressure in the fluid.

V.A.2.2.1 Motion

only mass transport can change mass density

1) $D_t \rho = -\rho div[\mathbf{v}] \quad \Leftrightarrow \quad \partial_t \rho = -div[\rho \mathbf{v}]$

force accelerates mass

2) $\rho D_t \mathbf{v} = \mathbf{f}$

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forces depend on the attributes of the fluid

$$\text{3a)} \quad \mathbf{f}_i = \underbrace{\rho \mathbf{g}_i}_{weight} + \overbrace{\partial_j}^{\text{divergence of}} \overbrace{\left\{ \underbrace{-P\delta_{ij}}_{pressure} + \underbrace{\tilde{\sigma}_{ij}}_{viscous\ stress} \right\}}^{stress}$$

$$\text{3b)} \quad \mathbf{f}_i = \underbrace{\rho \mathbf{g}_i}_{weight} + \overbrace{\partial_j}^{\text{divergence of}} \overbrace{\left\{ \underbrace{-P\delta_{ij}}_{pressure} + \underbrace{\zeta\left[T,P\right]\left(\mathbf{v}_{n,n}\delta_{ij}\right) + 2\eta\left[T,P\right]\left(\frac{\mathbf{v}_{i,j} + \mathbf{v}_{j,i}}{2} - \frac{1}{3}\delta_{ij}\mathbf{v}_{n,n}\right)}_{viscous\ \text{stress}} \right\}}^{stress}$$

η is called the "Coefficient of Shear Viscosity" or the "dynamic viscosity"

ζ is called the "Coefficient of Bulk Viscosity". It often goes unmentioned

because ζ only effects compressible flows, a difficult topic.

After writing F=ma in dimensionless form, one finds that the contribution of each of the three forces to the acceleration is controlled by a dimensionless ratio: weight is measured by Lg/v^2, pressure gradient by $P/\rho L$ and viscosity by $\eta/\rho v L$. After choosing the fiducial length, L, to be pipe diameter, the third ratio becomes the inverse of the Reynolds Number.

Before stating the other basic equations, we pause to consider the ways in which the momentum and the kinetic energy of a fluid within a volume can change with time.

First, consider the density of momentum. Equations 1, 2, and 3 imply that

$$\partial_t(\rho \mathbf{v}_i) = \partial_j(-P\delta_{ij} + \tilde{\sigma}_{ij} - \rho \mathbf{v}_i \mathbf{v}_j) + \rho \mathbf{g}_i$$

Consider a volume within a horizontal electrical cable. Suppose the cable is in steady-state operation.

$$0 = \frac{d}{dt}\int_{\text{cable volume}} d^3x\rho\mathbf{v}_i = \int_{\text{cable surface}} d\mathbf{S}_j(-P\delta_{ij} + \tilde{\sigma}_{ij} - \rho\mathbf{v}_i\mathbf{v}_j) + \int_{\text{cable volume}} d^3x\rho\mathbf{g}_i$$

One sees that the change in pressure between the two ends of the volume depends on the viscous stress. Engineers parametrize this by writing

$$P[x + \Delta x] - P[x] = -f\left(\frac{\rho\mathbf{v}\cdot\mathbf{v}}{2}\right)\frac{\Delta x}{D_{pipe}}$$

All the complexity of the flow manifests itself in one parameter, the friction factor *f*. It depends on the fluid's density and viscosity and the flow which also depends on the size the cable's wall as well as its gross shape and detailed shape. The pipe's gross shape is described by an effective diameter simply related to the wall's gross perimeter. The pipe's detailed shape is described by the pipe's roughness. It is conventional to write

$$f = f[N_{\mathrm{Re}}, \varepsilon] \qquad \text{where} \qquad N_{\mathrm{Re}} \equiv \rho \mathrm{v} \mathrm{D}_{\mathrm{pipe}}/\eta \qquad \text{and} \qquad \varepsilon \equiv \text{roughness}/\mathrm{D}_{\mathrm{pipe}}$$

Second, consider the density of kinetic energy. Equations 1, 2, and 3 imply that

$$\partial_t\left(\frac{\rho \mathrm{v}^2}{2}\right) = \underbrace{Pdiv[\mathbf{v}]}_{\substack{\text{manifests possibility} \\ \text{of compressible flow}}} - \underbrace{div\left[\rho\mathbf{v}\left(\frac{\mathrm{v}^2}{2} + \frac{P}{\rho}\right) - \mathbf{v}_k\tilde{\sigma}_{kj}\right]}_{\text{energy transport thru surface, } \mathbf{v} = 0 \text{ @wall}} + \underbrace{\rho(\mathbf{v}\cdot\mathbf{g})}_{\substack{\text{falling bodies} \\ \text{speed up}}} - \underbrace{(\partial_j\mathbf{v}_k)\tilde{\sigma}_{kj}}_{\text{viscous dissipation}}$$

Each of the first three terms on the right hand side can increase or decrease the kinetic energy within the volume. The first allows for dilution or concentration. The second term allows for energy transport, in either direction, through a surface. The third states that falling matter speeds up and rising matter slows down. But the last term is different; it can never increase kinetic energy. In fact, it almost always reduces it. This can be seen by writing out the last term. It is the sum of two squares.

$$\mathbf{v}_{i,j}\tilde{\sigma}_{ij} = 2\eta\left(\left(\frac{\mathbf{v}_{i,j} + \mathbf{v}_{j,i}}{2} - \frac{1}{3}\delta_{ij}div[\mathbf{v}]\right)\left(\frac{\mathbf{v}_{i,j} + \mathbf{v}_{j,i}}{2} - \frac{1}{3}\delta_{ij}div[\mathbf{v}]\right)\right) + \zeta\,(div[\mathbf{v}])^2$$

From considering the equations we get no clue as to what determines the temperature and pressure. We also have no idea of what becomes of the fluid's kinetic energy. The mechanical equations just predict its disappearance, V.**A.2.2.2 Temperature and Pressure**

To complete the picture, one must introduce two new ideas. One is called internal energy. The sum of the fluid's kinetic and internal energy should be time-independent when the fluid is isolated. The disappearing kinetic energy should reappear in the internal energy. The other is called entropy. It should increase just as the kinetic energy dissipates and the entropy increase should provide the means to increase the fluid's internal energy. These ideas are implemented by the following two equations

(mass) specific internal energy density varies with

(mass) specific entropy density and (mass) specific volume (or mass density)

4) $$D_t \underbrace{u}_{\text{internal energy}} = \underbrace{TD_t s}_{\text{heat rate}} - \underbrace{PD_t v}_{\text{work rate}} = TD_t s + \frac{P}{\rho^2} D_t \rho$$

(mass) specific entropy density can change

by transport of heat through its bounding surface

or by growth within the fluid

5) $$\rho T D_t \underbrace{s}_{\text{mass specific entropy density}} = \underbrace{(\partial_j \mathbf{v}_k)\tilde{\sigma}_{kj}}_{\text{viscous dissippation within the fluid}} - \underbrace{div[\mathbf{q}]}_{\text{heat flux through fluid's surface}}$$

in ordinary circumstances $\mathbf{q} = -\kappa \nabla T$

κ is called the fluid's Thermal Conductivity.

Taken together, the five fundamental equations imply that the sum of the kinetic and internal energy of an isolated system is conserved, as stated next. (Of course, there is no isolation from gravity.)

$$\partial_t\left(\frac{\rho v^2}{2} + \rho u\right) = \left\{\left(-div\left[\rho\mathbf{v}\left(\frac{v^2}{2} + u + \frac{P}{\rho}\right) - \mathbf{v}_i \tilde{\sigma}_{ij} + \mathbf{q}\right]\right) + \rho\mathbf{v}\cdot\mathbf{g}\right\}$$

V.**A.3 From the Basics to the Equation of Heat Transfer**

Equation (5) states how the entropy changes. Recalling how entropy depends on temperature and pressure

$$D_t s = s,_T D_t T + s,_P D_t P = \frac{c_p}{T} D_t T - v\alpha_T D_t P = \frac{c_p}{T} D_t T - \frac{\alpha_T}{\rho} D_t P$$

(above c_p denotes the specific heat at constant pressure and α_T denotes is the coefficient of thermal expansion at constant pressure), one finds how the change in temperature depends on heat flux, dissipation and change in pressure.

$$\rho c_p D_t T = -\underbrace{div[\mathbf{q}]}_{\substack{\text{heat flux through} \\ \text{fluid's surface}}} + \underbrace{(\partial_j \mathbf{v}_k)\tilde{\sigma}_{kj}}_{\substack{\text{viscous dissipation} \\ \text{within the fluid}}} + \underbrace{T\alpha_T D_t P}_{\substack{\text{changing pressure} \\ \text{affects entropy}}}$$

Upon neglecting the effect of pressure, the above becomes “the equation of heat transfer”.

V.A.4 Describing Properties of Specific Materials

A fluid may be described by a single function, its Gibbs Potential, g[*T*,*P*]. The same fluid can also be described by a pair of functions--one for its (mass) specific volume or mass density and the other for its (mass) specific entropy density.

The Gibbs Potential

$$g = G[T,P] \quad \text{and} \quad -s = G,_T[T,P] \quad \& \quad v = G,_P[T,P]$$

The Thermal Equation of State

$$v = G,_P[T,P] \qquad \text{or} \qquad \rho = \frac{1}{G,_P[T,P]}$$

"thermal equation of state" for a liquid is often expressed by a table.

Such a table for liquid nitrogen will be presented in the next section.

"thermal equation of state" for a gas is often expressed by a "virial expansion"

$$v = \frac{RT_c}{P_c}\frac{(T/T_c)}{(P/P_c)}\left(1 + v_1[T/T_c](P/P_c) + v_2[T/T_c](P/P_c)^2 + \ldots\right)$$

Two reasons commend the practice. It presents the behavior of a real gas at low pressure (or density) as a series of corrections to an ideal gas. The behavior near the liquid-vapor-gas critical point is common to all gases. Neither bears on cable cryogenics.

The Caloric Equations

Entropy

$$s[T_1,P_1] - s[T_0,P_0] = \int_{\lambda_0}^{\lambda_1} d\lambda \frac{d\tau}{d\lambda}\frac{c_p[\tau,\pi]}{\tau} - \int_{\lambda_0}^{\lambda_1} d\lambda \frac{d\pi}{d\lambda} \upsilon[\tau,\pi]\alpha_T[\tau,\pi]$$

Internal Energy

$$u[T_1,P_1] - u[T_0,P_0] = \int_{\lambda_0}^{\lambda_1} d\lambda \left\{\frac{d\tau}{d\lambda}?+\frac{d\pi}{d\lambda}?\right\}$$

V.A.5 Friction Factor and Properties of Liquid Nitrogen

The data cited in this section was taken from N.B. Vargaftik, Y.K. Vinogradov, V.S.Yargin, Handbook of Physical Properties of Liquids and Gases, Pure Substances and Mixtures, 3rd augmented and revised edition, Begel House Inc (New York, 1996). The numbers were reformatted to make their significance clearer. Some properties of some fluids are also posted on the web; for example see, http://webbook.nist.gov/chemistry/fluid/.

V.A.5.1 Equilibrium Properties

Some properties of some fluids are properties. The following tables present the relevant data for liquid nitrogen. Data for nitrogen vapor are highlighted in green.

Table V.A.5.1.1
Mass Density (kg/m3) of) of LN_2
Depends on
Temperature and Pressure

30 Bar	843.8	801.1	753.8	701.5	638.0	541.1
20 Bar	841.8	798.4	750.1	695.8	627.5	79.5
10 Bar	839.8	795.6	746.1	689.6	37.0	
5 Bar	838.7	794.1	744.1	18.9		
1 Bar	837.9	4.4	3.8			
Pressure						
Temperature	70 K	80 K	90 K	100 K	110 K	120 K

Table V.A.5.1.2
(Mass) Specific Entropy Density (kJ/K /kg) of LN_2
Depends on
Temperature and Pressure

30 Bar	2.611	2.887	3.139	3.350	3.570	3.823
20 Bar	2.617	2.894	3.137	3.362	3.589	79.5
10 Bar	2.622	2.901	3.147	3.375	37.0	
5 Bar	2.625	2.905	3.151	18.9		
1 Bar	2.628	5.5	5.6			
Pressure						
Temperature	70 K	80 K	90 K	100 K	110 K	120 K

Table V.A.5.1.3
Specific Heat at Constant Pressure (kJ/K/kg) of LN_2
Depends on
Temperature and Pressure

Pressure / Temperature	70 K	80 K	90 K	100 K	110 K	120 K
30 Bar	1.986	2.065	2.059	2.174	2.485	3.743
20 Bar	1.999	2.077	2.078	2.217	2.626	2.116
10 Bar	2.012	2.089	2.099	2.269	1.468	
5 Bar	2.018	2.096	2.110	1.255		
1 Bar	2.023	1.022	1.068			

V.A.5.2 Transport Properties of LN_2

The following tables present the relevant data for liquid nitrogen. Data for nitrogen vapor are highlighted in green.

TableV.A.5.2.1
Thermal Conductivity (10^{-3} W/K/m) of LN_2
Depends on
Temperature and Pressure

Pressure / Temperature	65K	70 K	78 K	80 K	90 K	94 K	100 K	110 K	120 K
30 Bar		151.2		135.6	117.3		99.2	81.3	62.4
20 Bar		150.5		134.6	116.0		97.5	78.8	vapor
10 Bar		149.9		133.6	114.7		95.7	vapor	
5.00 Bar						106.3	vapor		
3.60 Bar					113.8	vapor			
1.37 Bar				132.7	vapor				
1.09 Bar			136,4	vapor					
0.39 Bar		153.8	vapor						
0.17 Bar	154.6	vapor							
	vapor								

TableV.A.5.2.2

Coefficient of Shear Viscosity (10^{-6}Pa-second) of LN_2

Depends on

Temperature and Pressure

30 Bar	298.9	232.6		150.9	106.9		79.6	59.4	40.4
20 Bar	294.8	229.0		148.1	104.6		77.4	56.8	9.4
10 Bar	290.7	225.3		145.3	102.2		75.1	8.16	
5 Bar						89.0	vapor		
						7.19			
3.60 Bar					100.7				
					6.84				
1.37 Bar				142.9					
				5.95					
1.09 Bar			154.7						
			5.77						
0.39 Bar		221.8							
		5.05							
0.17 Bar	286.5								
	4.61								
Pressure Temperature	65K	70 K	78 K	80 K	90 K	94 K	100 K	110 K	120 K

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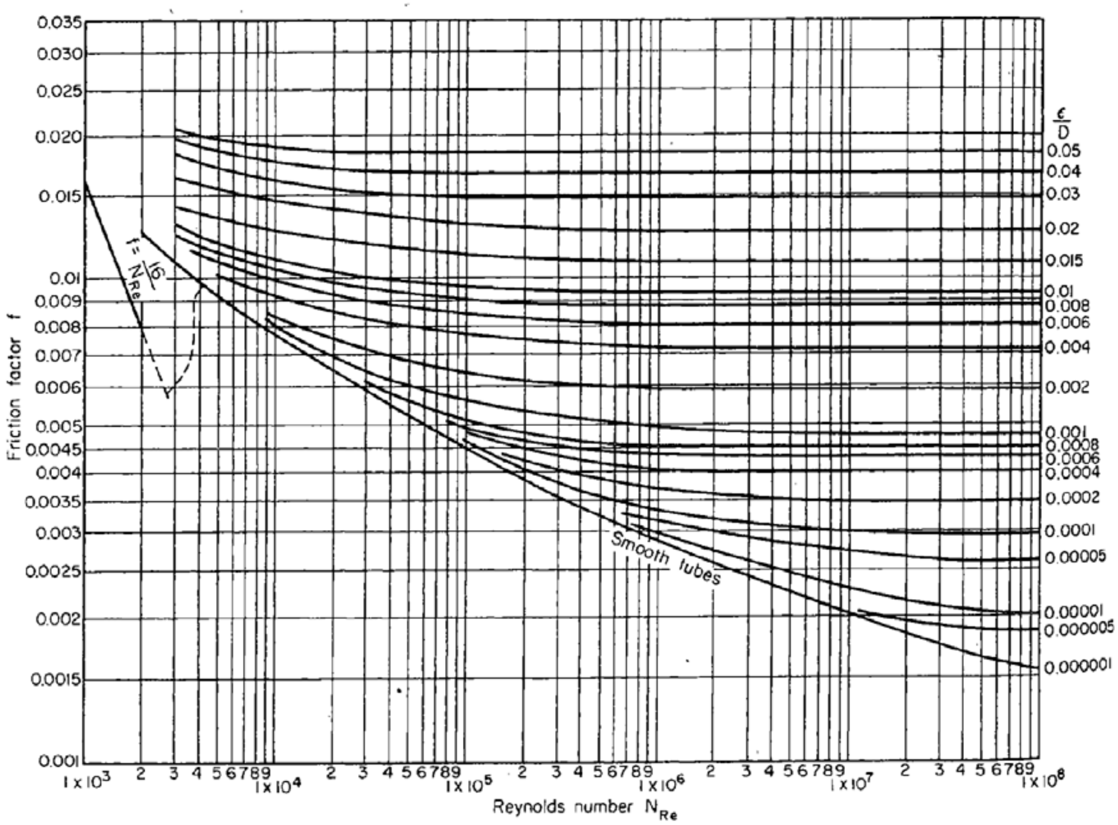
(02 December 2004).

TableV.A.5.2.3
Coefficient of Shear Viscosity of Saturated N_2

Temperature	Saturation Pressure	η_{liquid}	η_{vapor}
Kelvin	*Bar*	10^{-6} *Pa – seconds*	10^{-6} *Pa – seconds*
65	0.1742	286.5	4.61
66	0.2065	271.7	4.69
68	0.2852	245.0	4.87
70	0.3859	221.8	5.05
72	0.5126	201.5	5.23
74	0.6696	183.8	5.40
76	0.8614	168.3	5.59
78	1.093	154.7	5.77
80	1.369	142.9	5.95
82	1.694	132.4	6.13
84	2.074	123.1	6.31
86	2.515	114.8	6.49
88	3.022	107.4	6.66
90	3.600	100.7	6.84
92	4.256	94.6	7.01
94	4.995	89.0	7.19
96	5.824	83.9	7.36
98	6.748	79.1	7.53
100	7.775	74.6	7.70
102	8.910	70.4	7.88
104	10.16	66.3	8.06
106	11.53	62.5	8.24
108	13.03	58.8	8.44
110	14.67	55.2	8.65
112	16.45	51.7	8.88
114	18.36	48.3	9.14
116	20.47	44.9	9.44
118	22.72	41.4	9.81
120	25.15	37.8	10.3

Figure V.A.5.4
Fanning Friction Factors.
Reynolds number Re ≡ DVρ/μ
where D = pipe diameter, V = velocity, ρ = fluid density, and μ = fluid viscosity.
(Based on Moody, Trns. ASME, 66, 671 (1944).



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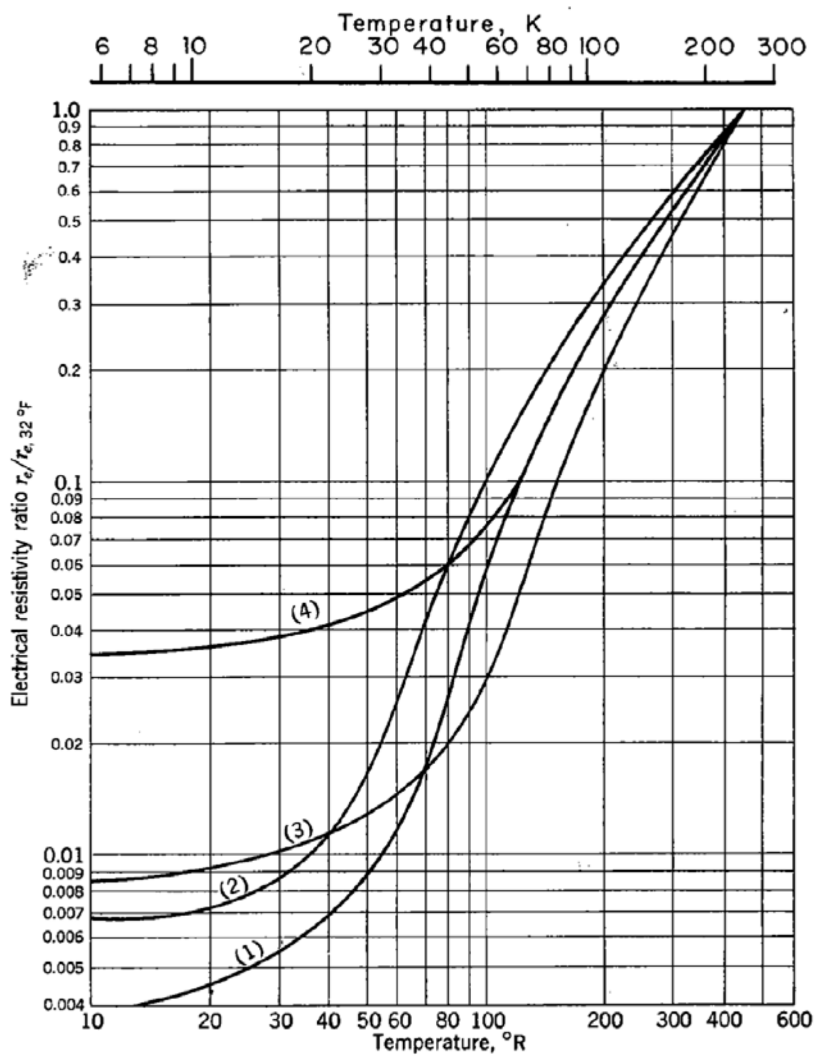
V.A.6 Electrical Resistivity of Ag, Al, Cu and Fe

Ratio of Low Temperature Resistivity to Ambient Temperature Resistivity

Figure V.A.6
Electrical Resistivity Ratio for Several Materials at Low Temperatures: (1) Copper; (2) Silver; (3) Iron; (4) Aluminum (Stewart and Johnson 1961).



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Note that the resistivity ratio depends on purity and condition of the material (annealed vs. cold worked.) The copper in cables may differ from what is presented in the chart. A good discussion on resistivity at low temperatures is available in chapter 5 of: "Materials At Low Temperatures", edited by R.P. Reed and A. F. Clark and published by the American Society of Metals, ©1983 (ISBN: 0-87170-146-4).[148]

[148] The author is grateful to the staff at Super-Power for drawing his attention to this reference.

V.A.7 Example of Pressure Drop and Energy Dissipation due to Viscosity

For the sake of illustration, consider a straight pipe within which LN_2 is intended to operate in the range 65-77K and a system that is designed to circulate the LN_2 at 10 – 50 liters/minute.

By consulting the properties tables presented above, one sees that the LN_2 mass flow rate is approximately 0.14 – 0.7 kg/second. Assuming the diameter of the central channel is 2.5 cm, the linear flow rate would be in the range 3.4 – 17 cm/second. With the same assumption of 2.5 cm diameter, the smallest Reynolds Number is $N_{\mathrm{Re}} = \frac{\rho v D}{\eta} \approx \frac{840 \times 3.4 \times 2.5 \times 10^{-4}}{223 \times 10^{-6}} = 3.2 \times 10^{3}$ and the largest is five times greater.

So the Reynolds Numbers will lie in the range $3.2 \times 10^{3} \leq N_{\mathrm{Re}} \leq 1.5 \times 10^{4}$. Consulting Moody's chart, one sees that the friction factor is in the range 0.015-0.007. And the pressure drop is 0.15-0.07 Bar/km.

The mechanical energy dissipated is:

$$\frac{dp}{dx} \times \frac{dv}{dt} = \begin{matrix} 0.150\, Bar/km \times 10\, liter/min = 0.003\ W/m\text{@operatingtemperature} \\ 0.007\, Bar/km \times 50\, liter/min = 0.006\ W/m\text{@operatingtemperature} \end{matrix}$$

Of course, an actual cable will include passages that are not straight. As a result, more dissipation is expected.

VI. Electrical Insulation for Cryogenic Cable

VI.1 Purpose and Scope

Low-temperature, high-voltage dielectrics are very important to the successful, future application of HTS cable. This chapter is meant to increase appreciation of its topic by non-experts, as well as drawing the attention of practitioners to work of potential interest. Many of today's practitioners brought their experience with materials science or metallic superconductors to the recent effort to develop cable incorporating ceramic superconductors. Fewer had experience with high voltages and low temperatures.

In fact, before present efforts to develop equipment incorporating HTS for the power sector, there was no need to pay attention to this chapter's topic. Thus, few people have experience with high-voltage (e.g., 69 kV) insulators operating at LN_2 temperatures.[149,150] Of course, attention was given to insulation for superconductors cooled by LHe and used in magnets.[151] These are relatively low-voltage devices. When a bending magnet quenches, the voltage difference across its leads might be 1-3 kV and future fusion magnets might give rise to 10 kV.

Though most effort in the HTS community has been and is directed to developing conductor, several demonstration projects have shown that functioning cryogenic, electrical insulation is crucial to the success of prototype devices.[152]

Section VI.2 introduces the relevant phenomena and reconciles the jargon of electrical engineering with the jargon of the physical sciences. Section VI.2.4 introduces a crucial

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[149] Among others, research on LN_2 dielectrics is being conducted at the Laboratoire Electrostatique et de Matériaux Diélectrique, CNRS Grenoble (France), University of Nagoya (Japan), and the University of Southampton (UK).

[150] For a summary of past LTS cable projects that emphasizes dielectric concerns, see E.B. Forsyth, *The High-Voltage Design of Superconducting Power Transmisson Systems*, IEEE Insulation Magazine, volume 6, number 4, (July/August 1990) pages 6-16.

[151] F. Krähenburhl et al, "Properties of Electrical Insulating Materials at cryogenic temperatures: a literature review", IEEE Electrical Insulation Magazine, vol. 10, 1994 pages 10-22. If the magnet's field were to change suddenly (e.g., as the result of quench), then a voltage difference between successive turns would appear.

[152] Though this report does not concern transformers, the writer believes that anyone reading this report should bear in mind the following declaration, dated 25 August 2003, by IGC on its Form 10-K to the US Securities and Exchange Commission: "We believe that Second Generation material will be required for commercial success of HTS transformers. In the interim, until Second Generation materials become commercially viable, further research and development will be necessary to address high voltage dielectric insulation requirements and the introduction of load tap changing capability."

engineering-economic consideration, the cable's electrical insulation's lifetime. Sections VI.3 and VI.4 relate the phenomena to present practice using overhead power lines and compressed gas insulated cables (CGIL) respectively. Sections VI.5 and VI.6 concern underground cable, cooled by LN_2. Finally Section VI.7 draws attention to the principal technical uncertainties. A word about the equations that appear in some sections: these equations are intended to aid those who want to follow up by consulting the professional literature; these equations can be skipped by anyone who finds them burdensome. Everything of import to a manager appears in the text.

VI.2 Technical Orientation

A few words about nomenclature might be helpful. Power engineers often use the terms "dielectric" and "electrical insulator" synonymously. For the sake of clarity, this report will distinguish between these terms. Here, insulator refers to performance and function, while "dielectric" refers to composition; insulators are made from dielectrics, just as conductors are made from metals.

VI.2.1 Conductor or Insulator or Neither

Though paper and oil are still in use, today's conventional cable often incorporates composites (e.g., polypropylene laminated paper) or synthetic polymer dielectrics (e.g., polyethylene or ethylene-propylene-rubber). Today's cable conductors are made from aluminum, though copper is still used.

Two properties distinguish conductors: (1) Charge, placed within a conductor, does not stay within it; after a brief time, equilibrium is established when the charge resides only on the conductor's surface. (2) Little energy dissipation is concomitant with electrical current. These two properties are related because current is moving the charge and unimpeded current allows the charge's mutual repulsion to disperse it as widely as possible. Insulators have the reverse properties: (1) charge can remain within an insulator, and (2) current flows only with difficulty.

These remarks do not exhaust the subject because the same material can act as either an insulator or conductor. There is nothing exotic about this. For example, over long times or for steady-state phenomena, the ground is a conductor, while for very short times (e.g., sudden transients) the ground is not a conductor. Below we address this theme in a way that is precise enough to be useful.

Bearing the above in mind, one asks: "How long does it take for concentrated mobile charge to disperse?" Its mutual repulsion will push the charge apart, but that repulsion is not the only force to be consider. The rest of the material also exerts force on the mobile charge. Here we show how to make the comparison.

Let ρ denote the density of mobile charge. It can only change as the result of a conduction current density, **J**. This relation is represented by the local conservation of charge:

$$0 = \partial_t \rho + div[\mathbf{J}]$$

The relation between the current density, **J**, and the observable electric field, **E**, reflects the constitution of the material. For some materials, called "ohmic", the constitutive relation is simple

$$\mathbf{J} = \frac{1}{\rho}\mathbf{E} = \sigma\mathbf{E}$$

(The only reason to introduce the conductivity is to provide a way to avoid writing equations with the overworked Greek letter ρ. That letter denotes both the resistivity and the charge density, each usage being long sanctioned by custom.)

Another property of the material is its polarizability — that is, how does an observable electric field affect the charged bodies that are not free to move within the material? The simplest electro-technical materials (e.g., air or water) can be described as follows:

$$\mathbf{P} = (\varepsilon_r - 1)\varepsilon_0\mathbf{E} = \kappa\varepsilon_0\mathbf{E} \equiv \chi_e\varepsilon_0\mathbf{E}$$

or, writing the same relation in a different but also traditional way,

$$\mathbf{D} \equiv \varepsilon_0\mathbf{E} + \mathbf{P} = \varepsilon_0\mathbf{E} + (\varepsilon_r - 1)\varepsilon_0\mathbf{E} = \varepsilon_r\varepsilon_0\mathbf{E}$$

where ε_r is the relative permittivity and κ and χ_e each customarily denotes the electric susceptibility. In power engineering literature, ε_r, is sometimes denoted by ε' and called the "real part of the complex dielectric constant." The "imaginary part" will be introduced in the next section, where we discuss the dissipation of electrical energy in the dielectric.

The relations $div[\mathbf{D}] = \rho$ and $0 = \partial_t \rho + div[\mathbf{J}]$ describe all materials. Particular materials differ from each other in their conductivity and permittivity. One finds the relaxation time of the charge density in a homogeneous material by the reasoning shown below.

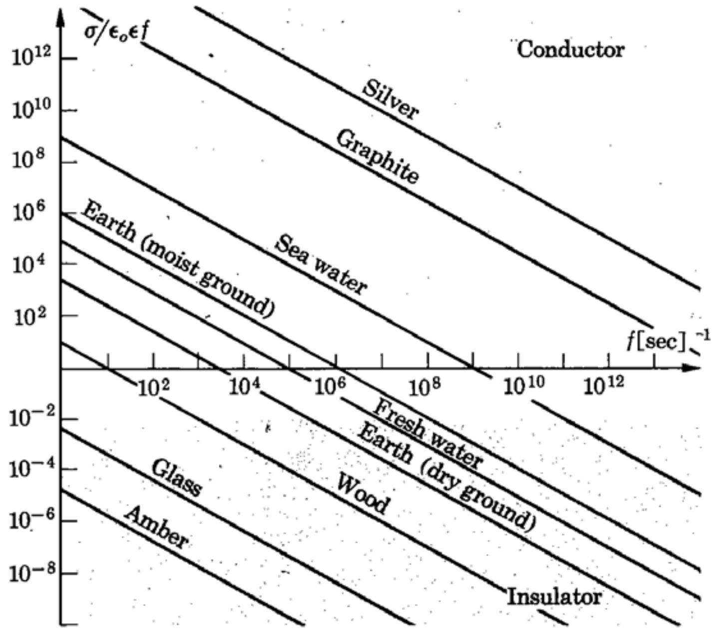
$$0 = \partial_t\rho + div[\mathbf{J}] \Rightarrow 0 = \partial_t\rho + div[\sigma\mathbf{E}] \Rightarrow 0 = \partial_t\rho + div\left[\frac{\sigma}{\varepsilon_r\varepsilon_0}\mathbf{D}\right] \Rightarrow 0 = \partial_t\rho + \frac{\sigma}{\varepsilon_r\varepsilon_0}\rho$$

So, the relaxation time of a particular ohmic material is $\frac{\varepsilon_r\varepsilon_0}{\sigma}$. To be informative, this relaxation time must be put in the relevant context. And so, another question presents itself: "How does the relaxation time compare with the other durations that characterize the process of interest?" For power engineers the dominant time scale is the reciprocal of the AC frequency, *f*, either 1/50 second or 1/60 second. Electrical engineers distinguish conductors from insulators according to the ratio of the relaxation time to the duration of one cycle, the figure of merit shown below:

$$\tan[\delta_{static}] \equiv f\,\frac{\varepsilon_r\varepsilon_0}{\sigma}$$

The name, $\tan[\delta_{static}]$is just a convention; it means no more than the ratio on the right-hand-side of equation. This quantity is different from the quantity to be introduced below that is sometimes named the "loss tangent". Figure VI.2.1 shows how the frequency affects whether or not a material is called an insulator or a conductor.

Figure VI.2.1
Ratio of Period to Electrostatic Relaxation Time
for Some Common Electro-Technical Materials



Whether or not something is an electrical conductor or electrical insulator depends on the context, in particular on the duration of interest. For a duration of more than over 0.02 s (corresponding to 50 Hz), silver behaves like a conductor and glass like an insulator. Dry ground is not easily categorized or approximated. During a lightning bolt's rise time (e.g., 2×10^{-6} s), dry ground and fresh water behave more like insulators.

Table VI.2.1
Resistivity of Earth[153]

Qualitative Character of Ground	Resistivity order-of-magnitude (ohm-meter)
swampy	$10\text{-}10^2$
dry	10^3
slate	10^7
sandstone	10^9

VI.2.2 Power Engineers' Conventional Insulators and Conductors

The conductivities, σ, of today's cable dielectrics are in the range$10^{-14}\text{-}10^{-18}$ $(\Omega\text{-m})^{-1}$.

For air, the real permittivity is $1.000563\times\varepsilon_0$, while for most solid and liquid insulators employed within cable, the value of $\varepsilon_r\times\varepsilon_0$ lies in the range $2.0\times\varepsilon_0$- $3.5\times\varepsilon_0$.[154]

As is well known, electro-technical equipment is designed and operated under the assumption that the earth is a conductor. Because nature does not always offer a "good" earth (its electrical resistivity varies with location and weather), power engineers construct electrodes to enhance their equipment's electrical contact with the earth. That contact is the primary determinant of earth's resistance, not the distance between electrodes.[155]

During the past twenty years, the most common insulators in newly purchased cable have been ethylene-propylene rubber (EPR), low density polyethylene (PE), and cross-linked polyethylene (XLPE). The last offers the best performance because its dielectric constant is the lowest, and its operating temperature is higher than that for other insulators. Today's most common conductor is aluminum because it is less expensive than copper.

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153 A.E. Guile and W. Paterson, Electrical Power Systems, vol.1 Pergamon Press (Oxford, 1977) page 87.

154 R. Bartnikas and K.D.Srivastava, Power and Communication Cables, IEEE Press and McGraw-Hill (New York, 2000) ISBN#0-7803-1196-5, page 94.

155 Most of the electrical resistance comes from the earth near the electrode's surface, because it is there that the current must "bunch up". For an introduction to the issue, taking account of different strata, see W.R. Smythe, Static and Dynamic Electricity, 3rd edition, McGraw-Hill (New York, 1968) page 262. N.B., Smythe cites Stefanesco and Schlumberger, *Journal de Physique*, vol.1, 1930 page 132.

VI.2.3 Losses During Normal AC Operation

During normal operation, dielectrics conduct only negligible transport current. However, their polarization does alternate. Most important, during each cycle, electrical energy dissipates and the dielectric's temperature rises. The rate of dissipation of electrical energy, $\dot{Q}$, is related to the rate of entropy increase, $\dot{S}$, and the time dependent field strengths, as shown below.

$$\oint dt \int_V d^3x \left(\mathbf{E} \cdot \left(\varepsilon_0 \dot{\mathbf{E}} + \dot{\mathbf{P}} \right) \right) = \oint dt \left(T[t] \dot{S}\left[T\left[t \right], \mathbf{P}[t] \right] \right) = \dot{Q}$$

Because the transport current is negligible, this effect is almost entirely separate from the "dispersion of mobile charge", described in Section VI.2.1. What engineering literature describes as "leakage current" is principally alternating polarization.[156] Most of the dissipation results from the dielectric's hysteresis, concomitant with continual reorientation of the constituents of the dielectric.[157]

Because power engineers and scientists are both working to apply HTS, this section expresses the dissipation, $\langle \dot{Q} \rangle$, in two ways: (a) the way familiar to scientists (see LHS below) and (b) the way familiar to power engineers (see RHS below).

$$\underbrace{\mathbf{E} \cdot \left(\varepsilon_0 \dot{\mathbf{E}} + \dot{\mathbf{P}} \right)}_{physics\ style} = \underbrace{\left(\frac{\mathbf{E}_{complex} + \mathbf{E}^*_{complex}}{2} \right) \cdot \left(\frac{(j\omega)\varepsilon_{complex}\mathbf{E}_{complex} + (-j\omega)\varepsilon^*_{complex}\mathbf{E}^*_{complex}}{2} \right)}_{power\ enginnering\ style}$$

where $\mathbf{E}_{complex}$ is proportional to $\exp[j\omega t]$

and where $\varepsilon_{complex} \equiv \varepsilon' - j\varepsilon'' = \varepsilon_r - j\left(\varepsilon_r \times \tan[\delta_{loss}] \right)$

The average rate of dissipation, $\langle \dot{Q} \rangle$, appears after integrating over one cycle.

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[156] Recall Maxwell's equation, $\mathrm{curl}[\mathbf{B}] = \mu_0(\mathbf{J}_{transport} + \mathrm{curl}[\mathbf{M}] + \partial_t \mathbf{P}) + c^{-2}\partial_t \mathbf{E}$.

[157] A.E. Guile and W. Patterson, Electrical Power Systems, volume 1, Pergamon Press (Oxford, 1977) page 166.

$$\langle \dot{Q} \rangle = \underbrace{f \oint dt \mathbf{E} \cdot \dot{\mathbf{D}} = f \oint dt}_{\textit{physics style}} = \underbrace{\left(\frac{j\omega\left(\varepsilon_{complex} - \varepsilon^{*}_{complex}\right) \int_V d^3x \left(\mathbf{E}_{complex} \cdot \mathbf{E}^{*}_{complex}\right)}{4} \right) f \oint dt}_{\textit{power engineering style}}$$

$$\langle \dot{Q} \rangle = \underbrace{f \oint dt \int_V d^3x \left(\mathbf{E} \cdot \dot{\mathbf{P}}\right)}_{\textit{physics style}} = \underbrace{\left(\omega \tan\left[\delta_{loss}\right] \frac{\varepsilon_r \int_V d^3x \left(\mathbf{E}_{complex} \cdot \mathbf{E}^{*}_{complex}\right)}{2} \right)}_{\textit{power engineering style}}$$

After integrating over the volume of the dielectric within a cable, as indicated above, one obtains the power engineer's lumped description of the rate of heat generation; it is shown below.

$$\dot{Q}_{dielectric} = \omega \times \tan\left[\delta_{\mathrm{loss}}\right] \times \frac{1}{2} \tilde{C} V^2 \times \left(\text{length of cable}\right)$$

where $\tilde{C}$ denotes the phase capacitance per unit length

and V denotes the rms voltage difference between conductors

and $\omega = 2\pi f$

Thus, the smaller the product of "loss tangent" and the relative permittivity, the less the dissipation per unit volume of dielectric. That product is one of the important characteristics of dielectric material.

The rate of dissipation depends on the square of the voltage difference because the rate depends on the volume integral of $\mathbf{E} \cdot \dot{\mathbf{P}}$. Operation at high voltage (i.e., large electric field) entails measurable dissipation.[158, 159] The concomitant heat must be removed from

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[158] These considerations are not academic. The New York Power Authority chose polypropylene laminated paper, rather than Kraft paper, for its 345 kV cable because of the latter was expected to dissipate 28.9 W/m while the former (PPLP) was expected to dissipate 11.9 W/m according to J. Grzan, E.I. Hahn, R.V. Casalaire, and J.O.C. Kansog, "*The 345 kV Underground/Underwater Long Island Sound Cable Project*", IEEE 92SM 368-1 PWRD, presented at IEEE PES 1992 Summer Meeting, Seattle Washington 12-16 July 1992.

[159] Dissipation depends on the dielectric and the voltage difference. Power engineers take account of dissipation in conventional cables having (solid) impregnated paper when the line -to-line voltage exceeds 1.732×38 kV, 1.732×63 - 127 kV are the threshold voltages for XLPE, PE and PLPP according to G. Ludasi, *Power Cable Systems*, appearing in R. Bartnikas and K.D.Srivastava, Power and Communication Cables, IEEE Press and McGraw-Hill (New York, 2000) ISBN#0-7803-1196-5 page 463.

the cable lest the dielectric's temperature rise to the point where it is obviously damaged or, more commonly, where its life as a functioning insulator is shortened.

Of course, all other things being equal, a dielectric having high thermal conductivity is preferred to one with low thermal conductivity.

Though dielectrics have been improved during the past 25 years, it is still true that difficulties raised by the need for heat transfer have limited the use of cable for high voltage, and thus, cable's use for transmission. Low voltage causes less dissipation, so heat-transfer problems are less severe and less expensive to mitigate. This is one reason (certainly not the only reason) why cable is more often used for distribution (low and medium voltages) than transmission (high voltage).

VI.2.4 Electric Breakdown and Its Probability Over Time

From time to time, abrupt, unwanted change occurs in electrical equipment. A dielectric can suddenly turn from insulator to conductor. This change is called "electrical breakdown." It is analogous to the sudden and unwanted appearance of cracks in structural material. In fact, when dielectrics are being discussed, power engineers tend to call the electric field the "electric stress." Power engineers relate the lifetime, τ, of the insulator to the rms electric field by an equation of the form

$$E^n \tau = const$$

where n depends on the dielectric and

const depends on the dielectric and the units for time and electric field

This relation can be made less *ad hoc* by asking for the "half-life" of equipment whose probability of failure at any time up to time t is

$$P_{failure}[E,t] = 1 - \exp\left[-\gamma\left(\frac{E}{E_0}\right)^a\left(\frac{t}{t_0}\right)^b\right]$$

One finds that the time, τ, when the probability of failure has risen to 0.5 is related to the rms electric field, E, by

$$\left(\frac{E}{E_0}\right)^{\frac{a}{b}}\left(\frac{\tau}{t_0}\right) = \sqrt[b]{\frac{\ln[2]}{\gamma}}$$

Because "breakdown" is never good for the affected equipment, a reliable estimate of an insulator's lifetime is always wanted and cable manufacturers continuously conduct accelerated ageing tests.[160,161,162] No customer wants to learn the lifetime of his insulation by observing his equipment fail. Because the circumstances and mechanisms for breakdown depend on the dielectric, more detail is deferred to subsequent sections where it appears in context.

One should expect that potential customers for cryogenic cable will ask about its lifetime and want to know about the lifetime of low temperature electrical insulation.

VI.3 Overhead Power Lines

A qualitative description of the parts of overhead lines and the function of each is easily provided. Overhead lines usually comprise a steel core surrounded by aluminum strands. The latter is meant to be the electrical conductor. The former provides the tensile strength that keeps the line from breaking or removes the need to space the supporting towers closer. Mechanical support is usually provided to the conductor by glass insulators, though other materials can be used.[163] Air insulates the conductors from each other. Though this description is sufficient for understanding normal operation, engineers must design and construct power lines to also cope with some abnormal conditions. In particular, the weather must be considered because the air surrounding overhead lines is part of a larger electrical system.

VI.3.1 Electrical Environment

Over one cycle, both the earth's surface and the upper atmosphere (e.g., above 80 km) are conductors (near 100 km, $\sigma=10^{-4}$ $(\Omega\text{-m})^{-1}$and $\varepsilon_r=1$). Most important, there is an average inward radial electric field, 130 *V/m*, at the earth's surface. Thus, on average, the earth's surface must have a net negative charge density[164], while the ionosphere (e.g., above 80-

[160] It is common practice to test dielectrics with frequency, temperature and electric fields that are greater than the intended operating frequency, temperature and field in order to accelerate the ageing processes.

[161] For a general review addressed to the power engineer see, G.C. Montonari, *A Comparative Investigation of Electrothermal Endurance Models for Insulating Materials and Systems Characterization*, IEEE, Electrical Insulation Magazine, vol.13, number 3 (May-June, 1997) pages 13-25 and 35.

[162] For review of aging tests and cryogenic dielectrics, see G.C. Montanari and L. Simoni, *Aging Phenomenology And Modeling,* IEEE Trans on Electrical Insulation 28 (5): 755-776 October 1993

[163] CRIEPI's facility in Yokosuka has contributed to the use of polymers in insulation arms and line spacers by increasing the polymers' insulating performance and mechanical strength.

[164]

$$div[\mathbf{D}] = \rho \;\Rightarrow\; \text{surface charge density} = \varepsilon_0 \mathbf{E}\cdot\hat{\mathbf{r}} = 8.85\times10^{-12}\times130\; coulomb/m^2 = 1.15\times10^{-9}\; coulomb/m^2$$

km) has a net positive charge. The voltage difference is estimated to be 360 kV. The concomitant electric field drives only a tiny current[165] through the air because of the scarcity of ions; their concentration is affected by the flux of cosmic rays and the intensity of terrestrial radioactivity. A great deal of physics is summarized by saying that the resistance of the atmosphere is roughly 200 ohms, and the atmosphere's capacitance is 2.9 F, and the average leakage current is 1.8 kA. Thus, one estimates that the electrical energy dissipates at the rate of 650 MW_e. In short, the terrestrial system is a leaky capacitor having a time constant of roughly 10 minutes (i.e., RC≈600 s).

How does this situation persist? The answer is that rain, sleet, snow and lightning bolts usually deliver negative charge to the earth. While the formation of lightning bolts is not our concern (in fact, it is not wholly known), their potential effect on transmission and distribution cable is our concern and we return to it in Section VI.3.2.4.

The slow leakage, through air, of negative charge from earth to the upper atmosphere leads one to rightly expect that overhead power lines might also "leak" and the rate might depend upon the voltage difference between air and conductor. (In fact, the effect limits the voltages used in overhead, AC transmission. Today, $\sqrt{2}\times(765/\sqrt{3})$ kV is the usual maximum voltage difference between conductor and ground.) The leakage should raise another question: How much gas will render a partial vacuum useless as an electrical insulator?

VI.3.2 Air's Breakdown

VI.3.2.1 Mechanism

When the electric field is small and temperature is normal, electrical conduction results from the motion of the (very few) charge carriers that are produced by ambient radiation or liberated from bounding conducting surfaces. When the gas density is high, the few charge carriers cannot go far without colliding with a neutral gas molecule. However, when the gas density is very low, the number of charge carriers is very low. This is why "near vacuum" can insulate.

However, if the gas density is low and the electric field is high, a charge carrier may pick up enough energy between collisions to ionize the next gas molecule with which it collides. When this happens, the number of charge carriers rises swiftly and one sees a

[165] Over land, the current density is 2.4×10^{-12} A/m^2 while over the oceans it is $3.7\times4\times10^{-12}$ A/m^2; the corresponding conductivities are 1.8×10^{-14} (ohm-meter)$^{-1}$ and 2.8×10^{-14} (ohm-meter)$^{-1}$, according to J.A. Chalmers, Atmospheric Electricity 2nd edition, Pergamon Press (Oxford, 1967) page 450.

spark. This is "breakdown".[166] Fluorescent lights exhibit the same effect. The relation between current and electric field (or voltage difference, if the boundaries are fixed) is sketched in Figure VI.3.2.1.1.

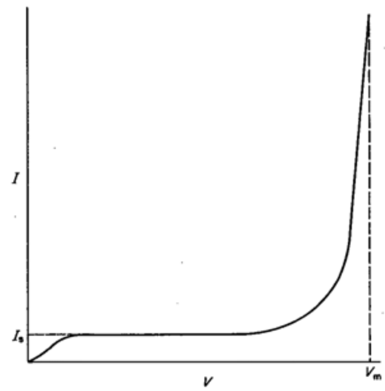

Figure VI.3.2.1.1
Current vs. Voltage Difference for a Gas

Following Paschen, the breakdown field (or voltage difference) is usually mapped by "Paschen curves," as illustrated in Figure VI.3.2.1.2.

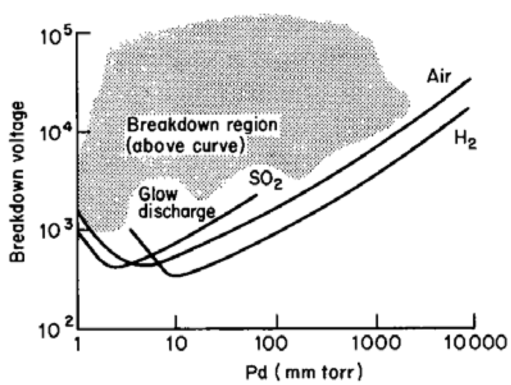

Figure VI.3.2.1.2
Voltage Breakdown Occurs Above the Paschen Curve

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[166] For a semi-quantitive introduction see G.P. Harnwell, Principles of Electricity and Electromagnetism 2nd edition, McGraw-Hill (New York, 1949) pages 272-276.

As stated elsewhere in this report, overhead lines are feasible because air serves as both coolant and insulator. However, air has its limits, which are reached when a faint violet glow appears, concomitant with a slight hissing noise and the smell of ozone. This phenomenon is called "corona."

VI. 3.2.2 Power Loss and Corona

Corona is a partial discharge (i.e., an incomplete failure of the air) appearing at a value of the electric field somewhat below the breakdown field. At slightly lower electric fields, an unwanted increase in power loss occurs.

It is important to understand that the local electric field can be much higher than the ratio of average voltage difference to a typical separation. Local electric fields depend on the curvature (or roughness) of the conductor's surface.[167] Power engineers take account of this with a roughness factor, *M*. Below we show how power engineers relate the local electric field (also called the "electric stress") to the parameters that describe a three-phase overhead power line.

Corona power loss is expected when

$$\mathrm{E}_{\text{conductor surface}} \geq E_0 \frac{\text{mass density of air}}{\text{mass density of air at NTP}} = E_0 \frac{(\mathrm{P/1\ bar})}{R(\mathrm{T/293K})}$$

where $E_0 \equiv 30\ kV/cm = 3\times10^6\ V/m$ and $R \equiv 82\ (Bar\text{-}cm^3)/(gram - mole - Kelvin)$

For a three phase line, with surface roughness factor M (typically, M is less than 0.75 for stranded conductor),

$$\mathrm{E}_{\text{conductor surface}} \approx \frac{1}{M} \times \frac{V_{line\ to\ neutral}}{r \ln\left[\frac{D_m}{r}\right]} = \frac{1}{M} \times \frac{V_{line\ to\ line}/\sqrt{3}}{r \ln\left[\frac{D_m}{r}\right]}$$

where

D_m is the distance between conductors

and

r is the radius of each.

---

[167] For the effect of a hemispherical bubble in an otherwise plane conductor, see J. Schwinger, , L.L. DeRaad, K.A. Milton and W. Tsai, Classical Electrodynamics, Perseus Books (Reading, Mass, 1998), ISBN#0-7382—0056-5, pages 274-276.

One sees that to avoid corona loss (*a fortiori*, breakdown), one must build lines having greater radii for each phase and/or greater separation between phases for higher voltages. Greater separation requires higher towers and wider rights-of-way. By using two bundles of conductors for each phase, one can get the effect of greater radii.

The formulae just presented are reliable when air is a good insulator (i.e., fair weather). In fact, air's ability to insulate is weakened by fog and rain, leading to greater power loss than in fair weather.

VI. 3.2.3 Low Gas Density

As suggested by the Paschen curve shown in Figure VI.3.2.1.2, the breakdown strength of a gas below atmospheric pressure (but above a moderate vacuum) is poor, a fact that suggests caution when considering the use of vacuum as an electrical insulator. Fortunately, N_2 is not readily ionized.

VI. 3.2.4 Lightning-The Connection Between Earth and Sky

Lightning is the most spectacular instance of gas breakdown.[168,169] Substantial effort is devoted to protecting overhead lines from lightning. A "shield wire" (sometimes also called the "neutral") is usually placed above the three phases and this wire is grounded at every tower with the hope that the lightning bolt's charge will pass through the shield and into the earth, rather than through the conductors, which otherwise could be overheated to destruction.

Underground cable receives less attention. A widely used engineering textbook addresses the subject with just one sentence: "Underground cables are, of course, immune to direct lightning strokes and can be protected from transients originating on overhead lines."[170] The contrary opinion and more detailed discussion appear in the professional literature and will be cited later in this subsection.[171]

Of course, the charge brought to earth by the bolt does not simply stay at the spot that was struck. The earth is not a perfect insulator and currents that originate in the air do continue through the ground. The earth's variability from place to place makes anticipating the result of a lightning strike difficult.

We mention this matter for three reasons: (a) an HTS cable will probably require greater investment than a conventional cable and so deserve greater protection, (b) protecting an HTS cable with off-the-shelf surge arresters must be done outside the cable itself in order to avoid a heat leak into the cold region, and (c) a superconductor's critical current is sensitive to magnetic field, while copper's resistance is not. And so, the effect of transient currents (they can be tens of kiloamperes) within the earth might deserve analysis. More specifically, azimuthal currents induced in a cable's shield may affect the interior superconductor, while the same azimuthal currents might not affect copper or aluminum.

Here we introduce a few salient points about lightning and protecting cable from it.

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[168] U. Fantz, *Optical phenomena in the open air*, Contemporary Physics, vol.45, no. 2, March-April 2004 pages 93-108.

[169] C. Mogano, Thunderstorms, Elsevier (Amsterdam-Oxford-New York, 1980).

[170] W.D. Stevenson, Elements of Power System Analysis 4th edition, McGraw-Hill (New York, 1982) ISBN 0-077-061278-1, page 113.

[171] T.A. Short, Electric Power Distribution Handbook, CRC Press (Boca Raton, 2004) ISBN#0-8493-1791-6, pages 587-650, in particular see p.621-630.

First, some regions are struck by lightning much more often than others.[172] Second, a lightning bolt has several characteristics. According to M.A. Uman[173], the most relevant are (a) the currents and (b) electromagnetic fields. The most significant part of lightning is the return stroke; it is usually the largest. Protection against the return stroke will usually protect against the currents and fields from other lightning processes. Four properties of the return stroke's current relate to potential damage: (1) the peak current, I_{max}; (2) the maximum rate of change of current, $(d/dt\ I)_{max}$; (3) the integral of the current over time (i.e., the charge transferred $Q = \int dt\, I[t]$); and (4) the integral of the current squared over time (i.e., the so-called action integral $\text{"}\mathit{action\ integral}\text{"} \equiv \int dt\, I^2[t]$). [N.B. *The action integral is roughly proportional to the heat that would be dissipated in the HTS cable's stabilizer from a current surge*.] A typical value for transferred charge is 20-30 coulombs, though extreme lightning bolts transfer hundreds of coulombs. About 1 percent of negative strokes (the most common) to ground have action integrals exceeding 10^6 A^2-s. About 5 percent of positive strokes (less common, though reported from Japan[174]) are thought to exceed 10^7 A^2-sec.

VI.J. Malan describes the result of a lightning bolt from cloud to ground, as well as the present practice to mitigate what otherwise might be the consequence, as follows[26]:

> "At the point where a lightning flash strikes the ground the electrical energy is dissipated mainly downwards into the ground, but if the soil has a low conductivity the intensity of the electrical currents can still be appreciable near the surface of the ground up to considerable distances. Underground telephone or power-supply cables pass through such soils offer a low resistance path to these currents. If farther along its trajectory the cable happens to pass through moist soil of high conductivity it will tend to conduct lightning currents away from the low-conductivity region to be dissipated to earth in the high- conductivity soil. An underground cable can be effectively protected against the effects of not only earth currents but also induced surges from lightning flashes by burying guard wires above and alongside it where it passes through low-conductivity soils.

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172 For example, the Gulf Coast of the United States, particularly Florida, is struck by many more bolts than anywhere else in the US. Though the frequency in New England is not extraordinary, anecdotal accounts suggest the effect is significant to T&D.

173 M.A. Uman, "Application of Advances in Lightning Research to Lightning Protection", appearing in The Earth's Electrical Environment, National Academy Press (Washington DC, 1986), ISBN#0-309-03680-1

174 K. Nakahori, T. Ogawa, and H. Mitani, *Characteristics of winter lightning currents in Hokuriku District*, IEEE Trans. PAS-101, (1982) pages 4407-4412.

> The damage done by earth currents from lightning flashes to reinforced-concrete water pipes can be extensive and spectacular. As the steel reinforcement is not continuous from section to section of the pipe, the heavy current sparks across the electrical discontinuity, with the result that the pipes are shattered at their joints. It appears as if they had been blown apart by explosive violence.
>
> In two different localities not far from Johannesburg [South Africa], large reinforced-concrete water pipes passing underground through dry doleritic soils suffered extensive damage from lightning. After a thick copper wire was buried above the pipes, no further damage was experienced. The copper wire provided an electrically continuous and low-resistance path to lead the lightning currents away from the low-resistivity regions."[175]

The usual scenario for lightning's interaction with conventional cable and comments on that scenario follow.

> "Lightning hits an overhead line near the cable, and a surge travels into the cable at the riser pole. The most important item that makes cable protection difficult is:
>
> *Voltage doubling* — when a surge voltage traveling down a cable hits an end point, the voltage wave reflects back, doubling the voltage.
>
> Normally, for analysis of underground protection, we assume no attenuation in the surge and that the voltage doubles at open points. The surge impedance of cable is approximately 50 ohms [*N.B. may be less for HTS cable*] which is lower than the 400 ohm overhead line surge impedance. If a lightning current has a choice between the cable and an overhead line, most of it enters the cable. Normally, the cable has a surge arrester at the riser pole, and a conducting surge arrester has an impedance of less than five ohms so the surge arrester conducts most of the current. … With an arrester at the riser pole and no arresters in the underground portion, we must use twice the voltage at the riser pole, including the lead length… Lightning may also puncture the jackets in jacketed cable. Ros demonstrated that lightning current into a riser-pole ground created enough ground potential rise to puncture jackets and leave pin holes. Fifty-mil jackets [*were*] punctured with 150 to 160 kV, and 80-mu jackets [*were*] punctured with 155 to 170 kV. The voltage impressed across the cable jacket is the surge current times the ground resistance at the riser pole, which may be very high with poor

[175] D.J. Malan, Physics of Lightning, The English Universities Press, Ltd (London, 1963) page 150.

grounds. Ros' tests found semiconducting jackets did not allow nearly the voltage to develop across the jacket.

Lightning can also damage cables from strikes above the ground. EPRI tests found that rocket-triggered lightning strikes to the ground above buried cables caused extensive damage. Lightning normally breaks down the soil and arcs to the cable. We tested three cable configurations: unjacketed direct buried, jacketed direct buried, and jacketed cable in conduit. All were single-conductor 220-mil XLPE cables with a full copper neutral. Lightning above the ground damaged them all to varying degrees. Lightning melted most strands of the concentric neutral and punctured the jacket and conduit if present. In some cases, lightning also damaged the insulation shield. What made the damage particularly bad was that lightning hit the soil surface and continued an arcing path 3 ft (1 m) underground directly to the cable. Measurements showed that 15 to 25% of the lightning currents reached the padmounted transformers on either side of the flash point. This type of cable damage would not show up immediately. More likely, cable failure would accelerate from increased water entry and localized neutral heating. Voltages we measured across the cable insulation were not a significant threat (they were less than 17kV). The tests also pointed to secondary voltages as a concern. We found nearly 4 kV on the closest transformer secondary. Surge entry into the secondary stresses the transformer insulation and sends possibly damaging surges into homes. Current entering into the secondary neutral terminal of the transformer induces voltages that stress the primary winding. Williams presented evidence that padmounted transformers fail from secondary-side surge entry in similar percentages to overhead transformers.

During the rocket-triggered lightning tests, strokes to the cable attached from as far away as 15 ft (5 m). Furrows from trees to underground cables as long as 300 ft (100 m) have been found. Sunde derived a model for lightning attraction to buried cables based on the lightning current and the soil resistivity. The amount of heating damage to the neutral and to the insulation is primarily a function of the total charge in the lightning flash (since arcs exhibit a fairly constant voltage drop at the point of attachment, the energy is a function of $\int I dt$). Burying shield wires above the cables is one way to offer protection against this type of damage. An AT&T handbook (1985) provides estimates on shield-wire effectiveness. Note that there is no current power industry practice for this type of protection, and the amount of damage (percent of cable faults) is unknown."[176]

[176] These passages are excerpted from p.621-630 of T.A. Short, Electric Power Distribution Handbook, CRC Press (Boca Raton, 2004) ISBN#0-8493-1791-6.

Today, the usual "lightning simulation" for conventional equipment is called Basic Impulse Loading (BIL). The simulator raises the voltage suddenly ($1.2\text{x}10^{-6}$ seconds) to its peak value and then lets the voltage decay more slowly, declining to half its peak in $50\text{x}10^{-6}$ seconds.

To the writer's knowledge, little attention has been given to lightning protection that is specific to an underground cable incorporating HTS conductor. Three aspects may deserve attention:

a) As already mentioned, azimuthal currents in the conducting shield can induce magnetic fields within the cable. These fields are likely to be too weak to influence either aluminum or copper conductor. One should consider whether or not they might affect HTS conductor performance.
b) If employed, the cable's adjacent guard wires, described by both VI.J. Malan and by T.A. Short, take up space. One should consider if and when they would be employed with HTS cable and whether or not guard wires would reduce the effective power density of the cable or cables.
c) If and when long HTS cables are designed, one should consider how the intermediate cryocoolers could be incorporated so that they do not provide penetrations through which either significant transient fields or significant transient currents can enter the superconductor. Today's cable lengths can be served by one cryocooling station having input and output streams conveyed by glass or some other insulator.

Of course, the relative importance of lightning protection will depend on the intended location of the HTS cable and the frequency of lightning strikes. A cable in Miami Beach is more likely to be struck than one in Manhattan.

VI.4 "On the Ground" or "Near the Ground" Power Lines

The principal objection to putting power lines on or near the ground is that they would impede traffic. From a utility's perspective, near-ground lines are more vulnerable to accidents than overhead lines. No electro-technical problem prevents the practice. In fact, power lines are sometimes located on pylons, in troughs, or in shallow trenches in some electrical power plants, switchyards, or utility rights-of-way.

When this is done, Compressed Gas Insulated Lines (CGIL) are usually used.[177,178,179,180] Instead of air, these lines use high pressure gas, almost always SF_6. High pressure entails high density and thus greater impediment to current flow. SF_6 is chosen for a more subtle reason.

Our discussion of breakdown centered on the circumstances when a collision between a charge carrier and a neutral gas molecule might ionize that molecule, creating more mobile charge carriers. The opposite possibility also exists. The molecule might capture the charge carrier and the resulting ion might be less mobile than the initial one. In fact, compounds containing fluorine and chlorine do just that, and sulfur hexafluoride, SF_6, is a practically important example. The principal objection to SF_6 is that it is the most pernicious greenhouse gas. For this reason, the power sector and SF_6 suppliers have tried to reduce leaks.

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[177] R. Bartnikas, "Cables, A Chronological Perspective", appearing in R. Bartnikas and K.D.Srivastava, Power and Communication Cables, IEEE Press and McGraw-Hill (New York, 2000) ISBN#0-7803-1196-5, pages 24-28.

[178] K.D. Srivasta, "Cryogenic and Compressed Gas Insulated Cables", appearing in R. Bartnikas and K.D.Srivastava, Power and Communication Cables, IEEE Press and McGraw-Hill (New York, 2000) ISBN#0-7803-1196-5, page 94.

[179] P.C. Bolin, "Gas Insulated Substations", appearing as Chapter 17.2 in D.G. Fink and H.W. Beatty (editors), Standard Handbook for Electrical Engineers 14th edition, McGraw-Hill (New York, 2000) ISBN 0-07-022-005-0

[180] E.C. Bascom III et al, "Transmission Systems", appearing as Chapter 14 in D.G. Fink and H.W. Beatty (editors), Standard Handbook for Electrical Engineers 14th edition, McGraw-Hill (New York, 2000) ISBN 0-07-022-005-0, page 14-127.

VI.5 Today's Underground or Underwater Power Lines, Always Known as Cables

Except for the limitations already discussed, air is an excellent insulator and coolant. The ground is not. Nothing can be taken for granted. Engineers must provide both electrical insulation and heat transfer for the cable.

Cable can either transmit or distribute power.[181] In this report, these terms refer to function, not to a precisely specified voltage.

Very important to the use of cable for distribution (most often 5-46 kV), particularly residential distribution, has been the reduction in trenching costs. More and more suburban subdivisions have been developed with cable in place. Voltages of 13 kV are typical.

As described in Chapter III, after the invention of the electrolytic processes that yield aluminum and copper, technical effort focused on the cable's dielectric. The goal has been ever greater voltage differences in the same cross-section (i.e., greater electric fields). They have been and are necessary to guide more power (proportional to $\mathbf{E}\times\mathbf{H}$) and thus increase transmission capacity. The past tense is important here. The conventional technical goal was to avoid increasing the current in the aluminum or copper because that would entail more dissipation (or more conductor) and so more heat transfer. Ceramic superconductors raise the possibility of guiding power ($\int\mathbf{E}\times\mathbf{H}\bullet d\mathbf{S}$), using more current (larger $\mathbf{H}$) instead of higher voltage (larger $\mathbf{E}$).

Today, the preferred dielectric is cross-linked polyethylene (XLPE).[182] It provides electrical insulation in both distribution and transmission cables. When compared with other dielectrics, XLPE offers low relative permittivity, low loss, high operating temperature and good breakdown strength. It is also convenient for the operator because,

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[181] These terms do not have unique meanings. Transmission lines play the role of arteries and veins. Distribution lines are capillaries. However, the distinction between a large capillary and a small artery or vein depends on context and local jargon. Often, any radial circuit is called distribution. Looped circuits may or may not be called transmission. Engineers often talk of transmission and distribution when they want to describe voltage level without being specific. For example, 235 kV and higher are transmission. voltages, the range 35-235 kV is often called sub-transmission voltage, and the range 4-35 kV is distribution voltage. Others include 600V in distribution. Nomenclature varies from utility to utility.

[182] For some relevant background, see the presentations given to the Insulated Conductors Committee Meeting of Fall '03. They are posted at
http://www.ewh.ieee.org/soc/pes/icc/subcommittees/subcom_e/education/education.htm#Fall%202004

unlike older technologies that incorporate both paper and oil, XLPE does not require a dielectric fluid. XLPE and its competitors (EPR and PE) are part of today's technology to which utilities will compare HTS cable.[183]

Today's XLPE was not developed suddenly. Development has been under way for roughly the past fifty years. An important result is the ability to manufacture XLPE without embedding moisture and to extrude XLPE without incorporating cracks or voids,[184] which can become places where the local electric field can be much greater than the average electric field. Indeed, the local field can become so great as to cause local ionization and so precipitate breakdown, either immediately or after further damage.

It should be noted that, until very recently, XLPE has not been found suitable for high-voltage DC cable.[185,186] Paper and oil is preferred. DC Cable must be able to sustain polarity reversals during which most of the change occurs during roughly 0.1 milliseconds (1/200 cycle).[187,188] DC cable is most often used where tens of kilometers must be traversed underwater.

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[183] The properties of conventional dielectrics are described by many references among which the following can be recommended. R. Bartnikas and K.D.Srivastava, Power and Communication Cables, IEEE Press and McGraw-Hill (New York, 2000) ISBN#0-7803-1196-5

[184] For more on cable material's process and properties see, R. Bartnikas, "Characteristics of Cable Materials" appearing in R. Bartnikas and K.D.Srivastava, Power and Communication Cables, IEEE Press and McGraw-Hill (New York, 2000) ISBN#0-7803-1196-5, pages 134-150.

[185] "The application of XLPE insulation on dc submarine cables has met with considerable adversity; the excellent low dielectric loss characteristics of polyethylene result directly from its deep charge traps wherein free charge carriers are trapped and immobilized. But it is precisely these deep charge traps that render polyethylene unsuitable for dc power transmission. Polarity reversal under dc operating conditions can readily precipitate breakdown of the polyethylene due to the additive field of the space charge residing within the deep traps. It is well known that the incorporation of conductivity additives in the polyethylene can disperse some of the space charges, but the long-term effectiveness of these compounds is unknown. The long, proven reliability of oil-paper systems for dc power transmission is difficult to improve upon. If it is desired to replace the oil-paper system for dc applications with substitutes, then perhaps it is more expedient to accomplish this with PPP tape composites than with XLPE containing additives." according to R. Bartnikas and K.D.Srivastava, Power and Communication Cables, IEEE Press and McGraw-Hill (New York, 2000) ISBN#0-7803-1196-5, page 23.

[186] ABB states it delivered a 90 kV (300 mm^2) DC cable (Troll A) incorporating XLPE to STATOIL and a 150 kV (1300 mm^2) DC cable (Cross Sound) incorporating XLPE to TransenergieUS during 2002. See Chapter XI for additional information.

[187] The author is grateful to P. Chowdhuri for pointing out this order of magnitude and its challenge to the insulating capabilities of dielectrics.

[188] For present practice in HVDC testing see pages 645-647 of R. Bartnikas and K.D.Srivastava, Power and Communication Cables, IEEE Press and McGraw-Hill (New York, 2000) ISBN#0-7803-1196-5

VI.6 Electrical Insulation for LN_2 Cables

Past and much present activity focuses on insulation for superconductors cooled by LHe and used in magnets.[189] The principal concern is the electric field concomitant with a sudden change (e.g., quench) in the magnetic field.[190] The principal customers are concerned with accelerator physics, magnetic fusion and Magnetic Resonance Imaging (MRI). Only the last is a commercial product and only the last is meant to be used by non-experts.

Equipment intended for application by the power sector must meet different demands and satisfy a different standard of reliability. The pertinent issues are not exhausted by considering only the dielectric properties of pure materials at 70-83 K. They appear to offer no difficulty; in fact, these properties appear to be as good or better than XLPE at its operating temperature. (Most HTS cable demonstrations have used paper laminated with polypropylene and impregnated with LN_2.[191]) However, chemical purity and physical uniformity cannot be taken for granted in an industrial dielectric.

The issues raised by cryogenic operating temperatures include:

a) fabricating the dielectric with desired purity and homogeneity
b) identifying acceptable purity for LN_2 and maintaining same during operation (NB the attention that that has been given to transformer oil during the past century)
c) achieving satisfactory cable performance at operating temperature after fabricating it at ambient, despite various changes in size and shape, concomitant with different thermal contractions of the cable's conductors and dielectrics.
d) constructing terminations that can handle both the temperature difference from ambient to operating, and the voltage difference between phases
e) for cable lengths of 10 km or more, constructing intermediate cooling stations whose penetrations do not make the cable vulnerable to ground faults

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[189] F. Krähenburhl et al, *Properties of Electrical Insulating Materials at cryogenic temperatures: a literature review*, IEEE Electrical Insulation Magazine, vol. 10, 1994 pages 10-22.

[190] Recall Faraday's Law of Induction: curl[**E**]=-∂_t**B**.

[191] For a description of the *prima facie* reasons, see F. Ombelloe, G. Attolini, P. Caracino, M. Nassi, S. Spreafico, G.C. Montonari, *Insulating Materials for Cold Dielectric Superconducting Cables*, IEEE Trans. On Dielectrics and Electrical Insulation, (December, 2002) pages 958-963.

At the time of this writing, these problems do not appear insuperable, though no one claims to have solved all of them.[192] An additional consideration is pertinent to DC cable. Its dielectric must sustain polarity reversals, many of which occur during 0.1 milliseconds. The author is not aware of any attempt to study cryogenic dielectrics under these conditions.[193,194, 195]

Beside the length of the cable, the cable's terminations deserve attention.[196,197,198] Their design and construction depends on whether the cable is warm dielectric or a cold dielectric. Below, we focus on what's known about insulating one phase from another within the cable. It is helpful to distinguish between solid dielectrics, liquid dielectrics, and combinations of the two.

VI.6.1 All-Solid Dielectric

When measured at LN_2 temperatures, the electrical properties of synthetic polymer dielectrics either remain the same as at room temperature or actually improve.

In particular, the heat generated by dissipation of electrical energy in the dielectric should be negligible when compared with either AC loss in the conductor, or even more important, the heat transferred through the cryostat wall. Further, both resistance to the growth of trees and breakdown strength of (non-polar) polymers should be improved.[199]

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[192] J. Gerhold, *Potential of Cryogenic Fluids for Future Equipment Insulation in the Medium High Voltage Range*, IEEE Trans on Dielectrics and Electrical Insulation vol.9, #6 (December, 2002) pages 878-890.

[193] The author is grateful to P. Chowdhuri for pointing out the relevance of the topic and saying that he too is unaware of any relevant work.

[194] R. Bartnikas and K.D.Srivastava, Power and Communication Cables, IEEE Press and McGraw-Hill (New York, 2000) ISBN#0-7803-1196-5, pages 647-648.

[195] For work that partially bears upon DC cable, see O. Miura, N. Ichiyanagi, H. Misawa, N. Hashimoto, *Characteristics of laminated tape insulation in high vacuum at cryogenic temperature*, ELECTRICAL ENGINEERING IN JAPAN 121 (3): 20-26 NOV 30 1997.

[196] C. Rassmussen et al, *Design of a termination for a high-temperature superconducting power cable*, IEEE Transactions of Applied Superconductivity, vol.9 number 2, June, 1999, pages 1273-1276.

[197] G.M. Hathaway, A.E. Davies, S.G. Swingler, *Dielectric considerations for a superconducting cable termination*, High Voltage Engineering, 1999. Eleventh International Symposium on (Conf. Publ. No. 467), Volume: 4 , 23-27 Aug. 1999, Pages:84 - 87 vol.4

[198] D.R. James, I. Sauers, M.O. Pace, A.R. Ellis, *High voltage breakdown of solid epoxies at room temperature and in liquid nitrogen*, Conference on Electrical Insulation and Dielectric Phenomena, 2002, 20-24 Oct. 2002, Pages: 542 – 545.

[199] Like paper, FRP's breakdown strength is non-isotropic. Fortunately, again like paper, FRP's breakdown strength appears sufficient in the direction perpendicular to the fibers, according to M. Kosaki, M. Nagao,

Cryogenic cable makers would welcome the same convenience that XLPE, EPR and PE have brought to operating conventional cables.[200] During their manufacture, the solid dielectric is extruded on the conductor, typically aluminum. However, the different thermal contractions of the dielectric and the conductor made from HTS/base metal composite have not encouraged a similar approach by the groups making prototype HTS cable.

Nonetheless, one report states, "An all-solid insulation has been developed as a competing technique in Japan for HTS cables. Ethylene Propylene Rubber (EPR), for instance, can be extruded over the conductor, even if the latter is radially stiff; the cores remain flexible and radial thermal contraction can be controlled safely down to 40 K. Any electrical stress along the cable route is limited to the extruded solid; the coolant is never stressed so bubble formation is not critical from the point of insulation performance. EPR is very resistive against treeing, and dielectric losses on the order of 10 at LN_2 temperature are very acceptable. This dielectric can be highly stressed during normal operation, and has been claimed to become some kind of electrical 'super-insulation'. Insulation quality control and tests can be carried out at ambient temperature in the factory, that means before laying down the full cable length on site and cooling it down. This can be a decisive advantage in practice. All-solid insulated cores are believed to result in an extremely small core size, which is essential for pulling a cable in already existing narrow ducts for retrofitting. However, longitudinal contraction is difficult to overcome; a design which fully satisfies this particular point is still outstanding … the all solid insulation still needs a great amount of improvement in order to meet all the thermo-mechanical needs of a long cable."[201] Others have expressed the same concern; "Extruded insulation for LTD [cold dielectric cable] could be discharge free, but there is a concern with thermo-mechanical stresses induced during the extrusion and cooling process and with the lack of experience of cooling thick, long volumes of extruded insulation."[202,203,204]

N. Shimizu and Y. Mizuno, *Solid Insulation and its deterioration,* Cryogenics, vol.38 (1998) pages 1095-1104.

[200] Extrusion of a solid on the conductor is not a new strategy. As noted earlier in this report, W. Siemens found a way to extrude gutta-percha on conductor. Subsequent work showed that paper is a good insulator when the field is perpendicular to the fibers. Thus the question arose of how to wrap paper around conductor. Inevitably there are gaps between sheets. It was realized that could impregnate the paper with oil in order to fill these gaps. To avoid bubbles in the oil, one could put it under more or less pressure. The same strategy for cryogenic cables will be discussed below.

[201] J. Gerhold and T. Tanaka, *Cryogenic electrical insulation of superconducting power transmission lines: transfer of experience learned from metal superconductors to high critical temperature superconductors*, Cryogenics, vol.#38 (1998) pages 1173-1188.

[202] A. Bulinski and J. Densley, *High Voltage Insulation for Power Cables Utilizing High Temperature*

Because every HTS cable must begin and end, special terminations are required. At least one group is developing terminations having solid dielectrics. Problems appeared when solid epoxy (Stycast FT, Stycast KT, Araldite 5808) was used for full size pieces, but not when smaller test samples were fabricated. Some refer to this as the "volume effect" in solid, cryogenic dielectrics. Below, we emphasize the problems raised by bubbles in liquid dielectric but solids raise similar concerns wherever the possibility of voids exists. Figure VI.6.1 shows such a void in the solid dielectric in a prototype termination.

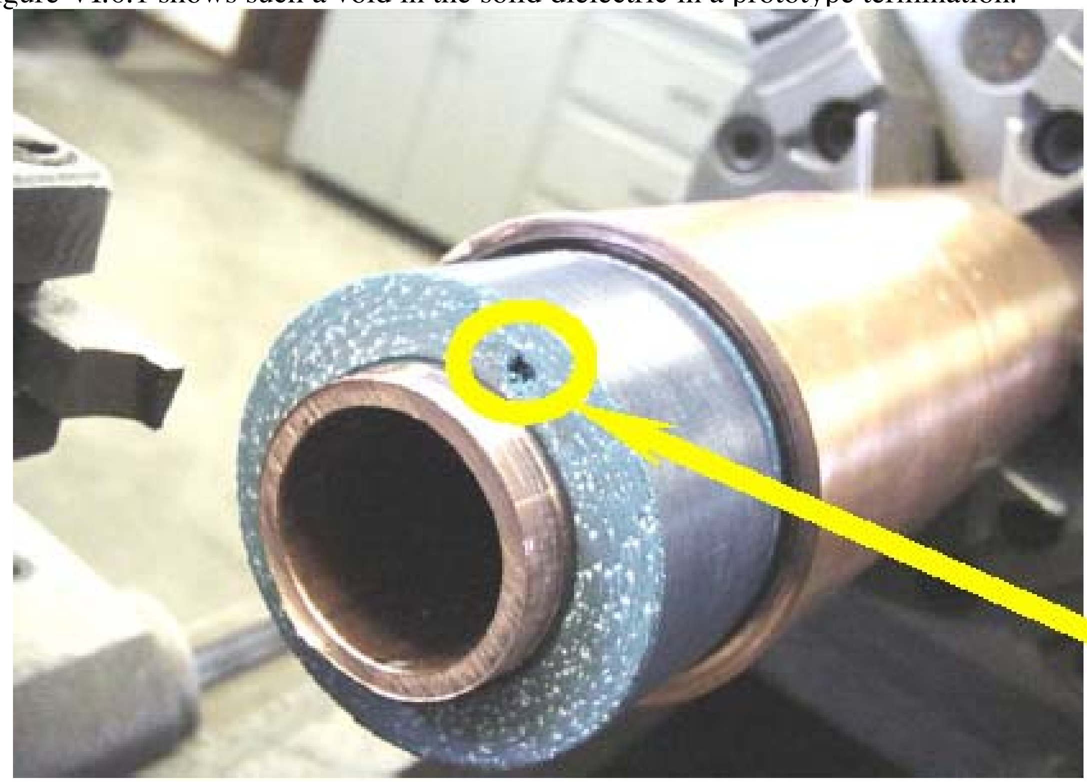

Figure VI.6.1
Undesirable Void Within Solid Dielectric

Superconductivity, IEEE Electrical Insulation Magazine, Vol. 15, No. 2, 1999, pages 14-22.

[203] D.R. James, I. Sauers, M.O. Pace, A.R. Ellis, *High voltage breakdown of solid epoxies at room temperature and in liquid nitrogen***,** Conference on Electrical Insulation and Dielectric Phenomena, 2002, 20-24 Oct. 2002, Pages: 542 – 545.

[204] M. Kosaki, M. Nagao, Y. Mizuno, K. Horii, and N. Shimizu, *Development and Tests of Extruded Polyethylene Insulated Superconducting Cable,* IEEE CH2587-4/88/0000 1988 pages 426-429.

In Prototype Termination for HTS Cable[205]

[205] USDOE 2003 Peer Review, unpublished work, I. Sauers, et al. ORNL , in High Temperature Superconducting Power Cable - D. Lindsay (Southwire), J. A. Demko (ORNL)

VI.6.2 All-Liquid Dielectric

At first sight, liquid nitrogen, LN_2, appears to be a candidate dielectric because its electrical properties are suitable. Nonetheless, the conductor would still have to be supported and separated from the shield, both in the factory and in operation, after cool-down. More important, an almost entirely liquid dielectric would be very vulnerable to the effects of bubble formation and migration. Note, cables are not always horizontal. In particular, the elevation of submarine cables varies. Bubbles could arise from one or more local hotspots, a fault current, loss of pressure, or failure of a cryocooler. Bubbles should be expected to migrate in response to the gradient of the electric field.[206] Bubbles themselves will have a larger electric field than the surrounding liquid because they have a smaller dielectric constant.[207] And so, bubbles are potential regions of breakdown.[208,209] For example, a cryocooler failure that precipitated two-phase flow might also precipitate electrical breakdown. In fact, bubbles have attracted some investigators who express concern.

> "There are some possible causes of bubble generation in insulating liquids. In SC apparatus, boiling due to a local hot spot on conductors by quench will become the most important bubble formation mechanism from the viewpoint of electrical insulation design. Even with the most careful design of SC apparatus, the possibility of a local hot spot appearing is not zero. In particular, a quench initiated in an SC coil but a hot spot will not only cause bubble formation but also create a high voltage drop across the coil layer and might cause a voltage

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[206] S. Bobbio, Electrodynamics of Materials, Forces, Stresses, and Energies in Solids and Fluids, Academic Press (San Diego, 2000) ISBN 0-12-108260-1.

[207] Dielectric constant depends on density as shown the Clausius-Mossotti Relation $\frac{\varepsilon_r - 1}{\varepsilon_r + 2} = \frac{N_A \alpha}{3M} \rho_{mass}$.

[208] D.J. Swaffield, P.L. Lewin, G. Chen, and S.G. Swingler, *The influence of bubble dynamics in liquid nitrogen with applied electric fields on superconducting apparatus,* in Proceedings of 13th International Symposium on High Voltage Engineering, pages CD-ROM, Delft, Netherlands.)

[209] It is difficult to estimate the curvature of real bubbles; they may not be spherical. In fact, bubbles may not be simply connected. For example, within liquids, shells of gas, each shell surrounding a liquid drop, have recently been observed. These are known as "anti-bubbles" because they are opposite to familiar soap bubbles. See S. Dorbolo, H. Caps, N. Vandewalle, *Fluid instabilities in the birth and death of antibubbles***,** New J. Phys. Vol.5 (December, 2003) page 161 and http://www.arXiv.org/abs/cond-mat/0305126. Anti-bubbles are meta-stable, but not stable. Their collapse and the consequent formation of simply connected gas bubbles may provide boundary conditions that enhance the breakdown within a fluid. Such phenomena have hardly been studied, let alone understood. Interested persons might wish to consult http://www.antibubble.org/ and P. Weiss, *The Rise of Anti-Bubbles*, Science News 15 May 2004 vol.165, pages 311-312 for further introduction and citations.

breakdown. This bubble-triggered breakdown has been investigated with simulated quench conditions and real dynamic quench conditions."[210]

A few investigators have studied pre-breakdown phenomena in LN_2.[211,212]

VI.6.3 Dielectrics Comprising Solid Tapes Impregnated with LN_2

All the cable projects, now underway, plan to use dielectrics comprising solid (but often fibrous) tape impregnated with LN_2.[213] Some groups plan to use paper tapes and other groups plan to use synthetic polymers.[214],[215],[216] KERI has investigated a material it calls TERLAM IPP[217] and Ultera uses a proprietary material that it calls Cryoflex™. The already expressed concerns about voids and cracks in the tape and bubbles in the liquid

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[210] M. Hara and H. Okubo, *Electrical insulation characteristics of superconducting power apparatus*, Cryogenics, vol.#38 (1998) pages 1083-1093.

[211] P.E. Frayssines, O. Lesaint, N. Bonifaci, A. Denat, S. Lelaidier, F. Devaux, *Prebreakdown phenomena at high voltage in liquid nitrogen and comparison with mineral oil*, IEEE Trans on Dielectrics and Electrical Insulation 9 (6): 899-909 December 2002 and P.E. Frayssines , N. Bonifaci, A. Denat, O. Lesaint, *Streamers in liquid nitrogen: characterization and spectroscopic determination of gaseous filament temperature and electron density,* JOURNAL OF PHYSICS D-APPLIED PHYSICS 35 (4): 369-377 FEB 21 2003.

[212] P.E. Frayssines, O. Lesaint, N. Bonifaci, A. Denat, F. Devaux, *Prebreakdown and breakdown phenomena under uniform field in liquid nitrogen and comparison with mineral oil*, IEEE Trans on Dielectrics and Electrical Insulation 10 (6): 970-976 December 2003.

[213] T. Takahaski, H. Suzuki, t. Okamoto, S. Akita, S. Maruyama, A. Kimura, *Dielectric Properties of 500m High-Tc Superconducting Cable*, presented at the Applied Superconductivity Conference, October 3-8, 2004, Jacksonville, Florida

[214] F. Ombello, G. Attolini, P. Caracino, M. Nassi, S. Spreafico, G.C. Montanari, *Insulating materials evaluation for cold dielectric superconducting cables*, IEEE Trans On Dielectrics And Electrical Insulation, 9 (6): 958-963 December 2002.

[215] N. Hayakawa, M. Nagino, T. Kobayashi, H. Okubo, T. Takahashi, K. Yasuda, *Dielectric Characteristics and Electrical Insulation Design of HTS Cables*, presented at the Applied Superconductivity Conference, October 3-8, 2004, Jacksonville, Florida.

[216] D.S. Kwag, S.M. Baek, V.D. Nguyen, S.H. Kim, H.J. Kim, *A Study on the Composition Dielectric Properties for a HTS Cable Insulation*, presented at the Applied Superconductivity Conference, October 3-8, 2004, Jacksonville, Florida

[217] H.J. Kim, K.C. Seong, J.W. Cho, D.S. Kwag, S.H. Kim, *Insulation Studies and Experimental Results of the 22.9kV Class High Tc Superconducting Power Cable,* presented at the Applied Superconductivity Conference, October 3-8, 2004, Jacksonville, Florida

remain relevant.[218] "Partial discharges can occur because of the lowered dielectric strength in vapor-filled butt gaps. This would be, in fact, an extremely dangerous condition."[219] The probability of this is reduced by having LN_2 present under some pressure. Thus, a crack might be filled with LN_2, having a different permittivity but not nearly as different as N_2 gas or vacuum. (A solid having the same permittivity as LN_2 would be ideal.[220])

When compared to all-solid dielectrics, the advantage of LN_2-impregnated tape consists in the feasibility of accommodating thermal contraction. When compared with an "almost all liquid" dielectric, the advantage lies in convenience of manufacture and use.

Though these advantages have been compelling, they do not ensure success. The tapes must be wound on the conductor at room temperature so that they will "lie correctly" at operating temperature, despite differences in thermal contraction. "Lie correctly" means that the gaps (known as "butt gaps") between the tapes will be filled with LN_2 and are small enough so as not to occasionally breakdown in whole or part. Many groups plan to wrap a solid dielectric, either paper or synthetic polymer, around the conductor during construction. The substantial thermal contraction of synthetic polymers might have effects that are both good and bad. Voids or cracks within the dielectric at room temperature might be reduced in size when the polymer contracts with decreasing temperature. On the other hand, "…if partial discharges occur in the butt gap at cryogenic temperatures, deterioration may proceed more malignantly than in the case encountered at room temperature… Plastics with fillers, in the case of ethylene propylene rubber (EPR), give excellent electrical performance in addition to the controlled thermal contraction at cryogenic temperatures."[221] More recently, some articles reporting results on LN_2 impregnated tape have appeared.[222,223,224,225,226,227,228,229,230,231,232] Very interesting and

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[218] M. Chiba, T. Nitta, *Surface Spark-Over Voltage on Solid Insulator in Sub-Cool Nitrogen*, presented at the Applied Superconductivity Conference, October 3-8, 2004, Jacksonville, Florida

[219] J. Gerhold and T. Tanaka, *Cryogenic electrical insulation of superconducting power transmission lines: transfer of experience learned from metal superconductors to high critical temperature superconductors*, Cryogenics, vol.#38 (1998) pages 1173-1188.

[220] For a discussion of two contrary cases: (a) a dielectric ellipsoid in an external field and (b) the dielectric constant of a mixture (e.g., powder or emulsion) in terms of the dielectric constants of its constituents see L.D. Landau and E.M. Lifschitz, Electrodynamics of Continuous Media, Pergamon Press (Oxford, 1960) pages 42 and 45.

[221] M. Kosaki, M. Nagao, N. Shimizu and Y. Mizuno, *Solid Insulation and its deterioration*, Cryogenics, vol.38 (1998) pages 1095-1104.

[222] A. Bulinski and J. Densley, *High Voltage Insulation for Power Cables Utilizing High Temperature Superconductivity*, IEEE Electrical Insulation Magazine, Vol. 15, No. 2, 1999, pages 14-22.

[223] Bok-Yeol Seok, H. Komatsu, M. Hara, *Partial breakdown characteristics in the simulated electrode*

of potentially great practical interest is the observation that many partial discharges do not start in the butt gaps. Instead, they appear between tapes.[233] Perhaps the tapes have surface irregularities that cause irregular electric fields. The likelihood of such partial discharges might be reduced by using thicker tape (and thus fewer layers). However, tape sizes are standard manufacture and also must allow for ease in winding and bearable radius of curvature.

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*system of high temperature superconducting coils***,** Dielectric Liquids, 1999. (ICDL '99) Proceedings of the 1999 IEEE 13th International Conference on , 20-25 July 1999 Pages:466 – 469

[224] Seok, B.Y.; Komatsu, H.; Suehiro, J.; Hara, M.; Okamoto, H.; *Partial and complete electrical breakdown in simulated high temperature superconducting coils*, IEEE Trans on Dielectrics and Insulation, Volume: 7 , Issue: 1 , Feb. 2000, Pages:78 – 86.

[225] M.O. Pace, I. Sauers, D.R. James, A.R. Ellis, *Aging of lapped tape insulated model cables at cryogenic temperature*, 2002 Annual Report Conference on Electrical Insulation and Dielectric Phenomena, 2002 IEEE Conference on Electrical Insulation and Dielectric Phenomena.

[226] *M. Hazeyama, Kobayashi, T.; Hayakawa, N.; Honjo, S.; Masuda, T.; Okubo, H., Partial discharge inception characteristics under butt gap condition in liquid nitrogen/ PPLP/sup /spl reg// composite insulation system for high temperature superconducting cable*, IEEE Transactions on Dielectrics and Electrical Insulation, Volume: 9, Issue: 6 , Dec. 2002 Pages:939 – 944

[227] *M. Hazeyama, Hayakawa, N.; Honjo, S.; Masuda, T.; Okubo, H., Partial discharge inception V-t characteristics for pressurized liquid nitrogen/PPLP/sup /spl reg// composite insulation system***,** Dielectric Liquids, 2002. ICDL 2002. Proceedings of 2002 IEEE 14th International Conference on , 7-12 July 2002, Pages:123 - 126

[228] H. Okubo, M. Hazeyama, N. Hayakawa, S. Honjo, T. Masuda*, V-t characteristics of partial discharge inception in liquid nitrogen/ PPLP/sup /spl reg// composite insulation system for HTS cable,* IEEE Transactions on Dielectrics and Electrical Insulation, Volume: 9 , Issue: 6 , Dec. 2002, Pages: 945-951

[229] H. Suzuki, T. Takahashi, T. Okamoto, S. Akita, Y Ozawa, *Electrical insulation characteristics of cold dielectric high temperature superconducting cable,* IEEE Transactions on Dielectrics and Electrical Insulation, Volume: 9, Issue: 6, Dec. 2002 Pages 952 – 957

[230] I. Sauers, D.R. James, A.R. Ellis, M.O. Pace, *High voltage studies of dielectric materials for HTS power equipment*, IEEE Trans on Dielectrics and Electrical Insulation] , Volume: 9 , Issue: 6 , Dec. 2002, Pages: 922 – 931

[231] E. Husain, M.M. Mohsin, A. Masood, M.U. Zuberi, M.S. Alam, *Dielectric behavior of insulating materials under liquid nitrogen*, IEEE Transactions on Dielectrics and Electrical Insulation 9 (6): 932-938 December 2002.

[232] S.M. Baek, J.M. Joung, J.H. Lee, S.H. Kim*, Electrical breakdown properties of liquid nitrogen for electrical insulation design of pancake coil type HTS transformer,* IEEE Transactions on Applied Superconductivity , Volume: 13 , Issue: 2 , June 2003 Pages: 2317 - 2320

[233] *M. Hazeyama, Kobayashi, T.; Hayakawa, N.; Honjo, S.; Masuda, T.; Okubo, H., Partial discharge inception characteristics under butt gap condition in liquid nitrogen/ PPLP/sup /spl reg// composite insulation system for high temperature superconducting cable*, IEEE Transactions on Dielectrics and Electrical Insulation, Volume: 9 , Issue: 6 , Dec. 2002 Pages:939 – 944

VI.7 Principal Technical Uncertainties

There is no reason to believe that the fabrication of dielectrics for LN_2 cable will present an insurmountable problem to cable use. There is every reason to believe that whatever problems have been disclosed deserve attention now, while cable is being developed. An electrical fault, or short circuit, can render a cable useless and provide the occasion for time consuming and costly delay and repair. The electric power sector has devoted a great deal of effort to successfully developing today's dielectrics. They are simple and reliable. The power sector will expect no less from a competing technology.

Technical concerns, if any, with dielectrics in HTS cable

- are likely to be more severe as voltage difference grows. Thus, 138 kV cable may present more of a challenge to its insulation than a 13 kV cable.

- may arise because of differences in the thermal expansion and contraction of conductor and insulator while the cable is being cooled to operating temperature or warmed to ambient temperature.

- may focus on the terminations, where the dielectric is subject to both temperature gradients and electric fields.

- may focus on the penetrations, where the coolant (e.g., LN_2) transfers heat to the cryocooler.

- may arise when considering whether or not a cryogenic failure will precipitate a failure of the electrical insulation (e.g., from bubble formation). Dielectric design should not be divorced from cryogenic design.

- may focus on adequate protection from lightning and/or repeated, transient over-voltages, whatever the causes.

The last topic, repeated transient over-voltages, is most pertinent to insulation with a high value of $n = a/b$ (see Section VI.2.4). That parameter controls the lifetime as a function of electric field. This parameter is roughly 11 for conventional dielectrics but rises above 20 for cryogenic dielectrics, suggesting that even brief over-voltages may leave the dielectric vulnerable to shortened life.[234] Recent work by Pace et al estimated this

[234] A. Bulinski and J. Densley, *High Voltage Insulation for Power Cables Utilizing High Temperature Superconductivity*, IEEE Electrical Insulation Magazine, Vol. 15, No. 2, 1999, pages 14-22

group's cable insulation could be characterized by n=26 and reported aging tests having durations from a few minutes to several weeks. [235] H. Okubo et al studied its insulation and reported values for n in the range, $80 < n < 100$.[236]

The potential problems, prompting the concerns just mentioned, also bear upon LN_2

- identify impurities, if any, in commercial LN_2 and the impurities' effect, if any, on commercial LN_2's insulating performance.

- consider the effect, if any, of the cable's design on bubble formation and bubble migration. This should be done for fault conditions, as well as normal operating conditions. When the cable's elevation changes, as it must for submarine cables, one should consider the effect of varying hydrostatic pressure and the possibility of bubbles migrating to low pressure regions.

Soon after a cable is put in service, the operator will know if the potential problems, that prompt the comments made above, manifest themselves.

Much more time will be required to disclose, two other kinds of problems about which designers should be concerned now. The relevant topics are:

- protection from lightning or other faults

- design, creation and validation of "accelerated aging tests"

Normally "accelerated aging tests" involve running the dielectric at higher than usual operating temperatures. This "thermal aging" is not relevant for a cryogenic dielectric, though naturally one should check on its behavior after several simulated failures of the cable's cooling system. Performance as a function of the number of "warm-ups" and "cool-downs" seems more relevant. Also, testing at frequencies higher than 50 Hz would appear reasonable. Tests up to 1 kHz are done for conventional cables. However, high frequency tests of HTS cable may be limited by the cable's ability to stay cool, despite higher than usual AC losses. To date, little attention has been given to how to relate frequency and test duration to 50 Hz and service life when the dielectric is operating at

[235] M.O. Pace, I. Sauers, D.R. James, A.R. Ellis, *Aging of lapped tape insulated model cables at cryogenic temperature*, 2002 Annual Report Conference on Electrical Insulation and Dielectric Phenomena, 2002 IEEE Conference on Electrical Insulation and Dielectric Phenomena.

[236] H. Okubo, M. Hazeyama, N. Hayakawa, S. Honjo,T. Masuda, *V-t characteristics of partial discharge inception in liquid nitrogen/ PPLP/sup /spl reg// composite insulation system for HTS cable* IEEE Trans on Dielectrics and Electrical Insulation, Volume: 9 , Issue: 6 , Dec. 2002, Pages: 945-951

LN_2 temperatures. Finally, since partial discharge is the principal concern, accelerated aging might be induced by subjecting the dielectric to ionizing radiation or sonication and monitoring the dielectric's performance.[237]

Guarantees of equipment lifetime will be important to potential customers, as illustrated by the following recent report of effort to improve over head power lines by reinforcing them with ceramic fiber (thus reducing sag and enabling more power through the same corridor or smaller corridors).

> "…But the companies that own transmission lines have been slow to adopt the new technology. John K. Chan, the project manager for overhead transmission cable at the Electric Power Research Institute, ….said there were several reasons.
>
> One is that conventional steel-core cable lasts "forever," he said, while no one is certain how long the newer materials will last."[238]

The only alternative to reliable accelerated aging tests is the cable manufacturer's guarantee that it will pay for repairs and any other costs incurred by equipment failure before an agreed upon date. Thus, risk-averse manufacturers also have an interest in the development of reliable accelerated aging tests.

While HTS cable may be first demonstrated and adopted for AC circuits, some persons discuss the use of HTS in DC cables. (See Chapter XI.) For that use it would be important to reconsider the insulation properties of various dielectrics. Anecdotal reports suggest a difference between AC and DC withstand for some dielectrics at LN_2 temperatures. Of course, one could design HTS DC cable having a warm dielectric to avoid the uncertainties just mentioned.

All of these topics deserve attention. None of these topics appears to present problems that are insurmountable, if the relevant research, development and demonstration is

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[237] Though no one has published work on acoustics for cryogenic dielectrics, the Canadian Electric Association has funded work to identify defects in conventional dielectrics with the help of ultrasonics. See H. Orton, A. Bannister, D. Allan and D. Tuttici, *PD Field Measurements on Cable Accessories Using Acoustic Emission, and* V. Buchholz, *Ultrasonic Detection as a Predictive Maintenance Tool for Cable Accessories, see also* (http://www.powertech.bc.ca/cfm/index.cfm?It=900&Id=47) *and* A. McGrail, A. Risino, D.W. Auckland and B. R. Varlow, *Use of a Medical Ultrasonic Scanner for the Inspection of High Voltage Insulation*, ELECTRICAL INSULATION MAGAZINE, volume 9, #6 (November, December 1993) L. E. Lundgaard, *Partial Discharge - Part XII: Acoustic Partial Discharge Detection - Fundamental Consideration*, ELECTRICAL INSULATION MAGAZINE, vol.8, #4 (July, August 1992).

[238] New York Times, 4 March 2004

supported and performed. That is very important because there is no other community from which pertinent expertise can be learned.[239]

Finally, the electric insulation community (e.g., IEEE Dielectrics and Electrical Insulation Society, CIGRE Working Group 15.14, Technical Committee on Dielectrics and Electrical Insulation, IEE of Japan) should be involved in testing, validation and the creation of appropriate standards so that technical success will be credible to potential users.

[239] Any doubt about this can be removed by confirming the paucity of the literature before 1995. The most relevant of the earlier publications include the following and references cited therein:

A.Bulinski and J. Juchniewicz, "Voltage Aging Tests of Layer Insulation Samples Impregnated with Liquid Nitrogen," CIGRE 1974, Rep. 15-03.

A. Bulinski, "Inception and Extinction Stresses of Partial Discharges in Layer Insulation Impregnated with LN_2 "Proc. Intern. Symp. HV Insul. Low Temp. Applications, Wroclaw, Poland, 1976, pp. 102-106.

A.Bulinski, "Long-Term Dielectric Strength of a Layer High Voltage Insulation Impregnated with Liquid Nitrogen," Ph.D thesis, Technical University of Wroclaw, Wroclaw, Poland, June 1976 (in Polish).
R.J. Densley, A.T. Bulinski, and T.S. Sudarshan, "Short-Term Characteristics of Some Polymeric Materials Immersed in Liquid Nitrogen," IEEE Trans. Electr. Insul, Vol. EI-14, No. 4, 1979, pp. 211- 221.

B.M. Weedy, Underground Transmission of Electric Power, Wiley (Chichester, 1980), Section 7.5, pages 252-257.

T. Tanaka, Advanced Power Cable Technology: Basic Concepts and Testing, CRC Press, (1983) # ASIN: 0849351650

Chapter VII Cost of Cable

VII.1 Introduction

The cost of transmitting and distributing electrical power by cable includes the cost of the cable itself and the cost of the infrastructure (underground or underwater) in which the cable is housed. The infrastructure is the most expensive component –in the range 5-10 million $/km-- thus, the wish to avoid this cost by increasing the capacity of existing infrastructure. See Section XII.1.3. for detail.

Nonetheless, the cost of the cable itself is relevant. And so this chapter describes the components of cost of presently foreseen cables incorporating High Temperature Superconductor. As emphasized in earlier chapters, cable includes three kinds of components, each performing a different function. One is the conductor, within which the current alternates. Another is the electrical insulator, across which the voltage differs. The last is the means for maintaining the conductor and dielectric at their operating temperatures. Of course, one must also protect each of the above from the environment by suitable armor and waterproofing.

VII.2 Conductor

VII.2.1. Ceramic Superconductor and Ordinary Metal Conductor

HTS cable includes two different kinds of conductor. One is the ceramic superconductor. It is within this that the current is intended to alternate. This component has received the most attention from the HTS community. It is agreed that it is important to reduce its price. Its dimensions and performance are indicated below. Then we show how to estimate how much is needed for cable.

The other conductor is conventional metal (e.g., silver alloy and/or copper). The conventional metal conductor is intended to provide a bypass or "shunt" in which current can alternate if the ceramic superconductor is unavailable (e.g., a tiny local break) or if a fault elsewhere on the grid overloads the cable with more current than the superconductor was sized to handle.[240]

[240] As discussed in Section IV.6.2.4, very little electrical energy dissipates when the rms current is well below the DC critical current. However when the rms current approaches the DC criticalcurrent or exceeds it, electrical energy does dissipate with a concomitant rise in temperature and the possibility of damage to the HTS, thus the desirability for a shunt. As mentioned, in Chapter V.2, the capacity of the refrigeration, affects how close the rms current can approach the critical current without damaging the cable over the long.

VII.2.2 HTS Tape including Superconductor and Metal Conductor, Enabling Current to By-Pass Occasional Tiny Breaks in HTS

Most of today's demonstration cables, incorporate Bi-2223 superconductor. It is placed in silver alloy tubes and the separate tubes are bundled and then drawn into tapes that finally contain many filaments of Bi-2223 within a silver alloy matrix. Roughly two thirds of the tapes' volume is silver alloy and one third is Bi-2223 filaments. As mentioned above, if one or even a few filaments are broken, the current simply flows around the breaks, through the silver alloy, and back into the superconductor. No harm ensues when the bypass or shunt handles only a tiny fraction of the alternating current, just as no harm ensues when the shoulder of highway provides a bypass for an occasional vehicle that must avoid an obstruction in the road.

Second generation conductor, also known as coated conductor, employs the same strategy with different materials. In this case, an REBaCuO coating is placed on other coatings (so called "buffer layers" intended to align the REBaCuO) which themselves have been placed on a base metal tape. (IBAD places buffer layers on hastalloy or stainless steel substrates; RABiTS uses Nickel alloyed with Wolfram [tungsten].) The REBaCuO may be sealed with a micron thick coating of silver. A copper overcoat is often added to provide the electrical bypass or shunt. The copper, like the silver alloy used in first generation tape, is both a good electrical conductor and a good thermal conductor. Thus, a small current in the metal will not precipitate a damaging temperature rise.

VII.2.3 Typical Dimensions of HTS tape

First generation tapes are approximately 4 mm. wide and 0.4 mm thick. The composition of the silver alloy varies with maker and intent but it is true that the alloy's resistivity exceeds the resistivity of pure silver (0.289×10^{-8} ohm-m at 80 K and 0.162×10^{-8} ohm-m at 60 K). Today's 4 mm tape might be expected to carry current in the range 70-130 A, under intended operating conditions, depending on the tape's manufacturer, price, and purpose.

For example, American Superconductor offers Bi-2223 tapes for cable having length 100-300 m, width 4.8mm, thickness 0.31 mm and having minimum critical currents in the range 115-135 A. The price for American Superconductor's tape is in the range 175-200 $/kA-m, depending on quantity ordered.

Second generation tapes are intended to have roughly the same dimensions and current carrying capacity (e.g., 300 A/cm width or 120 A for 4 mm width) as first generation tapes. The thickness of today's REBaCuO conducting film is roughly only 1 micron.[241] (Some hope that future films would be 2 microns thick with the same critical current density.) A thin silver layer may be placed above the REBaCuO. However, today's second generation tapes are not 2 microns thick. Instead, they may have a copper film or "overcoat" (roughly 50 microns thick) which is intended to serve as a shunt. (The resistivity of pure copper is 0.2158×10^{-8} *ohm-meters* at 80 *K* and 0.0971×10^{-8} *ohm-meters* at 60 *K*.) The copper overcoat is in addition to the tape's metal substrate (usually Nickel-Wolfram alloy or stainless steel); that provides mechanical support and some texture for the buffer layers and so, indirectly, for the REBaCuO. As stated in Section V.2, the desirable and feasible relations between the design of cable—including its cryogenics and copper stabilizer—and the design of second generation tape remains to be explored.

VII.2.4 Quantity and Price of HTS Tape Needed for Cable

HTS tape is required for each of the cable's three phases. The same current alternates within each of the phases. Some cable designs call for each phase to be coaxial, that is each phase has an HTS "go" and an HTS "return" conductor. One cable design (triaxial) has only three HTS conductors. As will be seen below, this triaxial design offers important cost savings wherever it can be implemented.

All cable must be flexible. To enable that flexibility HTS tapes are usually wound at an angle, the so-called "lay angle", with respect to the long axis of the cable. This lay angle affects the amount of tape needed, as explained below.

The HTS tapes, within a cable, are spirally wound on cylindrical surfaces.

If the tape has width, w, (e.g., 0.4 cm) and the cylinder has radius r (e.g., 1 cm) the maximum number of tapes that can be wound, with lay angle α on the cylinder, in one layer, is

$$\text{maximum number of tapes per layer} \equiv n_{layer}^{\max} = \frac{2\pi r}{w}\cos\left[\alpha\right]$$

$$\text{number of tapes per layer} \equiv n_{layer} \le n_{layer}^{max} = \frac{2\pi r}{w}\cos\left[\alpha\right]$$

The maximum rms alternating current that is carried down the cylinder is

[241] The critical current density of a one micron thick film, having a critical current of 300 A/cm-width, is 3×10^{6} A/cm^2 = 3×10^{4} A/mm^2.

$$I_z^{max} = \underbrace{\#_{layers}}_{\text{number of layers}} \times \underbrace{n_{layer}}_{\text{number of tapes per layer}} \times \underbrace{sJ_c\, w}_{\text{max rms AC in each tape}} \times \underbrace{\cos[\alpha]}_{\text{cosine of lay angle}}$$

When persons in the HTS community say the have tape that conducts 300 A/cm, they mean direct current. As discussed in Section IV.6.2.4, the maximum rms alternating current is less than the maximum direct current for given refrigeration capacity. This is reflected above by writing the max rms current as the product of a safety factor, s, and the DC critical current, $J_c w$. (This safety factor may also reflect degradation of some tapes (e.g., 10%) as the result of winding them into a cable.) Usually, the conductor design calls for an even number of counter-wound layers (or equivalent weaving).[242] The amount of tape, measured in DC kilo-amp-meters, in each layer is

[242] The (even number of) layers are counter wound so as to reduce the longitudinal magnetic field within the conductor's former. This reduces the induced EMF in any metal within the former and so reduces the ohmic loss to less than otherwise.

$$\text{kA - m of tape per layer} \equiv n_{layer} \times J_c w \times \underbrace{l}_{\substack{\text{length of} \\ \text{each tape}}}$$

$$\text{kA - m of tape per layer} = n_{layer} J_c w \frac{1}{\cos[\alpha]} \underbrace{L}_{\substack{\text{length of} \\ \text{layer}}}$$

$$\text{kA - m of tape at a given radius} \equiv \#_{layers}\, n_{layer} J_c wl = \#_{layers}\, J_c w \frac{n_{layer}}{\cos[\alpha]} \underbrace{L}_{\substack{\text{length of} \\ \text{layer}}}$$

$$\text{kA - m of tape at a given radius} \equiv \#_{layers}\, n_{layer} J_c wl \leq \#_{layers}\, J_c\, 2\pi r \underbrace{L}_{\substack{\text{length of} \\ \text{layer}}}$$

And so we can estimate the amount of tape in terms of the rms current in the phase

$$\text{kA - m of tape at a given radius per cable length} = \frac{I_z^{\max}}{s \times \cos[\alpha[r]]}$$

The designer can vary the lay angle with radius. Now we show how to estimate the minimum amount of tape needed for stated specifications. (Designers might well include more tape to handle over-currents or provide back up in case some tape degrades during the cable's manufacture.)

$$\frac{\text{Total HTS Tape for Cable}}{I_z^{max} \times \mathrm{L}_{route}} \approx \frac{1}{s}\begin{cases} \dfrac{3}{\left(\cos\left[\alpha_{go}\right]\right)} + \dfrac{3}{\left(\cos\left[\alpha_{return}\right]\right)} & \text{3 phases, each coaxial} \\ \dfrac{3}{\left(\cos\left[\alpha\right]\right)} & \text{3phases, each without an HTS shield} \\ \dfrac{1}{\left(\cos\left[\alpha_{inner}\right]\right)} + \dfrac{1}{\left(\cos\left[\alpha_{middle}\right]\right)} + \dfrac{1}{\left(\cos\left[\alpha_{outer}\right]\right)} & 3\,\mathit{phases, triaxial} \end{cases}$$

As indicated, the lay angle can vary with radius; indeed the lay angle of adjacent layers can also differ. However, details should not obscure the fact that the cost of the HTS tape within a kA-meter cable is proportional to the cost of the tape. Table VII.2.4 illustrates the cost trends by showing the results for a very simple example; each of the lay angles is taken to be π/6 radians (30°) and the safety factor, *s*, (the ratio of the maximum rms alternating current in the cable to the critical direct current of the tape as it left the factory) is taken to be 0.6. Several widely discussed prices of tape are shown. Other choices of the safety factor, s, and the lay angles, α, will change the numerical values but not the trends shown in Table VII.2.4.

Table VII.2.4
Approximate Minimum Cost of HTS Conductor Within Cable
for Several Prices of HTS Tape
and assuming
Maximum RMS Alternating Current = 0.6 Critical (Direct) Current at the Factory
and
Lay Angle = π/6

Cost of HTS Tape ($/kA-m tape)	Cost of HTS Tape within Triax Cable ($/kA-m cable route)	Cost of HTS Tape within 3 Co-Axial Phases ($/kA-m cable route)
200	1137	2,274
150	853	1,705
50	284	568
25	144	288
10	57	114

VII.2.5 Metal Conductor Enabling the Cable to Handle Fault Currents Until Circuit Breakers Isolate The Fault from The Network

As mentioned before, the consequences of short circuits require attention. Though impossible to anticipate, power engineers must be able to cope with these sudden, extraordinary increases in current. These are "fault currents" which are stimulated by "faults" (also known as "short circuits") somewhere in the grid or in the cable itself (e.g., a cable may be inadvertently be damaged by persons excavating a foundation for a building or digging a trench for a gas main)

Fault currents are much larger than normal operating currents. For example, a cable's normal operating current might be 1 kA while the cable might be required to briefly tolerate fault currents of up to 63 kA. Of course, the longer the fault current within the cable, the higher the cable's temperature would climb and the more likely that the cable would be damaged. To avoid this, "circuit breakers" are located throughout the grid so that the "fault" or "short circuit" can be isolated from the generating stations. Thus cables are built to tolerate a specified fault current (e.g., 80 kA) for a specified time (e.g., 5 cycles).

The silver-alloy of first generation tape and the copper alloy of second generation tape could not carry a fault current without a temperature rise that would promptly destroy the tape. Thus, an HTS cable must include more conductor than is embodied in the HTS tape. Since this conductor serves only during faults, this conductor should be inexpensive. Obvious possibilities are aluminum or copper. Copper is preferred because one wants to avoid the possibility that aluminum's easily acquired surface film of alumina, Al_2O_3, would insulate the shunt from the HTS tape.

Of course, the inclusion of copper stabilizer within HTS cable increases the cable's weight and decreases its flexibility when compared to a cable without it. One might consider a future alternative, placing a future fault current limiter in series with the cable. To be appealing, the FCL would have to be cheaper than the otherwise needed copper and act as quickly as fault current can be shunted. Below we sketch some of the technical issues bearing on the fault current stabilizing copper.[243]

VII.2.6 How the Fault Current Specification Bears Upon the Amount of Copper Stabilizer Within the Cable

As stated, a cable must sustain a fault current for a certain duration that terminates when the circuit breakers isolate the fault from the generating stations. During the fault, electrical energy dissipates in the copper stabilizer. Faults are too sudden to allow heat transfer from the stabilizer to the cooling fluid and so the stabilizer's temperature rises. If the rise is too great, bubbles might nucleate in the cooling fluid (e.g., LN_2) and precipitate electrical breakdown. As discussed in Chapter VI, this concern increases as the electric field increases (i.e., the ratio of the voltage difference across the dielectric to its thickness).

The stabilizer's temperature rise can be reduced by adding more stabilizer. The relation between materials properties and temperature rise is sketched below.

The amount of electrical energy dissipated, Q, is related to the duration of the fault, t_{CB}, fault current, I_{fault} and the stabilizer's conductivity and volume, as shown below.

$$Q = \int_{t_{fault}}^{t_{fault}+t_{CB}} dt \int_{stabilizer\ volume} d^3x\, \mathbf{J}\cdot\mathbf{E}$$

$$Q = t_{CB}\left(Volume_{stabilizer}\right)\frac{1}{\sigma_{stabilizer}}\left(\frac{I_{fault}}{A_{stabilizer}}\right)^2$$

[243] In addition to the issues to sketched in the following subsections, the avoidance of eddy currents within the copper, during routine operation of the cable must be considered.

As mentioned, sudden faults allow no time for heat transfer. Instead, the dissipated electrical energy raises the stabilizer's temperature. Thus, the stabilizer's mass density, ρ, specific heat, c_p, and dimensions, here described by a length and a cross-sectional area are relevant.

$$Q = \int_{T_{operating}}^{T_{operating}+\Delta T} dT \int_{stabilizer\ volume} d^3x \rho[x,T] c_p[x,T]$$

$$Q \approx \Delta T (Volume_{stabilizer}) \rho[\langle T \rangle] c_p[\langle T \rangle]$$

And so the stabilizer's temperature rise, ΔT, due to the fault current, can be estimated as shown.

$$t_{CB} \left(\frac{Volume_{stabilizer}}{\sigma_{stabilizer}} \right) \left(\frac{I_{fault}}{A_{stabilizer}} \right)^2 \approx \Delta T (Volume_{stabilizer}) \rho[\langle T \rangle] c_p[\langle T \rangle]$$

The schematic result appears below. The left hand side is the product of two factors, the first describes the heat capacity of the stabilizer (it depends on the density and specific heat). The second factor describes the fault (current and duration) and the stabilizers' electrical conductivity. The product of these two factors yields the cross-sectional area of the stabilizer and its temperature rise, as shown on the right hand side.

$$\left(\frac{1}{\rho[\langle T \rangle] c_p[\langle T \rangle]} \right) \left(\frac{I_{fault}^2}{\sigma_{stabilizer}} t_{CB} \right) \approx (A_{stabilizer})^2 \Delta T$$

To illustrate this result, we present the numbers for a pure copper stabilizer. In particular, we suppose that: (a) the temperature is 70 *K*, T= 70*K*, (b) the density of copper is not significantly greater than its density at room temperature, 8.94×10^3 kg/m^3, the circuit breaker will clear the fault after 5 cycles, t_{CB} = 0.083 seconds (5 cycles at 60 Hz) and, (c) the fault current is 40 kA, I_{fault} = 40 kA. The materials properties of pure copper are shown in Table VII.2.6.

Table VII.2.6
Some Properties Pure Copper

Wolsky, A.M., Chapter VII of **HTS CABLE—STATUS, CHALLENGE and OPPORTUNITY.** Work done for and sponsored by the signatories of the International Energy Agency *Implementing Agreement for a Cooperative Programme for Assessing the Impacts of High-Temperature Superconductivity on the Electric Power Sector* (02 December 2004).

	T = 60 *K*	T = 80 *K*	T = 100 *K*
c_p specific heat (*joule/mole-K*) (*joule/kg-K*)	8.595 135.3	12.85 202.2	16.01 252.0
1/σ resistivity (*ohm-meter*)	0.0971×10^{-8}	0.2815×10^{-8}	0.348×10^{-8}

It follows that for T≈70*K*, the temperature rise, ΔT, and cross-sectional area of the cable's copper stabilizer, $A_{Cu\ stabilizer}$ are related as shown.

$$\left(\frac{I_{fault}}{40\,kA}\right)\sqrt{\left(\frac{t_{CB}}{0.083\,sec}\right)}\times 4\,cm^2 \approx A_{Cu\ stabilizer}\times\sqrt{\frac{\Delta T}{1K}}$$

VII.2.7 The Cost of the Copper Stabilizer Within the 3 Phase Cable

As described above, the amount of copper stabilizer wanted within the cable depends on the duration and magnitude of the fault current that must be tolerated. The price of commodity copper is approximately 1.35 $/lb or 2.97 $/kg.[244] Of course, dephosphorizing the copper and then drawing it into wire will increase the price to the cable maker. However, for the sake of definiteness, a price of 3.00$/kg will be used below. The cost per meter of cable route of the cable's copper stabilizer is related to its cross-sectional area, as shown below.

$$\text{cost per route length} = \frac{3}{\cos[\alpha_{Cu}]} \times A_{stabilizer} \times \rho_{Cu} \times \text{price of Cu}\,(\$/\text{kg})$$

$$\text{cost per route length} = \frac{3}{\cos[\alpha_{Cu}]} \times \left(\frac{A_{stabilizer}}{4cm^2}\right) \times (4cm^2) \times 8.94(g/cm^3) \times (3.00\,\$/kg)$$

$$\text{cost per route length} = \left(\frac{A_{stabilizer}}{4cm^2}\right) \times \frac{1}{\cos[\alpha_{Cu}]} \times (32\,\$/m)$$

As described in the last section, the desired cross-sectional area of the copper stabilizer depends on the fault currents and their duration. However, the details are less important than the order of magnitude which appears in the range 30-60 $/m of route length. This is much smaller than the cost of the HTS.

VII.3. Electrical Insulator, also known as Dielectric

As described in Chapter VI, the dielectric materials (e.g., polypropylene laminated paper) that now provide electrical insulation for HTS cable are common, commercially available materials entailing no greater cost than those used in conventional cables. The cost of the cable dielectric is small compared with the other costs. The principal technical challenge is to fabricate inexpensive, reliable, and efficient terminations from these materials.

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[244] This is the cash price for full plate copper cathode; it appears on page B9 of the 14 August 2004, *New York Times*. (On the same day, the price of high grade copper on the CMX for delivery in November 2004 was 1.30 $/lb or 2.86 $/kg.) The cash price for aluminum was 0.78 $/lb or 1.72 $/kg. The cash price for silver was 6.640 Handy & Harman and the CMX price for silver delivered in May 2005 was 6.74 $/Troy Oz.

VII.4 Cryogenics

Because the HTS' operating temperature is below ambient, HTS cable makers seek reliable and inexpensive (capital and operating) means toward five goals:

1. Reduce the electrical energy dissipated within the cable. The mechanisms for that dissipation are: (a) ohmic loss, concomitant with eddy currents induced in conventional metals (e.g., conductor meant to carry fault currents) (b) hysteresis loss within the superconductor, concomitant with alternating magnetic fields.
2. Reduce the mechanical energy dissipated during the flow of LN_2 because of its viscosity.
3. Reduce the quantity of heat transferred from the ambient temperature environment to the volume within which the HTS' operating temperature is maintained.
4. Increase the efficiency with which refrigeration extracts heat from the volume within which the HTS' operating temperature is maintained and delivers that heat to the environment.
5. Reduce the heat that flows from the terminations to the volume within which the HTS' operating temperature is maintained.

Here we consider the associated costs.

Today, the capital cost of a flexible cryostat, having diameter approximately 150 mm, is 480 €/*m*.[245] The combined effects of increased demand and improvements in manufacturing might reduce this to 240 €/*m*. Obviously, cable designs that call for each phase to have its own cryostat will be more expensive than designs in which all three phases are in a single cryostat.[246,247]

Table VII.4.1

Order-of-Magnitude First Cost for Flexible Cryostat per Cable Length

[245] On 20 November 2004, 1 € = 1.20 $ = 124 Yen; exchange rates fluctuate.

[246] However, re call that the minimum diameter of the cable is limited by the breakdown strength of the dielectric. Thus high voltage cable must have a larger diameter than low voltage cable. High voltage cable is more likely to have each phase in its own cryostat.

[247] Of course, if the diameter exceeds 150 mm the price of the increases. For example, a 250 mm cryostat might cost about twice the quoted figure and it would be harder to wind on standard cable spool.

Nominal Price of Flexible Cryostat	3 Phases in One Cryostat	1 Phase Per Cryostat
480 €/m-cryostat	480 €/m-cable route	1480 €/m-cable route
240 €/m-cryostat	240 €/m-cable route	720 €/m-cable route

Today's cost is less than today's cost for HTS tape. However, cost of the cryostat is not negligible and does deserve attention. If and when the cost of the tape falls to roughly 25 $/kA-m, a widely discussed goal, the cryostat will remain a significant cost component. In fact, today's cryostat would cost more than the HTS. See Table VII.2.4.

The cost of the cryostat is not the only cryogenic capital cost. The heat that is transferred from the environment through the walls of the cryostat into the volume at operating temperature must be removed by refrigeration. That same refrigeration must also remove both the electrical energy dissipated within conductors and the mechanical energy dissipated by the viscous LN_2.

The rate of heat transfer through the walls of the cryostat will depend on its surface area (i.e., diameter of cryostat) and whether or not the cryostat is straight or bent. The latter degrades performance. Off-the-shelf, commercial flexible cryostats might offer heat transfer rates of 2-3 W/m for diameters in the range 100 –150 mm. Furukawa built a flexible cryostat for the demonstration cable at CRIEPI's Yokosuka Laboratory. Its average heat transfer rate is approximately 1.3 W/*m*. That heat transfer must be balanced by refrigeration.

Refrigeration must also remove heat resulting from the dissipation of electrical energy (eddy currents and hysteresis in HTS). As mentioned above, that dissipation depends on the design of the cable and how much metal is embodied in it. Various cable projects aim for losses in the range of 1 W/m. Less loss may be possible with the benefit of experience.

Also as mentioned above, the kinetic energy of LN_2 dissipates because of its viscosity. That dissipation manifests itself as a pressure drop along the cable. This pressure drop is sensitive to the speed of the LN_2, the dimensions of the channels in which it flows, and the roughness of the walls. However, in many circumstances, this source of heat will be smaller than the others and so we neglect it.

Because the designs for cables differ and the goals for the cost of refrigeration are less than today's prices, we tabulate the investment cost in refrigeration per meter of cable length under several assumptions. The highest first cost for refrigeration, 200$/W, refers to the total cost of today's refrigeration technology (including automation and controls and balance of plant) for removing heat from a cable operating near 77 K. For a cable operating at 77K, today's first cost for only the cooler is less, approximately 150-100 $/W. The lowest first cost, 50 $/W, is a goal (for only the cryo-cooler) whose future attainment will be affected by the amount of funds made available for Development and Demonstration.

Table VII.4.2

Order-of-Magnitude First Cost for Refrigeration per Cable Length

($/*m-cable*)

Depends on Heat Load and Cryocooler Costs

Capital Cost of Refrigeration	5 W/m-cable	4 W/m-cable	3 W/m-cable	2 W/m-cable	1 W/m-cable
200 $/W	1,000	800	600	400	200
150 $/W	750	600	450	300	150
100 $/W	500	400	300	200	100
50 $/W	250	200	150	100	50

VII.5 Summary and Perspective

The cost of today's demonstration cables incorporating HTS is much higher than the cost of conventional copper cable because today's HTS is more expensive than the copper and the cost of the cable must also include the cost of the cryostat and the cost of refrigeration. The total cost is very sensitive to the design of the cable, in particular, the total cost depends upon whether one cryostat or three cryostats are used.

Instead of recapitulating the information, already presented in the tables, we cite a particular case to suggest why many groups are working to develop and demonstrate HTS cable. We consider a cable of the following design

triaxial

Assuming the cost of HTS conductor is 25 $/kA-m, the cost of the conductor within the cable is approximately 144 $/kA-m of cable.

Beside the cost of HTS conductor is the cost of cryogenics. With today's prices and exchange rates (1€=1.20$=1.24¥), the cryostat costs 576 $/m and the total refrigeration costs roughly 200 $/W (at 77 K). If the total heat load is 2-3 W/m, the cryogenic first cost would be 976-1176 $/m.[248] This cost might be reduced by two effects: a larger market for cryostats might halve their cost (reducing it to 280 $/m) and funds devoted to development and demonstration of acoustic cryocoolers might yield cryo-coolers at 50 $/W (half of today's price). Even if future conductor is free, today's cryogenics is expensive and so deserves attention from RD&D aiming to improve price and performance.

While the costs just discussed, 1100-1300 $/kA-m describe a future cable that is more expensive than a conventional cable, these costs may less than the cost of building new infra-structure to accommodate conventional cable.

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[248] See Table VII.4.2 for a range of heat loads and costs. Recall, both the heat that leaked in and the AC losses must be removed.

VIII. GROUPS CONCERNED WITH POWER CABLE

VIII. 1 Introduction

Many organizations concern themselves with power cables. Here we cite those that have been and are most active. Slight emphasis is given to those that are not as well known as those within countries sponsoring this report. Many fine other organizations contribute to HTS RD&D but are not interested in cable; they are not listed. Table VIII.1 presents information on cable projects now underway.

Readers can pass over this chapter and return to it whenever they want to contact the groups described herein.

The following information is presented to (a) introduce the reader to important research groups, (b) enable the reader to contact these groups, thereby (c) allowing the interested reader to keep abreast of developments after this report is published, and (d) allow the interested reader to contact a potential constituency for innovation.

Because no survey can be exhaustive, some groups engaging in technically related activities may have inadvertently been omitted. Because no survey can be more current than its date of publication, we also cite professional organizations. They are relatively stable, and their members can provide useful information long after this report has been published and various firms may have changed their names in the course of future mergers and buy-outs.

HTS Cable Projects Are Underway Around The World

(as of 02 December 2004)

Project Management Characteristic	Innopower[4]	Chinese Academy of Science	KERI	KEPRI	SuperAce
Financial Status	Funded	Funded	Funded	Funded	Phase-I Funded
Demonstration Site	Puji Substation Kunming, Yunnan ChinaSouthernPowerGrid	Chang Tong Cable Facility (Lanzhou Province)	LG Cable Facility	KEPRI/KEPCOs Test Site at Kochang	CRIEPI's Lab at Yokosuka
Utility	Yunnan Electric Power Group	none	KEPCO	KEPCO	TEPCO, ChubuE, & KEPCO
Planned Start of Operation	April 2004	Winter 2004-2005	July 2004	Summer 2005	March, 2004
Type	AC	AC	AC	AC	AC
Phases	3	3	3	3	1
Voltage (phase-to-phase)	35 kV	15	22.9 kV	22.9 kV	77 kV
Current (within phase)	2 kA	1.5 ka	1.2 kA	1.2 kA	1.0 kA
Length	33.5 m	75 m	30 m	100 m	500 m
Design	Warm Dielectric XLPE 4 HTS layers per phase one phase per cryostat OD HTS phase 34 mm OD cable 112 mm Fault Spec: 2 sec, 25 kA	Warm dielectric	Cold Dielectric PPLP Triad HTS 3 cores, in one cryostat	Cold Dielectric 3 coaxial cores, in one cryostat OD Cable Fits in 175 mm Duct Fault Spec: 5 cycles, 25 kA	Cold Dielectric PPLP one coaxial in cryostat OD cable 133 mm Fault Spec: 25 cycles, 31.5 kA (500 millisec)
HTS	Bi-2223	Bi-2223	Bi-2223	Bi-2223 (SEI's CT-OPT, Controlled Over Pressure)	Bi-2223 suitable for AC (short sample of REBaCuO, if available)
AC Loss Goal	<1.0 W/m per phase	?	1 W/m per phase	50% of Conventional	measured value given here 1.3 W/m/phase @ 1 kA
Conductor Supplier Cable Fabricator	InnoST Nexans provided Electrical Insulation within Cryostat Shanghai Cable Works (terminations' goal <120W/unit Inst. Of Plasma Physics at Academia Sinica)	AMSC Chang Tong Cable Company	AMSC LG Cables	SEI SEI via Turnkey Contract	Furukawa SRL- REBaCuO Furukawa
Cryostat Type & Supplier	flexible goal <1.5 W/m Nexans-Hanover	flexible	?	included in Turnkey	flexible 1.0 W/m Straight Section Furukawa
Cryogen Refrigeration & Supplier	LN_2 70–80K, seven, 300W-GM CryoMech	LN_2 CAST	LN_2 70-80K Tank	included in Turnkey	LN_2 4 kW cable + 2kW terminations Suzuki Shoukan Aishin Sterling-cooler

Project Management Characteristic	ConduMex	Tratos Cavi	SuperPower	American Superconductor	Ultera[1,3]	Nexans
Financial Status	Funded	Funded	Funded	Funded	Funded	Funded
Demonstration Site	CIDEC Lab Phase II at substation near Queretaro	Pieve Santo Stefano (AR, Italy)	Albany, N.Y.	East Garden City, Long Island, N.Y.	Bixby Substation, Columbus, Ohio	? ? Spain ?
Utility	Commission Federal de Electricidad (CFE)	none	Niagara-Mohawk (a National Grid Company)	Long Island Power Authority	American Electric Power	E.On
Planned Start of Operation	Phase I: 2005 Phase II: 2006 (start)	Spring 2005	Jan-2006 Bi-2223 Dec-'06 YBaCuO	April, 2006	Spring 2006	? 2007 ?
Type	AC	AC	AC	AC	AC	AC
Phases	1(Phase I) & 3 (Phase II)	3	3	3	3	1
Voltage (phase-to-phase)	23 kV	45 kV	34.5 kV	138 kV	13.5 kV	10 kV
Current (within phase)	2 kA	2 kA	0.8 kA	2.4 kA	3.0 kA	1 kA
Length	5 m & 10 m Phase I 100 m Phase II	50m	350 m	660 m	200 m	30 m
Design	Warm Dielectric Polyethylene other participants in component design & selection IPN (Mexico City) VNIIKP (Moscow)	Warm Dielectric and 5 m, 45 kV cold dielectric	Cold Dielectric Triad HTS 3 coaxial cores, in one cryostat Fault Spec: 38 cycles, 23 kA (633 millisec)	Cold Dielectric each coaxial core in own cryostat (all in 355 mm pipe) Fault Spec: 15 cycles, 69 kA (250 millisec)	Cold Dielectric Cryoflex™[4] Triaxial HTS 3 inner HTS 1 outer Cu in one cryostat, OD ~140 mm Fault spec:15 cycles, 56 kA (250 millisec)	Cold Dielectric coaxial HTS
HTS	Bi-2223	Bi-2223	Bi-2223 (SEI's CT-OPT, Controlled Over Pressure) subsequent 30-m section of YBaCuO	Bi-2223	Bi-2223	REBaCuO on Stainless Steel
AC Loss Goal	?	?	<0.5 W/m per phase	?	?	?
Conductor Supplier Cable Fabricator	AMSC Nexans provides former ConduMex	AMSC Trithor Tratos Cavi	SEI Bi-2223, SuperPower YBaCuO SEI	AMSC Nexans	to be determined Ultera	EAS Nexans SC Nexans
Cryostat Type & Supplier	flexible Nexans-Hanover, 5 m Condumex, 10 m	flexible Tratos Cavi	flexible ~2.5 W/m SEI	flexible ~5 W/m^2 Nexans-Hanover	flexible ~5 W/m^2 Nexans-Hanover	flexible ~5 W/m^2 Nexans-Hanover
Cryogen Refrigeration & Supplier	LN_2 Phase II-Air Products, 4 kW	LN_2 Stirling	LN_2 6 kW @ 77K closed loop BOC	LN_2 5 kW @ 70 K Air Liquide AMSC-pulse tube	LN_2 Praxair & Praxair-QDrive	LN_2 Air Liquide

[1] Ultera is a joint venture of NKT and Southwire

[2] Southwire continues to supply electric power (26,000 hours at 100% load) to its cable manufacturing plant through an HTS, three-phase, 30 m cable of its own construction (each phase HTS coaxial, Bi-2223, cold dielectric, LN_2 cooling, 12 kV phase-to-phase, 1.2 kA, 27 MVA).

[3] It is a coincidence that Nexans' cryostat's trade-name is the same as the name of the dielectric material used by Ultera. They use different materials.

[4] InnoPower expects to build a 110 kV, 1-2 kA cable of several hundred meter length in the vicinity of Beijing during coming years.

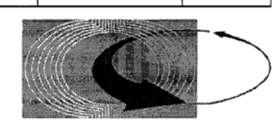

Table prepared 30 November 2004 by A.M. Wolsky, Operating Agent for *International Energy Agency's Implementing Agreement for a Cooperative Programme for Assessing the Impacts of High-Temperature Superconductivity on the Electric Power Sector*

Table VIII.1 Cable Table

VIII.2 Nonprofit Research Centers

VIII.2.1 Australia-University of Wollongong

The university's Institute for Superconducting and Electronic Materials (ISEM) involves more than 50 people. In the past, ISEM collaborated with MM Cables (affiliated with BICC before it was purchased by Pirelli). ISEM's recent effort in applied superconductivity focused on MgB_2 and Bi-2223, including AC losses. This fall, new funding was received to develop a novel technology for manufacturing flexible coated conductors to enhance the current-carrying ability of high-temperature superconducting coatings for future long-length, high-power applications. Drs. Dou and Horvat are active and collaborate with many people around the world. ISEM's other work concerns electronic materials, energy materials, thin film technology, and solid state physics. The ISEM is led by S. Dou. His contact information follows:

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URL: http://www.uow.edu.au/eng/research/ISEM

VIII.2.2 Austria-Technical University of Graz

The university's Technical Institute of Electrical Machines and Drives includes staff who investigate cryogenic dielectrics. Some effort is devoted to superconducting power equipment (e.g., J. Gerhold and C. Sumereder, *Insulation Systems for Superconducting Power Devices: Normal Operation Versus Abnormal Conditions,* Tenth International Symposium on Gaseous Dielectrics, 29 March 04, National Technical Univ. of Athens, and J. Gerhold, *Potential Cryogenic Fluids for Future Equipment Insulation in the Medium High Voltage Range*, IEEE Transaction on Dielectrics, Vol.9, No. 6, p. 878-890, and *Potential Cryogenic Liquids—A Prospective Insulation Basis for Future Power Equipment*, IEEE Transaction on Dielectrics vol.9, No. 1 pages 68-75). The group is led by J. Gerhold whose contact information follows:

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VIII.2.3. Canada-National Research Council (NRC)

NRC is Canada's metrology institute is home to A. Bulinski, who is one of the first to study dielectrics at LN2 temperatures. He remains interested () in the study dielectrics and his contact information follows:

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VIII.2.4 China

VIII.2.4.1 Applied Superconductivity Laboratory (ASCLab) of the Chinese Academy of Sciences (CAS)

The CAS's Applied Superconductivity Laboratory (ASCLab) will oversee a power cable project in Lanzhou province and a fault current limiter (FCL) project in Changsha City. Beijing-based Chang Tong Cable Company, together with CAS, will manufacture the 75-meter (250 foot) power cable using 12 kilometers of AMSC wire. CAS will also coordinate the assembly of the fault current limiter – an advanced design that will use 18 kilometers of AMSC wire.

ASCLab aims to be China's national research and development center for superconducting power technology and superconducting high-magnetic applications. The group engages in educating highly talented students and strives to be an important international base for academic exchange and cooperation. In the past several years, the Applied Superconductivity Lab sent more than 30 people to work/study at other institutions inside and outside of China.

The lab states that it is the only graduate education institute in China and has granted 40 masters degrees and 15 doctorates during the past 20 years. Presently, the ASCLab has a faculty of 26, among which are: 1 academician of the Chinese Academy of Sciences, 3 doctoral tutors, 9 professors, and 12 doctors.

AscLab was founded in 1970. Since then, more than 20 of its achievements have been recognized with awards from the Ministry of Science and Technology of the Peoples Republic of China and the CAS. More than 500 papers and monographs have been published domestically and overseas.

The AscLab describes itself as serving the development of China's economy, and states its research activities are supported by China's economic and technology development program. Further, AscLab has more than five projects per year that are funded by various industries. ASCLab is led by L.Y. Xiao, whose contact information follows:

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VIII.2.4.2 Applied Superconductivity Research Center, Tsinghua University

The Applied Superconductivity Research Center (ASRC) was formed in the year 2000. ASRC's research focuses on several areas, including BSCCO tapes, coated conductors, characterization, and new applications. ASRC collaborates in materials research and HTS (High Temperature Superconductor) applications with other departments at Tsinghua University. ASRC has close relations with industry, including InnoST and InnoPower. Prof. Zhenghe Han, the director of ASRC, is also the executive group leader of the national Applied Superconductivity Program supported by the Chinese Ministry of Science and Technology (MOST). Prof. Han's contact information follows:

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VIII.2.4.3 Northwest Institute for Non-Ferrous Metals Research

Though this institute is now reported to be inactive, in 1998, a 1m, 1000A HTS power cable prototype was developed successfully by the IEE, the Northwest Institute for Nonferrous Metal Research, and the Beijing General Research Institute for Nonferrous Metals, in preparation for a 6m HTS power cable that was later developed and tested with funds from the National Center for R&D on Superconductivity. The 6 m cable was tested at the Institute of Electrical Engineering (IEE), CAS, where it carried a current of 1473 A. Known contact information follows:

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Email: ??????????????
URL: ??????????????

VIII.2.5 Denmark--Technical University of Denmark

The Danish Technical University's Electric Power Engineering Department (ELTEK) has been a leader in the development of HTS cable. Recently, it began testing, dismantling, and inspecting the high-temperature superconductivity (HTS) cable that served Copenhagen at the Amager Substation. Some of its experience is reported in two papers: (a) *Operation experiences with a 30 kV/100 MVA high temperature superconducting cable system*. Invited paper at EUCAS 2003. Ole Tønnesen, Manfred Däumling, Kim Høj Jensen, Svend Kvorning, Søren K. Olsen, Chresten Træholt, Erling Veje, Dag Willen and Jacob Østergaard. Supercond. Sci. Technology 17 (2004) S1-S5 and (b) High Temperature Superconductivity 2 Engineering Applications A.V. Narlikar (Ed.) , Chapter in a book with 28 pages on the subject: *High Temperature Superconducting Cables* by Ole Tønnesen and Jacob Østergaard. Springer Verlag 2004, ISBN 3-540-40639-5 The department is also concerned with grid reliability and the avoidance of blackouts, as well as other topics which include: power quality, electric diagnostics, computer engineering, grid-connected wind farms, power system management, complex interactive networks, and experimental high voltage engineering. ELTEK is chaired by O. Tønnesen, whose contact information follows:

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VIII.2.6 Finland-- Technical University of Tampere

The Technical University of Tampere's staff actively contributes to the development of superconducting magnets and HTS cable. They recently participated in the SUPERPOLI project, and are now part of a team whose goal is a 30-meter cable made from "second generation" HTS conductor. That team is led by Nexans and includes Germany's ZFW. R. Mikkonen is one of the leaders in these efforts. His contact information follows:

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VIII.2.7 France—Laboratoire d'Electrotechnique de Grenoble, CNRS

Laboratoire d'Electrotechnique de Grenoble (LEG) describes itself as the most important French and European public research laboratory in electrical engineering. It states it has 120 researchers, technical, and administrative staff, and about 30 master's students and trainees. When investigating dielectric issues, LEG collaborates with Laboratoire d'Electrostatique et de Matériaux Diélectriques-CNRS Grenoble (http://www-lemd.polycnrs-gre.fr). LEG has an actively pursuing policy of industrial collaborations. More than three-quarters of its financial resources and half of its consolidated budget (including all salaries) stem from industrial contracts (60 running). In collaboration with CEDRAT (http://www.cedrat.com), LEG developed a 3D finite element code that includes a power law model of the current voltage curve for superconductors. This code could be useful for current distributions and ac losses in cables. Working with Centre de Recheches sur les tres Basses Température (CRBT), also in Grenoble, LEG devotes some of its effort to superconducting power devices. Work on HTS devices (e.g., transformers, FCL, permanent magnet motors with superconductive stators) for the power sector is centered in the Electric Machines Section. Now an 800 kJ SMES is being constructed that will incorporate Bi-2212 tape made by Nexans-Jeumont from precursors made by Nexans-Hurth. The Electric Machines Section is a SCENET node and is headed by P. Tixador, whose contact information follows:

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VIII.2.8 Germany

VIII.2.8.1 Georg-August-Universität Göttingen

Georg-August-Universität Göttingen is home to a group that is one of the world's leaders in the development of second generation HTS conductor that incorporates films of REBaCuO deposited on buffer layers which are themselves deposited on technically promising substrates. The group has been one of the leaders in each of two cable projects: SUPERPOLI (now finished) and a new project led by Nexans that is now underway. The latter's goal is to build and demonstrate a 30-meter AC single-phase cable incorporating "second generation" HTS conductor, incorporating REBaCuO. The group is led by H. Freyhardt whose contact information follows:

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URL: www.gwdg.de/freyhardt

VIII.2.8.2 Forschungszentrum Karlsruhe

FZK's Institut für Technische Physik (ITP) is a center for applied superconductivity and cryogenics, contributing heavily to LTS magnets and their applications, as well as very large cryopumps for fusion. Some of ITP's efforts have been devoted to HTS including electric power equipment (K.P. Jüngst), NMR high-field magnets (Th. Schneider), cryogenics (H. Neumann), and conductor materials development (W. Goldacker). ITP tested dielectrics and materials for the Siemens cable project before the company sold its cable business to Pirelli. In general, ITP's activities are aimed at developing systems-adapted conductor technologies and functional models, as well as at demonstrating the reliability of such components in cooperation with industry partners. ITP collaborates with industry and other research institutions around the world and is also part of SCENET. ITP's capabilities in cryogenics and high voltage engineering, in collaboration with neighboring universities, are very pertinent to the development of HTS cable. ITP is lead by P. Komarek, who is the President of the European Society for Applied Superconductivity (ESAS). His contact information follows:

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VIII.2.9 Japan

VIII.2.9.1 Central Research Institute of the Electric Power Industry

Central Research Institute of the Electric Power Industry (CRIEPI) maintains laboratories at several sites in Japan. CRIEPI’s work on power systems is located at its laboratory in Komae. CRIEPI’s Yokosuka laboratory is where power transmission technologies have been developed and tested since the 1970s. Now three different facilities, each focusing on transmission, are also located there: (1) A high-power test facilities having a short-circuit generator that produces high current of 63kA at maximum. Short-circuit testing simulates fault current caused by short circuits on power distribution/transmission facilities. This helps evaluate the limits of power equipment and clarifies the behavior of AC arcs, contributing to the improved reliability and safety of distribution/transmission lines. Its DC high-power test facility can produce 60kA current at maximum. (2) A compact power transmission test facility is now being used for research and development of compact high-performance insulation arm to construct 154kV compact transmission lines within the route width of existing 66kV transmission lines. The test facility temperature can be changed and can produce fogs. Progress toward improved insulating performance and mechanical strength of insulation arms and line spacers made from polymer materials has been achieved. (3) A large-capacity underground cable test facility enables evaluating the insulating performance of the cables for decades-long periods using accelerated aging tests. Now, 161kV XLPE cable and its connections are being tested for long-term reliability. A fourth facility is under construction and is intended to test Japan's 500m HTS cable, beginning in spring of 2004. This work is part of Japan's Super-ACE program. The program's cable project is led by T. Okamto, whose contact information follows:

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CRIEPI’s work on Power Systems is located at its laboratory in Komae and is led by S. Akita, whose contact information follows.

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VIII.2.9.2 International Superconductivity Technology Center (ISTEC)

International Superconductivity Technology Center (ISTEC) has four functions: (1) surveys and studies; (2) basic research and development, comprising high-temperature superconductivity theory, materials exploration, innovative processing methods, and other research activities; (3) education and information dissemination, and (4) international exchange. ISTEC performs research on coated conductor at its laboratories in Tokyo and Nagoya, where Y. Shiohara leads the national effort. This research is a part of the NEDO-METI national project on research and development of coated conductors as collaborative research and development of fundamental technologies for superconductivity applications. Y.Shiohara is also acting as a Project Leader of the national project. In addition to ISTEC itself, this project's participants are drawn from universities, research institutions and industries, including Kyushu University; Yokohama National University; Waseda University; Japan Fine Ceramic Center (JFCC); Sumitomo Electric Industries, Ltd. (SEI); Fujikura, Ltd.; Furukawa Electric Co.; Showa Electric Wire & Cable Co, Ltd.; and Chubu Elect Power, Inc. The whole organization of ISTEC is headed by S. Tanaka. ISTEC's contact information appears below and Y. Shiohara's follows.

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Dr. Yuh Shiohara, Division Director
Superconductivity Research Laboratory
Division of Superconducting tapes & Wires
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VIII.2.9.3 Kyushu University

The Department of Electrical and Electronic Systems Engineering includes two divisions: Electric Power and Energy, and System Control, which together investigate (1) electro-magnetic energy systems, (2) high-voltage and pulsed power systems, (3) electrical discharge application systems, (4) superconducting electromagnetic systems, and (5) high-temperature superconducting devices. Profs. Hara, Takeo, Suehiro and Kisu each lead groups whose activity concerns power engineering. Kyushu is also home to the Research Institute of Superconductor Science and Systems (RISS), a joint-use research center for the basic science and near-future application of superconductors, including improvements in electromagnetic properties of superconducting wires and films (e.g., AC loss in wires and cables), applications to superconductive devices and systems (in cooperation with the Graduate Schools/Faculties of Information Science and Electrical Engineering, Engineering, Engineering Sciences, and Sciences). RISS is directed by K. Funaki, whose contact information follows:

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VIII.2.9.4 Nagoya University

Prof. Hayakawa, his mentors and students have advanced the understanding of dielectric behavior at cryogenic temperatures. In particular, this group's work may enhance designs of dielectrics for HTS power equipment. N. Hayakawa's contact information follows.

Prof. Naoki Hayakawa
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Email: nhayakaw@nuee.nagoya-u.ac.jp
URL: http://www.nuee.nagoya-u.ac.jp/index-e.php

VIII.2.9.5 Yokohama National University

The Division of Electrical and Computer Engineering is home to several groups that investigate topics (e.g., AC loss) that bear on cable. These groups include those led by Prof. Tsukamoto, Prof. Oyama, and Prof. Amemiya. More can be learned by contacting O. Tsukamoto, whose contact information follows:

Prof. Osami Tsukamoto
Director Cooperative Research and Development Center
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Email: osami@tsukalab.dnj.ynu.ac.jp
URL: http://www.dnj.ynu.ac.jp/DNJ/index.html

VIII.2.10 Mexico--Centro de Investigación en Ciencia Aplicada y Tecnología Avanzada del Nationale Polytechnique Instituto (IPN-CICATA)

IPN-CICATA is a center for higher education (MS and Ph.D.; emphasis on mathematics) and research in Mexico. Both a biomedical laboratory and an NMR laboratory are located there. Staff members: Ciro Falcony, M. Jergel, and A. Morales contributed to the project described in Sections VIII.2.9 and VIII.3.8.2. Their contact information follows:

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amorales@fis.cinvestav.mx
URL: http://www.cicata.ipn.mx/

VIII.2.11 Russia-- All-Russian Cable Scientific Research and Development Institute (VNIIKP) Moscow

"VNIIKP" is a Russian technical center (VNIIKP meets ISO 9001) of the cable industry, as it was in the USSR. The Department of Superconductivity was founded in 1967 and the first work on superconducting (LTS) power cable occurred in the 1970s under a USSR program. The main results of VNIIKP's LTS cable effort are documented in:

(1) Meschanov G.I., Belij D.I., Dolgosheev P.I., Peshkov I.B., Svalov G.G., *The Present State and Prospects of the Research Effort in the Sphere of Making Flexible Cryocable in the USSR*. "IEEE Trans. on Magn." 1977, v. 13, N1, pp. 154-160.

(2)Meschanov G.I., Peshkov I.B., Svalov G. G., *The Results of Work Carried Out in the USSR on Creation of Superconducting and Cryoresistive Cable for Electric Power Lines*. "IEEE Trans. on Magn." 1983, v. 19, v. 3, pp. 656-661.

Research on HTS cable began in 1996 under a contract from Southwire with a Moscow firm Cabix Consulting. VNIIKP analyzed the first test results of Southwire samples 1 and 2 and calculated the multilayer cable core with uniform current distribution between layers. The core design with inner half of layers winding in one direction and the outer half of layers winding in another direction was offered to Southwire in the beginning of 1997 and now is the conventional core design. In 1999, VNIIKP contracted with Condumex (Mexico) to consult in creating its cryogenic laboratory, cable design, and cable technology. In two years, the laboratory was completed and 1-meter and 5-meter cable models were made and tested. Staff exchanges between VNNIKP and Condumex were made. The results of this joint effort were presented at ASC 2002 and published as V. Sytnikov, P. Dolgosheev, M. Soloviev, D. Belyi, J.L. Nieto, A. Perez, A. Gonzalez, M. Maya, F. Ortiz, *The Current Test Results for Two Models of HTS Cable on CASAT Project*. At present there are no superconducting cable projects in Russia. A cable project and others (FCL, SMES, transformer and investigation of grid with s/c devices using mathematical and physical models) are under consideration. A decision is expected by February 2005. In the meantime, VNIIKP has established contact with some tape producers and created a commercial tape database including tapes from AMSC, NST, VAC, InnoST, Trithor, Bochvar and C&C (G-2). Tape behavior during overloading is under investigation. V. Sytnikov is involved in the HTS cable work and is VNIIKP's Deputy Director. His contact information follows:

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VIII.2.12 Slovak Republic-Institute of Electrical Engineering, Slovak Academy of Science

The Institute focuses on the research and development of semiconductor, superconductor, oxide and magnetic materials and devices. Special attention is devoted to the preparation and testing of high-*T*c ceramic superconducting tapes developed for high-*T*c superconducting magnets, power transmission cables, and transformers. Composite conductors from high-*Tc* Bi-2223 phase and MgB_2 are prepared using non-conventional metal deformation techniques. Experimental methods are developed to study the mechanisms limiting current-carrying capability as well as the problem of AC losses. The results of these investigations serve as a starting point for designing and optimizing devices, such as power transmission cables, including Pirelli’s recent HTS cable project. Also, high-temperature (Y-123, Tl- and Hg-based), medium- temperature (MgB_2), and low-temperature (Nb, NbN) superconducting thin films, and weak- link structures (tunnel junctions, grain boundary junctions), are prepared for basic research and cryoelectronic applications (e.g., SQUIDs, microwave detectors and circuits). An important part of the institute’s efforts is devoted to the education of young researchers in condensed matter physics, electronics, electrotechnology, and electrical engineering. The effort to apply superconductivity to the power sector is led by F. Gomory whose contact information follows:

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VIII.2.13 Sweden-Kungl Tekniska Högskolan

Now underway are four projects: (1) electric power applications of HTS, (2) control windings for magnetic circuits with HTS, (3) AC losses in HTS in arbitrary magnetic field orientation, and (4) controllable reactors with HTS control windings. These projects occupy three graduate students and all are led by S. Hörnfeldt, ABB retired. His contact information follows:

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VIII.2.14 Switzerland-PSI Villigen

In the late 1990s, a team from PSI, led by G. Vecsey collaborated with Brugg Kabel to build and demonstrate a neon-cooled HTS cable. Some of this work is alluded to in Wesche R, Anghel A, Jakob B, Pasztor G, Schindler R, Vecsey G, *Design of Superconducting Power Cables*, CRYOGENICS, 39 (9): 767-775 SEP 1999. The paper states, "The design studies indicate that for Bi-2223 cables with warm dielectric an operating temperature well below 77 K is favored. For operating temperatures of 45-50 K low-cost Bi-2212 superconductors could be an alternative to Bi-2223. The superconductor properties required for the cable application are briefly discussed. Finally, a design concept for a loss-optimised superconducting 112.5 MW single-phase transmission cable is presented." Closely related work appears in Anghel A., Jakob B., Pasztor G., Wesche R., Vecsey G., Bieri H., Baumann H., Hansen F.X., "*Design, construction and operation of a neon refrigeration system for a HTS power transmission prototype cable*", Adv. Cryog. Eng. 45 (2000). Vecsey is now retired. His most recent business contact information follows, as does contact information for R. Wesche, who remains active:

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http://crppsc.web.psi.ch/Team/wesche.html
http://crppsc.web.psi.ch/History/suleika_cab.html

Dr. Georg Vécsey (retired)
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VIII.2.15 United Kingdom

VIII.2.15.1 Manchester Centre for Electrical Energy

The Manchester Centre for Electrical energy (MCEE), located at the University of Manchester, is an important centre for power engineering, having 50 academic staff, 150 post graduates, and 600 students. MCEE includes the National Grid Transco High Voltage Research Centre. The department's professors are N. Jenkins, D. S. Kirschen, G. Strbac, and S. Williamson. UMIST, DTI, and Areva are discussing a future project bearing upon the reliability and stability of power distribution in the UK. Inquiries can be directed to the department office:

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E-mail: eeps@umist.ac.uk
URL: http://www.ee.umist.ac.uk/mcee/

VIII.2.15.2 University of Southampton

This university has been home to expertise on cryogenics, a topic of great importance to the practicality of HTS cable. D. P. McDonald (+44 023 80593938) leads Southampton's Institute for Cryogenics. C. Beduz (+44 023 8059 4760) heads Southampton's Thermal Fluids and Superconductivity group, which includes eleven students. The group states that collaborative programs are being conducted with Pirelli, Oxford Instruments, Merck Ltd., and CERN in the field of high-temperature superconductivity; that EPRC and EU grants support studies on the reduction of AC losses; and, an EPSRC grant is funding the construction of a 100kW prototype superconducting generator. A recently completed EU project, BIG-POWA, concerned high current Bi-2223 conductors with innovative wire geometry for AC power applications. C. Beduz' contact information appears below. Dielectrics are studied in the Electrical Engineering Department where National Grid and Pirelli Cables funded an investigation of some problems concomitant with using LN_2 as both coolant and electrical insulation. (see D.J. Swaffield, P.L. Lewin, G. Chen, and S.G. Swingler, *The Influence of Bubble Dynamics in Liquid Nitrogen with Applied Electric Fields on Superconducting Apparatus*, in Proceedings of 13th International Symposium on High Voltage Engineering, pages CD-ROM, Delft, Netherlands.) P.L. Lewin was a PI; his contact information appears below.

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VIII.2.16 United States

VIII.2.16.1 Los Alamos National Laboratory (LANL)

Los Alamos National Laboratory (LANL) is a key contributor to the U.S Department of Energy's HTS program. In addition to conductor development, LANL has contributed to HTS cable development by measuring AC losses with a calorimetric technique. The prototype multistrand conductor (PMC) is thermally isolated except at the two ends. Heat generated uniformly in the conductor results in a parabolic temperature profile along the conductor's length. This profile is measured with platinum resistance thermometers. A heater at the center of the PMC is used to determine thermal conductance. The AC loss is then determined from the simple one-dimensional heat flow equation. LANL has measured a total of nine different PMCs made by three different companies: American Superconductor Corporation, Pirelli Cable & Systems, and Southwire Company. The efforts to measure AC Loss is led by S. Ashworth whose contact information follows:

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URL: http://www.lanl.gov/mst/stc//power_aclosses.shtml

VIII.2.16.2 Oak Ridge National Laboratory (ORNL)

Oak Ridge National Laboratory (ORNL) is a key contributor to the U.S Department of Energy's HTS program. In addition to conductor development, ORNL contributes to HTS cable development. This work is done in two laboratories: (1) the Cable Test Development Laboratory, and (2) the Dielectrics Research Facility. Southwire collaborates with ORNL in the first laboratory. It is used for testing HTS cables and cable components including power supplies, terminations, joints, and cryogenic systems. Cables up to 5-meters long have been tested in a straight configuration. The laboratory has the following capabilities: 200-kV impulse testing, short-circuit testing to 25,000 amperes, 100-kV AC power supply, DC current to 3000 amperes, AC current to 2000 amperes, and a liquid nitrogen cable cooling system with sub-cooling to 67 K and pressurization to 15 atmospheres.

The Dielectric Research Facility contains unique a national laboratory for research and development of electrical insulation for high-temperature superconducting devices. A special feature of this laboratory is the ability to characterize dielectric performance at cryogenic temperatures under a variety of pressure conditions ranging from high vacuum to 15 atmospheres in liquid nitrogen. Equipment includes:
High-voltage power supplies: 500-kV Haefely-Trench Impulse Generator with rise/fall time = 1.2/50 s; 100-kV, 10-kVA, American high voltage, manually controlled AC power supply; 150-kV, low noise (<3pC), Phoenix Technologies, AC power supply with Allen-Bradley programmable logic control; and 100-kV, Steelman DC power supplies.

High voltage breakdown test facilities: High-pressure (up to 15 atm) cryogenic model cable test vessel; two chambers (one for short-term breakdown tests and one for long-term aging studies under cryogenic conditions); high pressure (up to 15 atm) cryogenic sheet breakdown; chamber for gas and vacuum breakdown; and atmospheric pressure cryogenic tape tester.

Other facilities and capabilities: model cable wrapping facility; epoxy mold and fabrication for high voltage testing; electrical shielding (2 RF shielded room enclosures) and tests for a range of electrode geometries; uniform field electrodes [profiled electrodes], and non-uniform field electrodes [point-plane, sphere-plane, cylindrical ….

Diagnostic Equipment: Partial discharge analysis; tan delta bridge (power loss factor); Ultra high-speed streak/framing camera (to 20M frames/s); gas chromatography-mass spectrometer (state-of-the-art bench analytical system; positive and negative ion capability offering unique selectivity; and chemical ionization source for high sensitivity); cryogenic enrichment gas chromatography with electron capture detection (parts-per-billion sensitivity in complex backgrounds); gas chromatography with thermal conductivity detector; extra high-pressure mass spectrometer (direct sampling from high pressure up to 1atm and detection of short-lived ionic and radical species); UV/VIS/IR spectrophotometer; and fast digital storage oscilloscopes (to 2G samples/s).

HTS Application: For research and development of electrical insulation for high-temperature superconducting devices. A special feature of this laboratory is the ability to characterize dielectric performance at cryogenic temperatures under a variety of pressure conditions ranging from high vacuum to 15 atmospheres in liquid nitrogen. ORNL's program is managed by R. Hawsey whose contact information follows:

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Manager, Superconductivity Program
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E-mail: hawseyra@ornl.gov
URL: http://www.ornl.gov/sci/htsc

VIII.2.16.3 Center for Electric Power (CEP) of Tennessee Technological University

Prof. Pritindra Chowdhuri recently completed a preliminary study of the electrical issues that the design of an HTS DC cable must take into account. Attention is being given to (1) fault currents, (2) losses due to harmonics and (3) transient voltage differences within the cable. The report's title is, "*Feasibility Of Electric Power Transport By Dc Superconducting Cables In Tennessee*" (October, 2004). P. Chowdhuri's contact information follows:

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Electrical and Computer Engineering
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VIII.2.16.4 Center for Applied Power Systems, Florida State University

CAPS intends to: 1) develop a graduate and undergraduate program for advanced power system engineering; 2) simulate and model advanced power systems supported by test facilities, materials research and superconductivity technology; 3) develop partnerships between government, industry, and the academic research community; and 4) advance the state-of-the-art in electric power technology by identifying and developing technology of joint interest to civilian & military sponsors. USDOE is funding CAPS to disseminate information to the utility industry, private sector, state organizations, educational institutions, and public advocacy groups on the technical, economic, and environmental feasibility, benefits, and effectiveness of HTS technologies, with emphasis on technology and system integration. The goal is to make policy makers, state organizations, industry decision makers, and the public aware of the potential of HTS technologies to contribute to the future delivery and use of electric power. S. Dale directs the CAPS Advanced Power Systems Lab. His contact information follows:

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URL: http://www.caps.fsu.edu

VIII.3 For-Profit Organizations

Although for-profit organizations are listed by country, many of these firms sell their products and services throughout the world and maintain offices in many countries.

VIII.3.1 China

VIII.3.1.1 Chang Tong Cable Company

This firm is reportedly preparing to fabricate an HTS cable for the Chinese Academy of Science's Applied Superconductivity Lab. The HTS conductor will be provided by American Superconductor. Nothing more is known about this firm.

Chang Tong Cable Company
?????
??????
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Fax: +86 ???????
E-mail: ?????????
URL: ??????

VIII.3.1.2 InnoPower Superconductor Cable Co., Ltd.

Innopower Superconductor Cable Co., Ltd. (InnoPower) is focusing on an R&D program to fabricate a 30 meter, 3-phase, 2kA, 35kV power transmission HTS cable system cooled by LN_2 (70-80 K) and to install it in a power station China's Southern Power Grid in 2004. The cable will have a warm dielectric separating the four conducting layers of HTS from the environment (outdoors at 2000 m, -15°C to +40°C). The goal is not more than 0.1 W/m for AC loss 100 Mpa for tensile stress. InnoPower is the first HTS power cable manufacturer in China. During the next five years, InnoPower plans to manufacture HTS cables with greater length and higher capacity, develop other innovative devices, superconducting or otherwise, for power utility applications, and venture into other areas of superconductor technology. Innopower was established in July 2001 and its major shareholders include the Yunnan Electric Power Group (YEPG) and Beijing Innova Superconductor Technology Co., Ltd (InnoST). The company is located in the Beijing Economic and Technological Development Area (BDA) and was awarded high-tech enterprise certificate. Innopower is backed by Tsinghua University's Applied Superconductivity Research Center and InnoST in superconductor technology, and backed by YEPG in applied electric technology. InnoPower's General Manager is Y. Xin whose contact information follows:

Dr. Ying Xin, General Manager &
Kunnan Cao, Deputy General Manager,
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VIII.3.1.3 Innova Superconductor Technology (InnoST)

Innova Superconductor Technology (InnoST) is now focused on HTS wire production and applications. The Beijing facility, completed at the end of 2001, gives the company a total production capacity of 200 km/year of BSCCO HTS wire. The production line is now fully operational and its HTS wire has already been sold to both Chinese and international customers. InnoST plans to expand production capacity further to 500 km/year by 2004. InnoST has also focused on HTS applications, including HTS cables, magnets, transformers, fault current limiters, generators and motors, magnetic separators and current leads, etc. Also, InnoST is involved in the cryo-technology required for HTS applications and uses its own HTS wire to fabricate several HTS magnets for materials processing. InnoST works very closely with Tsinghua University as well as InnoPower. InnoST is managed by Q. Liu whose contact information follows:

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VIII.3.2 Denmark--NKT and Ultera

NKT has been interested in HTS cable for sometime. Its subsidiary, NST, manufactured the 30-meter HTS cable that was installed and operated at the Amager substation near Copenhagen. That same cable is now being tested at DTU (see Section VIII.2.3). NKT sold NST's assets to American Superconductor and on 6 December 2002, NKT formed ULTERA, a 50/50 general partnership with Southwire Company of Carrollton, Georgia, USA. Approximately 25 ULTERA personnel are domiciled in both the United States and Denmark, involving people from both organizations who have all participated in the development work for superconducting cable systems. ULTERA has one cable project underway to build and install an HTS cable at American Electric Power's Bixby substation. ULTERA proposed another project, involving RWE and others, to the EC. ULTERA's lead in Denmark is D. Willén, whose contact information follows:

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www.nktcables.com
www.southwire.com

VIII.3.3 France

VIII.3.3.1 Areva

Areva employs 75,000 persons around the world and recently acquired Alstom's Transmission and Distribution, which was located in the UK. See Section VIII.3.12.2. Areva's T&D products range from transformers, switch gear and circuit breakers to energy software for deregulated energy markets. The firm offers expertise for transmission projects, such as HVDC, and has solutions for renewable energy grid connection. Alstom's office in Paris (now Areva's office?) is shown below:

ALSTOM Power
25 Avenue Kleber
Paris 75116
FRANCE
Telephone: +33 1 4755 2000
Fax : +33 1 4755 3699
E-mail:
URL: http://www.areva-td.com

VIII.3.3.2 EdF

EdF's interest in HTS has been manifested by both its work at the EdF R&D Center, its cable project with Pirelli, its role in the sales of power quality LTS SMES, its participation in SCENET, and its investment in American Superconductor. In 2000, EdF announced "EDF R&D and Pirelli Cable had completed the first stage of a ground-breaking project on superconductors: the construction of the first high-temperature superconductor EHV cable designed to withstand 225 kV (phase-to-phase). This will allow researchers to assess the feasibility and profitability of energy transmission links via superconductor cables. The next step will involve the construction of a 50m prototype link. It will be tested on site in 2002. It was reported that "… The cable is of the 'cold dielectric' coaxial design and matches the requirements of European transmission networks. The 20-m (66-ft) prototype cable can carry up to 2600 A ac with superconductor electrical losses of less than 1 W/m. …In a three-phase transmission system, this HTS cable would enable a transmitted power of 1000 MVA…" The engineering literature includes two papers: (1) Ladi`e P *et al* 1999 *Jicable Conf.* pp 97–102. (2) M Nassi, *HTS Prototype for Power Transmission Cables: Recent Results and Future Programmes*, Supercond. Sci. Technol. **13** (2000) 460–463. Nothing is publicly known about the result, if any, of the project. At EUCAS 2001, EdF's P. Manuel (now retired) reported that EdF had compared superconducting cables with several conventional alternatives at several sites and found one in which the economics appeared comparable. EdF continues to survey opportunities for future HTS equipment. Several people in the European power sector have spoken of congested transmission between the Rhone Valley and northern Italy and one person has remarked on the potential need for more capacity between France and Spain. EdF's present representative to SCENET is E. Sandré who is familiar with power quality and whose contact information follows:

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EdF R&D
Les Renardières
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FRANCE
Telephone: +33 01 60 737274
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E-mail: eric.sandre@edf.fr
URL:

VIII.3.3.3 Nexans

Formed from Alcatel Cables and Components, Nexans is the worldwide leader in the cable industry and offers an extensive range of advanced copper and optical fiber cable products to the infrastructure, industry and building markets. With an industrial presence in 28 countries and commercial activities in 65 countries, Nexans employs 17,150 people and had sales in 2002 of 4.3 billion euros. The company states its cables and cabling systems can be found in every area of people's lives, from telecommunications and energy networks, to aeronautics, aerospace, automobile, railways, building, petrochemical and medical application. Now, Nexans is developing HTS power cables, as well as terminations and joints for such cables. Nexans also has the capability to make PIT tape in Jeumont, HTS precursor in Germany (see Section VIII.3.4.1.2), flexible cryostats in Germany (see Section VIII.3.4.1.1), and submarine cable in Norway. Nexans HTS capabilities are managed by J. Saugrain whose contact information follows:

Mr. Jean-Maxime Saugrain, Superconductivity Activity Manager for Nexans
Nexans, France
4-10 Rue Mozart
92587 Clichy
FRANCE
Phone: +33 (0)1 55 62 73 18
Fax: +33 (0)1 55 62 78 08
E-mail: Jean_Maxime.Saugrain@NEXANS.com
URL: http://www.NEXANS.com
http://www.nexans.com/dyn/site.php3?page_id=3
http://www.nexans.com/medias/img_objet/htemp2.gif

VIII.3.3.4 Schneider Electric S.A.

Schneider Electric has had a long-standing interest in applying HTS to the power sector. Publicly available documents focus on fault current limiters, though no present activity is known. Schneider Electric's contact with SCENET is J. Bach whose contact information follows.

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Schneider Electric S.A.
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FRANCE
Telephone: +33 476 579 664
Fax: +33 476 577 862
E-mail: julien_bach@mail.schneider.fr
URL:

VIII.3.4 Germany

VIII.3.4.1.1 Nexans-Hannover (Cryogenics)

See Section VIII.3.3.2 for an introduction to Nexans. A capability of great importance for cable is Nexans' capability to build flexible cryostats. At present, Nexans Hannover is the world's only commercial supplier of such cryostats and has been in that business for many years. Of course, Nexans Hannover also offers transfer lines for liquid gases (e.g., LNG). The cryogenics section is led by K. Schippl whose contact information follows:

Klaus Schippl

Section Head
Cryoflex Transfer Lines
Nexans Germany Industries GmbH & CO. Kg
Kabelkamp 20
CryoFlex Transfer Lines P.O. Box 260
30179 Hanover
GERMANY
Telephone: +49 511676 3250
Fax: +49 511676 3250
E-mail: cryoflex.transferlines@Nexans.com
http://www.nexans.de/dyn/site.php3?page_id=274
http://www.nexans.de/dyn/site.php3?page_id=641

VIII.3.4.1.2 Nexans-Hannover (Cable)

The Nexans-Hannover Superconducting Systems Group (SCSG), which was created in order to start the development of HTS cables and deal with the aspects of transmission and distribution cables. Nexans has been awarded a sub-contract from American Superconductor, to manufacture the cable and cryogenic insulation for the USDOE project to demonstrate a cable in the grid of the Long Island Power Authority (LIPA). Nexans' facilities in France and Norway are also participating in this project. The project is being managed by Frank Schmidt who participated in the past Siemens/Pirelli HTS cable project at Berlin and his contact information follows:

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Nexans Deutschland Industries GmbH & Co. KG
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Geb. 713, Raum 103
Telephone: +49 (0)511-676-3159
Fax: +49 (0)511-676-3777
Mail: frank.schmidt@nexans.com
http://www.nexans.com/medias/fichier_objet/030423/230403_en.pdf

VIII.3.4.2 Nexans Superconductors GmbH (NSC)

NSC describes itself as Europe's leading manufacturer of HTS bulk materials. For the past two years, NSC has also been working on YBCO tape (second generation tap"). NSC emerged from Aventis Research and Technologies, a subsidiary of the former Hoechst AG. During the past 15 years, NSC's core team has been at the forefront of the HTS development; and now has 23 members. The team's skills include specific knowledge in chemical and material engineering, through materials characterization, and electro-technical and application expertise. The group's HTS products include powders, precursors, bulk materials and components thereof. NSC in particular leads in worldwide production of superconducting bulk components based on melt cast BSCCO-2212. The Melt Cast Process (MCP) is proprietary to Nexans. HTS current leads made of this material have been used commercially since 1995. NSC has participated in German and European projects. Among these is the German Fault Current Limiter (SFCL) project, a 10 kV 10 MVA prototype, for which NSC developed and manufactured bifilar coils based on MCP BSCCO-2212. The device is now being tested in Germany on RWE's grid. Recently, NSC has been awarded the contract to supply the HTS components for the USDOE's $12-million Matrix Fault Current Limiter (MFCL) project led by IGC-Superpower. This device is expected to be the world's first SFCL for the 138kV transmission level. NSC is a node within the European SCENET-2 network and a member of CONCECTUS. NSC is headed by J. Bock whose contact information follows:

Dr. Joachim Bock
Managing Director
Nexans Superconductors GmbH
Chemiepark Knapsack D-50351 Hürth
GERMANY
Telephone: +49-(0)2233-486658
Fax: +49-(0)2233-48-6847
E-mail: Joachim.Bock@nexans.com

VIII.3.4.3 Trithor GmbH

As of May 2003, Trithor began offering Bi-2223 conductor with J_e=7,500 A/cm^2 and n=20. Trithor describes itself as an enterprise for the commercialization of superconductivity. The company was established during 1999, in Bonn, and now has partners, MVV Energie AG and the venture capital company, TTIB GmbH. Trithor's technological know-how is based on the experience of its employees, who have successfully worked in other German firms in the same business. Trithor states its staff knows how to convert high-tech products into marketable products. At the beginning of 2001, Trithor's headquarters and high tech production facility moved to Rheinbach (10km west of Bonn). Trithor is represented to SCENET by M. Baecker whose contact information follows:

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Trithor GmbH
Heisenbergstrasse 16
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GERMANY
Telephone: +49 (0) 2226 - 90 60 - 0
Fax: +49 (0) 2226 - 90 60 – 900
E-mail: info@trithor.de
URL: http://www.TRITHOR.de

VIII.3.4.4 European Advanced Superconductors (EAS), Devolved from Vacuumschmelze (VAC)

After separating from VAC in 2003, EAS is now a wholly owned subsidiary of Bruker BioSpin, a world leader in high resolution NMR. EAS offers Bi-2223 tape having $I_e \approx 100$A and $35 \leq n \leq 40$. Also, EAS offers tape comprising transposed layers of Bi-2223 tape with an AC loss of only 0.25 W/kA-m. This tape was used by Siemens in its project to build an onboard railroad transformer. These accomplishments are built on long experience with this material. EAS' J. Tenbrink originated the now universally used powder-in-tube method for fabricating conductor from Bi-2212 and later Bi-2223. EAS' business focuses on all types of technical superconductors (low-temperature and high-temperature superconductor). EAS has recently purchased the assets of C&C, a firm started by H.C. Freyhardt. By so doing, EAS plans to offer REBaCuO tape (second generation conductor). The president of EAS is H. Krauth, whose contact information follows:

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European Advanced Superconductors
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Fax: +49 6181 - 383159
E-mail: Helmut.Krauth@AdvancedSupercon.com
URL: http://www.AdvancedSupercon.com

VIII.3.4.5 Siemens Aktiengesellschaft

Siemens is one of the world's largest electrical engineering and electronics companies. It was a pioneer in HTS cable until its cable division was purchased by Pirelli. Siemens remains active in HTS; it is a node of SCENET-2 and is represented on SCENET's steering committee. Now, Siemens is working toward an HTS motor. Siemens' experience includes building prototype/demonstration fault current limiters, motors, magnetic bearings and MRI (LTS). These projects have been funded by BMBF and EU. Siemens' applied HTS program is led by H.-W. Neumueller whose contact information follows:

Dr. Heinz-Werner Neumueller
Department Head, CT-EN
Siemens Ag
PO Box 32-20
3 Paul Gossen Street 100
Erlangen, 91050
GERMANY
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Fax: +49 9131-7-21339
E-Mail: Heinz-Werner.Neumueller@Siemens.Com
URL: http://www.Siemens.Com

VIII.3.4.6 THEVA

In 1996, THEVA was spun off from the Technical University of Munich. Since then it has pursued R&D in high-temperature superconductivity, and developed the thermal co-evaporation technique for depositing complex oxide compounds like $REBa_2Cu_30_7$. THEVA states it is the global market leader in the REBCO film business, having customers in electronics (e.g., cellular base station filters). THEVA states it is making a major effort to fabricate coated conductor and that it is using a proprietary inclined substrate deposition (ISD) technology to align buffer layers on flexible metal tape. A pilot plant was supposed to come online in CY2003. Using ISD, THEVA has made samples of tape that are more than 10 m long. THEVA plans to find customers who will make cable and Fault Current Limiters, as well as NMR and electronics. For further information concerning THEVA, contact Mr. Prusseit, whose E-mail address follows:

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85737 Ismaning
GERMANY
Telephone: +49 89 92 33 46 0
Fax: +49 89 92 33 46 10
E-Mail: prusseit@theva.com
URL: www.theva.com

VIII.3.5 Italy

VIII.3.5.1 Ansaldo Superconduttori

During the last 18 months Ansaldo Superconduttori stated its intent has been to explore the potential for using MgB_2 in large-scale commercial applications. Before this, Ansaldo Supercondududuttori was exclusively concerned with large LTS magnets. For additional information, direct your queries to R. Penco whose contact information follows:

Dr. Roberto Penco
Ansaldo Superconduttori
Corso Perrone 73-R, I-16152 Genova
ITALY
Telephone: +39 010 655 6629
Fax: +39 010 655 6485
E-mail: penco.roberto@as-g.it
URL: http://www.as-g.it

VIII.3.5.2 CESI

Established in 1956, since the beginning CESI has been a market leader in testing, certification of electromechanical equipment and electrical power system studies offering these services to electrical utilities, electromechanical manufacturers and large-scale users of electric power. In the frame of the privatization of the Italian electric system and the consequent reorganisation of the National Electric Company, CESI acquired from ENEL (the main Italian Electric Utility) its RTD activities in generation, transmission, distribution, end-use of electricity, environment and renewable energies. The merger increased the size of the company to about 1000 employees, covering all electro-energy sectors. During the period 2000-2003, CESI was in charge to manage and develop the so called Research Dealing with the System (RdS) to sustain the competitiveness of the

Italian Electric System by improving economy, security and quality in the context of market liberalisation and in agreement with sustainable development criteria. The RdS activity, that is funded by a levy on electricity bills, has to be related to the general needs of the Electric System and of applied and innovative nature in a long term prospective. In regards to power cables, the main activity of the CESI Superconductivity laboratory, that has been researching HTS and its applications since 1989 participating in many National and European projects, dealt with an RdS project devoted to study the possible application of HTS cables as an effective mean to increase the current transport capacity. In the framework of this project, the Superconductivity laboratory was extensively involved in the testing of high amperage ($I>6000A_{rms}$) HTS cable models made by Pirelli Cable, critical current measurements and ac losses by the calorimetric method on HTS conductors for cable applications. Moreover, the specifications (including test site and testing procedure), for a 132kV, 3000A HTS cable prototype to be purchase and installed at CESI for testing were completed. Currently, the second period projects of RdS (2003-2005) have been launched by CESI. Concerning superconductivity, beside a 4MEuro project for the design, simulation, development and testing of a SFCL prototype, CESI is carrying out power system studies on potential applications of HTS cables and their impacts on utility networks by means of digital models developed in ATP (Alternative Transients Program). The model itself is a useful tool for a correct dimensioning of the real component and can supply the designer with important information about feasibility and operational conditions. Owing to the long term perspective of RdS activity these studies focus not only on the existing network configurations, but also on future scenarios with a high penetration level of Distributed Energy Resources and/or the presence of other superconductive components (SMES, Flywheels, FCL, …). CESI's lead person for these projects is L. Martini whose contact information follows.

Luciano Martini
CESI Spa
Funzione Attività Specialistiche
ING - ERI
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ITALY
Phone: +39 02 2125.5376 (5414)
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E-mail: lmartini@cesi.it

VIII.3.5.3 Europa Metalli

Europa Metalli (recently acquired by Outokumpu) states that for the past 25 years it has produced and marketed wires and cables made from in Nb/Ti, Nb_3Sn and HTS. Its HTS products are not known to the author. A. Sbrana's contact information follows:

Eng. A. Sbrana
Europa Metalli S.p.A., Divisione Superconduttori
via della Repubblica 257, I-55052 Fornaci di Barga (Lucca)
ITALY
Telephone: +39 - 0583 - 701470
Fax: +39 - 0583 - 701471
E-mail a.sbrana@europametalli.it
URL: http://www.europametalli.it

VIII.3.5.4 Pirelli Cavi

Pirelli employs about 41,000 people around the world and is organized into 78 production units in 14 countries. Pirelli's business comprises two main sectors: tires and cables. The latter has 17,000 employees and 52 factories operating in 11 countries in Europe, North and South America, Africa and Australia, and sales of around 2,200 million Euro. Pirelli states that its Cable Sector has the world's second largest share of the cable market. Pirelli Cavi operates three businesses: power cables, telecommunication cables and turn-key systems. The company produces all sorts of cables, from undersea energy cables connecting continents to enameled wires found in car engines. Pirelli Cavi is best known for its high-technology cables (e.g., optical fibers) and for its advanced manufacturing facilities. Pirelli entered the HTS cable business by purchasing the Siemens HTS cable enterprise and its HTS projects are centered in Milano. A summary of its efforts as they stood in 2000 is provided by M Nassi, *HTS Prototype for Power Transmission Cables: Recent Results and Future Programmes*, Supercond. Sci. Technol. 13 (2000) 460–463. Also see http://www.pirelli.com/en_42/cables_systems/energy/innovation/projects.jhtml for a summary of 5 cable projects: (1) 110 kV, 400 MVA, 4 kW refrigeration, dielectric and materials testing by FZK, conductor by AMSC and VAC, [each of the following used AMSC conductor], (2) 115 kV, 400 MVA, 50m lab prototype, (3) 132 kV, 680 MVA, single core with CESI, ENEL and Edison, (4) 225 kV, 1000 MVA with EdF, (5) 24kV, 100MVA at Detroit Edison's Frisbie Station. Pirelli worked to demonstrate a warm dielectric, HTS cable at Detroit Edison, where Lotepro provided the refrigeration. For Pirelli's report on this project, see www.energetics.com/meetings/supercon/pdfs/presentations/f4_update.pdf. For Pirelli Cavi's introduction to its vacuum cryostat production efforts, see http://www.pirelli.com/en_42/cables_systems/energy/innovation/hts_power_system.jhtml

At present, Pirelli is not trying to commercialize HTS cable. For further information, contact V. Boffa whose contact information follows.

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Pirelli Labs,
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E-mail: vincenzo.boffa@pirelli.com
URL: http://www.pirelli.com/
URL:
http://www.pirelli.com/en_42/cables_systems/energy/innovation/about_superconduttivity

VIII.3.5.5 Tratos Cavi

Tratos began in 1966 as a wire drawing company, and later transformed into a producer of telephone cables which were of general use and technologically simple. Since 1988 the firm has been producing Optical Fibre cables for the Italian Telephone Company (SIP) and for Italian Post and Telecomm - IRITEL (ex ASST) now merged and known as TELE-COM ITALIA. Roughly half of its sales are to the telecomm sector and half to low and medium voltage cable users. In 2001, Tratos began research to fabricate prototype superconductor cables having HTS High Strength Wire. To date, two types of cable and related accessories have been developed. They are:

1. Warm dielectric cable (W.D.) for 45 KV
2. Cold dielectric coaxial (C.D.C.) for 45KV
3. Terminations and accessories for the above cables

During the past year, 4 prototypes, each several meters long and having two or three layers of conductor, were produced. They have been tested in CESI Milano's laboratories where critical currents were measured. Now, the thermal balance of a 15 m cable system is being measured.

In the next few months, tests will begin on a new warm-dielectric cable, 50 m long and having two layers of conductors. This cable is intended to conduct approx 2000 Amperes, at 45 KV phase-to-phase and thus guide 150 MVA. The design of this cable's

LN_2 circuit is new and it is intended to ensure both hermetic sealing and short circuit protection while also reducing mass and size. This cable will be demonstrated at the Pieve Santo Stefano Factory where the cable will supply some of the factory's circuits.

(Terminations and accessories have been designed for the purpose.) Simultaneously, two prototype cold dielectric coaxial cables will be built. Each will have extruded special compound insulation, and each will test new approaches to circulating LN_2 and providing stabilizer to shunt fault currents. This work is being led by V. Giorgio whose contact information follows:

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Fax: +39 0575 794247
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URL: http://wwww.tratos.IT

VIII. 3.6 Japan

VIII.3.6.1 Sumitomo Electric Group Headquarters Sumitomo Electric Industries, Ltd. (SEI)

SEI has done R&D in superconductivity for more than 40 years, including more than 17 years in HTS R&D. The firm has been involved in several HTS demonstration projects in Japan, including a recently completed long-term aging test of a 100-meter, 66 kV project with Tokyo Electric Power Company installed at the Central Research Institute of the Electric Power Industry. That project demonstrated one year of trouble-free operation. (Also see K. Sato et al, *HTS large scale application using BSCCO conductor*, IEEE Trans Applied Superconductivity, 7 (2): 345-350 Part 1, June 1997.) SEI is also working with other firms in other parts of the world. In particular, SEI is working with IGC-Superpower, Niagara Mohawk and BOC to provide a 350m cable in real Utility network in Albany project funded by US Dept. of Energy and New York State Energy Research and Development Authority. Further, SEI and American Superconductor Corp. have agreed to license to each other their North American and European patents for first-generation HTS wires, electromagnetic coils, electromagnets and current lead devices. Separately, the two companies signed a letter of intent to grow the superconductor cable market by leveraging their complementary capabilities, specifically by marketing SEI power cables that utilize AMSC's HTS wire. SEI' s HTS General Manager is Mr. K. Sato. His contact information follows:

Mr. Ken-ichi Sato
General Manager
HTS R&D Department, R&D Unit
Sumitomo Electric Industries, Ltd.
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JAPAN 554-0024
Telephone: +81 6 6466-5633
Fax: +81 6 6466-5705
E-mail: sato-kenichi@sei.co.jp
URL: http://www.sei.co.jp/index.en.html
URL: http://www.SEI.co.JP./sn/2002/09/09p7t.html

VIII.3.6.2 Fujikura

In November 2000, Chubu E., Fujikura, and Showa announced its collaboration had developed a way to make conductor having unusually low AC losses. See Sections VIII.3.6.5 and VIII.3.6.6 for further information on this collaboration. Fujikura is also working on second generation tape. Fujikura's principal investigators are K. Goto and T. Saitoh, and their contact information follows:

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Fujikura Ltd,
Koto Ku, Tokyo 1358512
JAPAN
Telephone: +81
Fax: +81
E-mail:
URL:

VIII.3.6.3 Furukawa

Furukawa is an important participant in Japan's SuperAce Cable project for which Furukawa developed both the cable, one phase per cryostat and the flexible cryostat itself. Furukawa is represented by H. Kimura whose contact information is listed below. Furukawa is also working to reduce AC loss in the conductor by developing twisted, multi-filamentary tape incorporating Bi-2223. Furukawa's principal investigator is M. Mimura whose contact information follows:

Mr. Hitoshi Kimura
Furukawa Electric, Chiba Works
6 Yawata-kaigandori, Ichihara
Chiba 290-8555
JAPAN
Telephone:
Fax:
E-mail: HKimura@ch.Furukawa.or.jp
URL: http://www.Furukawa

Mr. Masanao Mimura
Superconductivity Research Dept
Furukawa Electric Co.
Kiyotaki, Nikko 321-1493
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Fax:
E-mail: ???@??Furukawa.or.jp
URL: http://www.Furukawa

VIII.3.6.4 Hitachi Cable Ltd.

Hitachi Cable has manufactured a variety of LTS conductors, including large current-carrying Nb_3Al, Nb_3Sn Superconductors and $(Nb, Ti)_3$ Sn Superconductors for use in high magnetic fields. Hitachi's HTS wire development has sought to fabricate round conductor from Bi-2212 (ROSaT) for NMR and MRI. Hitachi also makes flexible cables (e.g., 600 V for industry) and submarine cables from copper. The submarine cables are offered to the world's oil & gas contractors. The company states it has made special experimental devices for large capacity AC cable. Hitachi has recently shown interest in pursuing low AC loss conductor made from Bi-2223 surrounded by barriers. Mr. Ryosuke Hata is a cognizant member of Hitachi's staff.

Mr. R. Hata
Hitachi Cable Ltd
?????
?????
JAPAN
Telephone: **?????**
Fax: **?????**
E-mail: ????????????
URL: http://fuujinn.hitachi.co.jp
http://www.hitachi-cable.co.jp/en/hc-news/342/top1.html

VIII.3.6.5 Showa Electric Wire & Cable Co

Showa is a large electrical supply firm that offers many products, including 60kV DC cable having PE dielectric. In November 2000, Chubu E., Fujikura, and Showa announced its collaboration had developed a way to make conductor with unusually low AC losses. The collaboration's conductor included a thin wire with a mechanical strength three times that of conventional materials, making possible a transposition of filaments. The result also makes it possible to achieve a level of 1/10, or 0.1W/m, of the target current loss (1W/m) from the superconducting cable. This has enabled a more compact cable and reduced cooling equipment requirements. As a result, the construction cost for superconducting cable can be expected to be approximately the same as for conventional cable. Plans were announced to introduce a practical conductor and then practical applications. Subsequently, the collaboration published J. Nishioka, Y. Hikichi, T. Hasegawa (Showa Electric Wire & Cable); S. Nagaya (Chubu Electric Power); K. Goto, T. Saitoh (Fujikura), *Development of Bi-2223 Narrow Tapes for Superconducting Cable*, PHYSICA C-378: 1070-1072 Part 2 OCT 1 2002 in which they reported, "We developed Bi-2223 narrow tape for a transposed segment conductor. The tape was 0.23mm thick and 1.90mm wide, almost half the conventional tape width. It used a Ag-Mg-Sb alloy for the sheath material and consisted of Ag/SC ratio of 2.2 and 37 filaments. We adjusted the Ag/SC ratio to improve the mechanical strength of the newly developed narrow tape and obtained a tensile strength of 108 MPa. The narrow tape kept the initial Ic value until a flat-wise bending strain was up to 0.6% or an edge-wise bending strain was up to 0.3%. Moreover, we made short length superconducting cable with transposed segment conductor and evaluated performance of the tapes after cabling process. We developed a 15 m-long, 2.6 kA-class conductor which was made by winding a number of transposed segments around a stainless steel flexible former. The transposed segment consisted of five Bi-2223 tapes, which were strengthened with Ag-Mg-Sb sheath and insulated with resin individually. The conductor had a three-layer structure, which was taken by a method of equalizing impedance of each layer by adjusting spiral pitches. Current distribution in the same segments for the conductor was unified below changing rate of +/- 5%. Further, current distribution in three layers was homogenized below +/- 6% in the range from 200 to 2800 A. As the results, we successfully carried out a development of the low AC loss high-T-c superconducting cable, for which AC loss was 0.1 W/m at flowing 1000 A." Additional information about an REBaCuO collaboration of Chubu E. and Fujikura is presented in Section VIII.3.6.6. Showa's group leader is T. Hasegawa whose contact information follows:

T. Hasegawa
Showa Electric Wire & Cable Co Ltd,
4-1-1 Minami Hashimoto, Sagamihara
Kanagawa 2291133
JAPAN
Telephone: +81 03-5532-1911
Fax:
E-mail:
URL: http://www.swcc.co/jp/eng/overview.htm

VIII. 3.6.6 Chubu Electric

Chubu E. is supporting Japan ' s SuperAce Cable Project and Chubu may have its own cable project. As described in Section VIII.3.6.5, Chubu E., Fujikura and Showa have collaborated to develop a low AC loss conductor. In June, 2002, Chubu E. announced the successful development, in conjunction with Fujikura Ltd. of new technology to synthesize next-generation superconducting power line materials for practical use. While the yttrium-based superconducting wires previously developed by Chubu Electric Power were capable of transmitting large currents, the inferior crystal cohesion necessitated control to ensure the orderly connection of crystals when fabricating wires. Chubu E. claimed the development of a fast gas phase method that enabled fabrication of 100 meters of wire fabricated in 10 hours of continuous synthesis at a speed of 10 m/hr. Chubu said its next step would be to study mass production systems for wires of 500 m and longer which are required for the above superconducting equipments. Chubu E.'s HTS R&D is directed by S. Nagaya whose contact information follows:

Mr. Shigeo Nagaya Director, Superconductivity R&D
Chubu Elect Power Inc.
20-1 Kitasekiyama Ohdaka-cho, Midori Ku,
Nagoya, Aichi 4598522
JAPAN
Telephone: +81-52-621-6101
Fax: +81-52-624-3994
E-mail: Nagaya.Shigeo@chuden.co.jp
URL: http://www.chuden.co.jp/English/corporation/fr_randd

VIII.3.6.7 Tokyo Electric Power (TEPCO)

TEPCO has long been concerned with providing sufficient power to serve its growing load within densely crowded service area. Thus TEPCO and SEI collaborated in the development and testing of compact superconducting cable, for use within ducts having a 150 mm diameter. Recently, TEPCO’s load growth slowed and so has TEPCO’s activities bearing on HTS cable. For information on TEPCO’s HTS cable projects, contact T. Mimura whose contact information follows:

Mr. Tomoo Mimura, Assistant Senior Engineer, Superconductivity Group
Power Engineering R&D Center
Tokyo Electric Power Company
4-1, Egasaki-cho, Tsurumi-ku
Yokohama, 230-8510
JAPAN
Telephone: +81 45-613-5302
Fax: +81 45-613-7098
E-mail: Mimura.Tomoo@tepco.co.jp
URL: http://www.tepco.co.jp/index-e.html

VIII.3.7 Korea

VIII.3.7.1 Korea Electric Power Company-KEPCO

KEPCO states it wants to field test an HTS cable in order to obtain experience and data on the HTS cable operation. It invited bids (see website listed below) from the international community to participate in a turn-key project to be funded from KEPCO's own R&D budget. (This project is reported to be totally separate from the activity of KERI, described in Section VIII.3.7.2.) Sumitomo Electric Industries' proposal for a 100 m cable has been accepted. Further information about KEPCO's cable project can be obtained from???? whose contact information appears below:

KEPCO
????
????
?????
Republic of KOREA
Telephone +?????
Fax: +?????
E-mail: +?????
URL: http://www.kepco.co.kr/en/Welcome.html

VIII.3.7.2 LG Cables-KERI

The Korean Electric Research Institute (KERI) is developing a pilot HTS cable with funds from Korea's Ministry of Science and Technology, a collaboration of LG Cables and KERI. The cable is to be an AC, three-phase, 22.9 kV/50 MVA/30 m/cold dielectric. Each of its three phases will be in the same cable. Completion is scheduled for 2004 July. Mr. D.-W. Kim is familiar with this project. His contact information follows:

Do-Woon Kim, Associate Research Engineer
Electric Power Research & Technology Center (EPRTC)
LG Cables
555 Hogye-dong, Dongan-gu, Anyang-si, Kyungki-do
431-080
Republic of KOREA
Telephone : +82 31-450-8373
Fax : +82 31-450-8338
E-mail : kado0078@cable.lg.co.kr
URL: http://www/LGCables.co.kr
and http://www.LGCable4u.com/about/about_rnd03.asp

VIII.3.7.3 Nexans Korea (formerly Daesung Cable)

Nexans Korea (formerly Daesung Cable, established in 1960), produces energy cables, communication cables, copper and optical fiber, and automotive wires for the Korean market. Nexans Korea states it wants to expand its market and is investing in joint venture factories in Vietnam, China, Tanzania and the United States. The firm has been working on NbTi wire since 1991 and in 1998, constructed a plant at Choung-Won, which produces superconducting wire, tape, and applied superconducting cable. Nexans Korea states it will expand its research to superconducting magnets (MRI, NMR, SMES, high-field) in addition to wire. Recently, Nexans Korea has been working on Bi-2223 tape in collaboration with the Korea Electric Research Institute (KERI). For additional

information concerning Nexans Korea's development of Bi-2223 tape, one should contact Mr. I.Y. Han at the address below:

I.Y. Han
165 Sadong-Ri, Nami-Myun, ChoungWon-Kun,
Choong-Buk 363-812
Republic of KOREA
Telephone . : +82-43-270-0372
Fax: +82-43-270-0219
E-mail: I.Y.Han@nexanskorea.com
URL: http://www.nexanskorea.com/english/products/category.asp?c1id=17

VIII.3.8 Mexico

VIII.3.8.1 Mexico Commisión Federal de Electricidad

Mexico Commisión Federal de Electricidad (CFE) is the company that provides generation, transmission, and distribution of electrical power to 21 million customers, out of Mexico's population of nearly 80 million. CFE's Laboratory for Equipment and Material Testing is described at: URL: http://www.cfe.gob.mx/www2/home.asp

VIII.3.8.2 Condumex-CIDEC

Condumex offers cable for telecommunications and energy, including copper and aluminum energy cables, in a wide range of gauges for many applications, such as high-voltage cables up to 230 KV and cables for industrial and mining uses. Condumex Research and Development Center, CIDEC, collaborated with colleagues in Russia's VNIIKP to investigate HTS cable. The results of this joint effort are presented in M. Jergel, A. Morales, C. Falcony, V. Sytnikov, P. Dolgosheev, D.I. Belyi, A. Sierra, A. Perez, J.L. Nieto, A. Gonzalez, M. Maya, F. Ortiz, *Superconducting transmission*

23kV/2kA cable - first in Latin America, REVISTA MEXICANA DE FISICA 49 (6): 489-492 DEC 2003 and in two papers presented at AMSC 2002: (1) V. Sytnikov, P. Dolgosheev, M. Soloviev, D. Belyi, J.L. Nieto, A. Perez, A. Gonzalez, M. Maya, F. Ortiz, *The Current Test Results for Two Models of HTS Cable on CASAT Project*, and (2) A. Perez, J.L. Nieto, Condumex; V. Sytnikov, P. Dolgosheev, *Condumex Tests Model 10 kA HTS Cable*. Condumex' HTS effort is led by P. Dolgosheev whose contact information follows:

Petr Dolgosheev, Chief
Superconductivity
GRUPO CONDUMEX, S.A. DE C.V.
Miguel De Cervantes Saavedra 255
Col. Ampliación Granada
Del. Miguel Hidalgo
11529 México, DF
Telephone: +52 01442(2389047)
Fax: +52 01442(2180717)
E-mail: PDolgosheev@Condumex.com.MX
URL: http://www.condumex.com.mx/ing/cidec.html

VIII.3.9 New Zealand—Industrial Research Ltd

Industrial Research, Ltd. offers Bi-2223 and seeks partners for ventures to develop electro-technical devices, including cable.

Industrial Research Ltd
Auckland, Wellington, & Christchurch
New Zealand
Telephone +64 4 931-3000
Fax:
E-mail: info@IRL.cri.NZ
URL: http://www.IRL.cri.NZ

VIII.3.10 Sweden--ABB

The ABB Group of companies employs about 146,000 people in more than 100 countries. ABB is one of the world's leading cable companies. To date, it has not done R&D on HTS cable. ABB is included here for three reasons: (1) it will be among those that offer conventional alternatives to HTS cable; (2) ABB has installed more than half the HVDC systems in the world, including projects in North and South America, Africa, China, India, Australia and Europe; and (3) ABB is active in India and Russia, each having dense cities where compact cable might be valued. In December 2002, ABB announced it was opening a new production line, ABB Moskabel, for advanced medium- and high-voltage power cables with cross-linked polyethylene insulation in Russia. ABB has invested more than U.S. $10 million in ABB Moskabel since it opened in 1997. During that time, ABB Moskabel has produced and installed 175 km of cable for 110 kV and more than 2,500 km of medium-voltage cable for 10-35 kV. The company meets ISO 9001 and ISO 14001 international quality standards. ABB in Russia is made up of ten companies with their own production facilities that employ around 1,000 people and had revenues around U.S. $120 million. ABB (www.abb.com) is a leader in power and automation technologies that enable utility and industry customers to improve performance while lowering environmental impact. In September 2002, ABB announced it won a U.S. $48 million order to design, build and install a 500-megawatt high voltage direct current (HVDC) system that will connect two regional grids that feed power to millions of consumers in eastern and southern India. The Vizag II HVDC project will be installed at Gazuwaka, located at Vishakhapatnam on India's southeast coast. While ABB's FCL is conducted in Switzerland, other HTS work was performed in the Power Engineering Department of Corporate Research in Västerås. Its former manager was O. Albertsson. ABB's work on conventional cable is led by A. Ericsson whose contact information there follows:

Dr. Anders Ericsson
BU Cables Technology Manager
ABB Power Technologies AB
High Voltage Cables
Box 546
SE-371 23 Karlskrona
Sweden
Phone: +46 455 556 86
Fax: +46 455 822 45
Email: anders.k.ericsson@se.abb.com
URL: http://www.abb.se

VIII.3.11 Switzerland –Brugg Kabel

Brugg Kabel now offers products for several markets: telecoms, special cables, high-voltage systems, high-voltage accessories, and energy cables. See section VIII.1.12 for a description of a related HTS cable project. Brugg Kabel is now managed by H. Gyger whose contact information follows:

Heinz Gyger, Managing Director
Brugg Kabel AG
Klosterzelgstrasse 28
Postfach 5201 Brugg AG
SWITZERLAND
Telephone: +41 056-4603333
Fax: +41 056-4603536
E-mail: info@BRUGG.com
URL: http://www.BRUGG.com

VIII.3.12 United Kingdom

VIII.3.12.1 Alstom

Although Alstom did offer cable for transmission and distribution (T&D), its effort in superconductivity is focused on marine motors that would use HTS. (Alstom's T&D business was recently sold to AREVA; see Sections VIII.3.12.2 and VIII.3.3.1.) The HTS motor effort is being undertaken in partnership with American Superconductor with support from the U.S. office of Naval Research. Brian Pope is Alstom's U.S. contact and is located in Philadelphia. The location of ALSTOM's Power Conversion Business in the UK follows:

ALSTOM Power Conversion
Electrical Machines Business
Leicester Road
Rugby
Warwickshire, CV21 1BD
UNITED KINGDOM
Telephone: +44 (0)1788 542121
Fax: +44 (0)1788 541280
E-mail BrianPope@powerconv.alstom.com
URL: http://www.powerconv.alstom.com

VIII.3.12.2 Areva

Areva employs 75,000 people around the world. This firm recently acquired what was until very recently Alstom's Transmission and Distribution business; see Section VIII.3.3.1. Areva's T&D products range from transformers, switchgear and circuit breakers, to energy software for deregulated energy markets. The firm offers expertise for transmission projects, such as HVDC, and has solutions for renewable energy grid connections. Alstom's UK office (now Areva's UK office) is shown below:

Paul Barron
Country President
ALSTOM
34 Dover Street
London W1S 4NG
United Kingdom
Telephone: +44 (0)1788 545623
Fax: +44 (0)20 7290 5564
URL: http://www.areva-td.com

VIII.3.12.3 BICC (now part of Pirelli)

In the early 1990s with its subsidiary, Ceat Cavi, and with Ansaldo Recherche, BICC (Oak Rd, Wrexham LL13 9XP, Wales) worked on a DC cable project. The collaboration designed and tested a prototype HTS DC transmission cable designed to carry 10,000 A at 40 kV, operating at 40 K. Qualification testing was carried out from 4.2 K up to 40 K. At an operating temperature of 31 K the prototype cable had a current capacity of 11,067 A. The project is described in T.P. Beales, C.M. Friend, W. Segir, E. Ferrero, F. Vivaldi, L. Otenello, *A dc Transmission Cable Prototype Using High-Temperature Superconductors,* SUST (1): 43-47 JAN 1996. T. Beales is now associated with the group at the Univ. of Wollongang; see section VIII.2.1. C.M. Friend is now associated with C. Beduz' group at the Univ. of Southampton. See Section VIII.2.13.2.

VIII.3.13 United States

VIII.3.13.1 General Cable Technologies Corp.

General Cable Technologies Corporation develops, designs, manufactures, and sells copper, aluminum, and fiber optic wire and cable products for the communications, energy and electrical markets. In 1999, the firm acquired BICC Energy Cables and changed its name to BICCGeneral and added the Anaconda®, BICC® and Brand Rex brands. Bare and High-Voltage Transmission Cables BICC® Brand's complete line of TransPowr™ bare aluminum overhead cables and PowrMax™ insulated high-voltage cables for buried applications are available in numerous combinations of aluminum and steel strands and layers to meet the specialized demands of the electrical utility marketplace. Medium-Voltage Distribution Cables General Cable's extensive line of BICC Brand PowrServ™ and EmPowr™ copper and aluminum cables serves the total energy distribution needs of our customers in electrical utilities, rural electrical co-ops, and the public power market. In 1972, General Cable manufactured and installed 14 circuit miles of 230 kV high-voltage underground transmission cable at the Dallas-Fort Worth International Airport. General Cable is no longer working on superconducting cable.

General Cable Technologies Corporation
4 Tesseneer Drive
Highland Heights, Kentucky 41076-9753
USA
Telephone: +1(859) 572-8000
Fax: +1(859) 572-8458 and 8058
E-mail: info@generalcable.com
URLs: http://www.generalcable.com/

VIII.3.13.2 Southwire

Southwire develops, designs, manufactures, and sells copper and aluminum conductor to industry (e.g., 600V) and utilities for distribution (e.g., up to 13 kV), medium voltage (e.g., 13-69 kV) and high-voltage transmission above (69 kV). Southwire has built prototype superconducting cable which supplies Southwire's own factory with powers and has operated for more than 22,000 hours. Now Southwire is working with NKT on a joint venture, Ultera, to develop HTS cable; a demonstration at American Electric Power is under construction. The cable will be of triaxial design, a feature of which is three phases in one cryostat Southwire's director for this joint venture is D. Lindsay whose contact information follows:

David Lindsay, Director ULTERA™
Southwire
One Southwire Drive
Carrollton, Georgia 30119
USA
Telephone: +1 (770) 832-4242 or (770) 832-4916
Fax: +1 (770) 832-5017
E-mail: david_lindsay@southwire.com
URL: http://www.mysouthwire.com

VIII.3.13.3 Pirelli of North America

Pirelli employs about 41,000 people, organized into 78 production units in 14 countries. See Section VIII.3.5.3 for an introduction to Pirelli's overall HTS cable program. Pirelli of North America managed the construction of a 24 kV, 100 MVA, three phase, warm dielectric cable at Detroit Edison's Frisbie substation. AMSC provided the Bi-2223 conductor and Lotepro provided the refrigeration. Pirelli reported that its own vacuum cryostats leaked in two out of three phases, admitting gas that ultimately became conducting, thereby shorting the cable. For Pirelli's report, see www.energetics.com/meetings/supercon/pdfs/presentations/f4_update.pdf. Pirelli announced it would remove the cables and test their AC losses in Milano. For further information, contact J. Curley whose contact information follows:

Jim Curley,
Pirelli Power Systems and Cables
Research, Development, and Engineering
710 Industrial Dr.
Lexington, SC 29072
USA
Telephone: +1 (803) 356-7762
Fax: +1 (803) 356-7765
E-mail: jim.curley@us.Pirelli.com
URL: http:// www.energetics.com/meetings/supercon/ pdfs/presentations/f4_update.pdf

VIII.3.13.4 American Superconductor (AMSC)

American Superconductor (AMSC) states it has received orders for 700 kilometers of Bi-2223 tape from 21 customers in nine countries since January 2003. Its price in small quantities is approximately 200 $/kA-m. At EUCAS 2003, AMSC's representative stated that it would supply orders of 50 km or more for 135 $/kA-m. AMSC and Sumitomo Electric Industries Ltd. (SEI) have agreed to license to each other their North American and European patents for first-generation high temperature superconductor (HTS) wires, electromagnetic coils, electromagnets and current lead devices. Separately, the two companies signed a letter of intent to grow the superconductor cable market by leveraging their complementary capabilities, by marketing SEI power cables that utilize AMSC's HTS wire. AMSC is also the project manger for a prototype cable to be installed in a substation of the Long Island Power Authority (LIPA). That cable will be constructed by Nexans, incorporating AMSC's tape. The design calls for one phase per cryostat. AMSC is trying to develop second generation ("2G") tape, incorporating REBaCuO instead of Bi-2223. Toward that end, in the fall of 2003 the United States Department of Defense (USDOD) [Air Force] and United States Department of Energy (USDOE) awarded $400,000 to AMSC to begin planning a pilot production plant. Also, USDOE via Oak Ridge National Laboratory agreed to incrementally fund AMSC (up to $2.5 million over the next three years, AMSC will cost-share) to extend the manufacturing process by increasing the in-process width of the strips from one to four centimeters and extending the length up to 100 meters. The four centimeter-wide 2G strips will be slit lengthwise to produce eight finished 2G HTS wires, each with a width of 4 millimeters, the industry standard dimension for HTS wire. This manufacturing technology, known as wide-web coating, produces multiple wires rather than one with only a marginal increase in cost and is an essential next step in preparing for commercial production of 2G wire. AMSC will also focus on further enhancing the electrical performance of the 2G HTS wire. The potential demand for HTS conductor has increased because the firm and its partners recently won a contract to supply marine motors to the U.S. Navy. AMSC's Wires Business Unit is managed by A. Santamaria whose contact information follows:

Angelo Santamaria
Vice President and General Manager
HTS Wires Business Unit
American Superconductor Corp.
Two Technology Drive
Westborough, MA 01581
USA
Telephone:+1 (978) 842-3366
Fax+1 (978) 842 3100
Email: ASantamaria@AmSuper.com
URL: http://www.amsuper.com/html/products/htsWire/index.html

VIII.3.13.5 SuperPower, Inc. (owned by IGC)

SuperPower, Inc. is a wholly-owned subsidiary of Intermagnetics General Corporation. Intermagnetics. SuperPower is at the forefront of the development of high-temperature superconductor (HTS) applications to provide increased capacity and reliability for the transmission and distribution of electric power. SuperPower is concentrating on developing second generation coated conductor and HTS transmission and distribution devices such as power cables, transformers and fault current limiters. In November 2002 SuperPower announced a partnership with Sumitomo Electric Industries of Japan to build a 350-meter-long 34.5kV, 800A underground HTS cable between two major substations in the Niagara Mohawk Power Corporation (a National Grid Company) grid in Albany, New York. This cable will have three phases in one cryostat, as did SEI's cable for TEPCO. The BOC Group will provide the refrigeration. In a later phase of the project, a 30-meter section of the HTS cable will be replaced with second generation coated conductor. The project is expected to last four years, with total funding to be about $26 million. The project is partially sponsored by DOE and NYSERDA. SuperPower is led by P. Pellegrino whose contact information follows:

Philip J. Pellegrino, President
SuperPower, Corporation
450 Duane Avenue
Schenectady, NY 12304
USA
Telephone: +1 (518) 346-1414
Fax: +1 (518) 346-5622
E-mail: ppellegrino@igc.com
URL: http://www.igc.com/superpower

VIII.3.13.6 Several U.S. Electric Utilities

Several U.S. utilities have monitored progress toward commercialization of HTS cable and a few have participated in its development. These include American Electric Power (AEP), Long Island Power Authority (LIPA), New York State Power Authority (PASNY), Niagara-Mohawk, and the Tennessee Valley Authority (TVA).

Also relevant is EPRI's Power Delivery Applications of Superconductivity Task Force (established in 2001) which is intended to guide EPRI research related to superconductivity applications for electric power delivery. Formal membership in the group is open to all EPRI funders. Task force general meeting attendance is open to superconductivity industry and institutional stakeholders. Task force meetings provide oversight and feedback for existing and proposed EPRI projects on the integration of superconductivity components into all areas of electric power delivery, including underground transmission, substations, and distribution. The task force also sponsors dialogue with both government and industry stakeholders and vendors in order to facilitate cross-pollination of application ideas and elucidation of industry needs. EPRI will offer members a new, base-funded research program on power delivery applications for superconductivity beginning in 2004. Additional information can be obtained from S. Eckroad. His contact information follows:

Steve Eckroad, P.E.
Manager, Substations & Energy Storage, Science & Technology Development
EPRI
1300 West Harris Blvd PO Box 217097
Charlotte, NC 28262
USA
Telephone: +1 (704) 717-6424
Fax: +1(704) 547-6035
E-mail: SEckroad@EPRI.com
URL: http://www.EPRI.com

VIII.3.13.7 Vacuum Barrier Corp.

Vacuum Barrier Corporation describes itself as the leading manufacturer of dynamically pumped liquid nitrogen (LN_2) systems. Its customers are in the food and beverage, semiconductor, and automotive industries. The firm offers two products: SEMIFLEX® (copper), and COBRAFLEX® (stainless steel) LN_2 piping that might provide the basis for building flexible cryostats HTS cable. No such project is known.

Vacuum Barrier Corporation
4 Barten Lane
Woburn, MA. 01801
USA
Telephone: +1 (781) 933-3570
Fax: +1 (781) 932-9428
E-mail: sales@VACUUMBARRIER.com
URL: http://www.VACUUMBARRIER.com

VIII.4. Professional and Trade Associations

The following institutions consist of either professional or trade associations and related journals. They are world wide in their membership and influence. Interest in HTS cable, as well as in other topics, has stimulated the formation of joint working groups involving members of two or more of the cited organizations.

VIII. 4.1 Institute of Electrical and Electronic Engineers (IEEE)

The IEEE is a nonprofit, technical professional association of more than 377,000 individual members in 150 countries. Through its members, the IEEE is a leading authority in many technical areas, among which is electric power. The IEEE produces 30 percent of the world's published literature in electrical engineering, computers and control technology; holds annually more than 300 major conferences; and has more than 860 active standards with 700 under development. These standards are wholly voluntary and are subject to change. Indeed, every IEEE standard is reviewed every five years or less, after which the existing standard is affirmed or revised.

Within IEEE, the committee that concerns itself with superconductivity and transmission and distribution is General Systems, Subcommittee of the Transmission and Distribution Committee of the *IEEE Power Engineering Society*. The scope of the General Systems Subcommittee covers the analyses of transmission and distribution systems in their broadest sense; modeling and analysis of power systems, including distributed resources; utilization and analysis of superconductivity; power system switching; dynamic and temporary overvoltages; ferroresonance phenomenon; and insulation coordination; state-of-the-art simulation and analysis of FACTS and custom power devices; geomagnetically induced currents; and application of artificial intelligence methods, etc. The General Systems Subcommittee is chaired by A. Keri whose contact information follows:

A. J. F. Keri, Chair
American Electric Power Service
825 Tech Center Dr.
Gahanna, OH 43230-8250
USA
Telephone: +1 (614) 552-1965
Fax: +1 (614) 552-1676
E-mail: ajkeri@aep.com
URL: http://grouper.ieee.org/groups/td/

VIII.4.2 Institute of Electrical Engineers

The Institute of Electrical Engineers (IEE) states it is the largest professional engineering society in Europe and has a worldwide membership of just under 140,000. IEE's mission is to facilitate "… *the generation and dissemination of knowledge and advancement of science, engineering and technology through publishing, education and our networks – we help realise personal ambitions and positively benefit mankind.*" IEE includes Power Engineering division for which the point of contact is shown below:

Steve Riding
IEE
Savoy Place
London WC2R 0BL
UNITED KINGDOM
Telephone: +44 020 7344 5717
Fax: +44 020 7344 ???
E-mail: sriding@iee.org.uk
URL: http://www.iee.org.uk

VIII.4.3 European Committee for Electrotechnical Standardization (CENELEC)

CENELEC was set up in 1973 as a nonprofit organization under Belgian Law. The European Commission recognizes (see Directive 83/189/EEC) CENELEC as the official European Standards Organization for electrotechnical matters. CENELEC's members have been working together in the interests of European harmonization since the late 1950s, developing alongside the European Economic Community.

CENELEC works with 35,000 technical experts from 19 European countries to publish standards for the European market. CENELEC cooperates with the International Electrotechnical Commission (IEC, see Section VIII.4.4). Though these two organizations operate at two different levels, their actions have a strong mutual impact. They are the most important standardization bodies in the electro-technical field. CENELEC also convenes committees.

All interested parties are consulted during the CENELEC standards drafting, through involvement in technical meetings at national and European levels (to establish the content of the draft) and through inquiries conducted by the members. CENELEC's Technical Board coordinates the work of the technical bodies. The Technical Board, made up of one permanent delegate from each national committee, coordinates the work of the organization's Technical Committee's subcommittees and other ad hoc groups.

Also, the Technical Board decides on ratification, on the basis of national voting, of draft standards prepared by the technical bodies.

The Technical Committees (TCs) are established by the Technical Board with precise titles and scopes to prepare the standards. Technical Committees take into account any ISO/IEC work coming within their scope, together with such data as may be supplied by members and by other relevant international organizations, and work on related subjects in any other Technical Committees. Each Technical Committee establishes and secures Technical Board approval for its programme of work with precise title, scope and scheduled target dates for the critical stages of each project. These dates are reviewed at least once a year.

Subcommittees (SCs) may be established by a Technical Committee (after Technical Board approval on justification, programme of work, title and scope) having responsibility for a large programme of work in which :

- Different expertise is needed for different parts of the work, and
- The range of separate activities needs coordination over long periods of time.

The parent TC retains full responsibility for the work of its SCs.

The TBTFs (Technical Board Task Forces) are technical bodies set up by the Technical Board with a view to undertake a specific short term task within a target date and are composed of a Convenor and national delegations. A TBTF reports to the Technical Board, its parent body.

The TBWGs (Technical Board Working Groups) are technical bodies set up by the Technical Board to undertake a specific short term task within a target date. They are disbanded by its parent body once its task is completed. They are composed of a Convenor and of individual members appointed by the Technical Board and/or the National Committees to serve in a personal capacity.

There are several ways to start making a harmonized standard:

- An initial document comes from the International Electrotechnical Commission (80% of cases).
- A document of European origin arises in one of CENELEC's own technical bodies.
- A first draft of a European document comes from one of CENELEC's co-operating partners.
- A fourth source is the National Committees themselves. Under the Vilamoura Procedure, the NCs have agreed to notify CENELEC when they are planning any new work. CENELEC can, if it wants, take on this work.

When a suitable draft is available, it is submitted to the National Committees for CENELEC inquiry, a procedure that lasts six months. Then the comments received are studied by the technical body working on the draft and incorporated into the document, where justified, before a final draft is sent out for vote. The vote usually takes three months. At this stage, the members have weighted votes corresponding to the size of the country they represent. For instance, the larger countries like Germany, France, Italy and the UK have 10 votes each while the smaller ones have one or two votes. There are two requirements for ratification of the standard.
The vote must yield:

- A majority of NCs in favour of the document
- At least 71% of the weighted votes cast are positive

The shortest unambiguous reference to European Standards is to use its number. The number of a European Standard consists of the capital letters EN followed by a space and a number in Arabic numerals, without any space.
Example:
EN 50225:1996 (the year of availability of this EN is indicated by a colon)
EN 50157-2-1:1996 (the part number is separated by a hyphen)

The first two numerals indicate the origin of the standard.

- 40000 to 44999 cover domains of common CEN/CENELEC activities in the IT field
- 45000 to 49999 cover domains of common CEN/CENELEC activities outside the IT field
- 50000 to 59999 cover CENELEC activities
- 60000 to 69999 refer to the CENELEC implementation of IEC documents with or without changes

The IEC and the ISO have allocated themselves blocks of publication numbers: from 1 to 59999 for the ISO and from 60000 to 79999 for the IEC. CENELEC's standard for low- and medium-voltage public distribution systems is numbered EN50160, which also concerns the IEC Technical Committee 77 introduced below.

CENELEC is managed by its Secretary-General, ir. Pieter Parlevliet whose contact information follows. The Convenor of its working group on Power Cable is V. Banks whose contact information also follows:

ir. Pieter Parlevliet, *Secretary-General*
CENELEC
35 Rue de Stassart

B-1050 Brussels
BELGIUM
Telephone:+32 2 519 6871
Fax: +32 2 519 6919
E-mail: direction@cenelec.org
URL: http://www.cenelec.org

Mr. V.A.A. Banks, *CENELEC Convenor*
WG9 Cables for Use by Electricity Supply Companies of TC 20 Electric Cables
Pirelli Cables Ltd, Energy Cables Unit GB
Wrexham LL13 9PH
UNITED KINGDOM
Telephone: +44 1978 66 24 30
Fax: +44 1978 66 22 92
E-mail: Vic.Banks@PIRELLI.com
URL: http://www.cenelec.org

VIII.4.4 International Electrotechnical Commission (IEC)

The International Electrotechnical Commission (IEC) describes itself as the leading global organization that prepares and publishes international standards for all electrical, electronic and related technologies. These serve as a basis for national standards and as references when drafting international tenders and contracts.
The Commission's objectives are:

* Meet the requirements of the global market efficiently
* Ensure primacy and maximum worldwide use of its standards and conformity assessment schemes
* Assess and improve the quality of products and services covered by its standards
* Establish the conditions for the interoperability of complex systems
* Increase the efficiency of industrial processes
* Contribute to the improvement of human health and safety
* Contribute to the protection of the environment

IEC's international standards facilitate world trade by removing technical barriers to trade, leading to new markets and economic growth. Put simply, a component or system manufactured to IEC standards and manufactured in country A can be sold and used in countries B through Z.

IEC's standards are vital since they also represent the core of the World Trade Organization's Agreement on Technical Barriers to Trade (TBT), whose 100-plus central government members explicitly recognize that international standards play a critical role in improving industrial efficiency and developing world trade. The number of standardization bodies that have accepted the Code of Good Practice for the Preparation, Adoption and Application of Standards presented in Annex 3 to the WTO's TBT Agreement underlines the global importance and reach of this accord.

IEC standards provide industry and users with the framework for economies of design, greater product and service quality, more inter-operability, and better production and delivery efficiency. At the same time, IEC's standards also encourage an improved quality of life by contributing to safety, human health and the protection of the environment.

HTS Cable would be in the ambit of IEC Technical Committee 20, Electric Cables. The chairman is R. Stubbe whose contact information follows:

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Technical Committee 20 covers the preparation of standards for electric power cables. Its scope includes: preparing international standards for designing, testing and end-use recommendations (including current ratings) for insulated electrical power and control cables and their accessories and cable systems, for use in wiring, power generation, distribution and transmission. The applications cover an unlimited range of voltage and current. Cables specifically designed for marine applications, covered by SC18A, are excluded. All cables for communication, data transmission and other non-power applications are covered elsewhere.

TC20 has four working groups; they are:
WG 18: Burning characteristics of electric cables, Convenor: T.L. Journeaux
WG 19: Current rating and short-circuit limits of cables, Convenor: M.W. Coates
WG16 and WG17 concern themselves with issues that may involve future HTS cable. The membership of each working group is tabulated below.

WG 16: High -Voltage Cables convenor: Victor A.A. Banks

G.E. Balog	Lauri J. Hiivala	Frank Middel	Robert Rosevear

Jean Becker	Anders Jensen	Pierre Mirebeau	A. Rynkowski
Bjorn Dellby	K.W. Leeburn	Mika Mutru	N. Van Schaik
Pierre Deschamps	H. Marazzato	Ian Naylor	Martti Torikka
Eric Dorison	Sergio Meregalli	Bo Rasmusson	Masaru Watanabe
Bruno Fainaru	Dietmar Meurer	Frank H. Rocchio	W. Weissenberg

WG 17: Low-Voltage Cables, convenor: Luc Putnam

B. Fainaru	S.L. Mason	T. Peltonen	F.H. Rocchio
S. Hawkins	F. Müller	C.K. Reed	J.H. Schutten
O. Jarvid	U. Paroni		

Additional information about TC20 is posted at http://www.iec.ch/cgi-bin/procgi.pl/www/iecwww.p?wwwlang=E&wwwprog=dirdet.p&progdb=db1&committee=TC&number=20

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VIII.4.5 Conseil International des Grandes Réseaux Électriques (CIGRE) International Council on Large Electric Systems

CIGRE is a permanent, non-governmental and nonprofit international association having two purposes: (1) Facilitate and develop the exchange of engineering knowledge and information between engineering personnel and technical specialists in all countries related to the generation and high-voltage transmission of electricity, and (2) Make managers, decision-makers, and regulators aware of the synthesis of CIGRE's work in the area of electric power. More specifically, issues related to the planning and operation of power systems, as well as the design, construction, maintenance and disposal of HV equipment and plants are at the core of CIGRE's mission. Problems related to protecting electrical systems, to telecontrol and telecommunication equipment, are also part of CIGRE's ambit.

Both individuals and organizations (collective members) can be members of CIGRE. Today, it has 826 collective members and 3,747 individual members located in 52 countries.

CIGRE has 15 Study Committees. They are:

SC 11 Rotating Machines
SC 12 Transformers
SC 13 Switching Equipment
SC 14 HVDC Links and AC Power Electronic Equipment
SC 15 Materials for Electrotechnology
SC 21 HV Insulated Cables
SC 22 Overhead Lines
SC 23 Substations
SC 33 Power System Insulation Coordination
SC 34 Power System Protection & Local
SC 35 Power System Communications and Telecontrol
SC 36 Power System Electromagnetic Compatibility
SC 37 Power System Planning and Development
SC 38 Power System Analysis and Techniques
SC 39 Power System Operation and Control

SC21 concerns itself with AC and DC cable of 60 kV or greater and has published two articles in Electra (see http://www.cigre.org/GB/ELECTRA/fsElectra.htm) bearing upon HTS cable: (1) CE/SC : 21, Publié/Published : 2003, Electra, Ref. No. : 208, *High Temperature Superconducting Cable systems* and (2) CE/SC : 21, Publié/Published : 2000, Electra, Ref. No. : 193, *High temperature superconductor applications in electrical power systems*

SC21's working group, WG21-20, concerns itself with ***High Temperature Superconducting (HTS) cable systems.*** This working group's convenor is M. Nassi. WG21-20's responsibilities include:
* Review the emerging technologies and applications of HTS cable systems in the field of energy transmission and distribution, considering its scope of studies according to the areas of technical relevance to HTS cables in manufacture and application.
* Make recommendations to facilitate the definition, manufacture, introduction and integration of HTS cable technologies as appropriate into energy transmission networks.

The scope of WG21-20 comprises four areas of study :

- HTS System Components
- Testing
- Applications and Systems

- Techno-Economic Aspects

M. Nassi's contact information follows:

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CIGRE's URL is http://www.CIGRE.org/gb/indexie.htm

IX. Energy Loss in Transmission and Distribution

IX.1 Conserving Energy

Energy has been on the public agenda for many years. In the late 1960s, policy makers and some of their constituencies began to appreciate that energy use sometimes entails undesirable environmental impacts. After OPEC embargoed oil exports (November, 1973), "energy supply" and "energy efficiency" became a public concern. Indeed, the IEA was formed to facilitate international cooperation over related matters.

The private sector is also concerned about energy, particularly with the cost and availability of fuel and the capital cost of extracting shaft-power from fuel. "Energy loss" has been, and remains, one among many private concerns. In fact, the wish for low electricity prices and appealing profits has long stimulated the power sector to seek efficiencies.

The following sections introduce data describing national averages of annual data. They set the order of magnitude of T&D loss.

Of course, national averages of annual data are not the only facts to which the private sector looks when it considers the efficiency of a particular cable or an alternative. Three reasons explain this: (a) average T&D data include losses in transformers and overhead lines, (b) investment decisions take account of the projected cost of dissipating electricity, and (c) most losses within conventional cable occur when the cable's current is near its maximum value. The latter should be considered when comparing today's cables with potential future cryogenic cables. Their refrigerators must work all the time to remove heat that has flowed through the cryostat and terminations into the low temperature region. Today's refrigeration technology requires 16-20 W of shaft-power to remove 1 W of heat from 77 K.

The last section (Section IX.5) of this chapter introduces the way power engineers estimate losses within cable and the economic value of these losses. This is how the private sector judges the value of energy efficiency in cable.

IX.2 A Few Words About "Conserving Energy" and "Energy Conservation" as They Bear Upon the Power Sector

The "conservation of energy" is an important principle of natural science. Reducing fuel consumption or "conserving energy" is a goal to which many subscribe. The truth about the principle of conservation of energy does not ease the difficulty of "conserving energy". Here we disentangle the meanings of these two similar phrases.

While energy is never lost in the universe, it certainly arrives and departs from the earth. Energy can accumulate here (e.g., past solar energy is embodied in wood and today's fossil fuel resources) and depart (e.g., radiation into the night sky). Further, energy appears in many forms, some more wanted than others. Without denigrating light and heat, the most prized kind of energy is mechanical or "shaft-power".[249] Shaft-power liberates people from the need to perform their own manual labor or to depend upon draft animals.

Unfortunately, shaft-power is not without cost. One can take shaft-power from our environment using wind turbines or dams and water turbines but these are too expensive for most people. This explains the world-wide appeal of the less expensive approach, converting heat to shaft power. The easiest way to obtain that heat has been to burn dung, wood or fossil fuel. Today's alternatives include nuclear fission and solar collectors. (More or less direct conversion of light to shaft-power [e.g., photovoltaics] is still too expensive for common use, as is the more or less direct conversion of chemical energy to shaft-power [e.g., fuel cells].)

The overarching energy questions are:

(a) how easily can the fuel be obtained?

(b) how much shaft-power can be obtained from the fuel? and, at what cost?

(c) should the fuel be transported to the place where shaft-power is wanted, or should the shaft-power be transported from the mine-mouth, well-head or water-turbine?

Before transmission and distribution (T&D), the last possibility was rarely practical over more than a few meters. Today "long" propeller shafts are still used in some ships. One appeal of electric power is that it can be transmitted and distributed over long distances and then converted (via a motor) to shaft-power with almost 100% efficiency. As noted in Chapter II, electric T&D enables one "to transport shaft-power" to the end user from the mine, well, or dam.

Thus, one figure-of-merit of electric power transmission and distribution is the difference between the electric power that leaves the generators and the electric power that is delivered to the end-users. The difference is the rate at which electrical energy is dissipated and heat is generated in the T&D network.

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[249] In a few technical circles, shaft-power is said to be the rate at which "availability", "exergy", or "essergy" is delivered.

IX.3 Accounting Framework for Losses

Here, we cite what the principal sources write about their published data. The next section presents the data.

While the idea of electrical energy loss is straightforward, the significance of published data is not always clear. For example, one source attributes a loss of 10% to a particular country's T&D while another source attributes a 6% loss to that same country's T&D.

IX.3.1 IEA/OECD Electrical Energy Accounting Framework

The Organisation for Economic Co-Operation and Development (OECD) states its aim is "to promote policies designed to achieve the highest sustainable economic growth and employment and a rising standard of living in Member countries … and to contribute to the expansion of world trade on a multi-lateral, non-discriminatory basis…" The International Energy Agency (IEA) "…is an autonomous body which was established within the framework of the OECD to implement an international energy programme." Twenty-six of the OECD's thirty members belong to the IEA. The IEA publishes Electricity Information, a compendium of national annual average data that is compiled with the help of member governments. The data is presented in terms of one common accounting system, having the terms and meanings described below.

Gross Production = total public and private production,
including production from pumped storage

Net Production = Gross Production – Electrical Energy Consumed within Electric Power Plants

Electrical Energy Supplied = Net Production + Imports –Exports
- energy lost within pumped storage & electric boilers & heat pumps

Apparent Consumption = Gross Production + Imports- Exports

Final Consumption = Apparent Consumption – T&D Loss
– Electrical Energy Consumed in Energy sector (e.g., petroleum refinery)

Thus, the IEA's numbers for T&D Loss is the result of taking the difference between quantities for which records are kept. The numerical values published by IEA for T&D Loss are presented in Section IX.4.0.

IX.3.2 Continental Europe: UCTE's Electrical Energy Accounting Framework

Below, we introduce the electrical energy accounting framework adopted by The Union For The Co-Ordination Of Transmission Of Electricity (UCTE) whose headquarters are in Brussels.[250] This framework deserves attention for two reasons: (a) UCTE coordinates continental Europe's transmission systems, and (b) many other entities use a similar but not identical vocabulary.

UCTE describes itself as "the association of transmission system operators in continental Europe, providing a reliable market base by efficient and secure electric "power highways". Through the networks of the UCTE, 400 million people are supplied with electric energy; annual electricity consumption totals approximately 2100 TWh." In geographic terms, UCTE includes all contiguous nations from Portugal (in the west) to Denmark (in the north) to Poland, Rumania, and Bulgaria (in the east), and Greece and Italy (in the south). UCTE describes the role of the Transmission System Operator (TSO), thus, "In the liberalized electricity market that is developing in the European Union, the TSO is not itself a market party. Rather, it is the provider of the infrastructure and of the system management services that are the necessary prerequisites for the functioning of the market. As a provider of these services to market parties (generators, traders and suppliers of electricity) the TSO has not only the technical responsibility for system operations, but is also responsible for the fair and non-discriminatory access to these services by market participants. The neutral and independent TSO is a precondition for fair competition."

UCTE defines several quantities with which it describes the state of Europe's system. The quantities relevant to cable appear on the next page with the UCTE numbers (e.g. 2.1) of their definitions. After these definitions, the same ideas are expressed by a few simple equations.

UCTE 2.1 National net electrical consumption (GWh)

The national net electrical consumption is the sum of

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[250] Union for the Co-Ordination of Transmission of Electricity (UCTE)
15 Boulevard Saint-Michel
1040 Brussels
Belgium
Telephone: +3227416940
Fax: +3227416949
E-mail: info@ucte.org
URL: http://www.ucte.org/statistics/general_terms/e_default_energy.asp

(a) the amount of electrical energy supplied by the electricity service utility to ultimate consumers of the network under consideration.

(b) the amount of net electrical energy produced or directly imported from abroad by industrial or commercial concerns on the network and used directly for their own needs or to directly supply ultimate consumers.

(c) the amount of electrical energy consumed by establishments (offices, workshops, warehouses, etc.) of the electricity service utilities, but excluding the electricity absorbed by the auxiliaries of the power stations and the losses in the main transformers of the power stations, and that consumed for pumping and the network losses. These consumptions are commonly called "consumptions of the electricity sector" or "own" consumption.

UCTE 2.2 National electrical consumption (GWh)

The national electrical consumption is the net electrical consumption including the network losses without consumption for pumped storage.

UCTE 2.3 Electrical energy supplied to the network (GWh)

The electrical energy supplied to the network is the energy that has to be delivered to ensure the required supply to meet the national electrical consumption. In the special case of a national network, this is equal to the sum of the net electrical energy production supplied by all power stations within the country, reduced by the amount used simultaneously for pumping, and reduced or increased by exports to or imports from abroad.

UCTE 2.4 Electrical energy absorbed by pumping/consumption of pumps (GWh)

The electrical energy absorbed by the motor pumps in raising the water into the upper reservoir for the generation of electrical energy. It should include the electrical energy consumed by the auxiliary equipment and transformer losses during pumping.

UCTE 2.5 Gross electrical energy production (GWh)

The gross electrical energy production of a unit, a power station, a group of power stations, a region or a country during a given period, is the sum of the electrical energy production by all the generating sets concerned measured at the output terminals of the main generators.

UCTE 2.6 Electrical energy absorbed by generating auxiliaries (GWh)

The electrical energy absorbed by generating auxiliaries is the sum of the auxiliary power consumptions for all the generator sets under consideration during both the on-load and off-load periods of the generator sets.

UCTE 2.7 Losses in the main generator transformers (GWh)

The energy losses occurring in the main generator transformers during both the on-load and off-load periods of the generator sets. The losses may be either measured or evaluated.

UCTE 2.8 Net electrical energy production (GWh)

The net electrical energy production is equal to the gross electrical energy production less the electrical energy absorbed by the generating auxiliaries and the losses in the main generator transformers.

UCTE 2.18 Network Losses (GWH)

The network losses occurring in transmission and distribution networks are calculated as the difference between the electrical energy supplied to the network and the net electrical consumption.

The definitions above can be simply re-expressed by a few equations.

UCTE Gross Generation = Energy flowing out of the generators' terminals
UCTE Net Generation = Gross Generation
-Electric Energy Consumed by Plant Auxiliaries
-Electric Energy Consumed by Plant's Step-Up Transformers
UCTE National Energy Consumption ≡ Net Generation + (Imports - Exports)
– Energy consumed by Pumped Hydro
UCTE National Net Electrical Consumption ≡ National Energy Consumption
– Network Losses

Data describing some, but not all, of these categories is collected and published by UCTE. Specifically, UCTE collects and publishes data describing net generation, imports and exports, and pumped hydro. From this data, UCTE computes a number that it publishes under the name National Energy Consumption.

When one electric utility purchases power from another, the purchaser is not an ultimate consumer. Excepting the tiny amount of power used by its office staff, the purchasing utility only buys power in order to resell it.

Net electrical consumption means electrical energy provided to "ultimate consumers" and to the office staffs of electric utilities themselves.

Network Losses are the quantity of interest here. This quantity is the difference between UCTE's published National Energy Consumption and the Net National Energy Consumption defined by UCTE under 2.1 above.

Unfortunately, UCTE neither publishes nor collects Net National Energy Consumption and so one cannot deduce Network Losses from UCTE's publications.

IX.3.3 Nordic Countries

Nordel acts as an advisory and recommendatory body for co-operation between the Nordic system operators, and a forum for market participants and the system operators in Denmark, Finland, Iceland, Norway, and Sweden.[251] Nordel was established in 1963. Its primary task is to create prerequisites for efficient utilization of the Nordic electricity generation and transmission systems. Nordel's Annual Reports explain its accounting system and present data that bears upon system losses, as well as many other aspects of its network.

IX.3.4 United Kingdom—UK Department of Trade and Industry

UK DTI publishes data in a form that is recognizable.[252] Its categories include total production, imports, exports, pumped hydro, "consumption by electricity industry", and losses and final consumption. It appears that the sum

total production + (imports-exports) - pumped hydro

is close to what UCTE calls net production. The ambiguity arises because UCTE classes consumption by utility office workers, utility warehouses and utility machine shops with final demand while DTI does not. However, as will be seen below, this different categorization does not yield numerical uncertainty that is big enough to consider further.

IX.3.5 Japan

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[251] See http://www2.ing.puc.cl/~power/alumno99/Development%20of%20the%20Nordic%20Electric%20market/Nordel.htm
http://www.nordel.org/Content/Default.asp?PageName=Home%20news

[252] see http://www.dti.gov.uk/energy/inform/energy_stats/electricity/

Data on Japan and other countries is available from the Japan Electric Power Information Center.[253] However, their definitions are not made explicit. In the absence of explicit definition one can assume that this data conforms to UCTE definitions.

IX.3.6 Korea

Data on Korea was made available to IEA which presents that data in IEA's own framework with its own comments in the report The Energy Policies of IEA Countries: The Republic of Korea 2002 Review. This document is available from the IEA.

IX.3.7 U.S. Department of Energy (DOE) Electrical Energy Accounting Framework (EIA)

U.S. DOE's Energy Information Administration (EIA) synthesizes data submitted by U.S. electric utilities and by independent power producers (independent power producers are called "non-utilities" in some EIA publications.) IPPs own generating stations, whose output is transferred to the grid, transmits and then distributes it. IPPs are not regulated. In recent years, many U.S. utilities have sold their generating stations to IPPs.

The EIA's nomenclature and Electrical Energy Accounting Framework is almost identical to UCTE's framework. The following definitions appear in EIA documents.

> "Gross Generation: The total amount of electrical energy produced by a generating facility, as measured at the generator terminals…
>
> Net generation: Gross generation minus plant use from all electric utility owned plants. The energy required for pumping at a pumped storage plant is regarded as plant use and must be deducted from the gross generation."[254, 255]

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[253] See *Table 17: Transmission and Distribution Loss* appearing in Statistical Handbook 2002/2003, Electric Utility Industry in Japan, Data was taken from the statistics compiled by The Federation of Electric Power Companies (FEPC) of Japan. Useful data also appears in Electric Power Industry in Japan 2002/2003 and Overseas Electric Power Industry Statistics, (Japanese and English), each compiled by the Japan Electric Power Information Center (JEPIC).

[254] *Electric Power Monthly,* DOE/EIA-0226

[255] As noted, U.S. generators submit data to DOE which amalgamates it and publishes the result. The author is grateful to Mr. Rodney Dunn (DOE-EIA) for contacting five generating plant operators and learning that four operators measure output on the high voltage side of the step-up transformer (UCTE's definition) and one measures output on the low voltage side. One respondent stated that there is no single practice in the U.S. Because, the loss in power transformers, operating at rated load, is less 1% and because the actual load varies during the day, the author suggests that ambiguity between losses in generating auxiliaries and losses in T&D is roughly (4/5)x1%, too small to consider further.

Gross generation = energy out of the generators' terminals

Net generation (U.S. DOE) = gross generation
- Electric Energy Consumed by Plant's Auxiliary's
- Electric Energy Consumed by Plant's Step-Up Transformers
- Energy consumed by Pumped Hydro

National Energy Consumption (U.S. DOE) ≡ Net Generation + (Imports - Exports)

Retail Sales (U.S.D.O.E.) = Net Generation (U.S. DOE) + (Imports - Exports) - Network Losses

Network Losses = Net Generation (U.S. DOE) + (Imports - Exports) - Retail Sales (U.S. DOE)

Electrical energy consumption by pumped hydro is small (i.e. 0.3% in 2001) compared to net generation in the U.S.[256] Also, the net electrical energy imported by the U.S. is small (i.e., 0.6% in 2001) compared with net generation.[257] Retail sales (i.e., ultimate consumption of electrical energy) are reported by utilities to DOE on Form EIA-826. Net generation is now reported by utilities to DOE on Form EIA-906 and was in the past reported on Form EIA-759. Non-utility producers report on Form EIA-900. In the past, non-utility producers reported on Form EIA 860-IX.

The U.S. DOE's Energy Information Agency publishes three relevant time series: Net generation by Utilities (Table 3), Net Generation by Non-Utilities (Table 58), and Retail

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[256] In 2001, net generation was 3,450,565 x 10^6 kWhe and consumption by pumped hydro was 8,823 x 10^6 kWhe in the U.S. Thus consumption for pumped hydro was 0.26% of U.S. net generation.

[257] U.S. electrical energy imports (10^6 kWhe) and exports (10^6 kWhe) for CY2001 are shown below. Thus, the net electrical energy, imported by the U.S., was 20,305 x10^6 kWhe which is 0.59% of U.S. net generation. For other years, see Table 6.3 appearing in Electric Power Annual, DOE/EIA-0348(2001) available from http://www.eia.doe.gov/cneaf/electricity/epa/epa_sum.html

CY2001	10^6 kWhe
Canada	
Imports	38,380
Exports	17,806
Mexico1	
Imports2	99
Exports	368
Total Imports	38,478
Total Exports	18,173

Sales by Utilities (Table 44).[258] Most generation by "non-utilities" (sometimes known as "Independent Power Producers") is sold to utilities for subsequent transmission and distribution.

The ratio of net to gross electrical generation depends on the fuel and on the installed emissions control. In the U.S., approximately 98% of the gross power is available to the grid and therefore is net power.[259] Thus 2% is consumed by fans, water pumps, fuel handling and emissions controls.

-- consumed by the generator depends on the fuel and the emissions controls installed.

[258] These are shown in Table 3 (2001 & future data from Form EIA-906), Table 44 (20011990-2000 from Form EIA-759) and Table 58 of the *Electric Power Monthly*, DOE/EIA-0226, available from http://www.Eia.doe.gov/cneaf/electricity/epm/epm_sum.html

[259] See the *Electric Power Annual for 2000, volume II*, DOE/EIA-0348(00)/2 (November, 2002), page 110. Document available for download from URL
http://www.eia.doe.gov/cneaf/electricity/epav2/backissues.html

Prime Mover Type	Gross-to-Net Generation Conversion Factor
Gas (Combustion) Turbine)	.98
Steam Turbine	.97 (a)
Internal Combustion	.98
Wind Turbine	.99
Solar-Photovoltaic	.99
Hydraulic Turbine	. 99
Fuel Cell	.99
Other	. 97

(a) Factor reduced by .01 if the facility has flue gas particulate collectors and another .03 if the facility has flue gas desulphurization (FGD) equipment. Facilities under 25 megawatts and burning coal in traditional boilers (e.g. ., not fluidized bed boilers) are assumed to have particulate and FGD equipment.

IX.4 Data Bearing Upon T&D Loss in Several Nations

According to documents[260], recently published by the International Energy Agency, 6.8% is the average percentage of energy loss in the T&D systems of the 24 members of the OECD. Because such numbers result from aggregating and averaging many sources of data, a good deal of variation from network to network should be expected. Following are some estimates for all of OECD, as well as for individual countries.

IX.4.1 Data Describing OECD

Here we present data of T&D Loss within OECD countries, collectively (see Table IX.4.1.1) and individually (see Table IX.4.1.2).

Table IX.4.1.1

Estimates of Total Electrical Energy Loss within the Transmission and Distribution System of OECD Members
(TWh)

	1973	**1980**	**1990**	**2000**	**2001**
Electrical Energy Supplied[261]	4235.2e	5356.1e	7137.5	9057.6e	8970.0e
T & D Losses	**349**	**437.7e**	**552.4**	**604.0e**	**597.8e**
Energy Sector Consumption[262]	128.7e	179.1e	211.0	230.0e	236.5e
Final Consumption[263]	3757.5e	4739.4e	6374.2	8223.6e	8135.7e

Source: IEA/OECD Energy Statistics of OECD Countries.

e: Estimated Data

[260] See the IEA's series The Energy Policies of IEA Countries:…….which is available from http://library.iea.org/.
[261] Electrical Energy Supplied = Net Production – Used for Heat Pumps, electric Boilers and Pumped Storage + Imports – Exports.
[262] Energy Sector Consumption = electricity consumed by transformation industries for heating, traction and lighting purposes; excludes Own Use by Power Plant, Used for Heat Pumps, Electric Boilers and Pumped Storage.
[263] Final Consumption = Electrical Energy Supplied – Transmission and Distribution Losses – Energy Sector Consumption.

Table IX.4.1.2
Estimated Loss in T&D in Individual OECD Countries During 2001

	Supplied [264]	T&D	Energy Sector Consumption [265]	Final Consumption[266]	T&D Loss/Supplied x 100
Australia	204.1e	16.0e	7.6e	180.4e	7.84
Austria	60.7	3.3	1.0	56.5	5.44
Belgium	7.8	7.4	-1.7	8.8	9.49
Canada	545.4	44.4	22.8	478.2	8.14
Czech Rep.	58.7	4.9	2.9	50.9	8.35
Denmark	35.6	2.0	0.6	33.0	5.62
Finland	81.1	3.0	0.8	77.3	3.70
France	452.2	30.9	25.8	395.5	6.83
Germany	542.6e	25.8e	15.2	501.7e	4.75
Greece	51.3	5.0	1.8	44.5	9.75
Hungary	36.9	4.7	1.7	30.5	12.74
Iceland	7.7	0.4	0.1	7.2	5.19
Italy	304.8	19.4	7.8	277.7	6.36
Japan	966.4	37.0	10.0	919.4	3.83
Korea	268.2	17.9		250.4	6.70
Luxembourg	5.8	0.2		5.6	3.45
Mexico	199.1	30.3	5.5	163.3	5.22
Netherlands	107.2	4.2	3.5	99.4	3.92
New Zealand	38.5	4.2	0.2	34.1	10.91
Norway	121.e	8.6e	1.0e	112.3e	7.05
Poland	123.3	14.2	12.9	96.2	11.52
Portugal	44.6	4.1	0.6	39.9	9.19
Slovak Rep.	25.7	1.3	0.9	23.5	5.06
Spain	227.6	20.3	6.3	201.0	8.92
Switzerland	57.5	3.4		4.7	5.91
Turkey	120.4	23.3	1.8	95.3	9.35
United King.	375.6	32.2	9.6	333.8	8.57
United States	3653.3	219.2e	91.9	3342.2e	6.00

Source: IEA/OECD Energy Statistics of OECD Countries.
e: Estimate

[264] Electrical Energy supplied = Net Production – Used for Heat Pumps, Electric Boilers and Pumped Storage + Imports – Exports. Note: This includes electricity produced by public power plants and autoproducers.

[265] Energy Sector Consumption = electricity consumed by transformation industries for heating, traction and lighting purposes; excludes Own Use by Power Plant, Used for Heat Pumps, Electric Boilers and Pumped Storage.

[266] Final Consumption = Electrical Energy Supplied – Transmission and Distribution Losses – energy Sector Consumption.

IX.4.2 Data Describing China

Data describing Chinese electrical energy loss is not readily available in English. However, the International Energy Agency reported the disposition of electrical energy in China (People's Republic of China and Hong Kong China) during 2001 to be as follows:[267]

$$\text{domestic production + imports-exports} \equiv \text{domestic supply}$$

$$\text{domestic supply} = 1.50 \times 10^6 \text{ GWH in 2001}$$
$$\text{consumption by energy sector} = 0.22 \times 10^6 \text{ GWH in 2001}$$
$$\text{losses in distribution} = 0.11 \times 10^6 \text{ GWH in 2001}$$
$$\text{consumption by end users} = 1.17 \times 10^6 \text{ GWH in 2001}$$

The "consumption by energy sector" includes such things as electrical energy used to mine coal.

According to the World Resources Institute China's electricity consumption doubled between 1990 and 1999.[268]

IX.4.3 Data Compiled by Japan

Table IX.4.2 presents statistics, compiled by Japan's Federation of Electric Power Companies, for transmission and distribution loss, as well as thermal energy efficiency and annual load factor in several countries. Because each original data source might have used somewhat different categories and might have data of different reliability, we do not think that one can reliably consider the difference in T&D losses between countries. We do think that one can reliably compare T&D losses between different years in the same country. Most important we do think that the range of T&D losses is reliably suggested by these statistics. The smallest estimate of T&D loss is 5% and the largest estimate is 10%.

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[267] See *IEA Statistics* posted at http://library.iea.org/dbtw-wpd/Textbase/stats/electricitydata.asp?country=China

[268] See http://earthtrends.wri.org/searchable_db/index.cfm?step=countries&cID=38&theme=6&variable_id=271&action=select_years

Table IX.4.3
Country Comparison of Thermal Efficiency, Transmission and Distribution Loss, Annual Load Factor

		1980	1985	1990	1995	2000
	Thermal Efficiency	32.5	32.7	32.9	33.5	36.4
U.S.A.	Transmission and Distribution Loss	6.6	6.1	5.7	5.6	N/A
	Annual Load Factor	61.1	62.0	60.4	59.8	61.2
	Thermal Efficiency	32.1	32.9	33.9	36.2	36.2
U.K.	Transmission and Distribution Loss	8.5	8.7	8.1	8.6	8.9
	Annual Load Factor	59.4	57.8	62.2	65.4	67.4
Germany	Thermal Efficiency	(38.6)	(39.3)	(39.8)	39.9	40.4
(Former	Transmission and Distribution Loss	(4.7)	(4.8)	(4.3)	5.0	4.9
W. Ger.)	Annual Load Factor	(67.8)	(63.2)	(68.6)	(71.9)	76.8
	Thermal Efficiency	32.1	32.0	34.5	32.6	33.5
Canada	Transmission and Distribution Loss	10.0	9.2	7.7	8.4	8.8
	Annual Load Factor	65.4	65.1	65.7	66.8	66.3
	Thermal Efficiency	35.1	33.1	35.8	34.5	37.6
France	Transmission and Distribution Loss	7.1	7.7	7.5	7.3	7.0
	Annual Load Factor	64.2	57.6	62.9	67.9	69.3
	Thermal Efficiency	37.3	37.1	37.7	38.6	39.0
Italy	Transmission and Distribution Loss	9.2	9.0	7.0	6.7	6.4
	Annual Load Factor	58.1	53.7	52.4	50.3	59.0
Japan	Thermal Efficiency	(36.4)	(38.2)	38.8	38.9	40.6
Ten	Transmission and Distribution Loss	(5.8)	(5.8)	5.7	5.5	5.2
Companies (nine)	Annual Load Factor	(62.8)	(60.4)	56.8	55.3	59.5

Actual figures for 1998
Actual figures for 1999
Source: Overseas Electric Power Industry Statistics (2002)
The Federation of Electric Power Companies, *Electricity Review Japan,* http://www.fepc.or.jp/english/erj/data07.html

IX.4.4 Data from Europe, Describing Europe

Though Europeans are electrically connected to each other, the network operators divide themselves into four groups and each group publishes statistics describing its own area of responsibility. These four entities are coextensive with the United Kingdom, the Nordic countries, continental Europe and what was formerly the Soviet Union.

As noted, the largest area, continental Europe, is looked after by UCTE. UCTE does publish data corresponding to the quantity UCTE names gross consumption (UCTE definition 2.2 presented in Section IX.3.1). Unfortunately, UCTE does not collect or publish data corresponding to net consumption (UCTE 2.1) thus one cannot estimate network losses from its published data[269]

Data from the former Soviet Union was not been found.

Data from the Nordic countries (Denmark, Finland, Iceland, Norway and Sweden) is presented in Table IX.4.3.A. One sees that losses are roughly 7% of Gross Consumption (i.e., generation + (imports-exports).

[269] Letter, 19 June 2003, from O. Fiex (UCTE) to A.M. Wolsky. This inability to estimate network losses is easy to overlook because UCTE does publish summaries in which UCTE presents data under the names "production" and "consumption". For example, see "UCTE in Figures" appearing in Memo_2002 which is available as a pdf from URL http://www.ucte.org/publications/library/e_default_2002.asp.

Table IX.4.4A
Estimate of Per Cent Energy Loss in NORDEL Electrical Transmission and Distribution Computed from Related Data

	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002
Gross Consumption (GWh)[a]	339,661	347,992	355,261	360,685	364,735	374,473	377,300	383,894	393,923	390,883
Net Consumption (GWh)[b]	317,652	323,735	329,720	335,954	338,825	348,493	351,201	356,471	365,932	362,478
Losses (Gwh)[c]	22,009	24,257	25,541	24,731	25,910	25,980	26,099	27,423	27,991	28,405
% Net Consumption	94	93	93	93	93	93	3	93	93	93
% Losses	6	7	7	7	7	7	7	7	7	7

a. Line 1, entitled Gross Consumption, available from Annual Reports (1996-2002, Table S20); (1994-1995, Table S19); (1993, Table S21) found at http://www.nordel.org/Content/Default.asp?PageID=127
IX. Line 2, entitled Net Consumption, available from Annual Reports (1996-2002, Table S20); (1994-1995, Table S19); (1993, TableS21) found at http://www.nordel.org/Content/Default.asp?PageID=127
c. Losses are defined as the difference between Gross Consumption and Net Consumption.

Data from the UK is presented in Table IX.4.3.IX. One sees that losses are roughly 10% of Net Generation which is Gross Consumption (i.e., generation + (imports-exports)).

Table IX.4.4.B
Estimate of Per Cent Energy Loss in UK Electrical Transmission and Distribution Computed from Related Data

	1996	**1997**	**1998**	**1999**	**2000**	**2001**
Electricity Supplied Net (GWH)[a]	332,359	331,629	342,700	347,671	357,476	365,241
UK Sales (GWH)[b]	300,585	300,756	303,484	308,358	314,586	321,751
Losses[c] (GWH)	31,774	30,873	39,216	39,313	42,890	43,490
% Sales	90	91	89	89	88	88
% Losses	10	9	11	11	12	12

a) Line 14 entitled Electricity Supplied Net of Table 5.5, entitled Electricity Supply, Electricity Supplied (net), *Electricity Available, Electricity Consumption and Electricity Sales, Digest of United Kingdom Energy Statistics (DUKES) 2002,* available from http://www.dti.gov.uk/energy/inform/energy_stats/electricity

b) Line 38 entitled Electricity Supplied Net of Table 5.5, entitled Electricity Supply, Electricity Supplied (net), *Electricity Available, Electricity Consumption and Electricity Sales, Digest of United Kingdom Energy Statistics (DUKES) 2002,* available from http://www.dti.gov.uk/energy/inform/energy_stats/electricity

c) Losses are defined as the difference between generation and sales.

IX.4.5 Data Describing Israel

According to the IEA, Israel exports (i.e., 0.001×10^6 GWH) a small fraction of its domestic production of electrical energy (i.e., 0.044×10^6 GWH). The International Energy Agency reported the disposition of electrical energy in Israel during 2001 was as follows[270].

$$\text{domestic production + imports-exports} \equiv \text{domestic supply}$$

$$\begin{aligned}\text{domestic supply} &= 0.042 \times 10^6 \text{ GWH in 2001}\\ \text{consumption by energy sector} &= 0.003 \times 10^6 \text{ GWH in 2001}\\ \text{losses in distribution} &= 0.001 \times 10^6 \text{ GWH in 2001}\\ \text{consumption by end users} &= 0.038 \times 10^6 \text{ GWH in 2001}\end{aligned}$$

IX.4.6 Data Describing Italy

According to the IEA, Italy imports a substantial fraction (i.e., 0.049×10^6 GWH) of its domestic supply of electrical energy (i.e., 0.327×10^6 GWH). The International Energy Agency reported the disposition of electrical energy in Italy during 2001 was as follows[271]:

$$\text{domestic production + imports-exports} \equiv \text{domestic supply}$$

$$\begin{aligned}\text{domestic supply} &= 0.327 \times 10^6 \text{ GWH in 2001}\\ \text{consumption by energy sector} &= 0.030 \times 10^6 \text{ GWH in 2001}\\ \text{losses in distribution} &= 0.019 \times 10^6 \text{ GWH in 2001}\\ \text{consumption by end users} &= 0.278 \times 10^6 \text{ GWH in 2001}\end{aligned}$$

The "consumption by energy sector" includes such things as electrical energy used to mine coal.

[270] See *IEA Statistics* posted at http://library.iea.org/dbtw-wpd/Textbase/stats/electricitydata.asp?country=China

[271] See *IEA Statistics* posted at http://library.iea.org/dbtw-wpd/Textbase/stats/electricitydata.asp?country=China

IX.4.7 Data Describing Korea

According to the International Energy Agency, IEA, the Republic of Korea's electrical energy losses during T&D were 4.7% of generation which in the year 2000 was 266.4 TWH.[272] These losses are less than the OECD average, 6.8%. The Korean Electric Power Company, KEPCO, states that its losses in distribution were 1.76% during 2003.

The International Energy Agency reported the disposition of electrical energy in the Republic of Korea (South Korea) during 2001 to be as follows[273]:

$$\text{domestic production} + \text{imports-exports} \equiv \text{domestic supply}$$

$$\begin{aligned} \text{domestic supply} &= 0.283 \times 10^6 \text{ GWH in 2001} \\ \text{consumption by energy sector} &= 0.015 \times 10^6 \text{ GWH in 2001} \\ \text{losses in distribution} &= 0.018 \times 10^6 \text{ GWH in 2001} \\ \text{consumption by end users} &= 0.250 \times 10^6 \text{ GWH in 2001} \end{aligned}$$

The "consumption by energy sector" includes such things as electrical energy used to mine coal.

IX.4.8 Data Compiled by U.S. for U.S.

As noted above, U.S. DOE publishes data on Net Generation, Imports, Exports and Retail Sales. That data enables one to estimate U.S. T&D Loss, as follows.

Retail Sales + T&D loss = Net Generation + Imports-Exports

$$\%\text{T \& D Loss} \equiv 100 \times \frac{(\text{Net Generation} + (\text{Imports} - \text{Exports})) - (\text{Retail Sales})}{\text{NetGeneration} + (\text{Imports} - \text{Exports})}$$

$$\%\text{T \& D Loss} \equiv 100 \times \left(1 - \frac{\text{Retail Sales}}{\text{Net Generation} + (\text{Imports} - \text{Exports})}\right)$$

The data and result is shown in Table IX.4.7.1.

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[272] See The Energy Policies of IEA Countries: The Republic of Korea 2002 Review , page 56. This document is available from the IEA via its URL http://www.iea.org

[273] See *IEA Statistics* posted at http://library.iea.org/dbtw-wpd/Textbase/stats/electricitydata.asp?country=China

Table IX.4.8
Estimate of Per Cent Energy Loss in U.S. Electrical Transmission and Distribution Computed from Related Data

	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002
Net Generation(10^9kWhe)	3,038	3,074	3,084	3,197	3,248	3,353	3,444	3,492	3,620	3,695	3,802	3,734	3,841
% Change from Prior Year		1.1	.3	3.7	1.6	3.2	2.7	1.4	3.7	2.0	2.9	-1.8	
Imports (10^9kWhe)	18	22	28	31	47	42	43	43	40	43	49	38	
Exports (10^9 kWhe)	16	23	28	35	20	36	33	90	13	14	15	18	
Retail Sales (10^9 kWhe)	2,713	2,762	2,763	2861	2,935	3,013	3.101	3,146	3,264	3,312	3,421	3,370	
% Retail Sales	89	90	90	89	90	90	90	91	89	89	89	90	
% T&D Loss	11	10	10	11	10	10	10	9	11	11	11	10	

Source: Electric Power Annual 2001, Tables 1.1, 6.3 and 7.2

IX.5 Estimating Energy Loss and Its Economic Value for Conventional Cable

IX.5.1 A Framework Relating the Cable to Its System

Several mechanisms cause electrical energy to dissipate within conventional cable.[274] Chief among them is the resistance encountered by the current alternating within the cable. Most of this current is within the conductor and some is induced in the cable's shields and armor. Power engineers aggregate several different resistive loss mechanisms in one parameter, R, the cable's "apparent AC resistance". The maximum current that can alternate indefinitely within the cable without damaging it (i.e., without reducing the cable's lifetime to less than 30 years), is denoted by I_{max}. The rate of dissipation is I^2R and the average current during the h^{th} hour of the year is denoted by I[h]. Using these, the annual average rate of dissipation, $\langle \dot{Q} \rangle$, is expressed as follows

$$\langle \dot{Q} \rangle = \frac{1}{8760} \sum_{h=1}^{8760} \left(I^2[h] R \right) = R I_{\max}^2 \left\{ \frac{1}{8760} \sum_{h=1}^{8760} \left(\frac{I[h]}{I_{\max}} \right)^2 \right\}$$

[274] see G. Ludasi, *Power Cable Systems*, appearing as Chapter 11, in R. Bartnikas and K.D.Srivastava, Power and Communication Cables, IEEE Press and McGraw-Hill (New York, 2000) ISBN#0-7803-1196-5.

One estimates rate at which money is lost by multiplying the cost of electricity by the rate of dissipation.

$$\text{rate of monetary loss} = p_{electricity} \langle \dot{Q} \rangle$$

For any particular utility, the cost of electricity depends on voltage and time of day. For simplicity, a utility might charge itself for lost power at the same rate that utility would charge a large industrial customer. One can elaborate these simple considerations by summing the discounted costs for future years (including an assumption about fuel prices) and by projecting the future load on the cable.

Here we focus on the way that power engineers now estimate the annual average dissipation. It was displayed as the product of the maximum permissible steady-state dissipation and a quantity in curly brackets. That quantity is known as the Loss Load Factor.[275] It is abbreviated here by LLF.

$$LLF \equiv \frac{1}{8760} \sum_{h=1}^{8760} \left(\frac{I[h]}{I_{\max}} \right)^2$$

and so the annual average rate of dissipation within the cable appears as

$$\langle \dot{Q} \rangle = R I_{\max}^2 \times LLF$$

To go further, one must estimate the Loss Load Factor. This could be done by consulting records, if kept, of the hourly current in the cable that is being replaced. However, another way to estimate the Loss Load Factor is recommended within the power engineering community. That way can be understood as series of approximations. First, neglect any variation in voltage by assuming the current is proportional to the power transmitted or distributed. Second, assume that the power guided by the cable is proportional to the total power within the T&D network and so is proportional to the total generation (or consumption). The result is that the LLF is estimated from data describing system power, not cable current.

$$LLF \approx \frac{1}{8760} \sum_{h=1}^{8760} \left(\frac{load[h]}{peakload} \right)^2$$

[275] IEC, "Part 3: Sections on operating conditions—Section 2: economic optimization of power cable size," IEC Standard 287-3-2 (new expanded number 60287-3-2), (former number 1059), 1995. For related matters (e.g., ampacity), see the rest of IEC's series, "Electric cables—calculation of the current rating," IEC 287 standard series (new expanded number: 60287), International Electrotechnical Commission, Geneva, Switzerland and "Calculation of the cyclic and emergency current rating of cables", IEC-853 standard series (now expanded number 60853)

Note that this step assumes that the cable is fully loaded at the time of the system peak. This is often not the case. Usually there is extra T&D capacity to enable the system to handle outages at the time of the peak. Thus the method will often return an overestimate of the LLF.

The right hand side may remind the reader of the system load factor, LF, which is

$$LF \equiv \frac{1}{8760}\sum_{h=1}^{8760}\left(\frac{load[h]}{peak\ load}\right)$$

It is important to note how the quantities differ. The Load Factor is the annual average ratio of load to peak load. The Loss Load Factor is the annual average square of that ratio. The cable's Loss Load factor is always less than the system's Load Factor.

The final step is to say that the LLF can be estimated from the LF as shown below[276].

$$LLF = \frac{1}{8760}\sum_{h=1}^{8760}\left(\frac{I[h]}{I_{\max}}\right)^2 \approx \frac{1}{8760}\sum_{h=1}^{8760}\left(\frac{load[h]}{peakload}\right)^2 \approx \begin{cases} 0.3\times LF + 0.7\times (LF)^2\ transmission \\ 0.2\times LF + 0.8\times (LF)^2\ distribution \end{cases}$$

Table IX.5 shows the numerical results of this formula.

Table IX.5.1
Estimates of Loss Load Factor For Cables

System Load Factor	IEEE estimate of Loss Load Factor for Transmission Cable	IEEE estimate of Loss Load Factor for Distribution Cable
0.50	0.30	0.33
0.55	0.35	0.38
0.60	0.41	0.43
0.65	0.47	0.49
0.70	0.53	0.55

One sees that in these cases, the cable's Loss Load Factor is roughly two-thirds of the system's Load Factor.

As discussed in Section IV.6.2.4, the rate of dissipation within a superconductor has a contribution from the *n*+1 power of the current, not the square of the current. One could

[276] IEEE, Insulated Conductors Committee, Task Group 7-39, Cost of Losses, "Loss Evaluation for Underground transmission and distribution cable systems" IEEE Transactions of Power Delivery, vol.5 number 4, Nov. 1990 pages 1652-1650.

define a loss load factor that is appropriate to HTS cable and then approximate it in terms of the system load factor and its moments. However, the operating cost of the refrigeration for an HTS cable is not the major component of the cost of cryogenics for an HTS cable and so this task is not now urgent. More urgent is building cryo-coolers having acceptable performance when they are not called upon to operate at full load.

IX.5.2 Numerical Illustrations

For the sake of illustration, we consider a specific, hypothetical conventional cable and then vary its parameters. Our purpose is to identify the approximate amount of money that a utility would save by eliminating dissipation within a conventional cable.

First consider a cable that is 10 km long and was built to sustain, indefinitely, a loss of at most 20 W/m. Suppose this cable serves a system with a load factor of 0.6 and that the cable's Load's Loss Factor is 0.4. Further, suppose that the utility charges its large industrial customers 0.06 \$/kWh and so the utility values the avoidance of loss at this same rate. In that case, the value of avoiding the annual loss would be

$$\textit{general framework}$$

$$\text{rate of monetary loss} = p_{electricity}\left\langle \dot{Q} \right\rangle = p_{electricity} I^2 R \times LLF$$

$$\textit{hypothetical example}$$

$$\text{rate of monetary loss} = \left(0.06\,\$/kWh\right)\times\left(20kW/km\right)\times 0.4 \times (8760h/year)$$

$$\text{rate of monetary loss} = 4{,}280\left(\$/year\right)/km$$

Of course, the relevant numbers depend on the utility. So, one should now consider several costs and rates of dissipation. Here we present a table showing the rate of monetary loss for each of several costs of electricity and maximum steady-state rates of dissipation.

Table IX.5.2.A
Rate of Monetary Loss, when LLF=0.4
(\$/year) / km
Maximum Allowed Steady-State Dissipation
(W/m)

Cost of Electricity (\$/kWh)	20	30	40
0.05	3,504	5,256	7,008

0.10	7,008	10,512	14,061
0.15	10,512	15,768	20,124

The costs of electricity, 0.5 $/kWh, 0.10 $/kWh and 0.15 $/kWh in Table IX.5.2 where chosen because they indicate the range of the annual average prices paid by industry to the power sector in OECD countries. Table IX.5.3 shows average annual industrial costs by country. (Average annual costs to residential customers are higher.)

Table IX.5.2.B

Annual Average Electricity Prices for Industry in OECD Countries
(U.S. Dollars/kWh)

	1999	**2000**	**2001**	**2002**
Australia	0.035	0.033	0.031	0.036
Austria	0.057	0.038		
Belgium	0.056	0.048		
Canada				
Czech Republic	0.048	0.043	0.043	0.049
Denmark	0.066	0.058	0.060	0.070
Finland	0.046	0.039	0.038	0.043
France	0.044	0.036	0.035	0.037
Germany	0.057	0.041	0.044	
Greece	0.050	0.042	0.043	
Hungary	0.055	0.049	0.051	0.060
Ireland	0.057	0.049	0.060	0.075
Italy	0.086	0.089		
Japan	0.143			
Korea	0.056	0.062	0.057	
Luxembourg				
Mexico	0.042	0.051	0.053	
Netherlands	0.061	0.057	0.059	confidential
New Zealand	0.030	0.030	0.028	0.033
Norway			0.034	
Poland	0.037	0.037	0.045	0.049
Portugal	0.078	0.067	0.066	0.068
Slovak Republic	0.041	0.042	0.043	0.047
Spain	0.049	0.043	0.041	
Sweden				
Switzerland	0.090	0.069	0.069	0.073
Turkey	0.079	0.080	0.079	0.094
United Kingdom	0.064	0.055	0.051	0.051
United States	0.039	0.040	0.050	0.049
OECD Europe	0.060	0.052	0.046	
OECD	0.062	0.046	0.048	

Source: IEA/OECD Energy Prices and Taxes appearing on page 170 of
IEA Statistics, Electricity Information 2003, International Energy Agency.
Note: Data are not in current U.S. dollars. Price

X. CABLE IN THE GRID

X.1 Introduction to Today's Practice with Today's Materials

As already stated in this report, electric power can be guided to its final consumer by conductors placed overhead, on (or very near) the ground, or underground. Suitable equipment is commercially available for each alternative, and each alternative has been adopted by the power sector in one place or another. When overhead, the conductors and their mechanical support are called "power lines". When near the ground, underground or underwater, the needed conductors, dielectrics, coolants and armor jointly comprise what is called "power cable".

In most places, overhead power lines are the least expensive to construct and maintain. However, concern about safety and aesthetics (e.g., in urban areas) have ruled out overhead lines in some places. Elsewhere, effort to accommodate those concerns may lead to a choice between a circuitous overhead line and a more or less direct underground cable. In those situations, the cost of right-of-way (and sometimes the cost of land for substations) will affect the choice.

Because all known superconductors operate below ambient temperature, they must be thermally isolated from the environment. Because cryostats and LN_2 are needed[277], present effort is devoted to incorporating HTS in cable, not overhead lines.

Future HTS cable can be expected to compete for adoption with conventional cable. To enable better understanding of that competition, this section sketches the use of conventional cable in today's grid.

[277] Typically, overhead power lines comprise aluminum conductor and steel cable. The latter provides mechanical support. An HTS power line, placed overhead, would also require mechanical support and the HTS would have to retain its electrical properties through many cycles of flexing induced by the wind. In addition, one would need a flexible cryostat that could handle various winds and fluctuating ambient temperatures. The latter would cause various expansions and contractions in the outer shell of the cryostat. The possibility of overhead HTS power lines has not been explored by publicly funded projects. However, such lines are not *prima facie* impossible because the transfer of LNG between ships in the North Sea has been demonstrated. Much work would have to have been done before an overhead HTS power line, longer than the transfer distance between two LNG carriers, would be considered plausible rather than merely "not impossible". Most important, ship's captains can cancel a scheduled LNG transfer because of bad weather while a power line is intended to function despite bad weather.

X.2 Transmission and Distribution Systems

X.2.1 Redundance, Loops and Cuts

As mentioned in Section VI.5, the electrical transmission and distribution system is like the body's circulatory system. The latter conveys oxygen from the two lungs to each of many cells, while electrical T&D conveys power from the generators to each of many end-users. Large quantities of blood flow through arteries and veins to and from both lungs while each cell is adjacent to at least one capillary. Large quantities of power issue from each of several power stations and pass through the transmission system into more and more branches (known as sub-transmission and then primary distribution), each guiding less and less power until finally the primary distribution system fans out into the secondary distribution system to which most individual end-users are connected.

The two systems differ in one important respect. The system of major arteries and veins does not include much redundancy. Electrical transmission, and sometimes primary distribution, includes closed loops or rings that enable power to flow even when the loop is cut at one point. More loops enable the network to tolerate more cuts.[278] When one cut will disconnect a group of end-users, their part of the network is said to be radially connected to the rest.

Some persons call the distribution system that part of the network that is radial with respect to all the generators. Others say that distribution comprises all lines that connect to the last transformer Yet, other persons distinguish transmission, subtransmission, primary distribution, secondary distribution, etc., by the fraction of the peak power guided by each. In these usages, it is system context, not the electrical specifications of the individual piece of equipment, that determines whether a piece of equipment is "transmission" or "distribution."

X.2.2 Voltage Level

Above, the words "transmission" and "distribution" were used as nouns. However, the same words are often used as adjectives, as in "transmission-level voltage." When so used, these terms do refer to equipment specifications. Any voltage difference higher than 69 kV is commonly called transmission level. Lower voltages are sometimes called "distribution level voltage." Often anything less than 34.5 kV is called distribution level voltage. Often but not always, more specific names, such as the following, are used:

- Transmission level voltage > 235 kV

[278] One aspect of the network's reliability is characterized by answering the question, "How many cuts would isolate a part of the network from the rest?"

- Subtransmission level voltage 35 – 235 kV
- Primary distribution level voltage 4 – 35 kV
- Secondary distribution level voltage 0.6 – 4 kV

The correlation between the two meanings comes from power engineers' reluctance to build lines or cables that carry more than a few kiloamperes of current. As elaborated in the following paragraph, higher currents challenge circuit breakers' capabilities. Thus, in practice, greater power correlates with greater voltage differences. When considering AC circuits one also compares the cost of the conductor required by large current with the cost of a pair of transformers that step-up and step-down voltage.

At this time, the highest AC voltage used for transmission lines is 765 kV. At these voltages, one has to begin to think about the efficacy of dielectrics. In particular, one has to consider whether or not air will be an insulator.[279]

X.2.3 How Circuit Breakers' Ratings Affect Desired Maximum Current in Power Lines

The cost and availability of circuit breakers having various ratings influence the maximum current that power engineers desire in their grid. This may be important when considering the market for a cable that can handle unusually large currents. We introduce the topic below.

As stated, transmission systems include redundant paths for power flow. This enables engineers to disconnect part of a transmission line from the generators without interrupting power delivery to customers. (When a power line touches the ground, power flows into the earth rather than to the intended customers. That faulty segment must be disconnected.) The disconnection is accomplished by switches called "circuit breakers". Each breaker has two ratings. One is the steady-state current that can pass through the breaker without raising the breaker's temperature to the point where the breaker would be damaged (i.e., become unreliable in the course of time). This current is called the maximum operating current. In the recent past, this current was no more than 3 kA[280],

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[279] Roughly speaking, the vertical component of the electric field near the earth's surface is 130 V/m. Thus, there is a substantial electric field across the surface of a conductor having a voltage difference of 735/√3 kV with respect to ground. Roughly speaking, air is grounded. See Chapter V for additional detail.

[280] "Standard continuous [*current*] ratings include 600, 1200, 2000, and 3,000 A" according to T.A. Short, Electric Power Distribution Handbook, CRC Press (Boca Raton, 2004) p. 383.

though one can now spend more money and buy a 4 kA breaker.[281] Thus a cable that can handle 10 kA may not be particularly valuable to a utility having other cables and circuit breakers that were sized to handle at most 3 kA. Of course, there may be situations in which several 3 kA lines, each with its own breaker, could feed one 10 kA line which again feeds several 3 kA lines, each having its own breakers.

The other circuit breaker rating describes the much larger current that can be handled (without destroying the breaker) for a very brief time. This is called the maximum current that can be interrupted. Typically, a "3 kA breaker" can handle 50-63 kA for 5 cycles before interrupting it. Such great currents arise when the impedance on the line is suddenly reduced--for example by wind or a lightning strike that causes a line to touch the ground or another line causing a "short-circuit" or "fault". (From the utility's point of view, Fault Current Limiters promise to keep such fault currents within the ratings of already installed breakers, obviating the need for other alternatives -- either more expensive breakers or reduced redundancy, via "splitting the bus".) Though, utilities might prefer to avoid upgrading, breakers said to be capable of interrupting 80 kA fault currents are now offered.[282] Nonetheless, it is said that in some places (e.g., near newly built Independent Power Producers) fault currents are already approaching 80 kA.

Very large operating currents do appear in one place within today's grid. A 10-30 kV voltage difference exists between the terminals of most generators. Thus, the current alternating in the conductor between the generator terminals and the low-voltage side of the step-up transformer is much larger than the current anywhere else in the network. For this place, some firms offer breakers having very high operating currents.[283]

The price of circuit breakers depends upon their ratings. At this time, a new 145 kV, 3 kA breaker might sell for 55,000 – 75,000 $, depending on the quantity ordered. A 245 kV breaker that can handle 5 kA continuous and 80 kA interrupting is more expensive.

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[281] For 138 and 66 kV applications, ABB's high voltage breakers are typically limited to 4 kA continuous current and 63 kA interrupter rating. ABB states it could supply its highest current breaker for use at lower voltages than 242 kV for which it was designed . That highest current breaker is rated for 5 kA continuous current and 80 kA interrupting. For a view of what is commercially available see http://www.abb.com,global, then product guide, then "high voltage products", then "circuit breaker". A description for a dead-tank breaker with a 5 kA option is available from http://www.abb.com by finding W. Freeman and H. Heiermeier, *Simplifying Circuit Breakers, dead-tank circuit-breakers for 80 kA and 145-242 kV.*

[282] See for example, the ABB URL given above.

[283] To protect generators, Hitachi (for example) offers breakers that can handle 7.2 kA and 8.2 kA. The price of these breakers is not posted. The information that is posted can be found at http://www.hitachi.us/Apps/hitachicom/content.jsp?page=powerequipment/PowerTransmissionDistribution/GCB.

That breaker might sell for approximately 200,000 $. Much more expensive are the low-voltage, very high current breakers that protect generators. Having a maximum voltage of 30 kV, though most often used at 13.5 kV and 22.9kV, the price of generator breakers varies over a range suggested by the following: (1) 400,000 $ for 8 kA continuous and 80 kA interrupting, (2) 700,000 $ for 13 kA continuous and 130 kA interrupting and finally (3) 1,500,000 $ for 26 kA continuous and 200 kA interrupting.

In summary, today's RD&D offers the possibility of very high currents alternating within future HTS cable. The challenge, not yet addressed, is to identify what other changes must be made in the grid to benefit from this ampacity. Few changes would be needed where several conventional lines, each having a conventional breaker, terminate on a single bus bar to which is connected a single very high current cable. One need only identify the highest current breakers, (available at the desired voltage) to know how much current can alternate within the cable. Where one desires to reduce voltage and increase current, a step-down transformer could be placed between the bus-bar and the high current cable. However, these situations are unlikely to exhaust the potential applications of high current cable. It would be desirable to consider other situations—ones in which modest upgrades of other components (e.g., circuit breakers) in the network might enable a specific, future high current cable to bring substantial benefit to the whole network. Practicing power engineers, now reluctant to contemplate such cable, would be informed as to the validity of their reluctance and the promise of innovation. Similarly, cable makers and their suppliers could discuss their offerings more persuasively. A similar approach to clarifying a different issue -- the desirability of using Phase Angle Regulators with very low impedance cable -- will be suggested in Chapter X.

X.3 Electrical Impedance of Power Lines and Cables

Overhead lines are designed to benefit from two costless characteristics of air. It is an electrical insulator (a good dielectric) and a cooling fluid. Of course, one should avoid wind driven vibrations that are large enough to bring the conductors near enough to each other to precipitate a short circuit. Neither should the temperatures of conductors become high enough to cause the conductors to sag enough to touch each other or the ground. After taking account of these possibilities, as well as the means and cost of mechanical support, engineers have decided on the spacing between conductors that is everywhere visible.[284]

When considering cable, one must recall that both the earth and water are reasonable electrical conductors. Thus the engineered conductor within a cable can never be separated from another conductor (i.e. earth and water) by anything like the distance

[284] The accepted width of right-of-way and height of towers reflects the same considerations.

between two overhead phases. This difference has an electrical consequence. The capacitance between a cable's engineered conductor and the surrounding earth or water is much larger than the capacitance between any two overhead conductors or between any single overhead conductor and the earth. (Another consideration refines but does not alter this difference between line and cable. The engineered dielectric within the cable is usually not isotropic; it is usually strongest in the radial direction. Thus engineers desire the electric field within the dielectric to be radial and so they surround the dielectric by cylindrical conducting "screen" that is grounded. The distance between the engineered conductor and its screen becomes the distance between conductor and earth.)

In summary, cable has much higher capacitance per unit length than does overhead line. Since each of the magnetic permeabilities of air, earth and water are close to one, the surge impedance, $\sqrt{L/C}$, of overhead line is much higher than the surge impedance of underground cable.[285]

Thus, when one compares a proposed underground cable to a proposed overhead line, as one might in a suburb, one must take account of the effect of the differing impedances. That effect will be manifest in the rest of the network in which these alternatives would serve. This statement is independent of whether the cable is conventional or HTS. However, one should bear in mind that some HTS cable designs would have significantly lower surge impedance than conventional cable. Section X.1.4 discusses the expected and potential differences between HTS cable and conventional cable.

The relatively high capacitance of cable enables one to usefully think of an AC cable as a capacitor that alternately charges and discharges whether or not it terminates in open or closed circuit. An AC cable always has a "charging current" — the longer the cable, the larger the charging current. This charging current alternates in the conductor, dissipating electrical energy in the aluminum or copper, without guiding power to the end-user. For this reason, installed AC cables are rarely longer than 35 km. (However, the permittivity of today's dielectrics are less than those available in the past and so the plausible length of AC cable has increased significantly.[286] By comparison, the charging current is negligible in overhead AC lines and so they span long distances. Of course, the distance can be so long (a significant fraction of c/f, for example 1,000 km) as to raise this issue.

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[285] Detailed consideration would include the permeability of the steel in ACRS and the specific geometry of a particular cable. But, detailed consideration will only yield details and not a qualitative change the text's conclusion for today's cable and line.

[286] Mass impregnated cables ε . ˜ .. . pa . . . . ˜ .. . . . . ˜5 . . . = ˜ ˜ . ε G.E. Balog, N. Christl, G. Evenset, F. Rudolfsen, *Power Transmission over Long Distances with Cables*, CIGRE paper B1-306.

When it is, DC overhead lines provide today's alternative. Chapter XI describes the role of DC in today's network.

The "charging current" may also affect the result of a comparison between conventional cable and HTS cable. The absence of dissipation would remove one impediment to a "long" AC cable. Of course, the capital cost of the additional HTS conductor required to handle the charging current would be considered by potential users. Two scales seem likely to determine the maximum desired length of AC cable. These scales are set by (a) the circumference of a region within which overhead lines are not feasible (e.g., an urban center) and (b) the distance to be traversed underwater. Chapter XI presents more information on submarine cable and see Chapter XIII for cities that may deserve above average attention.

X.4 Cost and Availability of Right-of-Way of Power Lines

X.4.1 General Information

The construction of towers to support overhead lines is usually less expensive than the construction of tunnels or trenches within which to place underground cable. However, overhead lines must usually be protected from trees and the necessary pruning adds a maintenance expense. Also, part of the protection involves placing the overhead line in a wide, tree-free corridor — the wider the corridor, the greater the cost of the land. Generally speaking, when land is inexpensive, overhead power lines are cheaper than underground cable.

Land is expensive in cities. In fact, tall buildings are usually constructed to avoid the cost of buying land that would otherwise be needed. One cannot skimp on the width of the power corridor because overhead lines near tall buildings present fire and electrical hazards. This is the principal reason underground cable is usually installed in cities.

Safety, aesthetics, and security concerns also stimulate the use of cable in some non-urban areas.
These include:

(i) near airport runways
(j) when two overhead transmission lines would otherwise cross
(k) "get-aways" from generating stations
(l) in and near some industrial facilities (e.g., petroleum refineries)
(m) in some suburbs

Water crossings are another matter. The distance between the overhead line's towers determine the width of water that these lines can traverse. A span of several hundred meters is routine, and it is certainly possible to suspend power lines for longer distances. At some distances (less than a kilometer), submarine cable becomes more economical than building taller towers and providing greater mechanical support.[287]

X.4.2 Overhead vs. Underground for Transmission

After considering how to transmit electric power, the usual choice is overhead lines. The Verband der Netzbetreiber VDN e.V. beim VDEW (The German Association of Electricity Network Operators) summarizes the situation in the following words:

> Freileitungen sind heute wichtigster Bestandteil des Übertragungsnetzes. Sie gewährleisten eine verlustarme Übertragung mit 380 000-Volt-Höchstspannung, ermöglichen jederzeit ausreichende und zuverlässige Energieversorgung. Auch in absehbarer Zeit wird sich eine wirtschaftliche Übertragung von Strom nur über Freileitungen verwirklichen lassen, da sie gegenüber dem Kabel technische Vorteile haben und deutlich kostengünstiger sind. Die Netzbetreiber sind dabei stets um eine schonende Einbindung der Leitungstrassen in die Landschaft bemüht… Vereinzelt werden Kabel auch in dichter bebauten Gebieten, wenn nicht genügend Platz zur Verfügung steht, in der Hochspannungsebene eingesetzt.
>
> Beim Vergleich Kabel-Freileitung ist zu beachten, dass Kabel
>
> * bei gleichem Leiterquerschnitt eine geringere Übertragungsleistung haben,
> * nur sehr begrenzt überlastbar sind,
> * eine längere Zeit für Reparaturen benötigen und
> * das Mehrfache einer Freileitung kosten.
>
> Dabei gilt: Je höher die Spannung, desto teurer wird ein Kabel im Verhältnis zu einer Freileitung.[288]

For the quoted passage, this report offers the following, inexpert translation into English:

> Overhead lines are today a most important component of the transmission network. They enable low-loss transmission using 380 kV lines and make

[287] The author is grateful to G. Balog for drawing attention to the very unusual case in which a Norwegian fjord is traversed by a 6 km (overhead) line that droops 1 km into the fjord.

[288] See URL: http://www.vdn-berlin.de/freileitung_oder_kabel.asp

> possible sufficient and reliable power whenever it is wanted. Also, in the foreseeable future, overhead lines will continue to be used because only they can economically transmit the flow of power and because they have technical advantages when compared to cable. For this reason, the network's companies always try to carefully integrate power line corridors into the landscape.
>
> When comparing cable and overhead line, one should note that cables having the same conductor cross section as overhead line a) transmit less power and (b) are only very limited overload-proof and (c) require a longer time for repairs and (d) cost more than overhead line. In general, the higher the voltage, the more expensive a cable compared to an overhead line. Overhead lines and cables can change the landscape. The interference of an overhead line is more clearly visible, but cable routes also leave traces. They may neither be cultivated, nor with deep-being rooted plants to be unplanted. The necessary ditches intervene more strongly in the grown layer of soil than foundations of overhead lines.[289]

In some places, power is transmitted by underground cable. Usually this is done in densely populated regions. One example is the New York metropolitan area, where approximately 650 miles of underground transmission cable is owned by the local utility, Consolidated Edison. Among these cables is a very high voltage cable, 345 kV, 760 MW.[290] A cross-section is shown in Figure X.4.2. In 1989, 14.3 km (8.9 miles) of this cable cost approximately 9 million $, approximately 0.6 million $/km (1 million $/mile). (After adjusting for inflation in the US, the price in today's dollars would be approximately 40% higher.) This cable's nominal current (maximum steady-state capability) is 1.3 kA. The copper cross-section of each of the cable's three phases is 1,200 mm^2 (2,500 kcmil).[291] These phases are insulated from each other by two annuli (each 1.5 cm thick) of polypropylene laminated paper (also known as PPLP). The bundle of conductors and insulators floats in oil which absorbs heat that would otherwise raise the temperature of conductor and dielectric. The oil is maintained under pressure to reduce the likelihood of bubbles which would precipitate dielectric breakdown. To maintain operating temperature and achieve needed heat transfer, the cable cross-section (36,600 mm^2 = 366 cm^2) is made ten times larger than the conductor cross-section (3,600

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[289] translation by Alta Vista Babel Fish and A.M. Wolsky

[290] Both the underground and water portions of this cable are described in an informative paper. J. Grzan, E.I. Hahn, R.V. Casalina, and J.O.C. Kansog, "*The 345 kV Underground/Underwater Long Island Sound Cable Project*", IEEE 92SM 368-1 PWRD, presented at IEEE PES 1992 Summer Meeting, Seattle Washington 12-16 July 1992.

[291] This copper cable is designed to operate with a current density of 100 A/cm^2.

mm^2=36 cm^2). Temperature and heat transfer are important issues for all electrical cable, conventional or cryogenic.

However, oil filled cables sometimes leak. Indeed, recently made cables are most likely to have Cross-Linked Polyethylene (XLPE) dielectrics, and no oil. These cables must be operated at lower temperatures than the older ones and so have lower capacity to tolerate overcurrents (i.e., currents greater than the nominal rating).

Beside the cost of the cable, the cost of installing the cable must also be considered. That cost was approximately 27 million dollars. After adjusting for inflation in the US, the cost in today's dollars would be approximately 40% higher, which was three times larger than the cost of the cable itself. Stating the same costs in another way, the cost of the cable was 25% of the cost of cable plus installation. (See Section XII.1.3.) That cost does not include the price of the land or the non-monetary cost, if any, of disruption of transportation, etc. If the cost of new installation and new purchases of land can be avoided, the savings may far exceed the cost of conventional cable.

Figure X.4.2
345 kV, 760 MW Cable of the High Pressure Fluid (Oil) Filled Pipe Design

X.4.3 Overhead vs. Underground for Distribution Lines

Cable is placed underground in one of two ways; it can be directly buried or it can be placed in engineered ducts to which manholes and vaults give access. Direct burial is made feasible by plastic insulation, and it has been made less expensive than in past years by improved tools and techniques for plowing and trenching.

VDN summarizes the situation in Germany in the following way:

> Für die Energieverteilung im Mittel- und Niederspannungsnetz, in dicht bebauten Gebieten mit hohem Strombedarf, werden heute überwiegend Kabel eingesetzt. Auch in ländlichen Regionen gewinnt diese Technik zunehmend an Bedeutung. Die Kabel transportieren den Strom von den Verteil- zu den Ortsnetzstationen und von dort mit der üblichen Netzspannung zu den Kunden. Der Kabelanteil im Mittel-und Niederspannungsnetz wächst kontinuierlich.[292]

This report offers the following, inexpert translation into English:

> For the energy distribution in the central and low-voltage system, in closely cultivated areas with high requirements of electric current, today cables are used predominantly. Also in rural regions this technology is increasingly preferred. The cables transport the power flow from the distribution to the local area network stations and from there with the usual mains voltage to the customers. The cable portion in the central and low-voltage system grows continuously. Isolated cables are used also in more closely cultivated areas, if sufficient place is not available, in the high voltage level.[293]

In North America, direct burial is most often used in urban and suburban residential neighborhoods. Some U.S. utilities have been willing to install "direct buried" distribution cable (e.g., 12 kV) in areas where suburban residences are planned (that is, before homes have been built). This willingness might bear upon the future use of HTS cable if customers with high load factors plan to locate in these residential areas.

Cable is placed in ducts where the load density (kilowatts per square kilometer) is high or where ducts are required by safety and/or environmental considerations. High load density often characterizes a city's central business district.

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[292] See URL: http://www.vdn-berlin.de/freileitung_oder_kabel.asp

[293] Translation by Alta Vista Babel Fish and A.M. Wolsky.

Further, the choice between overhead and underground may be made in light of other considerations—particularly, the location of telephone lines and fiber optic cable. If the latter are strung overhead, the marginal cost of using the poles to support power lines is not large. Those who wish to put power lines underground should be cooperating with whoever is concerned with the communications infrastructure in the same area.

There are many places where the choice between overhead lines or direct buried cable and duct systems is not clear. Here we quote a recent summary, addressed to power engineers, of the issues.[294]

> Overhead or underground? The debate continues. Both designs have advantages (see Table X.4.3.1). The major advantage of overhead circuits is cost; an underground circuit typically costs anywhere from 1 to 2.5 times the equivalent overhead circuit (see Table X.4.3.2). But the cost differences vary wildly, and it's often difficult to define "equivalent" systems in terms of performance. Under the right conditions, some estimates of cost report that cable installations can be less expensive than overhead lines. If the soil is easy to dig, if the soil has few rocks, if the ground has no other obstacles like water pipes or telephone wires, then crews may be able to plow in cable faster and for less cost than an overhead circuit. In urban areas, underground is almost only choice; too many circuits are needed, and above-ground space is too expensive or just not available. But urban duct-bank construction is expensive on a per-length basis (fortunately, circuits are short in urban applications.
>
> On many rural applications, the cost of underground circuits is difficult to justify especially on long, lightly loaded circuits, given the small number of customers that these circuits feed.
>
> Aesthetics is the main driver towards underground circuits. Especially in residential areas, parks, wildlife areas, and scenic areas, visual impact is important. Undergrounding removes a significant amount of visual clutter. Overhead circuits are ugly. It is possible to make overhead circuits less ugly with tidy construction practices, fiberglass poles instead of wood, keeping poles straight, tight conductor configurations, joint use of poles to reduce the number of poles, and so on. Even the best though, are still ugly, and many older circuits look awful (weathered poles tipped at odd angles, crooked crossarms, rusted transformer tanks, etc.).
>
> Underground circuits get rid of all that mess, with no visual impacts in the air. Trees replace wires, and trees don't have to be trimmed. At ground level, instead of poles every 150 ft (many having one or more guy wires) urban construction has no obstacles, and URD-style construction has just pad-

[294] T.A. Short, Electric Power Distribution Handbook, CRC Press (Boca Raton, 2004) p. 95-98.

mounted transformers spaced much less frequently. Of course, for maximum benefit, all utilities must be underground. There is little improvement to undergrounding electric circuits if phone and cable television are still above ground. While underground circuits are certainly more appealing when finished, during installation [*of new trenches and tunnels*] construction is messier than overhead installation. Lawns, gardens, sidewalks, and driveways are dug up; construction lasts longer; and the installation "wounds" take time to heal. These factors don't matter much when installing circuits into land that is being developed, but it can be upsetting to customers in an existing, settled community.

Underground circuits are more reliable. Overhead circuits typically fault about 90 times/100 mi/year; underground circuits fail less than 10 times/ 100 mi/year. [N.B. 1 mile =1.6 kilometer] Because overhead circuits have more faults, they cause more voltage sags, more momentary interruptions, and more long-duration interruptions. Even accounting for the fact that most overhead faults are temporary; overhead circuits have more permanent faults that lead to long-duration circuit interruptions. The one disadvantage of underground circuits is that when they do fail, finding the failure is harder, and fixing the damage or replacing the equipment takes longer. This can partially be avoided by using loops capable of serving customers from two directions, by using conduits for faster replacement, and by using better fault location techniques.

Under ground circuits are much less prone to the elements. A major hurricane may drain an overhead utility's resources, crews are completely tied up, customer outages become very long, and cleanup costs are a major cost to utilities.

However, underground circuits are not totally immune from the elements. In "heat storms," underground circuits are prone to rashes of failures. Underground circuits have less overload capability than overhead circuits; failures increase with operating temperature.

In addition to less storm cleanup, underground circuits require less periodic maintenance. Underground circuits don't require tree trimming, easily the largest fraction of most distribution operations and maintenance budgets. The CEA (1992) estimated that underground system maintenance averaged 2% of system plant investment whereas overhead systems averaged 3 to 4%, or as much as twice that of underground systems.

Underground circuits are safer to the public than overhead circuits. Overhead circuits are more exposed to the public. Kites, ladders, downed wires, truck booms — despite the best public awareness campaigns, these still pose the public to electrocution from overhead lines. Don't misunderstand; underground circuits still have dangers, but they're much less than on overhead circuits. For the public, dig-ins are the most likely source of contact.

For utility crews, both overhead and underground circuits offer dangers that proper work practices must address to minimize risks.

We cannot assume that underground infrastructure will last as long as long as overhead circuits. Early URD systems failed at a much higher rate than expected. While most experts believe that modern underground equipment is more reliable, it is still prudent to believe that an overhead circuit will last 40 years, while an underground circuit will only last 30 years. [N.B. *Transmission cable is designed to last 40 years.*[295]]

Overhead vs. underground is not an all or nothing proposition. Many systems are hybrids; some schemes are:

• Overhead mainline with underground taps — The larger, high-current conductors are overhead. If the mains are routed along major roads, they have less visual impact. Lateral taps down side roads and into residential areas, parks, and shopping areas are underground. Larger primary equipment like regulators, reclosers, capacitor banks, and automated switches are installed where they are more economical — on the overhead mains. Because the mainline is a major contributor to reliability, this system is still less reliable than an all-underground system.

• Overhead primary with underground secondary — Underground secondary eliminates some of the clutter associated with overhead construction. Eliminating much of the street and yard crossings keeps the clutter to the pole-line corridor. Costs are reasonable because the primary-level equipment is still all overhead.

Converting from overhead to underground is costly, yet there are locations and situations where it is appropriate for utilities and their customers. Circuit extensions, circuit enhancements to carry more load, and road-rebuilding projects — all are opportunities for utilities and communities to upgrade to underground service.

[295] The author thanks G. Balog for drawing his attention to the goal for transmission cable lifetime which is distinct from the distribution cable lifetime.

Table X.4.3.1
Qualitative Comparison of Overhead and Underground

	Overhead Line	**Underground Cable**
Cost	Significantly less than underground	Significantly more than overhead [*when new underground infrastructure must be built*]
Lifetime	30-50 years	20-40 years
Annual operation and maintenance	Higher than underground because tree-trimming needed	Lower than overhead because tree-trimming is not needed
Voltage drop per kilometer	More due to higher impedance of overhead lines	Less due to lower impedance of underground lines
Overload capacity	More than underground	Less than overhead
Vulnerability	Greater than underground due to auto collisions and storms [*e.g., ice, high winds, hurricanes*]	Less than overhead due to absence of auto collisions and absence of wind and ice.
Speed of repair	Faster location of faults and faster repair than underground	Slower location of faults and Longer times required for locating faults and making repairs than overhead

Table X.4.3.2
Comparison of Underground Construction[a] Costs with Overhead Costs

Utility		Construction	$[b] [US]	Underground to overhead ratio
Single-Phase Lateral Comparisons				
NP	Overhead	1/0 AA, 12.5 kV, phase and neutral	8.4	
NP	Underground	1/0 AA, 12.5 kV, trenched, in conduit	10.9	1.3
AP L	Overhead	Urban, #4 ACSR, 14.4 kV	2.8	
APL	Underground	Urban, #1 AA, 14.4 kV, trenched, direct buried	6.6	2.4
Three-Phase Mainline Comparisons				
NP	Overhead	Rural, 4/0 AA, 12.5 kV	10.3	
NP	Underground	Rural, 1/0 AA, 12.5 kV, trenched in conduit	17.9	1.7
NP	Overhead	Urban, 4/0 AA, 12.5 kV	10.9	
NP	Underground	Urban, 4/0 AA, 12.5 kV, trenched in conduit	17.8	1.6
AP L	Overhead	Urban, 25 kV, 1/0 ACSR	8.5	
AP L	Underground	Urban, 25 kV, #1 AA, trenched, direct buried	18.8	2.2
EP	Overhead	Urban, 336 ASCR, 13.8 kV	8.7	
EP	Underground	Urban commercial, 350 AA, 13.8 kV, trenched, direct buried	53.2	6.1
EP	Underground	Urban commercial, 350 AA, 13.8 kV, trenched, direct buried	66.8	7.6

Source: CEA 274 D 723, *Underground Versus Overhead Distribution Systems*, Canadian Electrical Association 1992.

a This construction is for new infrastructure for conventional cable. AA means All Aluminum and ACSR means Aluminum Conductor Steel Reinforced

b Converted assuming that one 1991 Canadian dollar equals 1.1 U.S. dollars in 2000.

X.4.4 Power Line Length by Voltage Class

The foregoing sections described the considerations that affect the choice between overhead lines and underground cables. Here we present the data that describes present practice and past choices.

X.4.4.1 Power Line Length by Voltage Class in Japan

As shown in Table 4.4.1, most of Japan's T&D is above ground. Most transmission cable is operated at 66-77 kV. Of course, there is more distribution cable. However, the overwhelming fraction of distribution line length is above ground.

Table X.4.4.1
JAPAN
Transmission and Distribution Equipment

	Transmission Lines (km)				**Transformers**	
	Route Length		**Circuit Length**			
	Overhead	**Underground**	**Overhead**	**Underground**	**Number**	**Max. Output**
Voltage(kV)						
500	6,811	89	13.242	177	73	197,110
275	7,264	490	14,225	1,281	148	154,290
220	2,786	41	5,253	95	55	33,590
187	2,870	15	5,470	35	37	14,763
110-154	16,061	930	29,010	1,789	640	140,072
66-77	38,431	6,427	68,421	11,558	4,338	209,334
<55	8,896	3,117	10,267	4,846	1,160	9,122
	Distribution Lines (km)				**Transformers (MVA)**	
	899,999*	36,000*	3,852,000	60,000	277,812 (Overhead) 22,496(Underground)	

* As of 31 March 2002, according to FEPC.
**When high- and low-voltage lines run in parallel, the low-voltage line length is disregarded.
Source: Japan's Federation Electric Power Companies (FEPC)

X.4.4.2 Power Line Length by Voltage Class in Germany

As shown in Table 4.4.2, Germany's high-voltage power lines are likely to be overhead, while its lower voltage lines are underground.

Table X.4.4.2
GERMANY
Transmission & Distribution*

AC Voltage kV	Overhead Line circuit-km	Underground Cable circuit-km
220 & 380	38,500	100
36-110	70,000	4,500
6 to 36	165,000	308,000
0.4 to 6	185,000	761,000
DC		
Baltic Cable Project Germany & Sweden 450 kV (600 MW)		Underwater 250
Interconnect Germany & Czech Republic 160 kV (600 MW)		

*as of year 2000, according to *Verband der Netzbetreiber VDN e V. beim VDEW*, available from http://www.vdn-berlin.de/facts_figures.asp

In fact, the use of underground cable has increased during the past decade. VDN states:

> Mehr Kabel in deutschen Stromnetzen 1,6 Millionen Kilometer Stromleitungen: Drei Viertel unterirdisch
>
> Berlin (06.10.2003) - Die Stromversorger haben aus Gründen der Versorgungssicherheit sowie aufgrund behördlicher Auflagen immer mehr Leitungen unterirdisch verlegt: Der Kabelanteil am Stromnetz stieg von 1992 bis 2002 von 63 auf 71 Prozent. Die Gesamtlänge der Leitungen wuchs in diesem Zeitraum um 100.000 Kilometer (km) auf knapp 1,6 Millionen km.
>
> Kabel sind zwar teurer als Freileitungen, dafür aber unempfindlicher gegen Störungen wie Unwetter oder Blitzschlag. Seit 1992 sind rund 90.000 km Freileitungen abgebaut worden - überwiegend im Niederspannungsbereich. Über diese Netze - mit einem Kabelanteil von gut 80 Prozent werden vor

allem die Haushalte beliefert.

Der Umfang der Höchstspannungsnetze ist unverändert geblieben. In den überregionalen Transportnetzen gibt es aus wirtschaftlichenen Gründen kaum Kabel. Allerdings sind ältere Leitungen durch leistungsfähigere ersetzt worden.

For which VDN offers the following translation into English:

More cables in German electricity mains 1.6 million kilometers of electric cable: Three quarters underground Berlin (06.10.2003) –

the power suppliers shifted more lines underground for reasons of supply security as well as due to official editions ever: The cable portion of electricity mains rose from 1992 to 2002 of 63 to 71 per cent. The overall length of the lines grew in this period by 100,000 kilometers (km) on scarcely 1.6 million km. Cables are more expensive than overhead lines, more insensitive for it however to disturbances such as tempests or thunderbolt. Since 1992 approximately 90,000 km overhead lines were diminished - predominantly within the low-voltage range. Over these nets - with a cable portion of well 80 per cent above all the households are supplied. The extent of the extra-high tension nets remained unchanged. In the supraregional transportation nets there is hardly cable for economical reasons. However older lines were replaced by more efficient.[296]

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[296] Translated by AltaVista Babel Fish and A.M. Wolsky

X.4.4.3 Power Line Length by Voltage Class in the Republic of Korea

As shown in Table 4.4.3, the Republic of Korea's high-voltage power lines are likely to be overhead, while its lower voltage lines are underground. KEPCO states it will replace its present 66 kV lines. As shown, these are now a small fraction of the network.

Table X.4.4.3
Republic of Korea
Transmission & Distribution*

AC Voltage kV	Overhead Line circuit-km	Underground Cable circuit-km
765	662	none
345	7,520	224
154	16,741	854
66	1,028	3
DC		
180 kV	30	202 including Underwater to Jeju Island
22 kV ≥ distribution	Total 376,454 overhead and underground not reported separately**	

*as of the end of the year 2003, according to KEPCO, available from http://www.kepco.co.kr/en/Welcome.html

** Dr. OK-Bae Hyun states that underground is increasingly preferred near populated areas, while overhead lines are preferred in mountainous regions.

X.4.4.4 Power Line Length by Voltage Class in the UK

England and Wales are served by The National Grid plc which brings power from generators to local distribution companies**.**

Table X.4.4.4
National Grid Table

Technical Type	1999/00
Overhead lines	
400 KV	10,052 circuit km
275 kV	3,615 circuit km
132 kV and below	224 circuit km
Total	13,891 circuit km (6,985 route km)
Underground cables	
400 kV	132 circuit km
275 kV	425 circuit km
132 kV and below	64 circuit km
Total	621 circuit km
DC (Cross-channel link)	327 circuit km
Towers	21,812
Transformers/quad boosters/reactors	721
Substations	323

X.4.4.5 Power Line Length by Voltage Class in the U.S.

Table 4.4.4.1 presents cable length installed in the United States for each voltage class. The overwhelming fraction of cable is used at less than 22 kV. The author thinks it likely that most of this cable distributes power within residential neighborhoods. The data were voluntarily provided by utilities to the Edison Electric Institute, which graciously made it available for this report. More recent data not available.[1]

Table 4.4.5.1
U.S. Underground Cable in Use (Underground Cable Miles)

Voltage Level (kV)	1998 Underground Cable Miles Transmission	1997 Underground Cable Miles Transmission	1996 Underground Cable Miles Transmission	1996 Underground Cable Miles Distribution	1997 Underground Cable Miles Distribution
< 22	471	506	699	660,925	759,162
22-30	2,787	1,359	1,319	32,736	49,220
31-40	1,265	1,284	968	11,407	13,016
41-50	72	73	76	0	0
51-70	1,881	1,751	1,675	766	850
132-144	2,457	2,263	2,214		
144-188	13	18	6		
189-253	586	484	449		
254-400	402	481	316		
401-600	9	9	7		
600>	0	0	0		
ALL	13,080	11,453	9,845	705,834	823,346

Cable mile = total length of separately sheathed cables regardless of the number of conductors contained within a single sheath, for pipe type cables it is the total length of single conductor mileage. Typically, there are three conductors (phases) in each pipe; in that case a cable mile is three conductor miles

unpublished data kindly provided by EEI to A.M Wolsky

Table 4.4.5.2
Overhead Line in U.S. (Overhead Circuit Miles)
(1997 EEI Statistical Yearbook, Table 86)

Voltage Level (kV)	**1997**	**1996**
< 22	NA	NA
22-30	101,002	97,304
31-40	100,749	100,666
41-50	50,543	50,567
51-70	109,862	110,107
71-132	95,835	95,322
132-144	73,186	72,939
144-188	25,227	24,875
189-253	69,598	68,639
254-40	54,593	54,789
401-600	27,960	27,449
600>	3,142	3,142
ALL	711,698	705,799

Circuit mile = total length in miles of separate circuits whether one or more conductors per circuit. Typically there are three conductors (phases) in each circuit; in that case a circuit mile is three conductor miles

X.5 Submarine Cable

In some regions, electric power is transmitted for long distances across routes covered by water (e.g., Irish Sea, Baltic Sea, and Mediterranean Sea). The task is made possible by submarine cable. As noted elsewhere in this report, a cable is a capacitor—the longer the cable the bigger the capacitor. Every time the voltage difference alternates, the plates must be charged and discharged. That can only be accomplished by a current. Thus, a current alternates within AC cable even when there is no load. The charge and thus the charging current depends on the permittivity of the dielectric (i.e., the dielectric constant) and geometry. For "long enough" cable, the cost of accommodating this "charging current" rivals the cost of converting AC to DC and then inverting the DC to AC. Of course, the economic length of an AC cable depends on the year in which it was built. Tables are presented in Chapter XI. Recent work suggests that economic, conventional AC transmission cable might reach 100 km.[297]

Submarine cable also traverses short distances. Many cities are located on banks of navigable rivers or the shores of harbors. Submarine cable guides electric power across this water. As with underground cable, the largest component of the project cost is the installation, not the cable. Submarine trenches are excavated by water jets created by machines that can descend one km below the surface.

In heavily traveled water, ships' anchors require consideration. How should the cable be installed so as to reduce the probability it will be ruptured? What happens if it is ruptured?

Present practice alerts ships as to the location of electrical cable and forbids them from anchoring nearby. Nonetheless, ships and anchors can drift with damaging consequences. In particular, the crews of large ships may simply not notice the drag of their anchors after forgetting to haul them or when wind and current sets their ships adrift. Large anchors can gouge furrows into the water bottom. Their depth depends very much on the bottom material. Furrows in sandy or harder material might be no more than 3 m deep, while soft sediment might be vulnerable as deep as 10 m. Thus submarine cable must be installed below the water bottom. How much below depends on the bottom material.

Another choice must be made. Should each phase be installed in its own trench or should all phases be installed in a single trench? No single answer satisfies all circumstances. Each phase of a 345 kV cable under Long Island sound was installed in its own trench.

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[297] G. Balog, N. Christl, G. Evenset, F. Rudolsen, *Power Transmission Over Long Distances with Cables*, CIGRE paper B1-306

In addition, a fourth phase was installed in a fourth trench to provide a spare, in case one of the three was damaged. And, no trench was less than 150 m from its nearest neighbor to reduce the likelihood that more than one cable would be ruptured. On the other hand, a single pipe type cable containing three phases was installed under New York's East River. That single pipe type requires a submarine man-hole.

One thing can be said; for given location and depth, the cost of installation is linear in the number of separate trenches and the length of each. The distance of the cable route under Long Island Sound is 12.7 km (7.9 miles). The total cost of the installation under Long Island Sound was approximately 115 million $, while the total cost of the four submarine cables was 46 million $.

To reduce the likelihood of environmental damage, if a phase ruptures, these cables were chosen not to be pipe type cables. Instead they are of the Self Contained Fluid type. The pressurizing oil flows in a central channel within the conductor. The result is a larger diameter cable with a much smaller volume of oil. Figure X.5.1 shows the three submarine phases and the underground pipe-type cable to which the submarine cables connect. (A fourth cable is installed and serves as a "spare" phase.) The larger diameter of the submarine cable does not affect the cost of preparing the submarine trench.[298,299] Figure X.5.2 shows a close up of one of the phases.

[298] For both underground and underwater cable, cable diameter affects installation cost when considering the feasibility of retrofitting new cable into existing infra-structure. If one must build new infra-structure, the cost of the new infra-structure is not sensitive to cable diameter.

[299] Though we do not believe the difference in diameter will bear significantly on the comparison of conventional submarine cable with future HTS submarine cable, diameter does affect the ease and so the cost of cable laying. The author is grateful to R. Eaton for drawing his attention to the following practice. Generally torque balanced submarine cable cannot be coiled, and consequently it is stored (and installed) on turntables in the cable laying vessels. Larger diameter cable (and mass) requires larger turntables and vessels. Also larger diameter cable will have higher drag properties and per unit mass and will require more robust cable laying equipment. Note that lead alloy sheaths protect submarine cables from water that might otherwise leak in.

Figure X.5.1
Three Cross-Sections 345 kV Submarine AC cables of the
Self Contained Fluid (Oil) Filled Pipe Design
Under Long Island Sound
and the
Three Phase HPFF Underground Cable
to which
Submarine Cables Connect

Figure X.5.2
One of the Four 345 kV Submarine AC Cables of the Self Contained Fluid (Oil) Filled Pipe Design Under Long Island Sound

Wolsky, A.M., Chapter X of **HTS CABLE—STATUS, CHALLENGE and OPPORTUNITY**. Work done for and sponsored by the signatories of the International Energy Agency *Implementing Agreement for a Cooperative Programme for Assessing the Impacts of High-Temperature Superconductivity on the Electric Power Sector*
(02 December 2004)

XI. SITUATIONS IN WHICH THE POWER SECTOR WOULD CONSIDER DC TRANSMISSION

XI.1 Introduction

As will be elaborated below, today, there are a few circumstances in which power is transmitted by the overhead DC lines. With only three recent exceptions, DC cable is used only where long distances must be traversed underwater.[300] In a few places, DC is used to transfer power between two AC systems. Such links are very short, typically 5-10 m and are called "back-to-back". DC is never used in the grid to distribute power, though it is used within facilities where electrolytic reduction is practiced (e.g., $Al_2O_3 \rightarrow Al$).

Nonetheless, the possibility of using HTS to conduct DC continues to attract interest from some managers[301] and commentators[302,303,304] as well as technical physicists[305,306,307,308] and

[300] Two of three exceptions are in Australia and one is in Sweden. They are feasible because the cable is roughly 50mm in diameter and the soil allowed plowing a furrow and placing the cable within it at a rate of 3 km per day. The DC cable (made by ABB) is a 50 kV bipole and guides 220 MW. There is an old, underground DC cable near Kingsnorth in greater London.

[301] C. Starr, *National Energy Planning for the Century: The Continental SuperGrid*, Nuclear News, February 2002 pages 31-35. Also see T.J. Overbye, C. Starr, P.M. Grant, and T.R. Schneider, National Energy SuperGrid Workshop Report , sponsored by the UIU with support from the Richard Lounsberry Foundation, 6-8 November 2002. Plans call for a successor workshop sometime in 2004; it will be sponsored by NSF & Lounsberry Foundation & EPRI.

[302] Like, Bartlit et al, cited below, the following papers suggests simultaneous transmission of cryogenic fluid fuel (i.e., LH_2) and electricity (DC via superconductors). P. M. Grant, *Will MgB2 Work*?, Industrial Physicist, October, 2001 pages 22-23, and P.M. Grant, *Energy for the City of the Future*, Industrial Physicist, February-March, 2002, pages 22-25.

[303] Paul Chu, Invited Talk to Plenary Session of EUCAS 2003, held in Sorrento, Italy.

[304] R.L. Garwin and J. Matisoo, *Superconducting Lines for the Transmission of Large Amounts of Electric Power over Great Distances*, Proc. of the IEEE, vol.55, no.4 April, 1967 pages 538-548.

[305] D. Politano, M. Sjöström, G. Schnyder, and J. Rhyner, *Technical and Economic Assessment of HTS Cables*, IEEE, Applied Superconductivity Conference, 17-22 Sept., 2000

[306] S. Schoenung and W.V. Hassenzahl, System Study of Long Distance, Low-Voltage Transmission Using High Temperature Superconducting Cable, report WO-806512 for the Electric Power Research Institute (March, 1997).

[307] Like Grant's papers, cited above, the following paper by Bartlit et al suggests simultaneous transmission of cryogenic fluid fuels (i.e., LNG and LH_2) and electricity (either cryoresistive or superconducting). J.R. Bartlit, F.J. Edeskuty, and E.F. Hammel, *Multiple Use of Cryogenic Fluid Transmission Lines*, Proceedings of the Fourth International Cryogenic Engineering Conference, held in Eindhoven 24-26 May 1972

electrical engineers.[309,310,311,312,313,314] This chapter introduces some issues bearing upon the likely use of future HTS DC cable.

Some persons propose using superconductors instead of metal conductor, for DC transmission within today's context.

Other persons propose a different possibility for the far future, a pipeline in which a cryogenic fluid, such as hydrogen, would be transported from producer to consumer and also serve as the coolant for a superconducting DC cable.[315]

Another proposal, indeed a revolutionary proposal if acted upon, is the creation of a DC network instead of an AC network.

These different proposals should not be confounded. One refers to the near future and others include a vision of the far future. The latter require different development of ancillary technology. The two visions also address different economic circumstances. Sections XI.3, 4, and 5 bear upon the use of DC transmission between two places (sometimes called "point-to-point"), something that is done now and might provide a modest market for DC HTS cable in the future, if and when ancillary technologies (e.g., submarine cooling and submarine joints) is developed. Section XI.6 suggests what

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308 B.W. McConnell, *Applications of High Temperature Superconductors to Direct Current Electric Power Transmission and Distribution*, presented at the Applied Superconductivity Conference, October 3-8, 2004, Jacksonville, Florida.

309 G. Venkataramanan and B.K. Johnson, *A superconducting DC transmission system based on VSC transmission technologies,* IEEE Trans. On Applied Superconductivity 13 (2): 1922-1925 Part 2 June 2003

310 T. Ishigohka, *A Feasibility Study on a World-Wide-Scale Superconducting Power Transmission*, IEEE Trans, on Applied Superconductivity, vol.5 #2, (June, 1995) pages 949-952.

311 T. Ishigohka, *Possibility of DC Underwater Superconducting Power Cable Cooled by Long-Length Heat Pipe*, IEEE Trans, on Applied Superconductivity, March 2002 pages 1294-1297.

312 J. Østergaard, O. Tϕnnesen, J. Kaas-Pedersen, A.H. Nielsen, C. Traeholt, *A New Concept for Superconducting DC Transmission from a Wind Farm*, Physica C 372-376 (2002) pages 1560-1563.

313 Superconducting Low Voltage Current Networks (LVDC), EPRI Report # TR-103636 (Palo Alto, California, April, 1994)

314 B.K. Johnson, R.H. Lasseter, F.L. Alvarado, D.M. Divan, H. Singh, M.C. Chandorker and R. Adapa, *Superconducting Low Voltage DC Transmission Networks*, Electric Machines and Power Systems, vol. 22 (1994) pages 629-645.

315 P.M. Grant, *The Super Cable: Dual Delivery of Hydrogen and Electric Power*, presented at the Applied Superconductivity Conference, October 3-8, 2004, Jacksonville, Florida.

should be considered when talking about DC networks (i.e., loops); they would require circuit breakers and other means to control current and voltage.

XI.2 Electricity and Magnetism of DC Transmission

XI.2.1 Introduction

DC guides power by setting up a voltage difference between two conductors and dedicating one conductor to carrying current in one direction, while using the other conductor for the other direction. When one of the conductors is grounded, the line is called monopole and it is called bipole when the voltage of each of the two engineered conductors differs from the earth's. Though the current flows in one direction, it is not time-independent. Even in steady-state, the current has the harmonics that remain after adding the current from each of the three rectified AC phases that feed the line. Of course, the power guided depends on the load and the conditions in other parts of the grid. The load varies over the course of tens of minutes, while faults elsewhere in the grid can redirect power in a fraction of a cycle.

Nonetheless, less electrical energy dissipates in a DC line and cable than in AC line or cable (respectively). This is particularly true of high-voltage, conventional DC cable where the "dielectric loss" (from the oscillating polarization, see Chapter V) is negligible.

XI.2.2 Converting AC to DC and Inverting DC to AC

In conventional DC transmission, two mechanisms dissipate electrical energy: (a) the upstream "conversion" of AC to DC and the downstream "inversion" of DC to AC, and (b) the resistance to current flow within the electrical conductors. If, instead of aluminum or copper, an HTS superconductor were used, its electrical resistance would be negligible. However, electrical energy would be dissipated in the course of operating the cryogenic cooling system required to remove heat that had come from ambient through the cryostat into the low temperature region..

The dissipation during conversion and inversion is not negligible. Most loss occurs during the go part of the cycle. Figure XI.2.2 shows the schematic. Estimates for a two terminal cable range from 1.3-2% of the throughput for today's commercial technology.[316,317] Note that efficiencies are often quoted per terminal and a transmission line certainly requires two terminals and may require more.

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[316] A Swiss group states that 1% losses would be "rather optimistic"; see Schnyder, G., J. Rhyner, D. Politano, and M. Sjostrom, *Application of High Temperature Superconductivity in Power Systems*, ETG Tagung: Anwedung der Supraleitung und neuer Isolierstoffe in der elektrischen Verteilung, ETH Zurich, 21 Marz 2000.

[317] "For a fully compensated converter station, efficiency can to a large extent, be influenced by equipment design. Design therefore, is a function of the loss evaluation. For modern HVDC terminals, 0.65 to 1 %

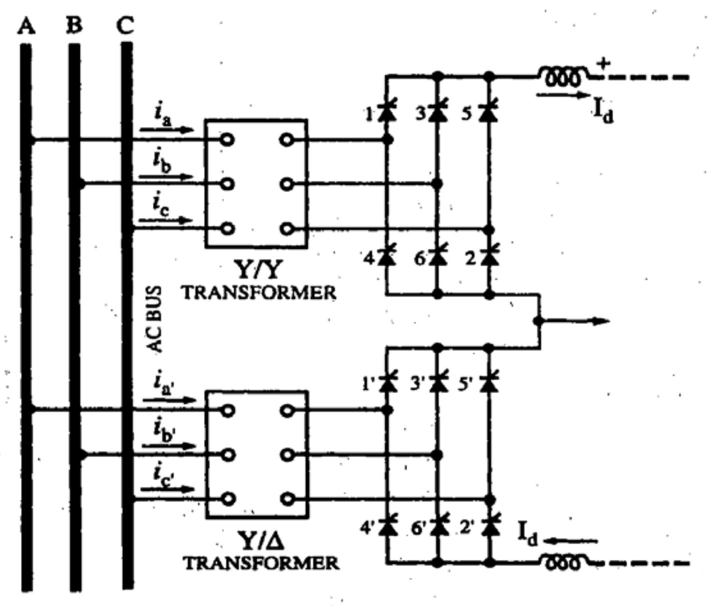

Figure XI.2.2
Basic Circuit of a 12-Pulse of an HDVC Converter

Estimates for a two terminal cable range from 1.3-2% of the throughput for today's commercial technology. In particular, LCC thyristors lose about 0.75% per terminal[318] and a transmission line certainly requires two terminals (i.e., 1.5% loss) and may require more. When VSC/IGBT are used the loss increases to 3.0-3.5% per station. Nonetheless, they are attractive because they require less land (i.e., smaller footprint) and are capable of starting up ("blackstart").[319]

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losses per terminal are typical" according to P.F. Albrecht et al, Section 15 *Direct Current Power Transmission*, appearing in D.G. Fink and H. Wayne Beaty, Standard Handbook for Electrical Engineers, 14th edition, McGraw-Hill (London, Milan and elsewhere, 2000) ISBN#0-07-020975-8

[318] The author is grateful to G. Balog, Nexans, for this estimate.

[319] The author is grateful to G. Balog, Nexans, for this estimate.

Recently, Voltage Source Converters (VSC), have been considered for power transmission.[320,321] VSCs are not yet commodities and so, their capital costs and efficiencies are most reliably obtained from vendors, such as ABB which calls its product HVDC Light,[322] Another vendor calls its system HVDC Plus. As emphasized elsewhere in this report, the private sector evaluates electrical energy dissipation in terms of the cost of fuel delivered to the generator and the cost of incremental system capacity at the time of the peak.

The private sector is also concerned about the total "capital cost" or "first cost" of any particular piece of equipment and its installation. That cost has prompted investors to finance DC lines when they are long enough to promise savings that compensate for the cost of the convertor-invertor.[323,324] In 1996, these costs were roughly 90 $/kW per terminal for 100 MW declining to roughly 65 $/kW per terminal for 2,000 MW.[325] Note, a transmission line requires at least two terminals.

However, the common measure—money per power—assumes that the thyristors within today's convertor-invertors can be arranged in series or parallel without significantly affecting the cost of the equipment. (Today's thyristors cannot handle more than 6 kV

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[320] J. S. Lai and F. Z. Peng, "Multilevel converters—A new breed of power converters," in *Proceedings of the IEEE-IAS'95 Annual Meeting*, 1995, pp. 2348–2356.

[321] S. Bernet, *Recent developments of high power converters for industry and traction applications*, *IEEE Trans. Power Electron*, vol. 15, no. 6, pp. 1102–1117, November 2000.

[322] An introduction to ABB's thoughts on HVDC is provided by R. Rudervall, J.P. Charpentier and R. Sharma, *High Voltage Direct Current (HVDC) Transmission Systems* Technology Review Paper, available from http://www.worldbank.org/.

[323] When both AC and DC cables (respectively overhead lines) can designed to yield economic minimums, the cost of DC cable (resp. line) is roughly 1/3 (resp. 2/3) of the cost of the AC cable (resp. line), according to P.F. Albrecht et al, Section 15 *Direct Current Power Transmission*, appearing in D.G. Fink and H. Wayne Beaty, Standard Handbook for Electrical Engineers, 14th edition, McGraw-Hill (London, Milan and elsewhere, 2000) ISBN#0-07-020975-8

[324] A still cited review of the method for comparing AC with DC lines is C.T. Wu (editor), *AC-DC Economics and Alternatives*, 1987 Panel Discussion Report, IEEE Trans Power Delivery, vol. PWRD-5, 1990 pages 1956-1976.

[325] "Over the years, thyristor current and voltage ratings have increased to a present rating of about 6 kV and a single thyristor current capability of about 3,000 A." P.F. Albrecht et al, Section 15 *Direct Current Power Transmission*, appearing in D.G. Fink and H. Wayne Beaty, Standard Handbook for Electrical Engineers, 14th edition, McGraw-Hill (London, Milan and elsewhere, 2000) ISBN#0-07-020975-8 page 15-66.

and 3 kA.[326]) Verification of this bears upon the economic attractiveness of "low-voltage, high current" system incorporating HTS superconductors. During the past five years, Voltage Source Converters have been suggested as a promising alternative to thyristors. Their potential impact on future HTS DC transmission is discussed in at least one paper.[327]

XI.2.3 Protecting from Faults

Utility engineers often explain some of their T&D practices by saying that they do not know how to interrupt very large currents.[328] Today's lines carry a few kA, at most. Of course, AC currents vanish twice during each cycle (i.e., every 8 or 10 millisecond). AC circuit breaker design capitalizes on this and a quarter cycle sets the time scale for the act of interruption.

The situation is different for DC transmission. The current has a large time-independent component. Current interruption becomes an immediate concern when one considers the possibility of a low-voltage, high current line or network such as might implemented using HTS conductor.[329] If the contemplated line DC line has only two terminals and would carry 6 or 9 kA, the low-voltage, high current line might be the nexus of two or three AC lines, each with its own circuit breaker (e.g., 3 kA operating current). The desire for such an arrangement depends, in part, on the existing network within which the contemplated line would be added.

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[326] P.F. Albrecht et al, Section 15 *Direct Current Power Transmission*, appearing in D.G. Fink and H. Wayne Beaty, Standard Handbook for Electrical Engineers, 14th edition, McGraw-Hill (London, Milan and elsewhere, 2000) ISBN#0-07-020975-8

[327] G. Venkataramanan and B.K. Johnson, *A superconducting DC transmission system based on VSC transmission technologies,* IEEE Trans. on Applied Superconductivity 13 (2): 1922-1925 Part 2 June 2003.

[328] This cryptic statement refers to two different currents. The first is the safe maximum steady-state current, (aka nominal rated current). That is often 3 kA. Circuit breakers introduce resistance and so electrical energy dissipates within the breaker and raises its temperature. The nominal current rating tells the engineer how much current the breaker can handle without "overheating" and compromising its long term reliability. The circuit breaker's other rating (e.g., 69 kA) describes its ability to handle fault currents for a certain brief times without being promptly and permanently damaged. From the utility's perspective, the virtue of proposed Fault Current Limiters is that they reduce the fault current and so avoid the need to replace existing breaker's (serving on systems with increasing fault currents) by ones with higher ratings and higher costs.

[329] For preliminary consideration of other aspects of the low-voltage, high-current DC transmission, see S. Schoenung and W.V. Hassenzahl, System Study of Long Distance, Low-Voltage Transmission Using High Temperature Superconducting Cable, report WO-806512 for the Electric Power Research Institute (March, 1997).

If the contemplated DC line has only two terminals ("point-to-point" transmission) and is intended to conduct today's typical current, it would be sufficient to rely on the convertor-invertor to act as a circuit breaker.

Today, there are few DC lines with more than two terminals.[330] Serious consideration of future DC networks entails a discussion of DC circuit breakers.[331]

In the superconducting cable or FCL communities, few consider the potential need to interrupt large DC currents. Here we cite a summary of power engineering practice in order to alert the HTS community (managers and technical contributors) to a topic of potential concern were utilities to consider a network of DC cable.

> **"**In case of a fault in the dc transmission network, three methods are available for clearing the fault. The methods are based on the kind of switching device used to isolate the faulted line. The most versatile and flexible method is the use of dc breakers capable of interrupting the maximum fault current that the system can produce.
>
> The breakers should be designed to react rapidly to a relay signal and interrupt the fault current in a matter of milliseconds. [*For an early discussion of fault clearing times on a HTS DC line, see Chowdhuri and Laquer*.[332]] A rapid and accurate fault-sensing or relay system is usually required as well. Fault sensing is local and structured similarly to one of the schemes presently used in ac systems.
>
> If the faulted line radially connects a converter to the remainder of the MTDC [*Multi-Terminal Direct Current*] system, its disconnection would result in isolation of the converter from the system. Consequently, coordinating current orders of the remaining converters in the MTDC system is necessary and should be done centrally, via high-speed communication, to achieve the best performance. By using the breaker

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[330] The only example of a multi-terminal DC line, known to the author, transmits power from James Bay (Canada) to Sandy Pond (New Hampshire, US).

[331] R.S. Thallum, Chapter 61.3 *HVDC Transmission*, appearing in R. Dorf, The Electrical Engineering Handbook, 2nd edition, CRC Press (Boca Raton, 1997) ISBN#0-8493-8574-1, page 1343.

[332] P. Chowdhuri and H.L. Laquer, "*Some electrical characteristics of a dc superconducting cable*", IEEE Transactions on Power Apparatus and Systems, Vol. PAS-97, No. 2, pp. 399-408, March/April 1978.

scheme, a fault in the dc transmission network may be cleared in approximately 10 ms.

Another method of clearing a fault is by using load break switches in conjunction with the converter controls. The switch is rated to interrupt direct currents as high as normal operating current—not the fault current. When a fault occurs on the dc transmission network and no other control action is implemented, the converter controls, by use of current regulators, reduce the fault current to less than normal values. The faulted line can then be isolated from the system by activating load break switches, in about 100 ms, and MTDC system operation may then be resumed. The requirements for balancing current orders in this case are similar to those for fault clearing by a dc breaker.

The third method forces all the converters to temporarily operate as inverters as soon as the fault is detected. The stored energy in the dc system is then delivered to the ac systems, resulting in deenergizing the entire MTDC system. When direct currents are driven to zero, the faulted line is disconnected by high-speed isolators. The MTDC system can then be restarted and resume operation. The requirements for current order balancing are similar to those discussed earlier. This protective measure may be implemented in 200 to 300 ms.

For MTDC systems that are energy ties, the third method of fault clearing is generally acceptable. The scheme, however, may not be desirable for an MTDC system with a relatively large number of converters and transmission lines. The scheme may even be unacceptable when the 200- to 300-ms period of MTDC shutdown may jeopardize rotor-swing stability of generators in the vicinity of the dc terminals. Disconnecting the faulted line by load break switches or dc breakers is more appropriate for these situations. Generally, the appropriate method of fault clearing is application-dependent and should be selected after sufficient system studies."[333]

DC Circuit breakers were mentioned above. Their status is summarized below.

"There are three principal problems in designing a dc circuit breaker:

[333] P.F. Albrecht et al, Section 15 *Direct Current Power Transmission*, appearing in D.G. Fink and H. Wayne Beaty, Standard Handbook for Electrical Engineers, 14th edition, McGraw-Hill (London, Milan and elsewhere, 2000) ISBN#0-07-020975-8 pages 15-41 and 15-42.

1. Forcing current zero in the interrupting element
2. Controlling the overvoltages caused by large *di/dt* in a highly inductive circuit
3. Dissipating large amounts of energy (tens of megajoules)

The second and third problems are solved by the application of zinc oxide varistors connected line to ground and across the breaking element. The first is the major problem, and several different solutions are adopted by different manufacturers. Basically, current zero is achieved by inserting a counter voltage into a circuit.

> In the circuit shown in Fig. XI.2.3. opening CD air-blast circuit breaker) causes current to be commutated to the parallel LC circuit. The commutating circuit will be oscillatory, which creates current zero in the circuit breaker. The opening of CB increases the voltage across the commutating circuit, which will be limited by the zinc oxide varistor ZnO_1 by entering into conduction. The resistance R is the closing resistor in series with switch S."[334]

[334] R.S. Thallum, Chapter 61.3 *HVDC Transmission*, appearing in R. Dorf, The Electrical Engineering Handbook, 2nd edition, CRC Press (Boca Raton, 1997) ISBN#0-8493-8574-1, page 1342-1343.

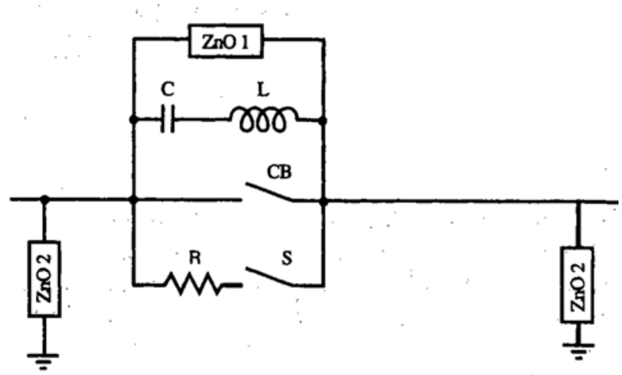

Figure XI.2.3
DC Circuit Breaker (one module)

The capacitor, C, is precharged from a dc source. When CB opens, it triggers the controlled switch (i.e., thyristor) to close. C discharges via L, setting up current oscillations and forcing the current through CB to zero, when the arc quenches.[335]

XI.2.4 Dielectric Behavior When Polarity is Suddenly Reversed

Charges accumulate within the interior of a dielectric subject to the more or less steady electric field concomitant with the more or less steady voltage difference between the conductors of a DC cable. In conventional DC cable, the polarity of the conductors can be very quickly reversed (e.g., by fault some where in the grid). By comparison, the dielectric's change is very slow. Thus, after the reversal the charges in the dielectric and conductor have opposite signs and an overstress appears near the conductor.[336] This difference in response time and consequent large electric field can stimulate the dielectric to breakdown. The behavior of candidate dielectrics for cryogenic DC cable deserves attention by those who would pursue such cable. To the author's knowledge, there are no papers in the open literature relevant to polarity reversal in cryogenic dielectrics.

XI.2.5 Technical Uncertainties

There is no reason to believe that DC HTS cable could not be built, installed underground and operated between two points under normal conditions. However, potential customers will ask about four other topics: (a) advantage over conventional DC overhead lines (b)

[335] The author is grateful to P. Chowdhuri for elucidating this point.

[336] B.M. Weedy, Underground Transmission of Electrical Power, John Wiley (Chichester, 1980)

advantage over conventional DC cable, (c) DC HTS cable behavior under fault conditions, and (d) the possibility of operating the DC HTS cable underwater.

- With regard to the power sector's past choice between DC overhead and DC underground, see the next section, Section XI.3.

- With regard to advantages over conventional DC cable, attention might be directed toward seeing if the efficiency of conversion-inversion might be improved as the result of synergy with the cryogenics required by HTS.[337] (Note that most underground DC cable is very short, 5-10 m, because its function is to connect two adjacent AC systems that may be asynchronous.)

- With regard to faults, to date, little work has been done on the behavior of cryogenic dielectrics under polarity reversal. As noted, after the polarity of the conductor changes but before the dielectric has caught up, the dielectric no longer screens; instead it "anti-screens". To avoid these unknowns, one could design a warm-dielectric cable.

- With regard to underwater operation, most DC cable were installed where more than 35 km are traversed. (As noted in Chapter X, some of today's dielectrics have lower permittivity than past dielectrics and so the charging current can be reduced and the range of AC can be increased to more than 35 km.[338]) Thus, it would be necessary to demonstrate the feasibility (e.g., reliability) and desirability of cooling HTS submarine over long distances with remotely located cooling stations.

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[337] Without commenting on the likelihood of cryogenic synergy, the following paper considered the effect on cost "If the power electronics part count can be reduced by 50% through lower voltage and possible cryocooling…". B.W. McConnell, *Applications of High Temperature Superconductors to Direct Current Electric Power Transmission and Distribution*, presented at the Applied Superconductivity Conference, October 3-8, 2004, Jacksonville, Florida.

[338] G. Balog, N. Christl, G. Evenset, F. Rudolsen, *Power Transmission Over Long Distances with Cables*, CIGRE paper B1-306

XI.3 Situations in Which the Power Sector Would Consider Conventional DC

Because the existing infrastructure was built for AC and because AC/DC convertors and DC/AC invertors are not inexpensive, electric utilities consider DC only in special circumstances. [339,340,341,342]

DC lines are used when

1. AC connection would enable fault current that would be too high (e.g., connection between Scandanavia and continental Europe).
2. AC transmission would have too much impedance (i.e. reactance).
3. AC transmission would require too much right-of-way.
4. AC transmission would have to connect networks having different or differing AC frequencies

"Too much" means that compensating for the needs of AC transmission is more expensive than building a DC system. "More expensive" may refer to comparisons of the first-cost of alternative transmission systems or to their lifetime costs--more quantitatively, the higher the assumed interest rate, the briefer the relevant duration. The choice depends on the utility and its planning horizon.

XI.4 Situations in Which the Power Sector Would Consider DC Cable

As stated above, DC transmission is used when AC transmission lines would have too much impedance.

Impedance is proportional to length. Thus when generation is far from consumption, DC is considered. For example, hydro-electric generators on the James Bay provide power via DC for New England, more than 1,600 km (1000 miles) away. The choice between

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[339] R.S. Thallum, Chapter 61.3 *HVDC Transmission*, appearing in R.C. Dorf (editor), The Electrical Engineering Handbook (2nd edition), IEEE Press & CRC Press (Boca Raton, 1997) ISBN#0-8493-8574-1

[340] P.F. Albrecht et al, Section 15 *Direct Current Power Transmission*, appearing in D.G. Fink and H. Wayne Beaty, Standard Handbook for Electrical Engineers, 14th edition, McGraw-Hill (London, Milan and elsewhere, 2000) ISBN#0-07-020975-8

[341] G.G. Karaday, Chapter 4.1 *The Concept of Energy of Energy Transmission and Distribution,* appearing in L.L. Grigsby, The Electric Power Engineering Handbook, CRC Press &IEEE Press (New York, 2001) ISBN#0-8493-8578-4

[342] J. Casazza and F. Delea, Understanding Electric Power Systems—An Overview of The Technology and the Marketplace, IEEE Press and John Wiley (New York, 2003) ISBN 0-471-44652-1.

overhead DC and DC cable is decided by the cost. Because the population density is low everywhere on the route except at the destination (e.g. downtown Boston), the price of right-of-way is low. The cost of excavating a trench in the right-of-way is almost never low.[343] Thus overland DC is almost always conveyed by overhead lines.

In general, no long distance right-of-way is densely populated enough to justify the cost of a dedicated underground cable. This has been situation for a long time. In 1980, Weedy wrote, "The only major [DC] land circuit to date is the British Kingsnorth—Willesden (London) connection using ±266 kV self-contained oil-filled cables."[344]

The conclusion might be different if the cost of the cable, in particular a cryogenic cable, and associated infrastructure were recovered by more than the sale of electricity, for example by the sale of a cryogenic fluid (e.g., LH_2, LNG) that cooled the electrical conductor.[345,346,347] However, excepting pipelines located within rocket launch sites (e.g., ARIANE), the author is not aware of any commercial pipeline that conveys liquid hydrogen. Commercial pipelines convey gaseous hydrogen.[348] It has been less expensive

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343 As mentioned earlier, there are three exceptions, two in Australia and one in Sweden. They are feasible because the cable is roughly 50mm in diameter and the soil allowed plowing a furrow and placing the cable within it at a rate of 3 km per day. Plowing would not be feasible for a larger diameter cable (e.g., 150 mm) (private communication, 18 November 2004, with A. Ericsson, ABB).

344 B.M. Weedy, Underground Transmission of Electrical Power, John Wiley (Chichester, 1980)

345 J.R. Bartlit, F.J. Edeskuty, and E.F. Hammel, *Multiple Use of Cryogenic Fluid Transmission Lines*, Proceedings of the Fourth International Cryogenic Engineering Conference, held in Eindhoven 24-26 May 1972

346 P. M. Grant, *Will MgB_2 Work*?, Industrial Physicist, October, 2001 pages 22-23, and P.M. Grant, *Energy for the City of the Future*, Industrial Physicist, February-March, 2002, pages 22-25.

347 Some see competition, not complementarity, between long distance energy transmission via chemical fuel or electricity. For example, in the late 1980s, consideration was given to the possibility of energy transmission via hydrogen pipeline and/or DC cable from Algeria to the Ruhr. See Kaske, G., P.Schmidt and K.-W.Kannengiesser, *Vergleich zwischen Hoch-spannungsgleichstromubertragung and Wasserstofftransport*, (*Comparison Between High Voltage DC Transmission and Hydrogen Transport*), VDI Energy Society Meeting (Stuttgart, Germany) 1989.

348 LH_2 is delivered in 15,000-gallon tank trucks to large customers, among which was U.S. NASA. It purchased LH_2 to fuel the U.S. Space Shuttle. Gaseous hydrogen is conveyed by pipeline. Air Liquide maintains a 240 km (150 miles) hydrogen pipeline in northwest Germany. For Air Liquide's perspective, see, Millet C., *Transportation and Storage of Liquid and Gazeous Hydrogen*, Actualite Chimique, (12): 38-42 December 2001. Air Products and Chemicals states it is the world's largest supplier of merchant hydrogen. In a posting, V. Raman (Air Products) writes that today Air Products operates at least seven H_2 pipelines. Their total length is 544 km (340 miles), and these lines connect 21 hydrogen plants, including six liquid hydrogen facilities, and 77 customers in seven countries. Praxair states it operates eleven pipeline complexes that supply customers with more than 390 million cubic feet of hydrogen each day. Praxair operates pipeline networks in the Gulf Coast area of Texas; on the southern shore of Lake Michigan (connecting Burns Harbor, Indiana with Whiting, Indiana); Ontario, California; Theodore, Alabama;

to produce the cryogenic fluid where it is needed, using fuel delivered as natural gas, CH_4, or electricity. Were circumstances to change and a long, multi-terminal DC line wanted, one should expect that suitable (i.e., economic and reliable) cryogenic DC circuit breakers would also have to be developed.

Returning to electro-technology, recall that the surge impedance, $\sqrt{L/C}$, is inversely proportional to the distance between parallel conductors. Cable has much lower impedance than overhead lines. Overhead lines are impractical where power must traverse more than one or two kilometers of water. In these cases, cable must be used. The question is whether it should be an AC cable or DC cable. The longer the AC cable, the greater its capacitance and thus its charging current. There is no universal rule for the maximum length of AC cable. That length depends on the price of the convertor-invertors required for competing DC lines. However, in the past, transmission cable lengths greater than 35 km raised the issue in planners' minds. Certainly, by 200 km, the choice would be DC cable. In 1980, Weedy wrote "nearly all major DC cable connections have been for underwater links."[349] The situation remains the same today, as shown in Tables XI.4.1, XI.4.2, and XI.4.3.[350]

Geismar, Louisiana; Ecorse, Michigan; and Edmonton, Alberta, Canada to supply hydrogen to customers in these areas. A report posted (http://www.ieagreen.org.uk/h2ch6.htm) by the IEA GreenHouse Gas group states that "The use of large-scale pipelines has been practiced for more than 50 years. Conventional mild steel pipelines in the Ruhr district of Germany have carried hydrogen between producers and consumers since 1938 without safety problems (sensors are fitted to detect possible difficulties, and there are regular safety inspections). Indeed, the main concern of the operators is subsidence caused by the network of coal mines in the area. This affects the alignment of the pipes and could cause leakage. Other countries also have extensive pipelines – there is a 170km system in Northern France and a total of some 1,500 km in Europe as a whole; North America has at least 700km. Existing hydrogen pipelines have comparable dimensions and pressures to the small-scale local pipelines now used for natural gas, being 25-30 cm in diameter and operating at pressures of 10-20 bar, though pressures of up to 100 bar have been used without difficulty.

[349] B.M. Weedy, Underground Transmission of Electrical Power, John Wily (Chichester, 1980)

[350] One submarine installation, connecting Spain and Morrocco, is said to comprise both 400 kV DC and 420 kV, oil filled AC.

Table XI.4.1 HVDC Cable Links

Year	Location	Type of Cable[b]	Voltage (kV)	Length (km)	Comments
1954	Swedish mainland to Gotland	Submarine solid type	100	100	1 pole
1961	England/France, Cross channel	Submarine solid type	100	65	2 poles
1965	New Zealand, Cook strait	Submarine high pressure gas filled	250	42	2 poles
1966	Italy to Sardinia	Submarine solid type	200	120	1 pole
1969-1971	UK (Kingsnorth-Beddington-Willesden)	Land based oil filled	266	40	2 poles
1969	Canadian mainland to Vancouver	Submarine solid type	266	27	2 poles
1970	Swedish mainland to Gotland to supplement 1954 cable	Submarine oil filled	150	96	2 poles
1973	Majorca/Menorca	Submarine oil filled	200		Initially a 3-phase 132 kV connection
1976	Canadian mainland to Vancouver	Submarine oil filled	266	27	2 poles
1977	Japan (Hokkaido-Honshu)	Submarine oil filled	250	65	2 poles
1977	Norway/Denmark (Skagerrak)	Submarine solid type	250	65	2 poles
1983	Swedish mainland to Gotland to supplement 1970 cables	Submarine solid type	150	100	1 pole
1984-1986	England/France, Cross channel	Submarine solid type	270	32	2 poles
1986	Italy to Corsica		200	415	1 pole
1987	Swedish mainland to Gotland to supplement 1983 cable	Submarine solid type	150	103	2 poles
1988	Sweden/Denmark Konti-Skan	Submarine, solid type	285	150	1 pole
1989	Sweden/finland Fenno-Skan		400	200	1 pole
1991	New Zealand, Cook Strait to supplement 1965 cable	Submarine solid type	350	42	
1992	Canada St. Lawrence River Crossing, Hydro Quebec	Oil filled. Installed in a tunnel	500	4	2 poles
1993	Skagerrak	Submarine, solid type	350	121	1 pole

[a] There is insufficient information available on several projects, for example, installations in the former USSR, the Baltic Cable project, the Scotland/Ireland cable project, the Greece/Italy cable project, and the Iceland/Scotland cable project.
[b] All the cables installed, so far, use impregnated-paper insulation.

Table XI.4.2 HVDC Lines and Cables

	HVDC Supplier†	Year Commissioned	Power Rating, MW	DC volts, kV	Line/ Cable, km	Location
		Mercury Arc Valves				
Moscow-Kashira[a]	F	1951	30	±100	100	Russia
Gotland I[a]	A	1954	20	±100	96	Sweden
English Channel	A	1961	160	±100	64	England-France
Volgograd-Donbass[b]	F	1965	720	±400	470	Russia
Inter-Island	A	1965	600	±250	609	New Zealand
Konti-Skan I	A	1965	250	250	180	Denmark-Sweden
Sakuma	A	1965	300	2125	B-B[f]	Japan
Sardinia	I	1967	200	200	413	Italy
Vancouver I	A	1968	312	260	69	Canada
Pacific Intertie	JV	1970	1440	±400	1362	USA
		1982	1600			
Nelson River I[c]	I	1972	1620	±450	892	Canada
Kingsnorth	I	1975	640	±266	82	England
		Thyristor Valves				
Gotland Extension	A	1970	30	±150	96	Sweden
Eel River	C	1972	320	2 × 80	B-B	Canada
Skagerrak I	A	1976	250	250	240	Norway-Denmark
Skagerrak II	A	1977	500	±250	240	Norway-Denmark
Skagerrak III	A	1993	440	±350	240	Norway-Denmark
Vancouver II	C	1977	370	-280	77	Canada
Shin-Shinano	D	1977	300	2 × 125	B-B	Japan
		1992	600	3 × 125		
Square Butte	C	1977	500	±250	749	USA
David A. Hamil	C	1977	100	50	B-B	USA
Cagira Bassa	J	1978	1920	±553	1360	Mozambique-S. Africa
Nelson River II	J	1978	900	±250	930	Canada
C-U	A	1979	1000	±400	710	USA
Hokkaido-Honshu	E	1979	150	125	168	Japan
		1993	600	±250		
Acaray	G	1981	50	25.6	B-B	Paraguay
Vyborg	F	1981	355	1 × 170 (±85)	B-B	Russia (tie with Finland)

TableXI.4.2 HVDC Lines and Cables (continued)

Duernrohr	J	1983	550	145	B-B	Austria

Gotland II	A	1983	130	150	100	Sweden
Gotland III	A	1987	260	±150	103	Sweden
Eddy County	C	1983	200	82	B-B	USA
Chateauguay	J	1984	1000	2 × 140	B-B	Canada
Oklaunion	C	1984	200	82	B-B	USA
Itaipu	A	1984	1575	±300	785	Brazil
	A	1985	2583			
	A	1986	3150	±600		
	A	1987	6300	2 × ±600		
Inga-Shaba	A	1982560	±500	1700	Zaire	
Pac Intertie Upgrade	A	1984	2000	±500	1362	USA
Blackwater	B	1985	200	57	B-B	USA
Highgate	A	1985	200	±56	B-B	USA
Madawaska	C	1985	350	140	B-B	Canada
Miles city	C	1985	200	±82	B-B	USA
Broken Hill	A	1986	40	2 × 17(±8.3 3)	B-B	Australia
Intermountain CrossChannel	A	1986	1920	±500	784	USA
Les Mandarins	H	1986	2000	±270	72	France
Sellindge	I	1986	2000	±270	72	England
Descantons-Comerford	C	1986	690	±450	172	Canada-USA
SACOI[d]	H	1986	200	200	415	Corsica Island
SACOI[e]		1992	300			Italy
Urguaiana Feq. Conv.	D	1987	53.7	17.9	B-B	Brazil(tie with Uruguay)
Virginia Smith (Sidney)	G	1988	200	55.5	B-B	USA
Gerhouba-Shanghai	B+G	1989	600	500	1000	China
		1990	1200	±500		
Konti-Skan II	A	1988	300	285	150	Swed-Den.
Vindhyachal	A	1989	500	2 × 69.7	B-B	India
Pac Intertie Expansion	B	1989	1100	±500	1362	USA
McNeill	I	1989	150	42	B-B	Canada
Fenno-Skan	A	1989	500	400	200	Finland-Sweden
Sileru-Barsoor	K	1989	100	+100	196	India
			200	+200		
			400	±200		
Rihand-Delhi	A	1991	750	+500	910	India
		1991	1500	±500		
Hydro Quebec-New EnXI.	A	1990	2000[g]	±450	1500	Canada-USA
Welch-Monticello		1995	300		B-B	USA
		1998	600			
Etzenricht		1993	600	160	B-B	Germany (tie with Czech)
Vienna south-East	G	1993	600	160	B-B	Austria

						(tie with Hungary)
DC Hybrid Link	AB	1993	992	+270/-350	617	New Zealand
Chandrapur-Padghe		1997	1500	±500	900	India
Chandrapur-Ramagundam		1996	1000	2 × 205	B-B	India
Leyte-Luzun		1997	1000	350	440	Phillippines
Haenam-Cheju I		1997	300	±180	100	South Korea
Baltic Cable Project		1994	600	450	250	Sweden-Germany
Victoria-Tasmania		1995	300	300		Australia
Kontek HVDC Intercon		1995	600	600		Denmark
Scotland-N. Ireland		1998	250	250	2x63	United Kingdom
Greece-Italy		1998	500			Italy
Tiang-Guang		1998	1800	500	903	China
Visakhapatnam	I	1998	500	205	B-B	India
Thailand-Malaysia		1998	300	300	110	Malaysia-Thailand
Rivera		1998	70		B-B	Urguay

†A-ASEA;
B-Brown Boveri;
C-General Electric;
D-Toshiba;
E-Hitachi;
F-Russian;
G-Siemens;
H-CGEE Alsthom;
I-GEC (formerly EnXI. Elec.);
J-HVDC W,XI. (AEG, BBC, Siemens);
K-(Independent);
AB-ABB Brown Boveri;
JV-Joint Venture (GE and ASEA
[a]Retired from service.
[b] 2 valve groups replaced with thyristors in 1977.
[c] 2 valve groups in Pole 1 replaced with thyristors by GEC in 1991.
[d] 50-MW thyristor tap.
[e]Uprate with thyristor valves.
[f] Back-to-back HVDC system.
[g] Multiterminal system. Largest terminal is rated 2250 MW.
Source: Data compiled by D.J. Melvold, Los Angeles Department of Water and Power.

Table XI.4.3 HVDC Projects Listing

	Year Commissioned	Power Rating, MW	DC Voltage kV	Line and/or Cable, km	Location
Mercury-arc valves					
Moscow-Kashira	1951	30	±100	100	Russia
Gotland I	1954	20	±100	96	Sweden
English Channel	1961	160	±100	64	England-France
Volgograd-Donbass	1965	720	±400	470	Russia
Inter-Island	1965	600	±250	609	New Zealand
Konti-Skan I	1965	250	250	180	Denmark-Sweden
Sakuma	1965	300	2 × 125	B-B*	Japan
Sardina	1967	200	200	413	Italy
Vancouver I	1968	312	260	69	Canada
Pacific Intertie	1970	1440	±400	1362	USA
	1982	1600			
Nelson River I	1972	1620	±450	892	Canada
Kingsnorth	1975	640	±266	82	England
Thyristor valves					
Gotland Extension	1970	30	±150	96	Sweden
Eel River	1972	320	2 × 80	B-B	Canada
McNeill	1989	150	42	B-B	Canada
Fenno-Skan	1989	500	500	200	Finland-Sweden
Sileru-Barsoor	1989	100	±200	196	India
	Future	400			
Rihand-Delhi	1991	750	±500	910	India
	1991	1500	±500		
Hydro Quebec-New. EnXI.	1990	2000	±450	1500	Canada-USA
Nicolet Tap	1992	2000			Canada
Welsh-Monticello	1995	600	160	B-B	USA
Etzenricht	1993	600	160	B-B	Germany(tie w/Czech)
Vienna South-East	1993	600	160	B-B	Austria(tie w/Hungary)
DC Hybrid Link	1993	992	+270/-350	617	New Zealand
Urguaiana	1994	50	15	B-B	Brazil-Argentina
Baltic Cable Project	1994	600	450	250	Sweden-Germany
Kontek-HVDC Intercon	1995	600	400	170	Denmark-Germany

Table XI.4.3 HVDC Projects Listing (continued)

Chandrapur-Padgh					India
Chandrapur-Ramagundum					India
Visakhapatnam	1998†	500	205	B-B	India

Table XI.4.3 HVDC Projects Listing (continued)

Leyte-Luzon	1997†	440	350	440	Philippines
Haenam-Cheju	1997†	300	±180	100	South Korea
Victoria-Tasmania		300	300		Australia
Higashi-Shimizu	1998†	300	125	B-B	Japan
KII Channel HVDC Link	2000†	1400	±250	102	Japan
		2800	±500		
Scotland-N. Ireland	2000†	250	150	60	United Kingdom
Greece-Italy	2000†	500			Italy
Tiang-Guang	2000†	1800	500	903	China
Thailand-Malaysia	2000†	300	300	110	Malaysia-Thailand
Rivera	1999†	70	—	B-B	Uruguay
Swepol	1999†	600	450	230	Sweden-Poland
Iceland-Scotland Link	2005†	550	400	950	
		1100	±450		
Leyte-Mindanao	2000†	400	—	—	Philippines
Sassram	2000†	500		B-B	India
IB Valley-Jaipur	2000†	2500			China
NorNed	2001†	600	500	600	Norway-Netherlands
Three Gorges I	2002†	3000	—	—	China
Three Gorges II	2005†	3000			China
Bakun	2003†	2130	3 × ±500	1335	Sarawak-Malaysia
Viking Cable	2003†	600	450	600	Norway-Germany
Eurocable	2002†	600	500	600	Norway-Germany
East-West Energy Bridge	2005†	500	600	1800	Germany-Poland-Russia
	2010†	1000			
Skagerrak I	1976	250	250	240	Norway-Denmark
Skagerrak II	1977	500	±250		
Skagerrak III	1993	440	350	240	Norway-Denmark
Vancouver II	1977	370	-280	77	Canada
Shin-Shinano	1977	300	2 × 125	B-B	Japan
	1993	600	3 × 125		
Square Butte	1977	500	±250	749	USA
David A. Hamil	1977	100	50	B-B	USA
Cahora Bassa	1978	1920	±533	1414	Mozmbique-So. Africa
Nelson River II	1978	900	±250	930	Canada
	1985	1800	±500		
CU	1979	1000	±400	710	USA
Hokkaido-Honshu	1979	150	125	168	Japan
	1980	300	250		
	1993	600	±250		
Arcaray	1981	55	25.6	B-B	Paraguay
Vyborg	1981	355	1 × 170(±85)	B-B	Russia(tie w/Finland)
	1984	1065	3 × 170		
	Future	1420	4 × 170		

Zhou Shan Project	1982	50	100	42	China
Duernrohr	1983	550	145	B-B	Austria
Gotland II	1983	130	150	100	Sweden
Gotland III	1987	260	±2150	103	Sweden
Eddy County	1983	200	82	B-B	USA
Chateauguay	1984	1000	2 × 140	B-B	Canada
Oklaunion	1984	200	82	B-B	USA
Itaipu I	1984	1575	±300	785	Brazil
	1985	2383			
	1986	3150	±600		
Inga-Shaba	1982	560	±500	1700	Zaire
Pac Intertie Upgrade	1984	2000	±500	1362	USA
Blackwater	1985	200	57	B-B	USA
Highgate	1985	200	±56	B-B	USA
Madawaska	Q1985	350	140	B-B	Canada
Miles City	1985	200	±82	B-B	USA
Broken Hill	1986	40	2 × 17(±8.33)	B-B	Australia
Intermountain	1986	1920	±500	784	USA
Cross-Channel	1986	2000	2 × ±270	72	
(Les Mandarins)					France-England
Des Cantons-Cmerford	1986	690	±450	172	Canada-USA
Sacoi	1986	200	200	415	Corsica Island
	1992	300			Italy
Itaipu II	1987	3150	±600	805	Brazil
Sidney (Vrginia Smith)	1988	200	55.5	B-B	USA
Gezhouba-Shanghai	1989	600	500	1000	China
	1990	1200	±500		
Konti-Skan II	1988	300	285	150	Sweden-Denmark
Vindhyachal	1989	500	2 × 69.7	B-B	India
Pac Intertie Expansion	1989	1100	±500	1362	USA

*Back-to-back HVDC system.
†Estimated.
Source: DC and Flexible AC Subcommittee of the IEEE Transmission and Distribution Committee and CIGRE Committee No. 14 on DC links and Power Electronic Equipment.

Table XI.4.4 Recent HVDC Light* Projects by ABB

Project	Customer	Country	Year	Quantity (m)	Voltage (kV)	Conductor (mm^2)
Troll A	Statoil	Norway	2004	284,000	60	300
Troll A	Statoil	Norway	2004	510	60	630
Cross Sound	Transenergie US	U.S.	2002	83,240	150	1300
Murraylink	Transenergie US	Australia	2002	223,200	150	1200
Murraylink	Transenergie US	Australia	2002	136,800	150	1400
GotLight	GEAB	Sweden	2002	410	150	630
Murraylink	Transenergie US	Australia	2002	1,450	150	630
Cross Sound	Transenergie US	U.S.	2002	1,500	150	630
Tjaereborg	ELTRA	Denmark	1999	9,000	10	240
DirectLink	Transenergie US	Australia	1999	390,000	84	630
GotLight	Gotland Energy	Sweden	1998	140,000	80	340

- The ABB cables cited above use ABB's proprietary version of XLPE.

Table XI.4.5 Older HVDC Projects by ABB

Project	Customer	Country	Year	Quantity (m)	Voltage (kV)	Conductor (mm^2)
MIND: Mass-Impregnated Non-Draining HVDC cables						
SwePol Link	SwePol Link AB	Sweden-Poland	1998	259,500	450	2100
Baltic Cable	Baltic Cable AB	Sweden-Germany	1994	243,000	450	1600
Cook Strait	Trans Power	New Zealand	1991	80,600	350	1400
Konti-Skan 1:91	Vattenfall	Sweden-Denmark	1991	64,000	285	1200
Fenno-Skan	Vattenfall – IVO	Sweden-Finland	1989	100,000	400	1200
Konti-Skan II	Vattenfall	Sweden-Denmark	1988	66,000	285	1200
Gotland III	Vattenfall	Sweden	1987	97,000	150	800
Gotland II	Vattenfall	Sweden	1983	95,000	150	800
Konti-Skan 1:74	Vattenfall	Sweden-Denmark	1974	32,000	285	630
Konti-Skan 1:64	Vattenfall	Sweden-Denmark	1964	64,000	285	630
Gotland I	Vattenfall	Sweden	1953	100,000	150	90

Total: 1,201,100 m delivered HVDC cable

XI.5 DC Cable Incorporating Metal Conductor vs. DC Cable Incorporating HTS

When comparing DC conveyed by aluminum or copper with DC conveyed by ceramic superconductors, an unusual possibility deserves attention.

The cable's convertor-invertor might be more efficient at sub-ambient temperatures than at ambient. In no more time than it takes to raise an eye-brow, the added cost of cooling would be normally dismissed as too high. However, if the infrastructure for refrigerating the cable is to be built anyway, the marginal cost of additional capacity to cool the invertor-convertors is not obvious and may deserve consideration. The economic comparison would be between the added capital and operating cost of incremental cooling and decreased operating cost, if any, concomitant with more efficient operation, if any, of the convertor-invertors.

The usual considerations also apply.

• Less electrical energy will be dissipated in the HTS than in aluminum or copper. The HTS must be cooled and so the needed refrigeration will consume shaft power (e.g., electrical energy). Thus, energy efficiency depends on the heat invasion through the terminations, through the cryostat, and the efficiency of the cryocooler.

• Energy efficiency in a DC HTS cable also depends on the hysteresis caused by the harmonics in the DC. At this time, the goal for AC losses in AC HTS cable is roughly 1 watt per meter. Therefore, rectified AC (also called half-wave DC) might be expected to have losses of somewhat less than 0.5 watt per meter. In fact, an early discussion of ripple losses concluded they would be very small.[351] On the other hand, aluminum or copper will have no hysteresis losses. Of course, if the generator consists of fuel cells, the harmonics might be negligible and so energy efficiency comparisons revolve around cryogenics.

• The HTS DC cable will weigh much less than the conventional DC cable.

However, what many in the HTS community do not consider is that the market for underground DC cable, of any kind is negligible. Most DC cable is used underwater. This location and length present many engineering challenges. They include the need for

[351] P. Chowdhuri and H.L. Laquer, "*Some electrical characteristics of a dc superconducting cable*", IEEE Transactions on Power Apparatus and Systems, Vol. PAS-97, No. 2, pp. 399-408, March/April 1978.

remote, underwater cooling stations and a cryogenic system that can serve a cable having varying depth, including great depth. Even the entrance to a bay can be deep; the depth of the Golden Gate is 130 m.

The HTS cable will almost certainly have a smaller cross-section than the competing metallic cable, particularly if the cable has lower voltage which requires less dielectric. It is here that capital costs for installation might be reduced. These costs are much larger than the cost of conventional cable itself. Indeed, the cost of submarine cable is dominated by the cost of burying the cable under the ground under the water. There is no shortage of space. However, if HTS cable were to require fewer trenches than conventional cable, a cost saving would result.

XI.6 Low Voltage DC Networks

Some have suggested that HTS might make feasible low voltage DC networks, and perhaps, desirable.[352,353] Proponents suggest that operating cost might be reduced. However, operating cost is not the only cost. Additional comparisons should be made before any action is taken. For example, a low-voltage DC system should be compared with a low-voltage AC system, each using superconductors, and the favored alternative should be compared with conventional technology. In particular, the capital cost and efficiency of today's transformer (located near the generator) should be compared with the cost and efficiency of conversion-inversion, as well as the availability of DC-DC voltage changing equipment. One might also consider today's PowerFormer (a generator with 69 kV across its output terminals)[354] instead of the usual separate generator and step-up transformer.

As stated the conversion cost in the recent past was at least 65$/kW per terminal. Improvement would be needed because today's step up transformers cost approximately 10 $/kW. It would also be necessary for convertors to be as efficient as transformers. Indeed, more efficiency would be required because the HTS system requires refrigeration.

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[352] B.K. Johnson, R.H. Lasseter, F.L. Alvarado, D.M. Divan, H. Singh, M.C. Chandorker and R. Adapa, *Superconducting Low Voltage DC Transmission Networks*, Electric Machines and Power Systems, vol. 22 (1994) pages 629-645.

[353] B. K. Johnson, R. H. Lasseter, F. L. Alvarado, D. M. Divan, H. Singh, M. C. Chandorkar, and R. Adapa, *High-temperature superconducting dc networks*, *IEEE Trans on Applied Superconductivity*, vol. 4, no. 3, pp. 115–120, September 1994.

[354] See *Powerformer a radically new rotating machine*. ABB Review (Feb., 1998) and more recent papers by M. Leijon.

A DC network would also require development of economic DC circuit breakers because the convertor-invertors are only located at the system boundary while there would be a need to interrupt and control current within the DC system.[355]

One group has considered low voltage, DC distribution cable. The group reports that in Japan, buildings have many "DC loads, such as Information Technology apparatuses. Those loads require high-reliable power supply system. In the meantime, most of dispersed power sources and batteries output DC and are connected to conventional power system through DC/AC inverters. Therefore, if those power sources directly link to DC loads using superconducting DC cables, total loss reduction could be realized. In this paper, we investigated feasibility of DC superconducting power feed system. We also designed and fabricated a coaxial DC superconducting power cable and a termination, successfully transmitted DC power to loads."[356]

[355] B. K. Johnson and H. L. Hess, *Active damping for electromagnetic transients in superconducting systems*, IEEE Trans on Applied Superconductivity, vol. 9, no. 2, pp. 318–321, June 1999.

[356] M. Furuse, I. Ishii, S. Fuchino, N. Higuchi, *Development of Superconducting Power Cable for Low voltage DC Distribution System*, presented at the Applied Superconductivity Conference, October 3-8, 2004, Jacksonville, Florida

XI.7 Prototype DC Cable Incorporating HTS

XI.7.1 BICC's Cable

During the first half of 1990s, a prototype HTS DC cable was built and tested by a team from BICC, Ceat Cavi Industrie, and Ansaldo Recerche.[357] The cable was designed to carry 10 kA at 40 kV, while operating at 40 K. Qualification testing was carried out from 4.2 K up to 40 K. When operated at 31 K the prototype cable had a current capacity of 11 kA, ten times more than the current conventional copper cable having a 1000 mm^2 cross-section.

This team built its prototype with the following length, cooling requirements, and cooling scheme in mind.

> "The cable design is based on a proposed force-cryocooled 100 km long, 10 000 A, 40 kV transmission line. The cooling would be maintained by two cryo-cooler plants, a pumping system at one end of the cable and a refrigerator at the other end. To maintain the cable temperature at 40 K it is calculated that the cooling system will need to initially pump owing helium at 0.2 kg s• 1 pressurized to 2 MPa at 15 K, with a resultant temperature rise along the cable to 65 K at the collection end. The total cooling losses are calculated to be close to 150 kW. Evaporation towers would be needed at each cooling plant to release heat generated by the compressors and turbines."

The dielectric consisted of "a carbon black semiconducting screen and a 4mm layer of oil-impregnated paper serving as the dielectric followed by a few more semiconducting screen layers." No report was published of tests of the dielectric's performance under fault conditions or under polarity reversal.

The cable was 1.4m long and the project ended before the anticipated second stage in which terminations were planned.

XI.7.2 Chinese Academy of Sciences

A Chinese group described its work on a prototype dc cable having a length of 6 m. The group reports:

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[357] T.P. Beales, C M Friend, W Segir, E Ferrero, F Vivaldi and L Ottonello, *A dc transmission cable prototype using high-temperature superconductors*, Supercond. Sci. Technol. 9 (1996) pages 43–47.

"A 1500 A/6 m HTS dc transmission power cable has been developed and tested at the Institute of Electrical Engineering, Chinese Academy of Sciences. The conductor of the HTS cable consists of 4 layers of Bi-2223/Ag tapes helically wound on a flexible stainless steel former. The Bi-2223/Ag tapes have been developed by the Northwest Institute for Nonferrous Metal Research and the Beijing General Research Institute for Nonferrous Metals. The cable core has a 45.3 mm outer diameter and 6 m length and is housed in a cryogenic envelope. The E-1 characteristic and the total joint resistance of the cable have been measured at 77K. The critical current of the cable is 1473 A and the total joint resistance is 0.1 Ω at 77 K. The main properties of the Bi-2223/Ag tape and the development and test results of the HTS cable are presented in this paper. The selection on the electrical insulation material for our HTS cable is easy for lack of the dielectric losses in dc cable. We used Kapton tape as the electrical insulation of the HTS cable. The insulation thickness *d* can be obtained from the following equation:

$$\frac{V_h}{E_{\max}} = r_{inner} \ln\left[1 + d/r_{inner}\right]$$

where V_h is the breakdown voltage of the cable, E_{max} is the designed electrical stress in the electrical insulation and r_{inner} is the inner radius of the insulation.

The breakdown voltage was taken V_h = 2.5 kV for the dc rated voltage of 1kV. Taking E_{max} = 15kV/mm and r_i = 22.35 mm, from above, we found d = 0.17 mm. Finally, Kapton tape thickness was set to 0.3 mm."

XI.7.3 Tennessee Technological University's Feasibility Study

TTU's recently completed a feasibility study of DC HTS cable.[358] The study is emphasized the following topics:

- Preliminary cable design for monopolar/bipolar operation
- Compatible converters at the cable terminals
- Analysis of:

[358] P. Chowdhuri and C. Pallern, *Feasibility of Electric Power Transport DC Superconducting Cables in Tennessee*, submitted to State of Tennessee, Department of Economic and Community Development, Energy Division, Nashville, TN 37243-0405, (October, 2004).

(a) short-circuit current
(b) harmonic losses
(c) transient overvoltages
(d) reactive power compensation

Future course of action:

For the sake of definiteness, one distribution site and one transmission site in Tennessee was considered. The specifications follow:

Table XI.7.3 Candidate Sites for TTU's Assessment

Site	Line Length, km	Rated Power, GW	DC Voltage, Current & Design
TVA	100	3.0	200 kV, 15 kA, monopole
	100	3.0	300 kV, 10 kA, monopole
NES	0.61	0.5	50 kV, 10 kA, monopole
	0.61	0.5	100 kV, 5 kA, monopole

XI.8 Technical Challenges to HTS DC Cable

XI.8.1 Cryogenic Dielectric

The first technical challenge is to offer a cryogenic dielectric that would be acceptable to potential customers.

Today's dielectric incorporates paper and oil. It is not obvious that anyone would use this at temperatures where the oil is solid. Synthetic polymers have not used for ambient temperature, high-voltage DC cables until very recently. In fact, as of the year 2000, there were no industry standards for synthetic polymer dielectrics for DC.[359] This absence is concomitant with the propensity of synthetic polymers to breakdown when the polarity of high voltage cable is reversed. ABB has advanced the use of synthetic polymer dielectrics for cable (ABB's HVDC Light) in the 60-150 kV range.[360] For a

[359] R. Bartnikas and K.D.Srivastava, Power and Communication Cables, IEEE Press and McGraw-Hill (New York, 2000) ISBN#0-7803-1196-5.

[360] ABB has conducted four tests of these cables that included polarity reversals (private communication with A. Ericsson (ABB) October, 2004.

cryogenic dielectric, one might try to use a noble gas (e.g., neon) for safety or one might try hydrogen, as was considered by BICC. But these issues have not been addressed since BICC's project ended.

Another technical question is whether paper impregnated with LN_2 would be satisfactory. To the author's knowledge this has not been investigated.

Fortunately, an HTS DC cable could guide power with the help of high currents and low-voltage. Thus, a technical issue that warrants investigation is whether an acceptable synthetic polymer and voltage difference can be found. Recall that the more current, the more HTS conductor and the higher the cable's capital cost. To the author's knowledge no such study has been performed.

The need for a cryogenic dielectric could avoided by using a warm dielectric design. However, this design brings a different change, raising the coolant to operating voltage without precipitating dielectric breakdown when the coolant passes from the refrigerator or heat exchanger (presumably at ground potential) to the high voltage interior of the cable.

XI.8.2 Very High Current Circuit Breakers

The use of large currents and low-voltage difference, rather than high-voltage difference and standard currents (i.e., more than a few kA) raises the second general challenge, satisfactory circuit breakers.

AC circuit breakers depend on the fact that the instantaneous current is zero every half cycle (10 milliseconds). The same is true of half wave, rectified AC. However, power engineers convert the AC to DC without the lowest frequencies and the currents are steadier.

Unfortunately, steady currents of more than a few kA are difficult to interrupt. Some suggest that the invertor-convertor can help. According to Albrecht et al, "In DC systems, fault currents can reach high values compared with the steady-state rating of different parts of the DC circuit. Automatic constant current control should bring this fault current within the limits of the converter steady-state current ratings in a short-time, depending on the characteristics of the faulted DC circuit. "[361]

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[361] P.F. Albrecht et al, Section 15.7.6 *Direct Current Power Transmission,* appearing in D.G. Fink and H. Wayne Beaty, Standard Handbook for Electrical Engineers, 14th edition, McGraw-Hill (London, Milan and elsewhere, 2000) ISBN#0-07-020975-8

Usually, an expensive capacitor bank is used to inject an opposing current and reduce the net flow to something that can be interrupted. To replace a 100kV cable carrying 1 kA with 10 kV cable carrying 10 kA, one may have to develop an affordable 10 kA circuit breaker.

The above issues are important wherever the cable might be located. However, as already stated, the biggest market for DC cable is underwater and the length of an individual cable is likely to exceed 35 km. In fact, most DC submarine cable is longer.

XI.8.3 Submarine Refrigeration

Challenges arises from the need to keep the cable at operating temperature throughout its length (e.g., greater than 35 km). One must consider the feasibility of intermediate, underwater cooling stations.

These could be spaced further apart than would now be necessary if the heat leak through cryostat were diminished. However this would not eliminate the whole issue because LN_2 is viscous and so shaft-power is dissipated during the flow of LN_2, raising its temperature. HTS submarine cable near the coasts of North America (e.g., Florida-Bermuda or Florida-Cuba), or traversing all or part of the Mediterranean, Baltic, Irish Seas or the Sea of Japan, would require underwater, remotely- operated cooling stations.

Such cooling stations would have to include cryocoolers that required very infrequent routine maintenance. (Perhaps future pulse tube cryocoolers would be an important step toward such refrigerators. See Chapter IV.) They would also have to be very reliable, despite their salt water and ocean bottom environment. To the writer's knowledge, no attention has been given to these issues.

XI.8.4 Submarine Jointing

Techniques have been developed for joining or splicing conventional cable underwater. The ability to do the like for HTS cable, taking account of cryogenics would have to be developed.

XI.8.5 Changes in Elevation

The elevation of submarine routes varies. Some routes, taken by today's submarine fiber optic cable, descend several hundred meters. Changes in LN_2 pressure and mechanical support for conductor assembly would require attention.

XII. SITUATIONS IN WHICH HTS CABLE WOULD HAVE ABOVE AVERAGE VALUE

Important progress has been made toward demonstrating the technical feasibility of cable incorporating ceramic superconductors. Their characteristics suggest the possibility of hitherto unavailable cable performance. Here we recall those characteristics and their bearing upon future benefits. Some situations in which the private sector may judge the benefits to be lucrative are indicated. In the next chapter, we identify some cities in which to look for these situations. By identifying specific places, this report illustrates and indicates areas that deserve further consideration. These two Chapters do not define or exhaust all promising areas. Local circumstances will dominate and local knowledge will be required to identify specific opportunities for HTS cable.

XII.1 Engineering Characteristics and the Benefits They Suggest

XII.1.1 Tiny Dissipation of Electrical Energy per Unit Volume

Superconductors can convey the same direct current with much, much less dissipation of electrical energy per unit volume of conductor than can copper or aluminum. Alternating current entails somewhat more dissipation than direct current, but still much less than copper or aluminum. (As discussed in earlier chapters, several loss mechanisms [i.e., current dependent losses, voltage dependent losses, losses from removing heat that was arrived from the ambient environment] bear on cable performance) This fact raises the possibility of two different future benefits.

One is that the total energy consumed by the operation of HTS cable would be less than the total energy consumed by aluminum or copper cable. This possibility awaits future advances in cryostats and cryo-coolers.

The other possibility is that HTS cable could have a smaller diameter than conventional cable. That possibility arises from both the small dissipation within the cable and the fact that the cable is force-cooled. (If the cable is designed with coaxial conductors, then currents are not induced in the cable's armor or nearby conductors and so one avoids dissipation in these places, too

XII.1.2 Total Energy Efficiency per Power Guided per Unit Length

If realized, the greater overall energy efficiency of superconducting cable would reduce the amount of fuel used. This would reduce the annual fuel cost as well as the environmental impact resulting from fuel extraction, processing and consumption.

As discussed in Chapter V, the total annual energy consumed to operate a cable depends on both the electrical energy dissipated and the amount of energy required by the cable's refrigeration. That refrigeration must remove heat from the volume at operating temperature (envisioned to be in the range 63-83 K). The heat results from both the dissipation of electrical energy and the heat flux from the environment (e.g., 298 K). And so, the engineering performance of two "non-superconducting" components affects total energy efficiency. These two are: a) the effectiveness of thermal insulation in reducing heat flux from the environment and b) the efficiency of the refrigeration.

The overall energy efficiency of the cable also depends on how much of the cable's capacity is used during the year. Conventional cable dissipates little electrical energy when little current alternates within it and thus when little power is guided by it.[362] A cryogenic cable—superconducting or not—must have its refrigeration working all the time, whether or not the cable is guiding power toward the end-user. In short, the total energy efficiency of an HTS cable (or any other cryogenic cable) will depend very much on the specific circumstances (e.g., "capacity factor," also called "load factor") under which the cable is operated. The most favorable situations are those in which the cable always guides its maximum rated power—that is, the cable is "base-loaded."

The efficiency with which the cable is connected to the rest of the grid is also relevant. When a DC cable is compared with an AC cable, the efficiency with which AC can be "inverted" to DC and then "converted" back to AC will merit attention, as will the capital cost of the inverter-converter stations. Similarly, the efficiency increase or decrease due

[362] Losses in conventional cable arises from resistance in the conductor, eddy currents in the shielding and polarization losses in the dielectric. In most cases, losses in conventional cable only become significant at the time of the peak load, thus the Loss Load Factor, discussed in Chapter IX.5. However, the dielectric loss [dependent on voltage] is not negligible in very high voltage cable. A 760 MW, 345 kV cable insulated with Kraft paper might dissipate 29 W/m in its dielectric at operating temperature while a PPLP cable might dissipate 11.9 W/m according to J. Grzan, E.I. Hahn, R.V. Casalaire, and J.O.C. Kansog, "*The 345 kV Underground/Underwater Long Island Sound Cable Project*", IEEE 92SM 368-1 PWRD, presented at IEEE PES 1992 Summer Meeting, Seattle Washington 12-16 July 1992. To compare dissipation in conventional cable with the energy requirements of cryogenic cable one must consider its heat leak and its refrigerator's inefficiency, as well as its dissipation in the conductor and shield.

to a change in the system's transformers concomitant with a new AC cable should be considered.

XII.1.3 Small Diameter Cable

An HTS cable could guide more power through the same cross-sectional area than a conventional cable for two different reasons.

First, much more current can flow through a given cross-section of superconductor than through copper or aluminum without overheating the material. Describing the same capability in another way, HTS enables much, much less conductor cross-section than does copper or aluminum. Thus, the diameter of the cable could be smaller for the same maximum power guided by the cable.

Second, space must be left between conventional cables. This space allows the heat generated within the cables to flow into the surrounding earth at a rate sufficient to prevent over-heating. HTS cables do not need this space because their cooling system is already inside the cable.[363,364]

Both the small cross-section of conductor and the absence of need for surrounding space with good heat conductivity enable the HTS cable to guide unprecedented power through small underground cross-sectional areas. Experience with prototype HTS cables suggests at least three times more power can be guided. This engineering characteristic raises the promise of greatly reduced construction costs associated with increasing the power

[363] In principle, copper or aluminum cables could be built with forced cooling by water. See C.C. Barnes, Power Cables: Their Design and Installation, Chapman & Hall (London, 1966) for an early discussion. According to M. Daumling (NKT), one such cable was installed to serve Berlin. However, after installing it, the utility is said to have never operated the cable with forced cooling. The reason is not known. No other forced, water-cooled cable is known to the author. Forced cooling with oil is practiced, as noted in Sections III.12 and IV.9. The design literature for forced cooled transmission cable (e.g., 345 kV) is summarized in E.C. Bascom and J.A. Williams, *Underground Power Transmission* appearing in D.G. Fink and H.W. Beatty, Standard Handbook for Electrical Engineers, 14th edition, McGraw-Hill (London, Milan and elsewhere, 2000) ISBN#0-07-020975-8. The use of forced cooling in oil filled pipe type cable is introduced in a footnote to Section IV.9.

[364] In recent years, concern about electromagnetic interfence between power cable and communications cable has increased. That interference could be reduced by either separating the cables or by using a power cable of coaxial design, such as under development by some HTS groups trying to demonstrate "cold dielectric" cables.

supplied to a congested area (e.g., a city center). Trenches as narrow as 15-20 cm can be envisioned, as illustrated in Figure XII.2.3.1. Existing ducts, including decommissioned gas-lines or conduits for previously oil-filled lines, could be retrofitted.

As well known to city dwellers, the costs of constructing new infrastructure for underground cable are non-monetary (e.g., disruption of people's lives and lost time), as well as monetary (e.g., cost of trenching, loss of business in the area). Neither is negligible, as suggested by Figure XII.1.3 which shows two conventional cables in a newly opened trench in New York City.

Figure XII.1.3.1
Trench Having Two Conventional Cables
West 30th Street near Fifth Ave. in New York City

Instead of trenches, some utilities excavate tunnels in which cables are placed on trays. Such a tunnel without cable, is shown below.

Figure XII.1.3.2
Cable Tunnel in which Cables Have Not Yet Been Installed

If a new trench must be excavated, its cost is essentially independent of the cable diameter. Where new trenches or tunnels can be avoided, the savings are significant. As noted in Chapter X, the cost of installing a 345 kV cable in a trench in Westchester, north of New York City, was approximately 3 million $ per mile in 1989. (After adjusting for inflation that cost would be approximately 40% greater in today's dollars.) Recent estimates of projected total project costs can be obtained by looking at filings for the relevant public agencies.[365] The essence of two recent ones appears below:

> "[re: 345 kV transmission OH vs. UG]…the initial capital cost of a one mile long underground segment on the Beseck to East Devon portion of the line would be approximately $50 million, as compared to approximately $3.3 million per mile direct cost for the overhead construction proposed in this Application, including

[365] For example, see http://www.transmission-nu.com/residential/projects/middletown/default.asp

the relocation of the 115-kV lines."[366]

"Route length: Between 8.7 and 9.3 miles
CL&P is proposing two new underground 115-kV electric transmission lines that would run under streets from Stamford to Norwalk. CL&P proposes to use a type of power cable that has solid electric insulation and contains no fluid (cross-linked polyethylene or "XLPE" cable). Three sets of three conduits (or ducts) would be installed underground, within or adjacent to roads along the route. This would involve the excavation of a trench approximately 7 feet deep, with an approximate width of 4 feet at the bottom and 10 feet at the top…
Cost: approximately 120 million $"[367]

Of course, the cost of putting an already purchased cable underground depends very much on the cable route and on the infrastructure that is built to house the cable. Here we cite the principal items that cost money

- The engineering design and environmental impacts must be considered by the appropriate public agencies in light of their own expertise and concerns, if any, by the general public. Preparation for this scrutiny can be expensive and time consuming. As described in Section II.1, the permitting process is usually longer and more stringent for high voltage cable than for low voltage cable. For example, one year is the minimum time for considering a proposed line of 200 kV or more in California by law.

- Property or easements to use others' property must be purchased.

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[366] 9 October 2003 by Connecticut Light&Power and United Illumination Co. to Connecticut Siting Council, re Middletown to Norwalk

[367] 9 October 2003 by Connecticut Light&Power and United Illumination Co. to Connecticut Siting Council, re Middletown to Norwalk

• The trench or tunnel must be excavated. The cost of excavation depends on the time required. A rough estimate in terms of length and diameter is given here. These estimates might be multiplied by 1.5 if advance through the terrain is slower than average or the work is delayed by other factors.[368]

Trenches for fiber optics		164-328 $ per meter
Tunnel Diameter < 60 cm	via directional drilling	656 $ per meter
60 cm <Tunnel Diameter < 120 cm	via micro-tunneling	1,641 $ per meter
120 cm < Tunnel Diameter	via standard Tunnel Boring Machine	4,925 $ per meter
	via more or larger Tunnel Boring Machines	14,775 $ per meter

• Added costs for excavating bends, vaults, ancillary entrances.

As described in Section XII.2.3.1, even the cost of widening a planned railroad tunnel to accommodate a conventional cable can be prohibitive.

XII.1.4 Cable Impedance

Some HTS cables differ from conventional cable in another respect; the surge impedance of some HTS cables is significantly less than the surge impedance of conventional cable.

Surge impedance is a characteristic of the cable or line that reflects the choice of dielectric and geometry and at the second remove, choice of conductor that makes a geometry feasible. Here we explain this interplay.

The surge impedance is the square root of the ratio of the cable's inductance per meter, here denoted by $\tilde{L}$, to the cable's capacitance per meter, here denoted by $\tilde{C}$.

$$Z_{surge} = \sqrt{\frac{\tilde{L}}{\tilde{C}}}$$

The surge impedance is deserves attention for two reasons: (a) it approximates the cable's or line's impedance when the route is short, the shorter the better the approximation.

[368] These estimates were kindly provided by E.J. Cording (Prof. Emeritus, Dept. of Civil Engineering, University of Illinois at Urbana-Champaign) in October, 2004.

This is relevant because almost all AC cables are "short" and (b) if a load's resistance equals the cable's impedance the load will absorb all of the cable's power. If not, the load will reflect some of the power flowing toward it. (The reverberating power, resulting from reflections within the network, is known as reactive power--a topic usually discussed in terms of phase shifts rather than time.)

As stated, a cable's (or line's) surge impedance depends on the cable's (or line's) geometry and materials.

Conventional cables guide three phase power with copper or aluminum conductors. Conductor cost is reduced by using three conductors, rather than six as would be required by three, "two-wire circuits". The electric and magnetic fields concomitant with the three currents and several voltages differences can induce charges and currents in nearby material. In particular, the rotating electric field in the (anisotropic) dielectric might cause it to "breakdown". To reduce that likelihood in cables having voltage differences greater than 11 kV, cable makers surround the dielectric with coaxial screens (or shields or sheathes) of grounded conductor. That forces the electric field to be radial and so it sees the dielectric from the direction least likely to breakdown.

However, the conducting screen (shield or sheath) does not carry current that would shield the phase's exterior from the magnetic field created by the current alternating within the phase's central conductor. To do so would double the cost of the conductor.

HTS cables can be designed in several ways. "Warm dielectric"(WD) cables are like the conventional cables just described. WD cables differ only by using HTS for the central conductor. It is surrounded by a cryostat and then the warm dielectric surrounds the cryostat and the conventional screen surrounds the dielectric. "Cold dielectric"(CD) cables may have a cold shield around the cold dielectric and a cryostat that surrounds the "cold shield". If the buyer is willing to pay for the cold shield made from enough HTS, a shielding current can alternate in it. In effect, the cable becomes three separate coaxial cables, each invisible to the electrical and magnetic environment. When handling a balanced load, the same invisibility is promised by the triaxial design, which uses less conductor than three coaxial cables.

Here we introduce two often used designs and the impedance of each.[369] Because many conventional cables, having extruded dielectrics, embody conductors in the "trefoil configuration"(the axis of each phase is passes through a vertex of an equilateral triangle), trefoil is considered here. Because HTS cable will aim for a market above 11 kV we assume its conventional alternative will have an electrostatic screen. The capacitance and inductance are shown and the notation follows.

$$\tilde{C}_{screen} = \frac{2\pi\varepsilon_0\varepsilon}{\ln\left[\frac{R}{r}\right]} \qquad \tilde{L}_{trefoil} = \frac{\mu_0\mu}{2\pi}\ln\left[\frac{D}{\alpha r}\right] \qquad \tilde{L}_{coax} = \frac{\mu_0\mu}{2\pi}\ln\left[\frac{R}{\alpha r}\right]$$

where (a) r is the radius of the central cylindricalconductor

(b) R is the radius of the shield (electrostatic in the trefoil while being both electrostatic and electromagnetic in the coax)

(c)D is the distance between the axes of the three conductors in the trefoil (nb $D \geq 2R$)

(d) α reflects the current distribution in the central conductor

uniform distribution within central conductor $\alpha = 1/\sqrt[4]{e} \approx 0.78$

concentrated on surface of central conductor $\alpha = 1$

For the sake of definiteness, we suppose that the trefoil embodies copper conductor and the coax embodies HTS operating at 77 K and the trefoil embodies copper operating at 398K. Neglecting the skin effect in the copper, the current will be uniformly distributed. To a good approximation the current in the HTS will be on the surface of the central cylindrical conductor. One finds that the surge impedances are:

[369] Having recalled the many conductors that comprise a cable and its environment conductors (e.g., three phases, three screens, a neutral wire, the "earth"), the reader may wonder why only one or two parameters (i.e., impedance, capacitance and inductance) suffice to describe the situation. The answer depends on the implicit question. If one wants both the surge impedance and the propagation speed, s, one must consider both inductance and capacitance because $s = 1/\sqrt{LC}$. If one only wants to describe situations in which the voltage differences and currents differ in phase by 120^{o} but do not differ in magnitude then simplification occurs, yielding "the cable's inductance" and "the cable's capacitance". This situation is the standard one for power engineers. In truth, inductance and capacitance are each described by its own matrix, having elements that describe the interaction of pairs of conductors. When the usual correlations are absent, engineers speak of "unbalanced faults" and matrices are needed to precisely describe the situation.

$$Z_{Cu,trefoil} = \frac{1}{2\pi}\sqrt{\frac{\mu_0}{\varepsilon_0\varepsilon_{wd}}}\sqrt{\ln\left[\frac{R_{Cu}}{r_{Cu}}\right]\ln\left[\frac{R_{Cu}}{0.78r_{Cu}}\right]}\sqrt{1+\frac{\ln\left[D_{Cu}/R_{Cu}\right]}{\ln\left[\frac{R_{Cu}}{0.78r_{Cu}}\right]}}$$

$$Z_{HTS,coax} = \frac{1}{2\pi}\sqrt{\frac{\mu_0}{\varepsilon_0\varepsilon_{cd}}}\sqrt{\ln\left[\frac{R_{HTS}}{r_{HTS}}\right]\ln\left[\frac{R_{HTS}}{r_{HTS}}\right]}$$

To go further, one notes that the distance between centers cannot be less than twice the radius of the screen $D_{Cu} \geq 2\ R_{Cu}$. When we compare two cables of same voltage and same shield radius, the ratio of the radius of the screen or shield, R, to the central conductor, r, is constrained by the wish that the electric field not be strong enough to breakdown the dielectric. At the surface of the central conductor, the electric field is

$$E[r] = \frac{1}{\varepsilon_0\varepsilon 2\pi r}\lambda_q = \frac{1}{\varepsilon_0\varepsilon 2\pi r}\tilde{C}V = \frac{R/r}{\ln\left[R/r\right]}\frac{V}{R}$$

and so one could choose the inner radius to minimize the field. The result is $R/r = e \approx 2.71$. However, because the minimum is shallow, other considerations can come into play, particularly for low voltage cable.

To see the order of magnitude of the ratio of the two surge impedances, the ratio was computed for the most compact trefoil (i.e., $D/R = 2$) in several cases.

$$\frac{Z_{Cu,trefoil}}{Z_{HTS,coax}} = \sqrt{\frac{\varepsilon_{cd}}{\varepsilon_{wd}}}\begin{cases} 2.5 & \text{for} \quad R_{Cu}/r_{Cu} = 2.71 \text{ and } R_{HTS}/r_{HTS} = 1.75 \text{ and } D_{Cu}/R_{Cu} = 2.0 \\ 1.5 & \text{for} \quad R_{Cu}/r_{Cu} = 2.0 \text{ and } R_{HTS}/r_{HTS} = 2.0 \text{ and } D_{Cu}/R_{Cu} = 2.0 \\ 0.9 & \text{for} \quad R_{Cu}/r_{Cu} = 1.75 \text{ and } R_{HTS}/r_{HTS} = 2.71 \text{ and } D_{Cu}/R_{Cu} = 2.0 \end{cases}$$

And the ratio was computed for a less compact trefoil (i.e., $D/R = 3$)

$$\frac{Z_{Cu,trefoil}}{Z_{HTS,coax}} = \sqrt{\frac{\varepsilon_{cd}}{\varepsilon_{wd}}}\begin{cases} 2.7 & \text{for} \quad R_{Cu}/r_{Cu} = 2.71 \text{ and } R_{HTS}/r_{HTS} = 1.75 \text{ and } D_{Cu}/R_{Cu} = 3.0 \\ 1.7 & \text{for} \quad R_{Cu}/r_{Cu} = 2.0 \text{ and } R_{HTS}/r_{HTS} = 2.0 \text{ and } D_{Cu}/R_{Cu} = 3.0 \\ 1.0 & \text{for} \quad R_{Cu}/r_{Cu} = 1.75 \text{ and } R_{HTS}/r_{HTS} = 2.71 \text{ and } D_{Cu}/R_{Cu} = 3.0 \end{cases}$$

These numbers suggest that the surge impedance of an HTS coaxial cable can be significantly less than the surge impedance of a Cu trefoil cable. Other conventional cables, for example one with its three phases in a line, should have a larger impedance than a trefoil.[370]

When two power lines are connected in parallel (e.g., each of two different cables terminating on the same pair of bus bars), more current will alternate within the line having lower impedance. Thus, switching unusually low impedance cables in or out of the network may cause substantial changes in current flow and thus realize the possibility of reducing the current in remote, overloaded parts of the system. One could also vary the impedance at each terminal of the cable. The cost of the variable impedance that would depend on the amount of power one wanted to control.[371]) The potential benefit from this possibility can only be evaluated within the context of a specific system.

There is another aspect to consider. A cable having impedance that increased during overload could be designed by placing the stabilizer outside the outer radius of the HTS and inside the inner radius of the HTS. Over-currents would alternate in the more widely separated conductors, increasing the cable's impedance. The increased impedance would reduce the fault current. However, it would not be possible to limit the current for a sustained period because the fault current would warm the copper stabilizer, increasing the cooling load. Sustained faults would have to be cleared by breakers. The potential benefit from the possibility of shunting the current to a stabilizer having higher impedance can only be evaluated within the context of a specific system.

XII.1.5 Cable Voltage

As described in Chapter IV, two of the cable's characteristics affect the maximum power that can be guided by the cable. One is the difference in voltage between the conductors. The other characteristic is the amount of current alternating within the conductors. The product of these two quantities essentially determines the maximum power.

The electrical energy dissipated within aluminum or copper cable depends primarily on the square of the current alternating within the conductors and somewhat on the electric

[370] Conventional cable can have geometries, other than trefoil. We pick trefoil because HTS cable is likely to compete with XD cable (in particular XLPE cable) in many potential applications and XD cable is often sold in a trefoil configuration.

[371] The author is not aware of the results of any systematic studies of such costs. As mentioned in SectionIV.6.2.6, the cost of a Phase Angle Regulator is roughly 1.25 times the cost of a transformer with the same MVA rating (e.g., 10 $/kW for modest power and declining to perhaps 5 $/kW for 800 MVA).

field alternating within the dielectric. Economic considerations (i.e., the cost of aluminum or copper) have always encouraged utilities to use large voltage differences and small currents whenever possible. This tendency is restrained by the fact that low voltage differences are wanted at the place of end use and by the cost of the transformers required to "step up" the voltage at the generating station and to "step down" the voltage for distribution. As already noted in Section X.2.3, current cannot be increased too much without taking account of circuit breakers' capacity and cost.

The cost of transformers includes both the cost of the equipment (roughly $10/kW) and the cost of the land on which they are situated. That cost depends on location. Consider the difference between the cost of land in the center of Berlin and Osterode, Chicago and Moline, Firenze and Pontedera, Geneva and Bonneville, Helsinki and Tampere, Jerusalem and Beersheva, London and Watford, Oslo and Trondheim, Paris and Clermont-Ferrand, Seoul and Anyang, Stockholm and Vasteras, or Tokyo and Sakura.

Some jurisdictions place an annual tax on the value of privately owned land. Where so, the assessed value of its land concerns the private sector. Herein lies the appeal of selling land now occupied by part, or all, of some urban substations and moving their large transformers to remote areas (i.e., ones with low assessed value) from where power would be brought to the end-user by lower voltage cables that might only require smaller, more easily sited transformers.[372] The relevant voltages are the same as the relevant voltages for cables that were described in Section II.2. Easier siting means less money spent on negotiating with local regulatory bodies and faster permitting. In some

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[372] "Dry transformers", that is, transformers having air instead of oil as the electric insulator and coolant, are preferred for use within tall buildings because these transformers do not create a fire hazard. Thus, they require less space. (see P. Payne in L.L. Grigsby, The Electric Power Engineering Handbook, CRC Press &IEEE Press (New York, 2001) ISBN#0-8493-8578-4) Attention might be given to the potential benefits, including the avoidance of "wet" distribution transformers, of relatively low voltage, high current distribution. Now, tall office buildings are often fed by 12.5 kV (phase to phase) lines having power that is transformed into 480 V (phase to phase). For more information on distribution within and near the end-user, both commercial and industrial, see IEEE Recommended Practice for Design of Reliable Industrial and Commercial Power Systems, IEEE (New York, 1998), colloquially known as the IEEE "Gold Book" and see IEEE Recommended Practice for Electric Power Distribution for Industrial Plants, IEEE (New York, 1993), colloquially known as the IEEE "Red Book" and see IEEE Recommended Practice for Electric Power Systems in Commercial Buildings, IEEE (New York, 1991), colloquially known as the IEEE "Gray Book". D.G. Fink and H.W. Beatty, Standard Handbook for Electrical Engineers, 14th edition, McGraw-Hill (London, Milan and elsewhere, 2000) ISBN#0-07-020975-8 also introduces this and related topics.

jurisdictions, lower voltage cables receive less scrutiny than higher voltage cables and thus may be approved more quickly.

In summary, guiding power with large currents (made possible only by HTS), rather than large voltage, raises the promise of reduced cost of substations in densely populated areas.

XII.1.6 Cable Weight

HTS underground cable would be much lighter than comparable conventional aluminum or copper cable because less conducting metal is needed.[373] In an HTS cable, most of the weight of conductor is the weight of the HTS stabilizer (e.g., silver, stainless steel or nickel-tungsten alloys comprising the HTS substrate and cryogenic copper which provides the capacity to handle fault current). That weight is much less than usual because the cryogenic operating temperature reduces the stabilizer's resistivity and so less of it is needed to handle the rated current than would be needed for a conventional cable which operates near ambient temperature.

The unusually light weight of HTS cable raises three possibilities:

(a) easier than usual installation (less tension is required to pull the cable through a duct, conventional cable requires mechanical support to avoid breaking)

(b) reduced "dead weight" of transport equipment (e.g., ships, trains, planes).

(c) reduced mechanical support needed for overhead structures incorporating HTS cable (e.g., a tall high-rise building or a wind turbine having a light weight HTS generator). At present, little attention has been paid to this potential benefit. On the supply side, one would have to consider the LN_2's pressure difference between top and bottom and, more generally, the ability of the cryogenic design to cope with elevation change. On the demand side, tall buildings can usually recover their capital from prestige rents and wind turbines have not yet shown they can be profitable in more than a few places. The cost of a small, lightweight HTS generator and cable would have to be compared with the reduced cost of mechanical support.

XII.1.7 Charging Current

We have already emphasized that HTS can carry much, more current through a fixed cross-sectional area than can copper or aluminum. In fact, the current density of HTS is so great, that its cross-sectional area is negligible when compared to the cross-sectional

[373] Recall that submarine cable often has a lead alloy sheath which is heavy and may be independent of conductor.

area of everything else in the cable. Thus, the maximum current in an HTS cable can be increased by adding more HTS and without significantly changing the other dimensions of the cable.

This may be useful in some situations where AC cable is wanted because the current, alternating within the cable, is the sum of two terms. One is the current that alternates in the load. The other is the "charging current"; it charges and discharges the surfaces of the conductors within the AC cable. (Note, the surfaces in a DC cable are also charged but there is no concomitant current because the charge stays where it was put, unless the polarity of the cable flips.)

For cables that are short compared with *c/f*, the charging current is proportional to the cable's length. However, such a cable can be long enough to have a big enough charging current to generate non-trivial losses in its copper or aluminum. Non-trivial means that the losses would raise the cable's temperature undesirably, unless something else was done. Two actions are possible: (a) use more copper or aluminum to keep losses per meter within the cable's ability to transfer heat to the environment or (b) increase the cable's ability to transfer heat. Either action would raise the cable's capital cost and may increase the geometric or effective outer diameter of the cable.

The past practice has been to buy AC-DC converter-invertors and DC cable for route lengths longer than some distance, typically 35 km. Today that distance may be longer because the permittivity of XLPE is less than older dielectrics, as discussed in Sections X.3 and XI.2.5. The exact distance has depended on the prices of conductor, converter-invertors and the relevance of space, at the time of investment. HTS cable offers the promise of much greater "ampacity" and thus longer AC cable for the same outer diameter.

Exceptional ampacity (whether for the load current or the charging current) would be valuable wherever space is limited. For example, the land required for converter-invertors may not be inexpensive (or even available), increasing the cost of DC (or eliminating its feasibility). Or, the outer diameter of cable might be limited by the wish to use existing infra-structure, for example the 150 mm ducts built in Japan. In such situations, an AC HTS cable would offer an alternative to expensive conventional alternatives.

It is important to understand that while exceptional ampacity is necessary handle exceptional charging currents within exceptionally long AC cable, exceptional ampacity is not sufficient for exceptionally long AC HTS cable. Such cable must be cooled and so the wish for long cable raises the need for intermediate cooling stations. This topic deserves attention and support for RD&D.

As noted in Section X.3, two scales seem likely to determine the maximum desired length of AC cable. On land, the scale is set by the circumference of a region within which overhead lines are not feasible. Often this is an urban center. If so, a circumferential HTS cable would be more valuable if either cold bus bars were developed or the heat leak at the (many) desired terminations were reduced below what has been reported to date. Underwater, the length scale is set by the distance to be traversed from shore to shore. Today, the longest cables are underwater; see Chapter XI.

XII.1.8 Summary

An HTS cable's extraordinary engineering current density, self-contained cooling, and low linear mass density raise the prospect for cable having a) greater energy efficiency, b) smaller diameter, c) lighter weight, d) lower impedance, and e) higher current and lower voltage than conventional cable.

XII.2 Situations in Which HTS Cable's Benefits Might Maximize Return on Investment

To identify situations in which HTS cable would likely be used, we consider the circumstances in which the private sector might find HTS cable's benefits to be lucrative.

XII.2.1 Considerations of Efficiency

When HTS AC cable advances to the point where it is more energy efficient, at rated load, than conventional cable, this efficiency will offer the biggest economic return to those who can "base-load" their cable.

XII.2.1.1 Base-Load Operation of Power Stations' Output Cables

High cable utilization occurs at the terminals of base-load power plants. Often, they are nuclear plants or large coal-fired plants.[374] In some locations large gas turbines, fueled by LNG, may be base-loaded. The generating station's capacity factor becomes the cable's load factor, if there is no redundancy.

Hydro-electric dams usually do not serve "base load."[375] The dam stores the energy of spring rain and the generator converts it to electricity on a schedule that takes account of downstream water demands. They often reflect irrigation and navigation, as well as demand for electric power. However, if the dam were base-loaded during some seasons (e.g., summer) and the cryogenics were shut off for other seasons (e.g., spring), the total annual energy efficiency of the cable would improve.

There is another reason to consider HTS cable at a generating station. The voltage at the terminals of most generators is in the range 15-30 kV and so large currents alternate in the conductors that connect the generator's terminals to the "step-up" transformers. This is where high-current and low-voltage already occurs within the network.[376]

Thus base-load generating stations, with their need to handle high load factor (e.g. 80%) and large currents, are places where HTS cable might be chosen over conventional cable or compressed gas insulated lines (CGIL). Of course, to be adopted, any cable must be

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[374] This assertion is illustrated by the capacity factors recorded in Japan, UK, and U.S.
During 2001, the capacity factors for Japan's generating stations, by fuel type, were: nuclear 80%, thermal 45%, (Japan Statistical Yearbook 2004, posted at http://www.stat.go.jp/english/data/nenkan/ and in Electric Power Industry in Japan 2002/2003, available from the Japan Electric Power Information Center).
During 2001, the capacity factors for UK generating stations were: nuclear 82%, conventional steam 44%, gas-fired combined cycle 59%, (UK Annual Abstract 2003, Tables 21.8 and 21.9 posted at http://www.statistics.gov.uk).
During 2002, the capacity factors for US generating stations, by fuel type, were: nuclear 90%, coal 70%, hydro 39%, other renewables (e.g., wind) 59%, natural gas & dual fired 24%. (Electric Power Annual 2002, USDOE DOE/EIA-0348(2002) (Dec., 2003), http://www.eia.doe.gov/cneaf/electricity/epa/epa_sum.html) primary data were collected from form EIA-906, *Power Plant Report*).

[375] For example, during the year 2000, the capacity factor for US hydro was 39%, as noted above.

[376] Pumps and generators are also located at "pumped hydro storage facilities" which are used every day. Parts of some of these facilities are located within mountains (see Section IV.7.3.1) where the cost of excavating new tunnels might be high.

more desirable than overhead lines from the generator to the "step up" transformer or beyond.

Another consideration may be pertinent. Generators should be and are protected from extraordinarily large currents occasioned by faults elsewhere. This protection is achieved by switching the generator out of the grid. Unfortunately, this strategy can occasionally contribute to system-wide black-outs.[377] Some work has been done to explore the possibility of protecting the generator by designing the HTS cable to also serve as fault current limiter.[378] If successful, such current-limiting cable would provide additional time to decide whether or not to “”trip out” the generator.

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[377] For a description of a large, recent black-out, see US-Canada Power System Outage Task Force, Interim Report: Causes of the August 14th Blackout in the United States and Canada, pages 63-65. For the Danish view of recent blackouts, see A.H. Nielsen, E. Herse, J. Holbøll, M. Lind, O. Tønnesen, BLACKOUTS, *OMFATTENDE STRØMAFBRYDELSER&STRATEGISK FORSKNING*, (Ørsted·DTU, 28. NOVEMBER 2003) available from http://www.oersted.dtu.dk/eltek/.

[378] From 1998 to 2001, one project, SUPERPOLI Brite/Euram Project No. BE97 4738, began to explore the technical feasibility of this application. One conclusion was that long lengths of REBaCuO tape would be necessary. Since then, progress toward such tape has been significant. SUPERPOLI is described in four papers. They are:

A. Usoskin, H.C. Freyhardt, A. Issaev, J. Knoke, J. Dzick, M. Collet, P. Kirchesch, and J. Lehtonen, *SUPERPOLI Fault-Current Limiters Based on YBCO-Coated Stainless Steel Tape*, paper no. 2LAOI presented at ASC 2002 Houston and appearing in IEEE T APPL SUPERCON 13 (2): 1972-1975 Part 2 JUN 2003.

J. Paasi, P.F. Herrmann, T. Verhaege, J. Lehtonen, J. Bock, L. Cowey, H.C. Freyhardt, A. Usoskin, G. Moulert, and M. Collett, Superconducting Power Link for power transmission and fault current limitation, Physica C354 (2001) pages 1-4.

J. Paasi, J. Lehtonen and T. Verhaege, "*Design performance of a superconducting power link*", IEEE T APPL SUPERCON 11 (1): 1928-1931 Part 2 MAR 2001.

T. Verhaege, P.F. Herrman, C. Cottevieille, J.B.A. Wolf, C. Moulaert G, H.C. Freyhardt, A. Usoskin, J. Lehtonen, J. Paasi, and M. Collet, *HTS materials for ac current transport and fault current limitation,* IEEE T APPL SUPERCON 11 (1): 2503-2506 Part 2 MAR 2001.

XII.2.1.2 Base-Load Operation of Customers' Feeder Cables

End-users differ in their consumption patterns. Generally speaking, residential consumers have the smallest load factors, commercial consumers have intermediate load factors, and certain segments of heavy industry have the greatest. A facility that operated at full capacity for two shifts and half capacity during the third shift might have a load factor of roughly 80%. Industrial facilities that operate on two or three shifts and consume large amounts of electrical energy include the following:

a.1) steel mills

a.2) with air separation plants. (They provide the oxygen to the mill's basic oxygen furnaces.)

a.3) with electric arc furnaces

b) aluminum smelters

c) electrolytic copper smelters

d) magnesium (metal) producers

e) chlorine (and other alkalis) production via electrolysis
(e.g., NaCl (*aq*) + H_2O (*l*)→NaOH+(1/2) Cl_2+ (1/2) H_2)

f) phosphorus (electrothermal)
(e.g., CaF_2*$3Ca_3(PO_4)_2$ + 9 SiO_2 + 15 C→ CaF_2 + 15 CO + 6 P)

g) silicon carbide production (electrothermal via resistive heating of carbon)
(e.g., SiO_2 + 2 C → 2 CO + Si)

h) Air separation plants (compressors are driven by electric power)
(i.e., air →3.77 N_2 + O_2)

i) LNG terminals (compressors are driven by electric power)
(refrigeration required to maintain the temperature of the LNG)

Other high-load factor and large electrical energy consumers may be suggested by regarding the above as examples of the following categories: electro-chemical (e.g., aluminum, copper, magnesium), electro-thermal (e.g., phosphorus, silicon carbide, steel), and Cryogenic (e.g., air separation, BOF, LNG terminals).

To ensure reliable supply, present prudent practice usually dictates more than one "feeder" cable to each such facility. (Each feeder would connect the customer at a different substation.) This practice lowers the load factor on any particular cable. However, if one cable were much more efficient than others, the efficient cable would be used more, while less efficient conventional cables would be relegated to standby status.[379]

Efficiency is one among several considerations for privately owned utilities. Operators will place a great premium on reliability; in fact, it is likely to be their principal concern. Investors and their agents will consider capital cost. The decision to install a new HTS cable is more likely to be made when new cable is sought, rather than when an existing cable is still working. New cable is most often sought for any of three reasons:

a) a specific new facility (industrial or generating station) is being built

b) old cable has "aged" so as to become unreliable (e.g., past overloads might have damaged the cable's electrical insulation)

c) the distribution system must increase its capacity to handle greater regional load

The first reason may bear upon situations that involve unusually large load factors and large currents. The second and third reasons are most likely to come into play in situations having average system load factor and in which alternative cables are present to ensure reliable distribution.

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[379] The Southwire Co uses its first prototype HTS cable to deliver power to Southwire's factory while the previously used conventional cables standby. This practice tests and demonstrates the reliability of Southwire's prototype cable system; this practice was not adopted to reduce operating costs.

XII.2.1.3 Summary of Considerations Bearing Upon Cable Load Factor

Though for short durations, some cables operate at or near 100% load factor, this situationb is exceptional. The highest lifetime load factor that one should expect is 90%. That was the load factor of the average U.S. nuclear station during 2002. An industrial customer, such as an aluminum smelter, that runs continuously probably has a maximum load factor of 80%, corresponding to full production for 2.5 shifts per day. Commercial and residential loads have smaller load factors.

The wish for reliability prompts most designers of electrical systems to include redundancy in the transmission and distribution systems. This redundancy usually reduces the cables' load factor by a factor of two or three.[380]

XII.2.2 Considerations of First Cost, also called Investment Cost

In addition to manufacturer's price for its delivered cable, the "first cost" or "investment cost" of a power line depends on other factors. The utility must purchase or lease the right to use the necessary land; must pay for the towers for overhead lines or the tunnels/trenches for cable; and must bear the initial cost of legal fees, licenses, and environmental impact assessments. In some cases, the utility will consider the cost of transformers at the terminations of an AC line. For DC lines, the utility must consider the cost of the concomitant converter-invertors. The cable entailing least total cost depends very much on the locations being considered.

As stated several times before**,** overhead line avails itself of the atmosphere for free cooling and is supported by relatively inexpensive towers. Cable is chosen when right-of-way for overhead line is not available (e.g., in many cities), when there are idle underground ducts (e.g., as in Detroit's Frisbie Station) or when an underground route can be made more direct and thus less expensive than a more circuitous (i.e., longer) overhead route. In some regions, the cost of right-of-way dominates all other considerations.

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[380] Because a low impedance cable will draw an unusually large amount of current when put in parallel with conventional cables, some suggest that the HTS cable will have a high low load factor. This won't affect the economic decision because the utility still has to amortize the now almost idle conventional cables.

One manufacturer provides an example by stating that it has compared two alternatives for serving the same load. One is an 80 km (50 mile) long, circuitous overhead line. (The overhead line must be circuitous because the load is in an urban area) The alternative is a 16 km (10 mile) long HTS cable. The HTS cable can be routed directly because it can be buried in existing right-of-way. The overhead line is estimated to cost 3.1×10^6 \$/km (5×10^6 \$/mile), while the estimate for the HTS cable was \$$6.25\times10^6$ /km (\$$10\times10^6$ \$/mi). Thus, the cable was projected to cost $150x10^6$ \$ less than the (longer) overhead line, a substantial saving.

XII.2.3 Potential Future T&D "Corridors" or Right-of-Way That Might Uniquely Suit HTS Cable

In or near cities, the central question is whether or not HTS cable can find less expensive "T&D corridors" or right-of-way than can conventional cable. To be consequential, the saving must more than compensate the difference between the cost of conventional cable and HTS cable.

Conventional cable is often placed in ducts or tunnels from which the cable can be removed. This infrastructure is very expensive to alter and so great attention should be, and is, paid to fitting HTS cable into such existing infrastructure. For example, because the diameter of its cable ducts is 150 mm, Japan's HTS cable projects are developing cable having a 130 mm diameter. The U.S. project at Detroit Edison's Frisbie Substation had the same objective, to install and demonstrate an HTS cable in an already built duct. The goal is to increase delivered power without the increased cost required by new infrastructure. It is widely asserted that this saving would be sufficient to favor future HTS cable.

While the possibility of retrofitting has long been anticipated by Tokyo Electric Power Company, and emphasized by many, increased demand for power will not always coincide with empty ducts or with ducts holding cables that are scheduled to be replaced just when more power is wanted.

More often, the question will be *"Can the infrastructure required by HTS cable be made significantly less expensive than the new infrastructure required for conventional cable?"*

While there is no site-independent answer to this question, many cities have common features that deserve attention.

XII.2.3.1 Potential Future Corridors Built for and Used by Inter-City Rail

Many city centers are connected to each other by rail. The right-of-way cuts through densely populated areas and provides space for telephone lines and internet (fiber optic) cable, as well as rail transport. This is illustrated by Figure XII.2.3.1. The photograph was taken where a peripheral 345 kV transmission corridor crosses the tracks that go directly to the center of the city of Chicago. It would be disruptive and impractical to put conventional cable under these tracks. Recall that some three-phase circuits are spread out over one meter. The space between the ties is 1.73 m, and so it is reasonable to imagine that one could install a cable of 15-cm diameter without significant disruption to rail traffic. Indeed, the cable could be brought to the site by rail, as could the equipment needed to move the ballast, dig a 20-cm channel, and then cover it.

In some places (e.g., Alpes Maritime), railroads tunnel through mountains, instead of going over them. (See Section XIII.2.) Those tunnels might provide useful corridor for HTS cables but not for conventional cable because conventional cable might require widening the tunnel while HTS cable would not.

For example, a rail line connecting Lyon, France with Turin , Italy has been considered for some time. "EDF and SNCF have looked into the possibility of using railway tracks and tunnels between Lyon and Turin to lay a 400 kV cable. According to a project study the 53 km future tunnel of the new high-speed train Lyon – Turin would be used to lay cables of a new 400 kV line. The tunnel route would involve the laying of a 400 kV cable on the other side of the track to the railway cables (and escape routes). This would also involve widening the tunnel from a diameter of 8 metres to 8.4 metres. The estimated extra cost for the electricity line was:

- FF 750 million for widening the tunnel;
- F 250 million for equipment to maintain the temperature between 25 and 30 °C;
- Between FF 200 and 700 million to reinforce 200 tunnel junctions.

The extra cost was therefore in the order of FF 1.2 to 1.7 billion (€ 183 to 260 million) compared to an estimated cost of FF 2.6 billion (€ 400 million) to build a new tunnel solely for the electricity cables. In addition, the cost of two 1,000 MVA cables was estimated between FF 1.5 and 2.0 billion making the total cost of the link between 3.0 and 3.5 billion (FF) (approximately 450 to 530 million €). "[381]

[381] Commission Of The European Communities, Undergrounding of Electricity Lines in Europe, background paper, Brussels (10 December 2003) page 19.

Figure XII.2.3.1
Looking From Suburbs, Along the Burlington Northern's Tracks, Toward the Center of Chicago

XII.2.3.2 Potential Future Corridors Built and Used by Intra-City Light Rail

Travel to and from work by light rail is common in densely populated cities. Such mass transit is variously called metro, underground, subway, elevated, or commuter train. The cuts, tunnels, and associated infrastructure already house the systems' power lines, as well as the systems' track, rolling stock, and platforms. Employees of light rail systems are already familiar with electrical equipment and electrical safety rules. As long as the voltage of the HTS able is similar to the voltage of already installed cable, there should be no reasonable concern over safety. As above, the small diameter (e.g., 15 cm) of HTS cable makes plausible the exploration of light rail's infrastructure for future siting of HTS cable. Figure XII.2.3.2 suggests that 15 cm is available wherever track is laid.

Figure XII.2.3.2
Intra-City Light Rail Station
(Note: trackside space.)

XII.2.3.3 Potential Future Corridors Built for and Used by Elevated Highways

Automobile travel to the centers of some densely populated cities is facilitated by elevated highways, as illustrated by Figures XII.2.3.3.A and XII.2.3.3.B. Conventional cable cannot be mounted on these structures because heat transfer from the conventional cable's wall to the air would be insufficient to maintain the desired temperature (less than 130 C) of the dielectric in copper or aluminum cable. (Though a combination of conventional cable and water pipes could be buried in the concrete when it was initially built.) Compressed Gas Insulated Lines (CGIL) is capable of operating in the air because CGIL has a built in cooling system.[382] However, CGIL is so big and so heavy that utilities only use it on the ground. By contrast, HTS cable is small and light enough to be placed on the side of, or under, elevated roadway making the cable immune automobile accidents. In any case, the pressure of its LN_2 is relatively low (e.g., between 15 and 20 bar) and highways are not usually very far above ground.[383]

Figure XII.2.3.3.A

Elevated Highway Bearing Auto Traffic Into and Out of City

Figure XII.2.3.3.B

Elevated Highway Bearing Auto Traffic within City

[382] SF_6 is used because it is an excellent dielectric and provides adequate heat transfer at pressures in the range of 4-6 bar.

[383] Such pressures are now routinely used by utilities in their conventional cables to reduce the chance that bubbles would form in the cables' coolant.

XII.2.3.4 Potential Future Corridors Built to Enable Water-Crossing (i.e., Bridges)

Many cities are located on the shorelines of bays or on the banks of one or more rivers. Often power is guided from one part of a city to another by cable placed underwater. This is expensive. Some underwater cables lie below the river or bay bottom where these cables are vulnerable to ships' anchors.

As described in Section XII.2.3.3 above, except for CGIL, conventional cable cannot be put in air because of the absence of good heat transfer. Specially designed cable can be put on bridges, though this is very rarely done.[384] The Seto-Ohashi Bridge's[385] cable,

[384] To the author's knowledge, only Sumitomo has built such cables and, as of 1990, these cables have been installed on only five bridges: (a) Japan, Minato-Ohashi , truss, 1,500 m (b) Japan, Ohnaruto, suspension, 1,600 m (c) Seto-Ohashi, suspension, concrete, truss, cable stayed, 8,000 m (d) USA, Seattle, concrete viaduct, 2000 m (e) Venezuela, Gen. Rafael Urdaneta, concrete, 8,300 m. See S. Miniemura, T. Tanaka, S. Morita, K. Kojima, I. Nishino, H. Komori, K. Murakami, T. Matsui, R. Hata, H. Kuki, K. Nakayama, S. Narisada, *Completion of 500 kV PPLP-Insulated Self-Contained Oil-Filled Cable Along Seto Ohashi Bridge for Honshu-Shikoku Interconnecting Transmission Line*, Sumitomo Electric Technical Review, no 29, January 1990, pages 191-212.

[385] Fig. X.2.3.4.A, shows one part of the Seto-Ohashi Bridge. The whole bridge, comprising nine different bridges, supports 8 km of specially built cable, for each of two three-phase, 500kV circuits, three- phase circuit guiding 1.2 GW.

Figure XII.2.3.4.A
The Seto-Ohashi Bridge supports 8 km of SEI's specially built cable.

The cable is operated by the Electric Power Development Association (traded under the name J-Power) which develops power sources, builds transmission lines, and sells electricity to Japan's 10 major electric power companies.

connecting Shikoku and Honshu, provides an example that deserves to be widely appreciated.[386]

Because of its light weight and small diameter, consideration should be given to placing HTS cable on bridges.

Figure XII.2.3.4.B
These Bridges Support only Automobiles

Figure XII.2.3.4.C
This Bridge Supports Automobiles, Electric Trains and Pedestrian Traffic.

[386] More than one utility's staff have told the author that it is impossible to put cable on a bridge.

Some bridges differ from elevated highways in three relevant ways. These bridges:

a) vibrate with traffic
b) flex with wind
c) expand and contract with temperature.

As noted, a few engineers have put cables on at least five bridges of varying kinds, and other engineers have shown how to transfer Liquefied Natural Gas (LNG) at cryogenic temperatures between rolling ships.[387] Of course, some scientists are familiar with the vibrations that cryo-coolers constantly generate, without harm, in their transfer lines. Here, we note that electric utilities want their cables to last for at least 30 years, with little maintenance. Guarantees of robust performance, despite long-term low-amplitude vibration, may be wanted. Because everything within the cryostat would be at LN_2 temperatures, much lower creep rates would be expected for most of the HTS cable than for a conventional cable; the latter operates at or above ambient temperature.[388] Concern might focus on the ambient temperature wall of the HTS cable's cryostat. It might be pertinent to consider the practices and experience of those who design, build, and maintain LO_2 pipelines. They supply the basic oxygen furnaces within integrated steel mills. Some other pipelines (e.g., oil pipelines) are supported by bridges when water must be traversed. One crosses the Danube between Bratislava and Vienna.

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[387] The author is grateful to K. Schippl (Nexans DE, Hannover) for telling him of a Nexans-STATOil project that showed how cryogenic fluid (i.e., LNG) could be transferred between ships in the North Sea where waves cause the ships' relative heights to vary by meters. The transfer lines (i.e., cryostats) were demonstrated over 10^6 cycles.

[388] When stress is time-independent, it is usual to talk of "creep". This refers to a non-zero rate of strain, $\dot{\varepsilon}$, which is usually described by

$$\dot{\varepsilon} = const \times (stress)^n \exp\left[-\frac{E}{k_{Boltzman}T}\right] \text{ where } E \text{ is the solid's activation energy for self - diffusion.}$$

When stress is cyclic, it is usual to talk of "fatigue". The number of cycles before failure depends on the maximum stress in each cycle. Also, fatigue may depend on frequency.

XII.2.3.5 Summary

Many densely populated areas are already crossed by intercity railroads, intra-city rail, elevated highways, and bridges. Conventional cable technology has not been sited in the corridors provided by this infrastructure. These corridors might be more easily used by HTS cable because of its self contained cooling, small diameter and light weight. Doing so might substantially reduce the total cost of increasing the capacity to transmit and distribute electric power within crowded cities and their environs. CRIEPI is taking a step toward this goal by building a bridge (10 m high) at its Yokosuka Laboratory over which its 77 kV HTS cable passes. This is shown in Figure XII.2.3.5.

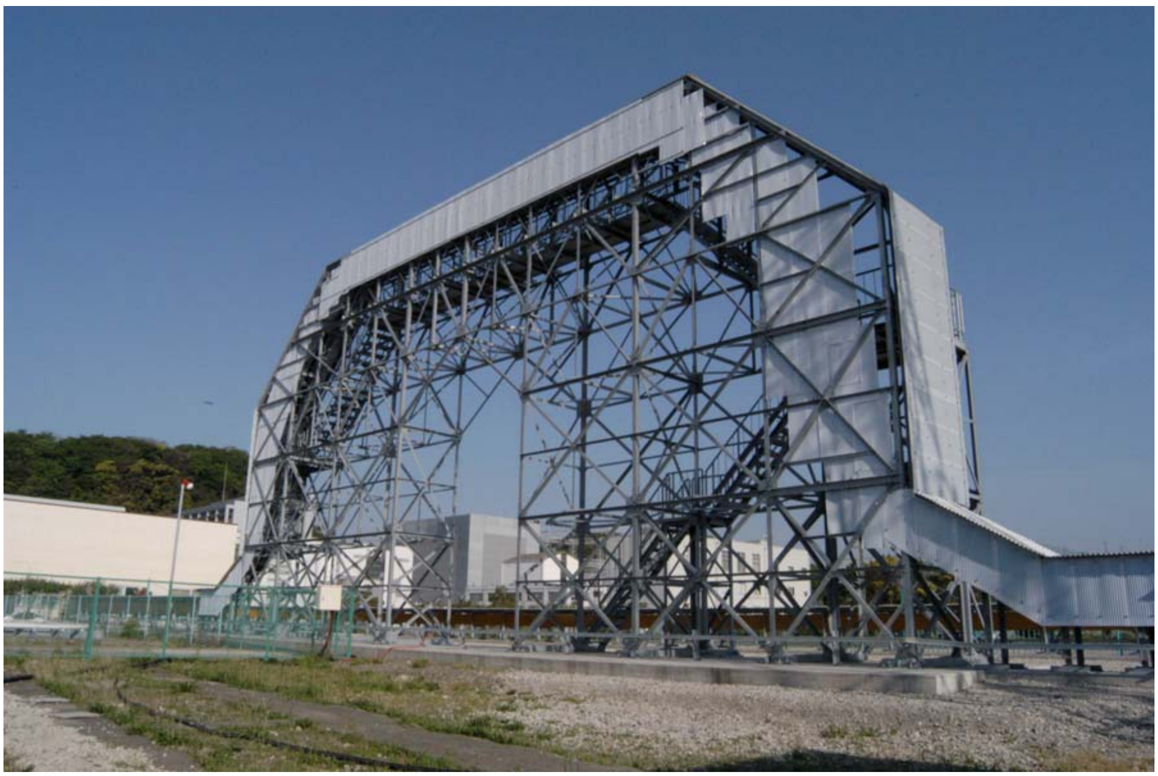

Figure XII.2.3.5
This Bridge (10 m high) is Part of the Route of the 77 kV HTS Cable Now Being Tested at CRIEPI's Yokosuka Laboratory.

XII.3 Who Might Initiate Use of Non-Traditional Corridors

While HTS cable may create new opportunities for power T&D, these new opportunities may or may not be taken, for non-technical reasons.

In some jurisdictions, utilities are now reluctant to invest in T&D because their rate of return is regulated while the return on generation is not. Other utilities may wish to "own their own turf" and not become involved with other institutions. Most often T&D is a regulated monopoly and thus the only concern is that the regulator might revoke the owners' license to operate, forcing them to sell their assets to others.[389] Such considerations disclose some of the non-technical and non-economic reasons for a conservative approach to technical change in T&D.

However, another possibility may bear upon future actions. In some jurisdictions, "merchant distribution lines" may be sanctioned by governments.[390] These lines would

[389] The author is not aware of any case in which this actually happened.

[390] Merchant transmission lines are already sanctioned in the United States. The HVDC 600MW cable under Long Island Sound provides one example. Another merchant submarine DC cable project, The Neptune Regional Transmission Project, envisions several thousand miles of HVDC cable along the coast of North America from New Jersey in the US to Canada's Maritime Provinces. The sponsors, Atlantic Energy Partners, LLC, envision a multi-phase project consisting of several thousand miles of HVDC cables that would connect generation in Maine, New Brunswick, and Nova Scotia with markets in Boston, New York City, Long Island, and Connecticut. The US Federal Energy Regulatory Commission approved Neptune RTS's Phase I application for two 600 MW merchant transmission cables from Sayreville, New Jersey, to New York City and to Newbridge on the south shore of Long Island. The Phase I project received its completeness determination from the New York PSC in February 2002, and has an expected in-service date of 2004 to 2005. Phase II, from Nova Scotia to New York City, has not been filed with the New York PSC. No applications have been filed for Phase IV, a marine cable connecting Connecticut with Maine and Maritimes Canada. Neptune's project partners include Siemens, Nexans, Energy Initiatives Group, PriceWaterhouse Coopers, Skadden Arps, Societe General, Alpine Ocean Seismic Survey and Ecology and Environment, Inc (see http://www.neptunerts.com.) Finally, we site a third merchant transmission cable project; this one is underground, not underwater. Empire Connection, lead by ITC, proposes to build 500kV DC cable that will guide power (1,150 MWe) along a 130 mile (208 km) underground route in the Hudson River Valley to New York City. The proposed start date is 2006. For more information, see http://www.kkr.com/press/09_09_03.html.

be built by independent entrepreneurs with no guarantee of profit. Government would require the network operator to allow such lines to be connected to its grid and would require that the entrepreneur provide the network operator with the means to control the flow of power into the merchant line. The merchant line's owners would collect a toll on the power that passed through their line. If and when governments adopt this approach, a strong incentive to pursue new, economical ways to distribute power will come plaand

XIII. WHERE HTS CABLE IS LIKELY TO HAVE MORE THAN AVERAGE VALUE

Section XII.2 describes situations in which the characteristics of HTS cable would be more likely than usual to offer an economic return to investors. These situations are most easily recognized by people who work or live in them.

Nonetheless, others might wish to look for such situations. They are more likely to occur in some places than in others. Here we report several places where more T&D capacity is wanted. Further, we describe a way to search for metropolitan areas in which HTS might be particularly valuable. We then identify specific metropolitan areas that are more likely than average to include areas of where the density of demand (kW/km^2) will increase. These specific places may deserve further consideration from the HTS cable community.

This chapter and the previous one does not and cannot define or exhaust all promising areas. Local circumstances will dominate and local knowledge will be required to identify specific opportunities for HTS cable.

XIII.1 General Considerations

Here and in the following subsections, we identify some places where these situations are more likely to occur than usual.

XIII.1.1 Impediments Due to Topography

Great expense may be required to construct and maintain overhead power lines that traverse mountains. Some of these ranges are already traversed by railroads and highways, which often take circuitous paths to avoid steep grades. However, in some places, tunnels have been dug through mountains to speed travel by train and automobile. The same tunnels might provide direct corridors for HTS cable.

As already noted (e.g., in Section X.2.3.4), there is a practical limit to the width of water that can be spanned by an overhead power line. When longer distances must be crossed, bridges or tunnels already built for rail and automobile traffic might serve as attractive alternatives to conventional submarine cable.

XIII.1.2 Impediments Due to Civilization

Some cities are cultural treasures (e.g., Kyoto, Venice) or are home to cultural treasures (e.g. Athens, Istanbul, Jerusalem, Rome) and other tourist attractions (e.g., Orlando). Where installation of conventional cable would impede visits and/or disrupt tourism, HTS cable might be particularly welcome.

Other cities (e.g., Shenzhen, Guangzhou) are growing as people leave rural areas to seek a higher standard of living. Cities characterized by one or more of the following trends

a) increasing demand for electric power
b) increasing residential population density and/or workforce density
c) increasing density of electric power consumption or peak demand density (kW/km^2)
d) money to invest to accommodate the above

may be promising places to look for situations in which HTS cable would offer an economic alternative to conventional cable.

The practice of traveling to work in a city concentrates the population during the day and so concentrates daytime power consumption far above night-time consumption. The presence of high-rise buildings facilitates dense population and dense day-time power demands (kW/ km^2). Recent and planned construction of high-rise buildings suggests future increases in the density of power consumption and the increased importance of avoiding T&D congestion and delay during the workday.

Dense cities also benefit from other infrastructure, in particular, electric mass transit. It is usually built to transport a population that has become too dense to move in any other way. Further, the construction and/or expansion of mass transit suggests the willingness and ability to invest money in the public sector.

As already described in Section XII.2.3.4 where electric power traverses water (e.g., crossing a bay or crossing a river), there may be unusual expense. Because big cities are often located on shorelines or river banks, these cities' utilities may take an interest in using existing "water- crossing infrastructure" to convey power to, or within, a city.

To assist identification of places where the small size of HTS cables would have unusual value, this report presents tables of cities having the characteristics discussed above. Specifically, all cities having, building, or planning to build electric mass transit are shown. The population and population density of each city is presented.[391] (Population density data reflect where people live, not where they work.)

As already suggested, the "day-time density" of people is better suggested by the height of buildings. This often varies over distances of one or two kilometers. Building height also suggests the price of land and the density of power consumption (kW peak/km^2). Higher than average land prices and higher than average density of power consumption suggest a higher than average value for compact cable. The data on buildings that are presented below was compiled by the international real estate business. The tables presented in this section show the number of high-rise buildings, also known as "skyscrapers," in each city having electric mass transit.[392] Realtors term any building that is 35-m or higher a "high-rise." This is consistent with the 19th century practice of terming any building having 12 or more floors a "skyscraper." To pass from height to peak power demand per kilometer^2, one should consider floor space and IEEE's recommendations.[393] Section X.5.4.1 returns to this topic.

Finally, the tables presented here show whether or not water is nearby that is likely to be traversed by electric power. The relevance of this proximity may be brought to mind by a few examples: (a) London is bisected by the Thames, (b) Tokyo is on the shores of a bay, and (c) San Francisco is on a small peninsula. In each case, it is likely that conventional submarine cables guide power into part, or all, of the city and that tunnels and/or bridges for automobile and rail traffic have already been built. These infrastructures might offer an inexpensive (at the margin, the investment has already been made) site for compact HTS cable that brings power to the city or, perhaps, power to

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[391] The population data is usually collected by governments and the data is organized by political jurisdiction. The significance of the result requires scrutiny by those interested in electrical infrastructure because power consumption may not reflect jurisdictional boundaries. The name "Guangzhou" (formerly Canton) denotes an urban center, a city, a municipality and a metropolitan area, each with a different population. Some heavily populated regions have no single collective jurisdiction. The neighboring cities of Dortmund, Düsseldorf, Essen, Gelsenkirchen, Hagen, Wuppertal and their adjacent towns collectively have a population of 9,000,000. Thus, the creation of an urban authority would bring forth one of the world's most populous cities. Published data describing population and population density are very sensitive to jurisdictional boundaries.

[392] Whether or not they are located in cities with electric mass transit, the number of high rise buildings, with much more detailed descriptions of each, is available from sources cited at the bottom of each table in this section.

[393] Useful floor space is affected by the space allotted to elevator shafts; the interior of lower floors is occupied by elevator shafts that reach higher floors. For guidelines relating floor space to power, see IEEE Recommended Practice for Electric Power Systems in Commercial Buildings, IEEE (New York, 1991), colloquially known as the IEEE "Gray Book."

electric mass transit.[394] Some cities are on the sea coast (e.g., Los Angeles); their utilities may or may not use submarine cable (e.g., the Palo Verde nuclear plant is near L.A. and also on the coast).

Though these tables do not show quantitative trends, these tables do show whether or not electric mass transit is expanding, under construction, or planned. Each designation suggests that the local authorities regard congestion as a problem and have the money to try to relieve it. Information about recent and expected growth is available from the international real estate business. Some of this is posted on http://www.emporis.info which maintains sites in English and German[395]. More detailed information is available for a fee.

XIII.2 Europe

Beside local factors, three different factors may influence the future adoption of HTS cables in Europe.[396] They are (1) demand density (2) deregulation and (3) European integration. We begin with integration.

As cited in Chapter II, the EC's Trans-European Electricity Networks group (TEN-E) describes the present and future "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." Several years ago, TEN-E identified 44 T&D needs that it described as of common (i.e., EU) interest. Some of these needs have been addressed by projects receiving EU funds; others have not yet been addressed. The already identified needs provide a first place to look for sites suitable for future HTS demonstration projects.[397]

[394] Some subways operate on relatively low voltage DC. In that case, the cryogenics of an HTS cable would not have to remove "steady state" AC losses, though transient loads would still generate some "AC losses."

[395] Deutschebank is a partner in the effort that has yielded this site. Other partners comprise Kingspan, KONE, and the Wacker Group.

[396] An example of a local factor: In response to a damaging December, 1999 storm, the January 2002 agreement *Accord "Reseaux Electriques et Environnement"* among the Ministries for Industry and the Environment, EdF and RTE envisages that 90 percent of all new medium voltage distribution network, two-thirds of all new low voltage distribution network and 25 percent of all high voltage transmission networks (i.e. 63/90kV) should be constructed underground, while equivalent lengths of existing aerial line should be transformed into underground cables.

[397] see http://europa.eu.int/comm/energy/ten-e/en/policy.html)

Deregulation[398] has raised increased congestion in some areas. Congestion of the continental European network has concerned some persons. According to VDN, an

> "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 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."[399]

The EC staff stated that additional underground cable could improve the European network published its view from which the following is quoted.

> "…Commission of the TransEuropean networks (TEN) Programme in energy since 1995, showed that many critical missing electricity links between Member States on the extra high voltage (400 KV mainly and 225 KV) could not be realized owing to strong local objections for environmental reasons. This situation has led the Commission to issue a Communication on "European Energy Infrastructure" in December 2001, stressing in particular the need to complete these missing links and in particular the cross-border links, in order that the internal electricity market to operate without barriers. It is generally expected that the use of underground cables in environmentally critical sections of the missing cross-border links could alleviate or minimize local oppositions to the construction of overhead lines, as underground cables are not visible and their effect on the environment is usually les than overhead lines."[400]

European Commission identified 7 priority projects in electricity networks of Europe.

- EL1: France-Belgium-Netherlands-Germany: electricity reinforcements needed

[398] Directive 2003/53/EC opens the electricity market for all non-household customers by July 2004, and for all customers by July 2007.
[399] Verband der Netzbetreiber VDN e.V. beim VDEW, VDN Annual Report 2002, page 30.

[400] Commission Of The European Communities, Undergrounding of Electricity Lines in Europe, background paper, Brussels (10 December 2003) page 1.

to remove frequent congestion across the Benelux region;

- EL2: Italian border to France, Austria and Switzerland; increasing electricity interconnectors capacities;

- EL3: France-Spain-Portugal; increasing electricity interconnectors capacity;

- EL4: Greece-Balkan countries: development of electricity infrastructure to connect Greece to the UCTE system;

- EL5: UK-Continental Europe and Northern Europe: increasing electricity interconnection capacity with France and establishing interconnection capacity with other countries (e.g. Netherlands and Norway);

- EL6: Ireland and both Northern Ireland and mainland UK; increasing electricity interconnectors capacity;

- EL7: Denmark-Germany: increasing interconnection capacity.

> "The use of underground cables in these environmentally critical sections of crossborder interconnections may solve the problems and therefore facilitate and speed-up the construction of the missing links in the near future. The extra costs for undergrounding these critical sections is expected to be outweighed by the additional benefits from the operation of an integrated electricity market in Europe without crossborder barriers, fact that will allow increased exchanges and trade of electricity and may lead to lower prices of electricity."[401]

Several persons in Europe's power sector have confirmed aspects of EC's view, by saying that Europe's transmission system is congested in two places: (a) the Dutch-German border, and (b) the French-Italian border. A person associated with a French utility stated that there may also be need for additional transmission capacity across the French-Spanish border. One might approach the last two problems by seeking an economical way to traverse the Pyrenees (French-Spanish border) and to traverse the Alpes Maritime (French-Italian border). Both mountain ranges are already traversed by railroads and highways.

We now consider the density of demand (kW/km^2) in metropolitan areas. Characteristics of some of Europe's cities appear in Table XIII.2.A and Table XIII.2.B. Though Europe's average population density exceeds most other areas of the world, except for London, Europe does not appear to have cities of extraordinary density. For example, the Ruhrgebeit, the agglomeration that includes Dortmund-Dusseldorf-Essen-Gelsenkirchen-Hagen-Wuppetal, has a total population of about 9 million, but the Ruhrgebeit does not

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[401] Commission Of The European Communities, <u>Undergrounding of Electricity Lines in Europe,</u> background paper, Brussels (10 December 2003) page 24.

appear to have the same density of people or of power consumption (peak kW/km^2) as London, and so there may be more places in London than in the Ruhrgebeit where compact cable would be highly valued.

In many European cities, the absence of density reflects civic decisions to maintain the character and attractiveness of these cities. For example, no one would countenance change in central Paris, and so, tall buildings were constructed in La Defense. Similar policies guide many cities in Germany and Italy. However, in some places, the wish to maintain the inhabitants' quality of life and to avoid impeding tourist traffic may favor the future installation of compact cable.

Of course, some European cities (e.g., Barcelona, Berlin, Frankfurt, and Milan) include dense business districts, and future increases in density are planned. See Section XIII.5.4.2.

Table XIII.2.A

Northwest Europe: Some Characteristics of Cities Having Electric Mass Transit

Country	City[a]	Population (10^6)[a]	Population Density (10^3/ km^2)[b]	High Rise Bldgs "Skyscrapers" (number)[c]	Water X Nearby[e]	Electric Mass Transit (status)[d]
Norway (1)	Oslo	0.5	2.4 / ?	127	shore	E & E
Sweden (2)	Stockholm	0.7	3.6	99	yes	E & E
Finland (3)	Helsinki	0.6	3.3	71	shore	E & E
Denmark (4)	Copenhagen	0.5	**27** / 2.9	61	yes	E & E
Scotland (5)	Glasgow	0.7	3.9 / ?	228	yes	E
England (6)	Birmingham	2.2	3.5	206	no	E & E
England (6)	Liverpool	1.1	3.8	94	shore	E
England (6)	London	7.2	**42** / 6.0	1,612	yes	E & E
England (6)	Manchester	2.4	3.3	132	no	
England (6)	Newcastle	1.0	3.1	47	yes	E
Netherlands (7)	Amsterdam	0.7	5.5	210	yes	E & E
Netherlands (7)	Rotterdam	0.6	2.8 / ?	288	yes	E & E
Belgium (8)	Antwerp	0.5	1.9	38	yes	
Belgium (8)	Bruxelles	0.1	**47** / 7.4	74	yes	
Belgium (8)	Charleroi	0.3	?	1	yes	E
France (9)	Lille	0.2	3.5	10	yes	E & E
France (9)	Lyon	0.4	4.9	49	yes	E & E
France (9)	Marseille	0.8	5.8	101	shore	E & E
France (9)	Paris	2.1	90 La Defense /3.5	136	yes	E
France (9)	Rennes	0.2	?	2	yes	E & E
France (9)	Rouen		?	2	yes	E
France (9)	Toulouse	0.4	2.5	25	yes	E & E
Germany (10)	Bonn	0.4	?	25	yes	
Germany (10)	Berlin	3.5	5.6	361	yes	E & E
Germany (10)	Bielefeld	0.3	?	4	yes	E
Germany (10)	Frankfurt	0.7	4.8	362	yes	
Germany (10)	Hamburg	1.7	**33** /4.0	180	yes	E & E
Germany (10)	Hannover	0.5	?	52	yes	E & E
Germany (10)	Köln	1.0	?	76	yes	E & E
Germany (10)	Ludwigshafen	0.2	?	4	yes	E
Germany (10)	München	1.2	**28** / 5.4	138	yes	E & E
Germany (10)	Nürnberg	0.5	2.2	21	yes	E & E
Germany (10)	Ruhrgebeit[f]	9.0	?	190	yes	E
Germany (10)	Stuttgart	0.6	5.6	22	no	E
Switzerland(11)	Lausanne	.06	?	1	shore	E & E
Switzerland(11)	Zürich	0.3	**42** / 4.7	21	shore	E

Please refer to the following page for the footnotes of Table X.4.2.A

Footnotes of Table XIII.2.A

[a] total population varies with the meaning of the city name (e.g., city boundary or "metropolitan area").
(1) This is 2003 data of municipalities from http://www.citypopulation.de/Norwegen.html
(2) This is 2002 data of municipalities from http://www.citypopulation.de/Schweden.html
(3) This is 2002 data of municipalities from http://www.citypopulation.de/Finland.html
(4) This is 2003 data of municipalities from http://www.citypopulation.de/Daenemark.html
(5) This is 2001 data of principal urban areas from http://www.citypopulation.de/Schottland.html
(6) This is (find source – not city population)
(7) This is 2001 data of city boundary from http://www.citypopulation.de/Niederlande.html
(8) This is 2002 data of city boundary from http://www.citypopulation.de/Belgien.html
(9) This is 1999 data of city boundary from http://www.citypopulation.de/Frankreich.html
(10) This is 2002 data of city census estimate from http://www.citypopulation.de/Deutschland.html
(11) This is 2002 data of city census estimate from http://www.citypopulation.de/Schweiz.html

[b] When two numbers appear, the greater refers to employment density (see comments below for source) and the lesser to residential population density (http://www.demographia.com/db-intlcitydens.htm). Population density varies throughout city. For detail, see www.demographia.com. The average residential population density over the whole city might be 2,000-3,000 persons per km^2 (http://www.demographia.com/db-intlcitydens.htm). The most dense neighborhoods might have ten times more people. http://www.demographia.com/db-hyperdense.htm. Also, see http://www.demographia.com/db-dense-rank.htm for a ranking among cities. Recall, that the raw data is almost always collected by residence and so this is the population density at night. The population density differs at the time of peak demand because people are at their employers' facilities. Thus, the density of electrical demand will differ from the density of population as determined by residence. Where available, we also show estimates of employment density for the central business district. They are about ten times greater than residential population density. Estimates, presented here, of employment density are posted at URL http:// http://www.demographia.com/db-intlcbddens.htm. These estimates are based on Jeffrey R. Kenworthy, Felix B. Laube et al, An International Sourcebook of Automobile Dependence in Cities: 1960-1990, US Census Bureau, Japan Statistics Bureau & Statistics Centre, Statistics Office of the UK and by Demographia.

[c] number depends on height of shortest "high rise" building, Here we use the definition of the real estate business, 35m; "skyscraper" is an older name for a twelve floor (35m) building. For more detail, see www.emporis.info/en/and www.skyscraperpage.com

[d] UC or Pl denotes "Under Construction or Planned". E&E denotes "Existing and Expanding" and E denotes "Existing, not expanding". For additional information, see www.metropla.net and each city's mass transit authorities.

[e] "yes" indicates nearby river that is likely traversed by electric power (e.g., Thames is "likely" traversed by London's electric power network). The entry "shore" indicates situations in which power may or may not traverse water (e.g., Both the Palo Verde nuclear generating station and Los Angeles are on the shore of the same bay).

[f] This region includes Bochun (14 hi-rise), Dortmund (23 hi-rise), Duisberg (13 hi-rise), Düsseldorf (73 hi-rise), Essen (38 hi-rise), Gelsenkirchen (5 hi-rise), Hagen (7 hi-rise), and Wuppertal (17 hi-rise).

Table XIII.2.B
Southern Europe: Some Characteristics of Cities Having Electric Mass Transit

Country	**City**[a]	**Population** (10^6)[a]	**Population Density** $(10^3 / km^2)$[b]	**High Rise Bldgs "Skyscrapers" (number)**[c]	**Water X Nearby**[e]	**Electric Mass Transit (status)**[d]
Portugal (1)	Porto	0.3	?	9	yes	E & E
Portugal (1)	Lisbon	0.6	5.9	76	shore	E & E
Spain (2)	Barcelona	1.5	9.4	421	shore	E & E
Spain (2)	Madrid	2.9	8.7	287	yes	E & E
Spain (2)	Bilbao	0.4	?	283	yes	E & E
Spain (2)	Valencia	0.8	6.5	132	yes	E & E
Italy (3)	Catania	0.3	?	0		E & E
Italy (3)	Genova	0.6	#25	35	shore	E & E
Italy (3)	Milano	1.3	5.1	661	yes	E & E
Italy (3)	Naples	1.0	4.2	35	shore	E & E
Italy (3)	Palermo	0.7	#27	0	shore	E
Italy (3)	Rome	2.5	5.6	9	yes	E & E
Italy (3)	Salerno	?	?	?	shore	UC & Pl
Greece (4)	Athens	0.7	8.4	44	yes	E & E
Bulgaria (5)	Sofia	1.1	?	10	yes	E & E

Please refer to the following page for the footnotes of Table X.4.2.B

Footnotes of Table XIII.2.B

[a] total population varies with the meaning of the city name (e.g., city boundary or "metropolitan area").
(1) This is 2001 data of principal localities from http://www.citypopulation.de/Portugal.html
(2) This is 2001 data of city boundary from http://www.citypopulation.de/Spanien.html
(3) This is 2001 data of city boundary from http://www.citypopulation.de/Italien.html
(4) This is 2001 data of city boundary from http://www.citypopulation.de/Greece.html
(5) This is 2001 data of city boundary from http://www.citypopulation.de/Bulgarien.html

[b] When two numbers appear, the greater refers to employment density (see comments below for source) and the lesser to residential population density (http://www.demographia.com/db-intlcitydens.htm). Population density varies throughout city. For detail, see www.demographia.com. The average residential population density over the whole city might be 2,000-3,000 persons per km^2. The most dense neighborhoods might have ten times more people. http://www.demographia.com/db-hyperdense.htm. Also, see http://www.demographia.com/db-dense-rank.htm for a ranking among cities. Recall, that the raw data is almost always collected by residence and so this is the population density at night. The population density differs at the time of peak demand because people are at their employers' facilities. Thus, the density of electrical demand will differ from the density of population as determined by residence. Where available, we also show estimates of employment density for the central business district. They are about ten times greater than residential population density. Estimates, presented here, of employment density are posted at URL http:// http://www.demographia.com/db-intlcbddens.htm. These estimates are based on Jeffrey R. Kenworthy, Felix B. Laube et al, An International Sourcebook of Automobile Dependence in Cities: 1960-1990, US Census Bureau, Japan Statistics Bureau & Statistics Centre, Statistics Office of the UK and by Demographia.

[c] number depends on height of shortest "high rise" building, we use the real estate business' definition, 35m; "skyscraper" is an older name for a 12 floor (35 m) building. For more detail, see www.emporis.info/en/ and www.skyscraperpage.com.

[d] UC or Pl denotes *Under Construction or Planned*. E&E denotes *Existing and Expanding* and E denotes *Existing, not expanding* . For additional information, see www.metropla.net and each city's mass transit authorities.

[e] "yes" indicates the likelihood of a nearby river traversed by electric power (e.g., The Tiber is "likely" traversed by Rome's electric power network). The entry "shore" indicates situations in which power may or may not traverse water (e.g., Both the Palo Verde nuclear generating station and Los Angeles are on the shore of the same bay).

Table XIII.2.C
Eastern Europe: Some Characteristics of Cities Having Electric Mass Transit

Country	City[a]	Population (10^6)[a]	Population Density (×10^3 / km^2)[b]	High Rise Bldgs "Skyscrapers" (number)[c]	Water X Nearby[e]	Electric Mass Transit (status)[d]
Czech R. (6)	Prague	1.2	4.9	37	yes	E & E
Austria (7)	Vienna	1.6	**38** / 6.8	111	yes	E & E
Hungary (8)	Budapest	1.8	5.1	20	yes	E & E
Romania (9)	Bucharest	1.9	?	15	yes	E
Ukraine (10)	Kryvyj Rih	0.7	?			E
Ukraine (10)	Kharkiv	1.5	?	2		E & E
Ukraine (10)	Kyiv (Kiev)	2.6	?	93		E & E
Ukraine (10)	Dnipropetrowsk	1.1	?	1		E & E
Belarus (11)	Minsk	1.7	?	5		E & E
Poland (12)	Warsaw	1.6	5.2	182	yes	E & E
Russia (13)	Chelyabinsk[f]	1.1	?	0	yes	UC or Pl
Russia (13)	Krasnoyarsk[f]	0.9	?	0	yes	UC or Pl
Russia (13)	Moscow	10.1	14.6	248	yes	E & E
Russia (13)	NizhniyNovgorod	1.3	?	?	yes	E & E
Russia (13)	Novosibirsk[f]	1.4	?	3	yes	E & E
Russia (13)	Omsk	1.1	?	0	yes	UC or Pl
Russia (13)	Samara	1.2	?	1	yes	E & E
Russia (13)	St. Petersburg	4.7	?	139	shore	E & E
Russia (13)	Volgograd	1.0	?	0	yes	E & E
Russia (13)	Yekatarinburg[f]	1.4	?	0	??	E & E

Please refer to the following page for the footnotes of Table X.4.2.C

Footnotes of Table XIII.2.C

[a] total population varies with the meaning of the city name (e.g., city boundary or "metropolitan area").
(6) This is 2003 data of city boundary from http://www.citypopulation.de/Tschechien.html
(7) This is 2001 data of city boundary from http://www.citypopulation.de/Oesterreich.html
(8) This is 2001 data of city boundary from http://www.citypopulation.de/Ungarn.html
(9) This is 2001 data of city boundary from http://www.citypopulation.de/Rumaenien.html
(10) This is 2001 data of city boundary from http://www.citypopulation.de/Ukraine.html
(11) This is 1999 data of city boundary from http://www.citypopulation.de/Weissrussland.html
(12) This is 2002 data of city boundary from http://www.citypopulation.de/Poland.html
(13) This is 2002 data of city census (provisional) from http://www.citypopulation.de/Russland.html

[b] When two numbers appear, the greater refers to employment density (see comments below for source) and the lesser to residential population density (http://www.demographia.com/db-intlcitydens.htm). Population density varies throughout city. For detail, see www.demographia.com. The average residential population density over the whole city might be 2,000-3,000 persons per km^2 (http://www.demographia.com/db-intlcitydens.htm). The most dense neighborhoods might have ten times more people. http://www.demographia.com/db-hyperdense.htm. Also, see http://www.demographia.com/db-dense-rank.htm for a ranking among cities. Recall, that the raw data is almost always collected by residence and so this is the population density at night. The population density differs at the time of peak demand because people are at their employers' facilities. Thus, the density of electrical demand will differ from the density of population as determined by residence. Where available, we also show estimates of employment density for the central business district. They are about ten times greater than residential population density. Estimates, presented here, of employment density are posted at URL http:// http://www.demographia.com/db-intlcbddens.htm. These estimates are based on Jeffrey R. Kenworthy, Felix B. Laube et al, An International Sourcebook of Automobile Dependence in Cities: 1960-1990, US Census Bureau, Japan Statistics Bureau & Statistics Centre, Statistics Office of the UK and by Demographia.

[c] number depends on height of shortest "high rise" building, we use the real estate business' definition, 35m; "skyscraper" is an older name for a 12 floor (35 m) building. For more detail, see www.emporis.info/en/ and www.skyscraperpage.com.

[d] UC or Pl denotes *Under Construction or Planned*. E&E denotes *Existing and Expanding* and E denotes *Existing, not expanding* . For additional information, see www.metropla.net and each city's mass transit authorities.

[e] "yes" indicates a nearby river is likely traversed by electric power (e.g., The Danube is "likely" traversed by Vienna's electric power network). The entry "shore" indicates situations in which power may or may not traverse water (e.g., Both the Palo Verde nuclear generating station and Los Angeles are on the shore of the same bay).

[f] east of Urals

XIII.3 Africa, Middle East and Central Asia

Table XIII.3 presents information on cities in Africa, the Middle East, and Central Asia. People in these regions are now moving to cities and infrastructure is being built or is planned. The change is greatest in Central Asia, where oil is being produced and more is expected.

Both India and Turkey have cities of unusually large size and high density, and where the private sector has been willing to invest in infrastructure. Ankara, Istanbul, and Mumbai (Bombay) are examples. Mumbai has a large population (9.9 million), high population density (16,000 persons/km^2), and 617 high-rise buildings. This density may manifest two facts; Mumbai is the financial capital and the film capital ("Bolleywood") of India, and Mumbai occupies seven islands. Indeed, construction is underway on the river banks where a new city, Navi Mumbai, has grown up.

A different consideration is illustrated by comparing two cities, Cairo and Tel Aviv. Congestion and the value attached to avoiding it are local phenomena. Cairo is home to roughly 6.7 million people who are spread over 215 km^2. Tel Aviv's population is 0.325 million; they occupy 52 km^2. Cairo has 127 buildings having 12 or more floors (heights equal to or greater than 35 m), 17 under construction and 2 proposed, while Tel Aviv has 175 built, with another 20 under construction, 53 approved and 34 proposed. Some of these buildings are hotels that offer views of the Mediterranean. Because of its density, compact cable may be more highly valued in the smaller city, Tel Aviv, than in the larger one, Cairo.

Table XIII.3

Africa, Middle East & Central Asia: Some Characteristics of Cities Having Electric Mass Transit

Country	City[a]	Population (10^6)[a]	Population Density (10^3 / km^2)[b]	High-Rise Bldgs "Skyscrapers" (number)[c]	Water X Nearby[e]	Electric Mass Transit (status)[d]
South Africa (1)	Johannesburg	1.5	3.9	77	no	E
South Africa (1)	Cape Town	2.4	?	108	yes	E
Algeria (2)	Algiers	1.5	?	3	yes	UC
Tunisia (3)	Tunis	0.7	?	3	no	E & E
Egypt (4)	Alexandria	3.3	?	9	yes	E
Egypt (4)	Cairo	6.7	25.3	146	yes	E & E
Israel (5)	Tel Aviv	0.4	6.1	291	shore	UC or Pl
United Arab Emirates(5)	Dubai	1.0	?	160	shore	UC or Pl
Syria (6)	Damascus	1.4	?	110	no	UC or Pl
Turkey (7)	Ankara	3.2	?	430	yes	E & E
Turkey (7)	Adana	1.1	?	41	yes	UC or Pl
Turkey (7)	Bursa	1.2	?	71	no	E & E
Turkey (7)	Istanbul	8.8	7.0	2226	yes	E
Turkey (7)	Izmir	2.2	?	125	shore	E & E
Georgia (8)	Tbilisi	1.1	?	2	yes	E & E
Azerbajan (9)	Baku	1.8	?	8	yes	E & E
Iran (10)	Esfahan	1.3	?	0	yes	UC or Pl
Iran (10)	Mashhad	1.8	?	0	no	UC or Pl
Iran (10)	Tehran	6.7	?	17	no	E & E
Kazakstan (11)	Almaty	1.1	?	5	no	UC or Pl
Uzbekistan (12)	Toshkent	2.1	?	7	yes	E & E
India (13)	Bangalore	4.3	?	51	no	UC or Pl
India (13)	Calcutta	4.6	11.7	123	yes	E & E
India (13)	Chennai	4.2	13.3	24	shore	E & E
India (13)	Delhi	9.9	17.7	1	yes	E & E
India (13)	Mumbai (Bombay)	9.9	18.3	617	shore	E & E

Please refer to the following page for the footnotes of Table XIII.3

Footnotes: Table XIII.3

[a] total population varies with the meaning of the city name (e.g., city boundary or "metropolitan area").
(1) This is 1996 data for principal urban area from http://www.citypopulation.de/SouthAfrica-UA.html
(2) This is 1998 data for city boundary from http://www.citypopulation.de/Algeria.html
(3) This is 2001 data for city boundary from http://www.citypopulation.de/Tunisia.html
(4) This is 1996 data for city boundary from http://www.citypopulation.de/Egypt.html
(5) This is 2002 data for city boundary from http://www.citypopulation.de/Israel.html
(6) This is 1994 data for city boundary from http://www.citypopulation.de/Syria.html
(7) This is 2000 data for city boundary from http://www.citypopulation.de/Tuerkei.html
(8) This is 2002 data for city boundary from http://www.citypopulation.de/Georgia.html
(9) This is 2002 data for city boundary from http://www.citypopulation.de/Azerbaijan.html
(10) This is 1996 data for city boundary from http://www.citypopulation.de/Iran.html
(11) This is 1999 data for city boundary from http://www.citypopulation.de/Kazakstan.html
(12) This is 1999 data for city boundary from http://www.citypopulation.de/Uzbekistan.html
(13) This is 2001 data for city census (provisional) from http://www.citypopulation.de/Country.html?E+Indien$India

[b] This is the residential population density (http://www.demographia.com/db-intlcitydens.htm), not the population density at the time of peak demand

[c] The number depends on height of shortest "high rise" building, we use the real estate business' definition, 35m; "skyscraper" is an older name for a 12 floor (35 m) building. For more detail, see www.emporis.info/en/ and www.skyscraperpage.com.

[d] UC or Pl denotes *Under Construction or Planned*. E&E denotes *Existing and Expanding* and E denotes *Existing, not expanding*. For additional information, see www.metropla.net and each city's mass transit authorities.

[e] "yes" indicates the likelihood of a nearby river traversed by electric power (e.g., The Nile is "likely" traversed by Cairo's electric power network). The entry "shore" indicates situations in which power may or may not traverse water (e.g., Both the Palo Verde nuclear generating station and Los Angeles are on the shore of the same bay).

XIII.4. Northeast Asia

XIII.4.1 China, Including Taiwan

During recent years, China’s economy has grown. Table X.4.4.1 shows its cities with electric mass transit. More detailed investigation would show that extraordinary density, wealth, and growth can be found in the Pearl River Delta. That region includes Hong Kong, Shenzhen, Guangzhou (Canton), and many other jurisdictions. The willingness to invest here (e.g., six new railroads are planned or under construction) and the high density suggest that HTS cable might be particularly appealing to planners in the Pearl River Delta. Shanghai (roughly 13 million persons) is another city in which HTS cable might be found more attractive than conventional alternatives. Shanghai is said to have produced one-twelfth of China's GDP and consumed 55 million MWH in 2002. Recently, Shanghai has been upgrading its network, including transforming overhead lines to underground cables and replacing old underground cables. (Shanghai's first underground power cable was laid down in the1910s.) .

Table XIII.4.1
China, Including Taiwan: Some Characteristics of Cities Having Electric Mass Transit

Country	City[a]	Population (10^6)[a]	Population Density (10^3/km^2)[b]	High Rise Blds "Skyscrapers" (number)[c]	WaterX Nearby[e]	Electric Mass Transit (status)[d]
China (1)	Beijing	5.7	14.5	238	no	E & E
China (1)	Changchun	1.7		8	no	UC or Pl
	(Jilin Province)		?			
China (1)	Chengdu	1.7	?	33	no	UC or Pl
China (1)	Chongqing	2.3	22.6 / ?	173	no	UC or Pl
China (1)	Dalian	1.7	?	126	shore	UC or Pl
China (1)	Hangzhou	1.1	?	23	yes	UC or Pl
China (1)	Harbin	2.5	16.1	5	yes	UC or Pl
China (2)	Hong Kong	6.7	Victoria/46.6	7,701	yes	E & E
China (2)	Hong Kong Isle	1.3	Kowloon76			?
China (2)	Kowloon	2.0	CBD 171		shore	?
China (2)	New Territories					?
	Shenzen	3.0	46 / ?	202	yes	UC or Pl
China (1)	Guangzhou	2.9	41[402] / ?	114	yes	E & E
	(Canton-Kuangchou)					
China (1)	Nanjing	2.1	17.3	42	yes	UC or Pl
China (1)	Qingdoa	1.3	?	23	shore	UC or Pl
China (1)	Shanghai	7.6	16.4	604	yes	E & E
China (1)	Shenyang	3.6	11.0	31	no	UC or Pl
China (1)	Tianjin	4.5	21.5	41	no	E & E
China (1)	Wu Han	3.2	17.3	67	yes	UC or Pl
China (1)	Xi'an	2.1	15.3	16	no	UC or Pl
Taiwan (3)	Kaohsiung	1.5	?	51	shore	UC or Pl
Taiwan (3)	Taipei	2.6	?	91	no	E & E

Please refer to the following page for the footnotes of Table X.4.4.1

Footnotes: Table XIII.4.1

[a] total population varies with the meaning of the city name (e.g., city boundary or "metropolitan area" or "urban agglomeration"). For example, the urban agglomerations centered in Beijing and Taipei have populations of 9.9 million and 6.8 million persons (see http://www.citypopulation.de/World.html).

(1) This is 1990 data for city boundary from http://www.citypopulation.de/Country.html?E,China
(2) This is 2001 data for city boundary from http://www.citypopulation.de/Hongkong.html
(3) This is 2001 data for city boundary from http://www.citypopulation.de/Taiwan.html

[b] When two numbers appear, the greater refers to employment density (see comments below for source) and the lesser to residential population density (http://www.demographia.com/db-intlcitydens.htm). Population density varies throughout city. For detail, see www.demographia.com. The average residential population density over the whole city might be 2,000-3,000 persons per km^2. The most dense neighborhoods might have ten times more people. http://www.demographia.com/db-hyperdense.htm. Also, see http://www.demographia.com/db-dense-rank.htm for a ranking among cities. Recall, that the raw data is almost always collected by residence and so this is the population density at night. The population density differs at the time of peak demand because people are at their employers' facilities. Thus, the density of electrical demand will differ from the density of population as determined by residence. Where available, we also show estimates of employment density for the central business district. They are about ten times greater than residential population density Estimates, presented here, of employment density are posted at URL http:// http://www.demographia.com/db-intlcbddens.htm. These estimates are based on Jeffrey R. Kenworthy, Felix B. Laube et al, An International Sourcebook of Automobile Dependence in Cities: 1960-1990, US Census Bureau, Japan Statistics Bureau & Statistics Centre, Statistics Office of the UK and by Demographia.

[C] number depends on height of shortest "high rise" building, we use the real estate business' definition, 35m; "skyscraper" is an older name for a 12 floor (35 m) building. For more detail, see www.emporis.info/en/ and www.skyscraperpage.com.

[d] UC or Pl denotes *Under Construction or Planned*. E&E denotes *Existing and Expanding* and E denotes *Existing, not expanding*. For additional information, see www.metropla.net and each city's mass transit authorities.

[e] "yes" indicates the likelihood of a nearby river traversed by electric power (e.g., Thames is "likely" traversed by London's electric power network). The entry "shore" indicates situations in which power may or may not traverse water (e.g., both the Palo Verde nuclear generating station and Los Angeles are on the shore of the same bay).

XIII.4.2 Japan and Korea

Table X.4.4.2 shows cities in Korea and Japan having power consumption that is both large and dense; the biggest is Tokyo. Of course, Tokyo, Seoul, and cities like them have already installed electric power transmission and distribution. Three relevant questions are (a) when will replacements for today's cables be needed (b) will load grow, and at what rate, and (c) will the peak load density change from one part of the city to another? Note, new construction can raise the need for new distribution cable, even when the total peak load of the service area remains unchanged.

Table XIII.4.2
Japan and Korea: Some Characteristics of Cities Having Electrical Mass Transit

Country	City[a]	Population (10^6)[a]	Population Density (10^3 per km^2)[b]	High Rise Bldgs "Skyscrapers" (number)[c]	Water X Nearby[e]	Electric Mass Transit (status)[d]
R of Korea (1)	Busan	3.7	7	90	yes	E & E
R of Korea (1)	Daegu	2.5	5	21	yes	E & E
R of Korea (1)	Gwangju	1.4	?	2	no	UC or Pl
R of Korea (1)	Incheon	2.6	5	18	shore	E & E
R of Korea (1)	Seoul	10.3	58 / 17	736	yes	E & E
North Korea(?)	Pyongyang	2.7	?	24	yes	E
Japan (2)	Fukuoka	1.2		42	shore	E & E
Japan (2)	Hiroshima	1.1	12 / 6	46	yes	E & E
Japan (2)	Kawasaki	1.3	9	84	no	UC or Pl
Japan (2)	Kitakyushu	1.1	4.7	7	yes	E
Japan (2)	Kobe	?	10 / ?	100	shore	E
Japan (2)	Kyoto	1.5	16 / ?	13	yes	E & E
Japan (2)	Nagoya	2.2	24 / 3	122	shore	E & E
Japan (2)	Naha	?		3	no	E
Japan (2)	Osaka	2.6	35 / ?	693	yes	E & E
Japan (2)	Sapporo	2.0	5	57	no	E
Japan (2)	Sendai	1.0	4	39	no	E & E
Japan (2)	Tokyo	31.2	CBD 58 / ???	1,404	yes	E
Japan (2)	Yokohama	3.4	11 / 8	162	shore	UC

Please refer to the following page for the footnotes of Table X.4.4.2

Footnotes of Table XIII.4.2

[a] total population varies with the meaning of the city name (e.g., city boundary or "metropolitan area").
(1) This data for city boundary from http://www.citypopulation.de/KoreaSouth-UA.html#Stadt_gross
(2) This data for city boundary from http://www.citypopulation.de/Japan-Tokyo.html

[b] When two numbers appear, the greater refers to employment density (see comments below for source) and the lesser to residential population density (http://www.demographia.com/db-intlcitydens.htm). Population density varies throughout city. For detail, see www.demographia.com. The average residential population density over the whole city might be 2,000-3,000 persons per km^2. The most dense neighborhoods might have ten times more people. http://www.demographia.com/db-hyperdense.htm. Also, see http://www.demographia.com/db-dense-rank.htm for a ranking among cities. Recall, that the raw data is almost always collected by residence and so this is the population density at night. The population density differs at the time of peak demand because people are at their employers' facilities. Thus, the density of electrical demand will differ from the density of population as determined by residence. Where available, we also show estimates of employment density for the central business district. They are about ten times greater than residential population density Estimates, presented here, of employment density are posted at URL http:// http://www.demographia.com/db-intlcbddens.htm. These estimates are based on Jeffrey R. Kenworthy, Felix B. Laube et al, An International Sourcebook of Automobile Dependence in Cities: 1960-1990, US Census Bureau, Japan Statistics Bureau & Statistics Centre, Statistics Office of the UK and by Demographia.

[C] Number depends on height of shortest "high rise" building, we use the real estate business' definition, 35m; "skyscraper" is an older name for a 12 floor (35 m) building. For more detail, see www.emporis.info/en/ and www.skyscraperpage.com.

[d] UC or Pl denotes *Under Construction or Planned*. E&E denotes *Existing and Expanding* and E denotes *Existing, not expanding*. For additional information, see www.metropla.net and each city's mass transit authorities.

[e] "yes" indicates the likelihood of a nearby river traversed by electric power (e.g., The Han River is "likely" traversed by Seoul's electric power network). The entry "shore" indicates situations in which power may or may not traverse water (e.g., Tokyo is on the shore of Tokyo Bay. The location of its power plants is ???).

XIII.5 Southeast Asia and Australia

Some cities in Southeast Asia and Australia are unusually dense and have grown. Table X.4.5 shows that the buildings and population of Singapore now resemble those of Tokyo, London, and New York. Malaysia's Penang Island does not appear because there is no record of electric mass-transit. However, Penang Island is a densely populated city and tourist destination having many high-rise buildings, including high-rise hotels.

Table XIII.5
Australia & South East Asia: Some Characteristics of Cities Having Electric Mass Transit

Country	City	Population (x 10^6)[a]	Population Density (10^3 per km^2)[b]	High Rise Bldg "Skyscrapers" (numbers)[c]	Water X Nearby[e]	Electric Mass Transit (status)[d]
Philipines(1)	Manila	1.6	23 / 8	38	shore	E & E
Vietnam (2)	Ho Chi Minh City (Saigon)	3.0	36	39	yes	UC or Pl
Thailand (3)	Bangkok	6.3	13 / 14	835	yes	E & E
Malaysia (4)	Kuala Lumpur	1.3	6	607	yes	E & E
Singapore(5)	Singapore	4.0	37 / 10	3,836	yes	E & E
Indonesia (6)	Jakarta	8.3	7	118	shore	UC or Pl
Australia (7)	Brisbane	1.3	53 / 1	220	yes	E & E
Australia (7)	Sydney	3.5	2	772	yes	E & E
Australia (7)	Melbourne	2.8	53 / 2	549	yes	E & E

Please refer to the following page for the footnotes of Table X.4.5

Footnotes of Table XIII.5

[a] total population varies with the meaning of the city name (e.g., city boundary or urban agglomeration).
(1) This is 2000 data for city boundary from http://www.citypopulation.de/Philippines.html
(2) This is 1992 data for city boundary from http://www.citypopulation.de/Vietnam.html
(3) This is 2000 data for Bangkok metropolis from http://www.citypopulation.de/Thailand.html#Land
(4) This is 2000 data for urban areas from http://www.citypopulation.de/Malaysia.html
(5) This is 2000 data for residential population (capital) of Singapore from http://www.citypopulation.de/Singapore.html
(6) This is 2000 data for province population from http://www.citypopulation.de/Singapore.html
(7) This is 2001 data for principal urban centers from http://www.citypopulation.de/Australia-UC.html

[b] When two numbers appear, the greater refers to employment density (see comments below for source) and the lesser to residential population density (http://www.demographia.com/db-intlcitydens.htm). Population density varies throughout city. For detail, see www.demographia.com. The average residential population density over the whole city might be 2,000-3,000 persons per km^2. The most dense neighborhoods might have ten times more people. http://www.demographia.com/db-hyperdense.htm. Also, see http://www.demographia.com/db-dense-rank.htm for a ranking among cities. Recall, that the raw data is almost always collected by residence and so this is the population density at night. The population density differs at the time of peak demand because people are at their employers' facilities. Thus, the density of electrical demand will differ from the density of population as determined by residence. Where available, we also show estimates of employment density for the central business district. They are about ten times greater than residential population density Estimates, presented here, of employment density are posted at URL http:// http://www.demographia.com/db-intlcbddens.htm. These estimates are based on Jeffrey R. Kenworthy, Felix B. Laube et al, An International Sourcebook of Automobile Dependence in Cities: 1960-1990, US Census Bureau, Japan Statistics Bureau & Statistics Centre, Statistics Office of the UK and by Demographia.

[C] number depends on height of shortest "high rise" building, we use the real estate business' definition, 35m; "skyscraper" is an older name for a 12 floor (35 m) building. For more detail, see www.emporis.info/en/ and www.skyscraperpage.com.

[d] UC or Pl denotes *Under Construction or Planned*. E&E denotes *Existing and Expanding* and E denotes *Existing, not expanding*. For additional information, see www.metropla.net and each city's mass transit authorities.

[e] "yes" indicates the likelihood of a nearby river traversed by electric power (e.g., The Mekong River is "likely" traversed by Ho Chi Minh City's electric power network). The entry "shore" indicates situations in which power may or may not traverse water (e.g., both the Palo Verde nuclear generating station and Los Angeles are on the shore of the same bay).

XIII.6 Western Hemisphere

Several cities in the western hemisphere have an extraordinary number of tall buildings. These include Chicago, Rio de Janeiro, New York, Sao Paulo, and Toronto. Many other cities have a large number of high-rise buildings; examples are Atlanta, Boston, Caracas, Los Angeles, Recife, Montreal, and Vancouver. Table X.4.6 also shows that despite the relative absence of tall buildings (a zoning decision), San Francisco has an unusually large employment density.

Table XIII.6
Western Hemisphere: Some Characteristics of Cities Having Electric Mass Transit

Country	**City**	**Population** (10⁶)[a]	**Population Density** (10^3 / km^2)[b]	**High Rise Bldg** "Skyscrapers" **(numbers)**[c]	**Water X Nearby**[e]	**Electric** Mass Transit **(status)**[d]
Canada (1)	Calgary	0.9	29 / 1	210	yes	E & E
Canada (1)	Edmonton	0.7	22 / 1	254	yes	E & E
Canada (1)	Montreal	3.4	22 / 2	445	yes	E & E
Canada (1)	Ottawa	0.8	2	289	yes	**??**
Canada (1)	Vancouver	1.8	2	501	shore	E & E
Canada (1)	Toronto	4.3	3	1,858	shore	E
USA (2)	Atlanta	0.4	1	232	**no**	E & E
USA (2)	Baltimore	0.6	?	149	shore	E & E
USA (2)	Boston	0.6	30 / 1	233	shore	E & E
USA (2)	Buffalo	1.0	1	61	shore	E
USA (2)	Chicago	8.3	145 / 2	1,426	shore	E
USA (2)	Cleveland	0.5	1	150	shore	E & E
USA (2)	Dallas	1.2	1	268	no	E
USA (2)	Detroit	1.0	26 / 1	219	yes	E
USA (2)	Houston	2.0	1	352	no	E & E
USA (2)	Jacksonville	1.0	1	64	yes	E
USA (2)	Las Vegas	0.5	2	118	no	E & E
USA (2)	Los Angeles	3.7	45 / 2	408	shore	E & E
USA (2)	Miami	0.4	2	255	shore	E & E
USA (2)	New York	18.0	Midtown 234/2	5,556	yes	E
USA (2)	Philadelphia	5.1	1	376	yes	E
USA (2)	St. Louis	0.3	1	176	yes	E & E
USA (2)	San Francisco	0.8	74 / 2	309	yes	E & E
USA (2)	Seattle	0.5	56 / 1	216	shore	UC or Pl
USA (2)	Washington, DC	0.6	69 / 1	283	yes	E & E
Mexico (3)	Mexico City	8.6	12	188	no	E & E
Mexico (3)	Monterrey	1.1	?	14	yes	E & E
Mexico (3)	Guadalajara	1.6	?	12	**yes**	E & E
Columbia (4)	Medellin	1.9	?	7	**yes**	E & E
Venezuela (5)	Caracas	1.8	16	679	**yes**	E & E
Brazil (6)	Belo Horizonte	2.2	5	190	yes	E & E
Brazil (6)	Brasilia	2.1	2	53	yes	E & E
Brazil (6)	Curitba	1.6	3	511	no	UC or Pl
Brazil (6)	Goiânia	1.1	3	87	no	UC or Pl
Brazil (6)	Porto Alegre	1.3	4	59	yes	E & E
Brazil (6)	Recife	1.5	?	408	shore	E & E
Brazil (6)	Rio de Janeiro	6.0	8	1,600	yes	E & E
Brazil (6)	Salvador	2.4	?	218	shore	E & E
Brazil (6)	São Paulo	10.0	8	2,577	yes	E & E
Chile (7)	Santiago	4.7	5	91	no	E & E

Please refer to the following page for the footnotes to Table X.4.6

Footnotes for Table XIII.6

[a] total population varies with the meaning of the city name (e.g., city boundary or "metropolitan area" or "urban agglomeration". An example is provided by the several meanings demographers attach to "New York" and the resulting populations 8 million, 18.6 million 21.8 million see http://www.citypopulation.de/America.html

(1) This is 2001 data for urban areas from http://www.citypopulation.de/Canada-UA.html
(2) This is 2002 estimates for city boundary from http://www.citypopulation.de/USA.html
(3) This is 2000 data for urban areas from http://www.citypopulation.de/Mexico.html#Stadt_gross
(4) This is 2003 data for city boundary from http://www.citypopulation.de/Colombia.html#Stadt_alpha
(5) This is 2001 data for city boundary from http://www.citypopulation.de/Venezuela.html
(6) This is 2003 data for city boundary from http://www.citypopulation.de/Brazil.html
(7) This is 2002 data for city boundary from http://www.citypopulation.de/Chile.html

[b] When two numbers appear, the greater refers to employment density (see comments below for source) and the lesser to residential population density (http://www.demographia.com/db-intlcitydens.htm). Population density varies throughout city. For detail, see www.demographia.com. The average residential population density over the whole city might be 2,000-3,000 persons per km^2. The most dense neighborhoods might have ten times more people. http://www.demographia.com/db-hyperdense.htm. Also, see http://www.demographia.com/db-dense-rank.htm for a ranking among cities. Recall, that the raw data is almost always collected by residence and so this is the population density at night. The population density differs at the time of peak demand because people are at their employers' facilities. Thus, the density of electrical demand will differ from the density of population as determined by residence. Where available, we also show estimates of employment density for the central business district. They are about ten times greater than residential population density. Estimates, presented here, of employment density are posted at URL http:// http://www.demographia.com/db-intlcbddens.htm. These estimates are based on Jeffrey R. Kenworthy, Felix B. Laube et al, An International Sourcebook of Automobile Dependence in Cities: 1960-1990, US Census Bureau, Japan Statistics Bureau & Statistics Centre, Statistics Office of the UK and by Demographia.

[c] number depends on height of shortest "high rise" building, we use the real estate business' definition, 35m; "skyscraper" is an older name for a 12 floor (35 m) building. For more detail, see www.emporis.info/en/ and www.skyscraperpage.com.

[d] UC or Pl denotes *Under Construction or Planned*. E&E denotes *Existing and Expanding* and E denotes *Existing, not expanding* . For additional information, see www.metropla.net and each city's mass transit authorities.

[e] "yes" indicates the likelihood of a nearby river traversed by electric power (e.g., The East River is "likely" traversed by New York's electric power network). The entry "shore" indicates situations in which power may or may not traverse water (e.g., both the Palo Verde nuclear generating station and Los Angeles are on the shore of the same bay).

XIII.7. When Might HTS Cable be Wanted?

XIII.7.1 The Importance of Local Factors

Having identified situations (Section XIII.2) and places (Section XIII.4) where compact, high-current cable might be valued, one must also consider when that cable might be wanted. Two topics are relevant: (a) the excess capacity in the existing T&D infrastructure and (b) the anticipated growth in peak demand density.

The first topic, excess T&D capacity, is most reliably explored with the help of the local electric utility and will not be discussed here.

The second topic, anticipated growth in peak demand, might be projected in the short term (i.e., ten years), because that is about as far as announcements of new projects go.

The writer suggests that principal causes for increased growth in peak demand density (kW/ km^2) in urban areas will be future construction of high-rise buildings and ever greater adoption of computers, entailing their air-conditioning. We elaborate these generalities below in Sections XIII.5.2.3.4. Section XIII.5.5 names places where we foresee growth in peak demand density during the next decade.[403]

XIII.7.2 Generality: Replacement

First, conventional cable is intended to last at least 30 years. If presently used cable was installed at a roughly constant rate, then it should be ripe for replacement at roughly the same rate. At most, 3% of the existing cable would be replaced each year. Of course, 3% of the cable under Hong Kong, Seoul, Tokyo, New York, or London is likely to provide a bigger demand than 5% of the cable under Kaohsiung, Washington, D.C., Paris, or Valencia. In short, big congested cities have more cable that will have to replaced than do smaller cities. The actual replacement rate depends on both history (in some parts of the world, large amounts of cable were installed as part of post WWII reconstruction) and today's availability of financial capital. Absence of available financial capital might induce some utilities to defer replacement.

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[403] As they become wealthier, expect increased energy consumption throughout China and India, derived from the use of air-conditioning, motors and television. HTS cable may or may not compete successfully with conventional cable, depending on whether the circumstances enumerated in Chapter XII bear upon the local situation.

XIII.7.3 Generality: Growth

Some cities have been sites for recent, extraordinary investment and recent, extraordinary density. Examples are provided by Navi Mumbai (New Bombay) and Shenzhen (a one million person suburb of Hong Kong). More generally, China's Pearl River Delta has been a region of astonishing growth and density. Many other urban areas in Asia and South America have passed from the developing world into the developed world during the last few decades. Most important, these cities and their environs are likely to continue to grow and some are likely to become even more dense. Some cities in eastern Europe may attract future investment for reconstruction in ways that preserve their cultural treasures and increase their density (high-rise hotels near, but not in, neighborhoods of historic value). Taking a longer view, investment in Central Asia, particularly the "oil-stans", may bring forth new cities and new urban infrastructure, in particular electrical infrastructure, during the coming decades. In such places, the best ways to anticipate the desire for compact cable is to look at anticipated growth in high-rise buildings and electrical generation (e.g., China's Three Gorges hydro projects).

XIII.7.4 Generality: T&D Redundancy for Reliability

Recent outages in North America and Europe have drawn attention to the value of reliability. Besides reliable illumination and reliable shaft-power, more and more telecommunication may soon rely on the grid for power, further increasing the importance of grid reliability.[404]

The traditional way to increase reliability is to build redundant systems. If future government policy encourages reliability via redundant T&D, increased redundancy, without large new investment in infrastructure, would be desirable, and HTS cable would be an enabling technology in dense, metropolitan areas.

XIII.7.5 Specifics: Where Construction of Future High-Rise Buildings is Foreseen

As already emphasized, the business districts of large, dense cities may be places where the small size of HTS cable would attract investors. Below, we suggest one way to anticipate in which cities more power and more power density will be required during the next ten years, and identify cities where new high-rise buildings or skyscrapers are

[404] Major "fixed wire" phone companies and their newly established competitors have announced plans to offer telephony via Voice over Internet Protocol ("Voice over IP"). In many places, this would be powered by the grid, not the low-voltage power system maintained by traditional telephone companies. Wireless networks often use grid power for their transmitters and relays.

foreseen. Section XIII.5.4.1 illustrates the order of magnitude of the load of a commercial building and Section XIII.5.4.2 names the cities that the writer has identified.

XIII.7.5.1 The Peak Power Demanded by High-Rise Buildings

To facilitate estimates of the demand from a particular building, we present the order-of-magnitude requirements disseminated by IEEE.[405] They relate power to floor space, as shown in Tables XIII.5.4.1.A and XIII.5.4.1.B

Table XIII.7.5.1.A
Approximate Load for Various End Uses
In Commercial Buildings

End Use	Order-of-Magnitude	Comments
Lighting		
Area Lighting	$3.5\ W/ft^2 \approx 35.\ W/m^2$	see IEEE Gray Book[A]
Closets	$3.5\ W/ft^2 \approx 35.\ W/m^2$	see IEEE Gray Book[A]
Stairwells	$3.5\ W/ft^2 \approx 35.\ W/m^2$	see IEEE Gray Book[A]
General Purpose Receptacles	$1.0\ W/ft^2 \approx 10.0\ W/m^2$	see IEEE Gray Book[A]
Air Conditioning	$10\ W/ft^2 \approx 100.0\ W/m^2$	see IEEE Gray Book[A] actual load depends on Climate, Building Occupants, and Computer Load
Dedicated Data Processing	varies greatly	depends on occupants (hotel or office building)
Fire Pumps	see Table X.5.4.1.B	depends on building height

Table XIII.7.5.1.B
Power (kW) For Fire Pumps[A]

Area (ft^2)/Floor`	5 floors	10 floors	25 floors	50 floors
05,000	40	65	150	250
10,000	60	100	200	400
25,000	75	150	275	550
50,000	120	200	400	800

[A] source: IEEE Recommended Practice for Electric Power Systems in Commercial Buildings, IEEE (New York, 1991, reaffirmed 1997) pages 73-99.

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[405] See pages 73-99 of IEEE Recommended Practice for Electric Power Systems in Commercial Buildings, IEEE (New York, 1991), colloquially known as the IEEE "Gray Book".

For the sake of illustration, consider a building with 25 floors and 25,000 ft^2 (2,500 m^2) on each floor. A rough estimate of the electrical load is: fire pumps, 0.3 MW; lighting and general purpose receptacles, 2.8 MW; and air-conditioning, 6.25 MW. Overall, the rough estimate is 10 MW for a 25-floor building, with each floor having 2,500 m^2 of space. This rough estimate should be modified for any particular building to reflect the climate, whether or not the building is shadowed by others, number of persons in the building (body heat 100 W/person), and whether the occupants require dedicated computing or kitchens, etc. The 10 MW would be delivered to a small footprint (e.g., 150 m x 50 m).[406] Of course tall office towers would require much more. Using the same assumptions, a hypothetical 50-floor, 5000 m^2 per floor, building would have a lighting and receptacle load of 11 MW. The concomitant air-conditioning might add 25 MW; therefore, it is easy to see such buildings requiring 36 MW or more.[407] Thus, the construction of such buildings deserves attention from those who offer compact cable.

XIII.7.5.2 Cities in which Construction of High-Rise Buildings is Foreseen

The status and construction of high-rise buildings concerns the Emporis Corporation, a consortium comprising Deutsche Bank, Kingspan, KONE, and the Wacker Group. This consortium makes available some data on construction plans, as well as some data on existing buildings. It is with this data that the following tables were created.[408] These tables are intended to aid those who wish to take a first step toward finding some future users for new, compact cable. The next step should be a more detailed study of the cities and the buildings foreseen. After some acquaintance with potential concerns, it would be appropriate to contact local authorities to find out their actual concerns, if any, with T&D and congestion. These authorities might now have excess T&D capacity that was installed in anticipation of future growth, soon to be realized.

The results of our initial step are easy to state. Seven cities are foreseen to be the locations of more than 150 new high-rise buildings each during the next decade. These seven are Sao Paulo (Brazil), Hong Kong (China), Tokyo (Japan), Singapore (Singapore), Toronto (Canada), London (UK), and Mumbai (India).

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[406] This hypothetical building with 2500 m2 is assumed to sit on a 7500 m^2 plot because the writer supposes that local zoning will forbid the building from using most of the land area allotted to it. Otherwise, the streets would almost always be in shadows, something that does occur in some cities.

[407] Such buildings are not likely to be in another building's shadow for a significant part of the day.

[408] More detailed data is available for a fee.

Ten other cities are foreseen to be the sites of between 75 and 150 new high-rise buildings each during the same period. They are Seoul (Korea), Chicago (USA), Bangkok (Thailand), Melbourne (Australia), Recife (Brazil), Tel Aviv (Israel), Istanbul (Turkey), New York (USA), Rio de Janiero (Brazil), and Kuala Lumpur (Malaysia).

Table XIII.5.4.2.A presents more detail about these and other cities where high-rise construction is foreseen. Subsequently, Tables XIII.5.4.2.B-XIII.5.4.2.F present more detail for each different region of the world.

Table XIII.7.5.2.A
Cities Where Construction of Many High-Rise Buildings[a] is now Foreseen*

foreseen≥300	300>foreseen ≥150	150>foreseen ≥75	75>foreseen ≥40	40>foreseen ≥20
Sao Paulo (539)	Singapore (286)	Seoul (135)	Miami (73)	Rotterdam (35)
Hong Kong (432)	Toronto (267)	Chicago (128)	Frankfurt (71)	Boston (35)
Tokyo (336)	London (204)	Bangkok (125)	Sydney (69)	San Francisco (35)
	Mumbai (156)	Melbourne (121)	Vancouver (63)	Makati (33)
		Recife (115)	Barcelona (60)	Milan (32)
		Tel Aviv (115)	Berlin (54)	Ankara (32)
		Istanbul (112)	Moscow (49)	Niteroi (31)
		New York (90)	Gold Coast City (49)	Fortaleza (29)
		Rio de Janeiro (89)	Valencia (48)	Vitoria (29)
		Kuala Lumpur (84)	Montreal (47)	Penang Island (29)
			Montreal (47)	Brisbane (29)
			Beijing (46)	Atlanta (29)
			Yokohama (45)	Victoria (29)
			Shenzhen (43)	Penang Island (29)
			Auckland (41)	Brisbane (29)
			Osaka (40)	Atlanta (29)
				Adelaide (27)
				Caracas (26)
				Curtiba (26)
				Perth (25)
				Houston (24)
				Philadelphia (24)
				Abu Dhabi (22)
				Hamburg (21)
				Perth (25)
				Houston (24)
				Philadelphia (24)
				Abu Dhabi (22)
				Hamburg (21)
				Calgary (21)

[a] A high-rise building is at least 35 m tall. "Skyscraper", a building with at least 12 floors, is the older name.
* "Number Foreseen" is defined as the sum of the buildings under construction, on hold, approved and proposed.

Table XIII.7.5.2.B

Europe: Some Cities in which High-Rise Buildings[a] are Completed, Under Construction, Approved, and Proposed*

Country	City[a]	Completed	Foreseen[c]	Under Construction	Approved + On Hold	Proposed
England	London	1,272	204	38	68	98
Germany	Frankfurt	261	71	10	9	51
Spain	Barcelona	358	60	28	16	16
Germany	Berlin	297	54	7	9	38
Russia	Moscow	196	49	33	13	3
The Netherlands	Rotterdam	248	35	18	5	16
Italy	Milan	626	32	27	2	3
Germany	Hamburg	153	21	5	9	7
The Netherlands	Amsterdam	189	19	9	3	7
The Netherlands	The Hague	138	16	7	1	8
Scotland	Glasgow	210	15	6	8	1
Spain	Santa Cruz	164	13	6	3	4
Lithuania	Vilnius	148	12	9	2	1
Spain	Madrid	319	11	4	5	2
Spain	Bilboa	292	11	5	3	3
Spain	Benidorm	310	9	6	2	1
Spain	L'Hospitalet de Llobregat	134	9	7	2	-
England	Birmingham	172	8	1	1	6
Russia	St. Petersburg	131	8	7	-	1
France	Paris	135	0	-	-	-

[a] A high-rise building is at least 35 m tall. "Skyscraper", a building with at least 12 floors, is the older name.
[b] all data in this table was provided by the Emporis Corporation, January, 2004.
[c] Foreseen ≡ Under Construction+ Approved + On Hold+ Proposed

Table XIII.7.5.2.C

Asia: Some Cities in which High-Rise Buildings are Completed, Under Construction, Approved, and Proposed*

Country	City[a]	Completed	Foreseen[c]	Under Construction	Approved + On Hold	Proposed
China	Hong Kong	7224	432	260	137	35
Japan	Tokyo	1136	336	307	19	10
Singapore	Singapore	3477	286	236	37	13
India	Mumbai	461	156	139	-	17
South Korea	Seoul	579	135	113	12	10
Thailand	Bangkok	706	125	40	61	24
Israel	Tel Aviv	182	115	21	60	34
Turkey	Istanbul	2086	112	54	37	21
Malaysia	Kuala Lumpur	512	84	55	5	24
China	Shanghai	520	80	50	18	12
China	Beijing	191	46	37	-	9
Japan	Yokohama	117	45	37	2	6
China	Shenzhen	158	43	23	6	14
Japan	Osaka	651	40	32	-	8
Philippines	Makati	120	33	14	7	12
Turkey	Ankara	396	32	23	6	3
Malaysia	Penang Island	157	29	22	1	6
UnitedArabEmirates	Abu Dhabi	128	22	15	3	4
China	Dalian	114	12	4	4	4
Israel	Haifa	148	11	6	2	3

[a] A high-rise building is at least 35 m tall. "Skyscraper", a building with at least 12 floors, is the older name.

[b] all data in this table was provided by the Emporis Corporation, January, 2004.

[c] Foreseen ≡ Under Construction+ Approved + On Hold+ Proposed

Table XIII.7.5.2.D

Oceania: Some Cities in which High-Rise Buildings are Completed, Under Construction, Approved, and Proposed*

Country	City[a]	Completed	Foreseen[c]	Under Construction	Approved + On Hold	Proposed
Australia	Melbourne	412	121	34	76	11
Australia	Sydney	643	69	22	20	27
Australia	Gold Coast City	212	47	24	8	15
New Zealand	Auckland	84	41	28	6	7
Australia	Brisbane	177	29	17	1	11
Australia	Adelaide	83	27	4	11	12
Australia	Perth	92	25	3	15	7
Australia	Parramatta	27	12	6	5	1
Australia	Redfern	35	10	7	1	2
Australia	Chatswood	23	6	1	2	3
Australia	North Sydney	91	5	2	1	2
Australia	St. Leonards	23	5	5	-	-
Australia	Canberra	14	3	2	-	1
Australia	East Sydney	57	3	1	2	-
New Zealand	Wellington	30	2	2	-	-
Australia	Bondi Junction	21	1	1	-	-
New Zealand	Christchurch	12	1	1	-	-
Australia	Manly	14	1	1	-	-
Australia	Sutherland Shire	11	-	-	-	-
Australia	Hobart	10	-	-	-	-

[a] A high-rise building is at least 35 m tall. "Skyscraper", a building with at least 12 floors, is the older name.
[b] all data in this table was provided by the Emporis Corporation, January, 2004.
[c] Foreseen ≡ Under Construction+ Approved + On Hold+ Proposed

Table XIII.7.5.2.E

North America: Some Cities in which High-Rise Buildings are Completed, Under Construction, Approved, and Proposed*

Country	City[a]	Completed	Foreseen[c]	Under Construction	Approved + On Hold	Proposed
Canada	Toronto	1582	267	50	115	102
USA	Chicago	1020	128	30	27	71
USA	New York City	5245	90	49	7	34
USA	Miami	171	73	22	20	31
Canada	Vancouver	502	63	24	15	24
Canada	Montreal	385	47	16	16	15
USA	Boston	186	35	9	15	11
USA	San Francisco	270	35	7	11	17
USA	Atlanta	185	29	8	2	19
USA	Houston	318	24	7	7	10
USA	Philadelphia	307	24	2	4	18
Canada	Calgary	190	21	6	10	5
Canada	Mississauga	197	18	6	1	11
USA	Honolulu	431	17	1	6	10
Canada	Ottawa	271	18	9	-	9
USA	Washington	242	17	14	1	2
Canada	Edmonton	220	16	4	8	4
USA	Dallas	214	13	1	3	9
USA	Los Angeles	394	7	2	2	3
Puerto Rico	San Juan	189	4	4	-	-

[a] A high-rise building is at least 35 m tall. "Skyscraper", a building with at least 12 floors, is the older name.
[b] all data in this table was provided by the Emporis Corporation, January, 2004.
[c] Foreseen ≡ Under Construction+ Approved + On Hold+ Proposed

Table XIII.7.5.2.F

South America: Some Cities in which High-Rise Buildings are Completed, Under Construction, Approved, and Proposed*

Country	City[a]	Completed	Foreseen[c]	Under Construction	Approved + On Hold	Proposed
Brazil	Säo Paulo	2055	539	491	40	8
Brazil	Recife	293	115	115	-	-
Brazil	Rio de Janeiro	1636	89	57	26	6
Venezuela	Valencia	61	48	48	-	-
Brazil	Niterói	149	31	31	-	-
Brazil	Fortaleza	140	29	29	-	-
Brazil	Vitória	235	29	27	2	-
Venezuela	Caracas	650	26	21	4	1
Brazil	Curitiba	482	26	25	1	-
Brazil	Balneário Camboriú	144	22	22	-	-
Brazil	Cuiabá	216	22	16	6	-
Brazil	Salvador	200	18	16	2	-
Brazil	Belo Horizonte	174	16	11	-	5
Brazil	Vila Velha	118	14	14	-	-
Brazil	Londrina	82	13	12	1	-
Argentine	Buenos Aries	1410	9	2	7	-
Brazil	Governador Valadares	58	8	5	3	-
Uruguay	Montevideo	287	6	3	3	-
Brazil	Maringá	60	5	5	-	-
Chile	Santiago	89	2	1	1	-

[a] A high-rise building is at least 35 m tall. "Skyscraper", a building with at least 12 floors, is the older name.
[b] all data in this table was provided by the Emporis Corporation, January, 2004.
[c] Foreseen ≡ Under Construction+ Approved + On Hold+ Proposed

XIII.8 Summary Remarks

HTS cable promises to be compact. Compact cable is likely to have above average value in places where:

(a) the price of land is high
(b) the cost of disruption is high
(c) new demands within small spaces must be accommodated.
(d) existing infrastructure (railroads, tunnels, bridges etc)
can be adapted to additional use.

Such places include the centers of cities with tall buildings. Note it is not only the peak demand, averaged over a whole city, that affects the wish for compact cable. The wish to satisfy increasing peak demand averaged over a smaller area, the city center, may also raise the wish for compact cable.

Table XIII.7.5.2a identifies cities that meet these criteria. Of course, other cities also include places where compact cable might be wanted. One must contact local utilities to learn about their excess T&D capacity, if any, that would allow them to accommodate growth in demand density (kW/km^2) without growth in their in their own T&D capacity.

Cities are not the only places where compact cable may be valuable. Wherever a circuitous and expensive overhead route can be avoided by putting a cable through existing infra-structure, rather than building new infra-structure, compact cable maybe wanted. Considering the *Alpes Maritime* or the *Pyrennes* may suggest examples to readers with local knowledge.

Growth in peak demand density can be foreseen in many cities of northern Asia. These cities include Hong Kong, Tokyo and Seoul, as well as many others. An exceptional amount of infrastructure is being built or planned for China's Pearl River Delta, which includes Hong Kong, Shenzhen and Guangzhou (Canton). The Shanghai metropolitan area is also large, growing and relatively prosperous.

Southeast Asia includes several cities of exceptional density and prosperity. Among them are Bangkok, Kuala Lumpur, Melbourne, Mumbai, Penang Island, and Singapore.

Central Asia also has several large, dense, and relatively prosperous cities, including Ankara and Istanbul.

The western hemisphere also has large, dense, growing and prosperous cities where growth in density of peak demand may be expected. Among them are Sao Paulo, Chicago, Recife, New York, Rio de Janeiro, and Toronto. Others, like San Francisco and New York are bounded by water and so even modest load growth can stimulate the search for alternatives to conventional cable when crossing water.

The places named above and the others identified earlier in this section do not exhaust the locations where HTS cable may be desirable. The named places are simply those where an above-average number of opportunities are likely to appear in the next decade and beyond.

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.[409] 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.

[409] 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.