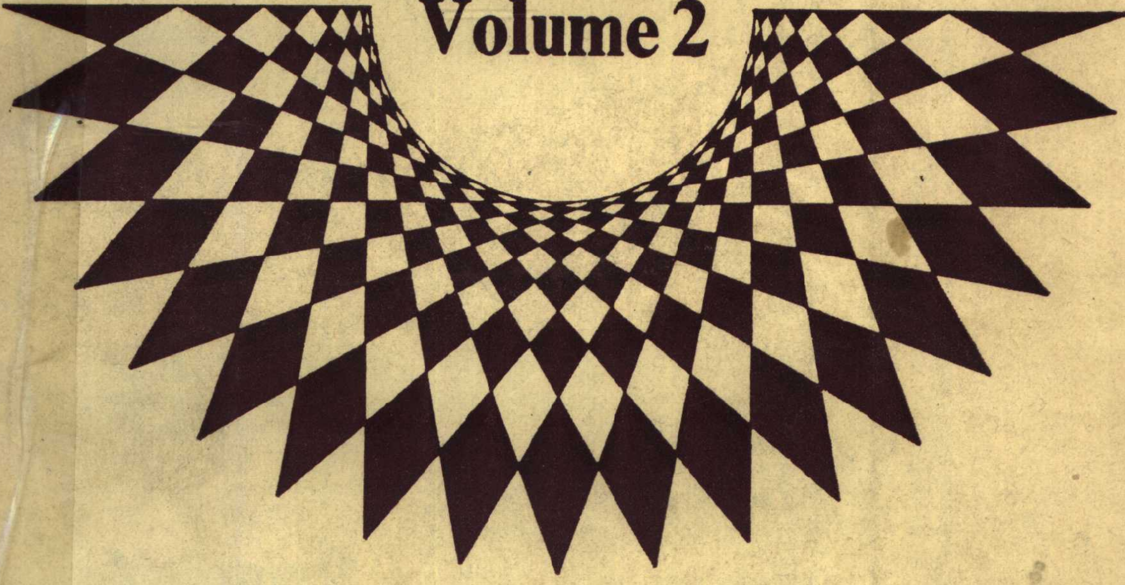
The Science and Technology of Superconductivity

Volume 2



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Proceedings of a summer course held August 13-26, 1971,
at Georgetown University, Washington, D. C.

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Volume 2

PLENUM PRESS • NEW YORK–LONDON • 1973

CONTENTS OF VOLUME 2

PART III: TECHNCLOGICAL APPLICATIONS

CONTENTS OF VOLUME 1

PART I: INTRODUCTION AND BACKGROUND

PART II: SUPERCONDUCTING MATERIALS

Part III

Technological Applications

SUPERCONDUCTING POWER TRANSMISSION *

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At the present time it is predicted that the electric utilities will need to double their capacity every ten years. This rate of growth, about 8% per year, is not in itself awe-inspiring until one considers the present size of the electric industry. The estimated demand in the United States for the year 1990 is in excess of 10^9 kW. In order to meet this demand, the electric utilities will have to install approximately 7.5 x 10^8 kW of additional generating, transmission, and distribution capacity at an estimated cost of 300-350 billion dollars.

The availability of low cost and more efficient means of transporting and distributing large blocks of power may be the most significant factor which will determine the ability of the electric power industry to meet these rapidly growing demands. This is due to several factors. First, in place of the 3,000 plants in existence today, most of the new generating capacity installed in the next 20 years is expected to come from 250 huge plants, each of which will have an installed capacity of 2,000-3,000 mVA.[1] Kusco[2] has predicted that some of the plants built between 1980 and 1990 will have capacities up to 10,000 mVA. Kusko's conclusions are supported by the predictions of Boesenberg and Zanona[3], presented in Figure 1, for the future growth of a system having a 1970 peak load of 10,000 mVA. Boesenberg and Zanona predict that, with the increase in size of generating stations, there will be a concomitant increase in the capacity of transmission lines. Second, although at 345 kV, underground cables, including right-of-way, cost 15 to 16 times as much as overhead lines in suburban areas and 18 to 19 times as much in rural areas[4], both the increasing cost of right-of-way and the increasing public opposition to overhead power lines will necessitate an increase in the use of underground power

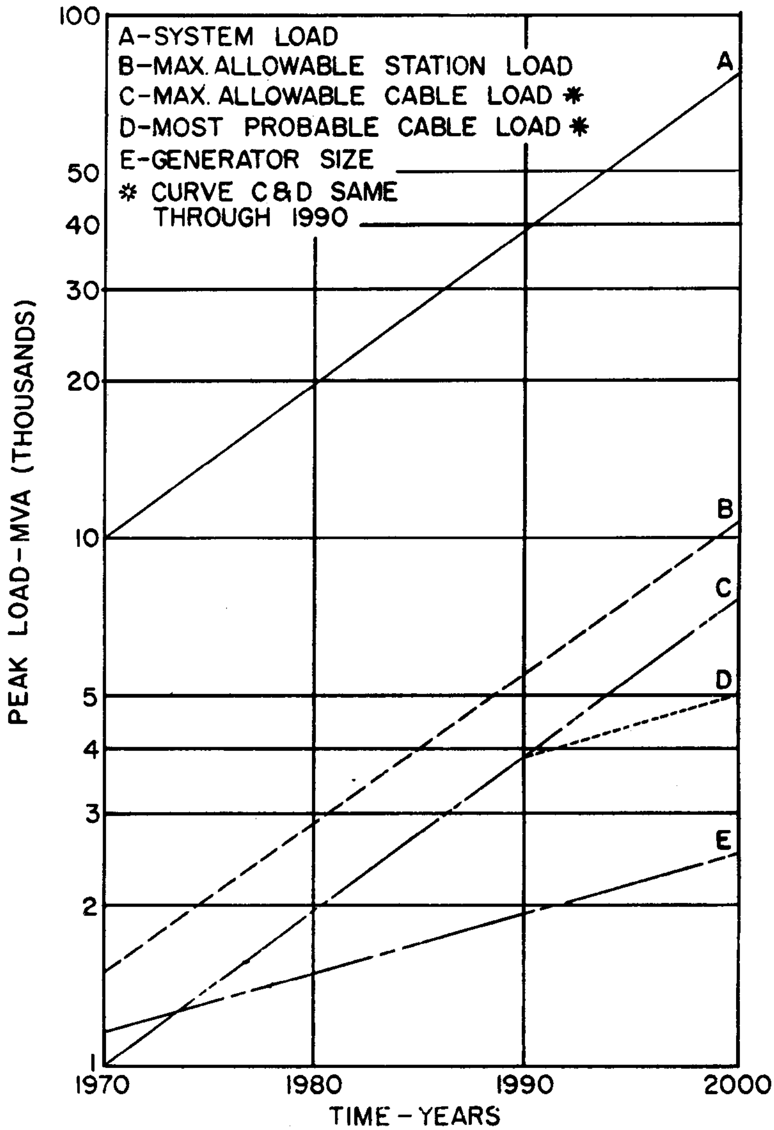

Figure 1. Peak load forecast for a 10,000 mVA system (Reference 3)

lines. For these reasons the electric utilities will be faced with the problem of transporting, via undergound cables, blocks of power even larger than those now carried by overhead lines. It is generally agreed that the present technology of underground power transmission is not capable of both efficiently and economically meeting anticipated requirements and a new technique for transporting power underground is needed.

A number of alternatives to present methods of underground power transmission have been proposed. Some of these alternatives which have been recently reviewed by others include microwave power transmission,[5,6] vacuum insulated cables operating at liquid nitrogen temperatures (77°K),[7] resistive cryogenic transmission lines,[8] and a combination in a single envelope of a cryogenic power transmission line and a liquefied natural gas transmission line.[9] Boesenberg and Zanona[3] have reviewed some of these new concepts for underground power transmission and have estimated both the power ratings at which of these systems would be economical as well as the year each of these systems would be available. Their conclusions are summarized in Figure 2. On the basis of these results, as well as other similar analyses, I believe that superconducting transmission lines hold the greatest promise for efficiently and economically meeting the requirements anticipated for the years following the mid-1980's. In the remainder of this paper, I have attempted to review the present state-of-the-art of superconducting underground power transmission.

HISTORY OF SUPERCONDUCTING POWER TRANSMISSION

The decade of the 1980's will, I believe, be characterized in part by the introduction of superconducting power lines, while the 1970's will be the decade in which the major portion of the engineering development and testing will be completed. Before beginning to assess the present state-of-the-art in superconducting power transmission, it is of value to review the work done during the early 1960's.

Superconductors may be divided into two classes, type I and type II. The type I superconductors, for example, lead, tin, and indium, have been known for many years. The use of a type I superconductor for power transmission was considered in some of the early studies described below. However, it is now generally agreed that the relatively low critical temperatures of the type I superconductors coupled with the fact that their low critical magnetic field, H_c, requires the use of large diameter conductors in order to maintain the surface magnetic field below H_c preclude their use for power transmission. Type II superconductors, for example, NbZr, NbTi, and Nb_3Sn, which were discovered in the 1950's, are

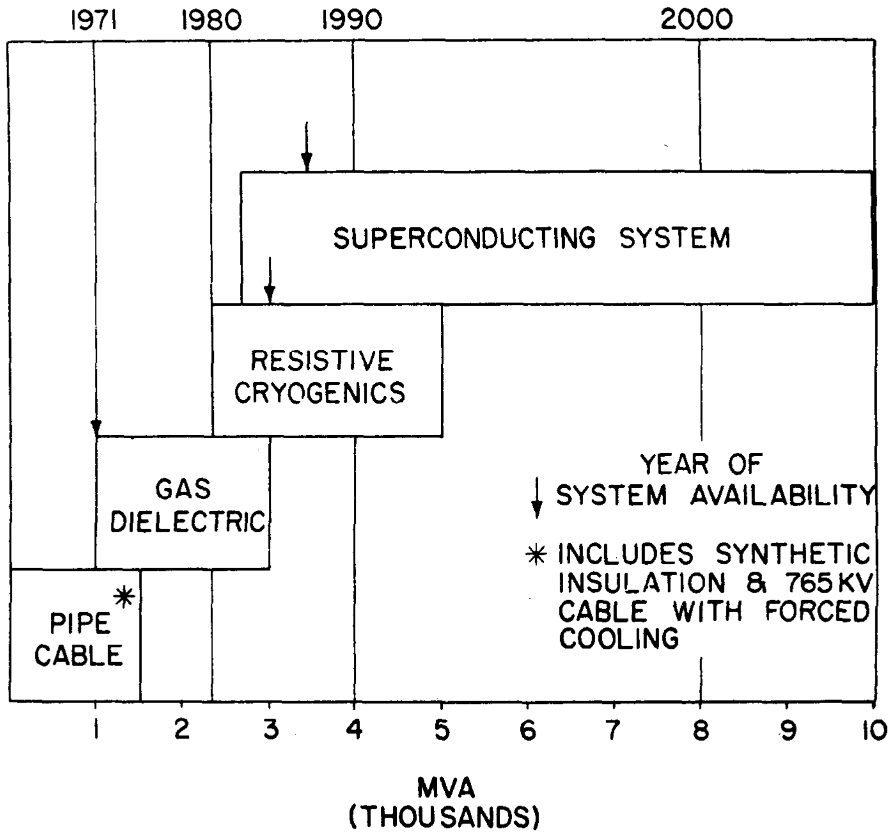

Figure 2. Capabilities of new underground transmission system (Reference 3)

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characterized by relatively high critical temperatures and their ability to carry large currents in very high magnetic fields. Unfortunately, these highly irreversible type II superconductors have losses when placed in ac magnetic fields. For this reason, type II superconductors, with the exception of pure niobium, are considered to be applicable only for dc power transmission.

In 1961, McFee[10] was one of the first to seriously consider superconducting power transmission, although he did not consider the over-all system economics. McFee proposed the use of a 3 cm diameter Nb_3Sn conductor in a dc line operating at 200 kV with a rating in excess of 100,000 mVA as well as a 600 mVA single-phase ac cable using coaxial lead conductors having diameters of 3 and 6 cm operating at 3,000 A. A coaxial lead cable was also discussed by Atherton[11] in 1963. Klaudy[12] in 1965 discussed the use of NbZr in an ac transmission line; however, like both Atherton and McFee, he did not provide cost estimates for the line.

One of the first studies to include an economic analysis was that of Gauster, Freeman, and Long[13] who proposed a 10 GW line operating dc at 150 kV, using hard niobium tubes as the conductors. The cost of such a line 1,000 miles (1 mile = 1.6 km) long, including the converters at each end of the line, was estimated to be $1,240 million ($124 per mVA-mile). This cost plus the operating cost was stated[13] "to compare well with similar calculations for 700 kV ac and 'conventional' ± 500 kV dc power lines." In 1967, Garwin and Matisoo[14] considered a 100,000 mVA dc line similar to that proposed earlier by McFee.[10] They concluded that a 625 mile line of this capacity operating at 200 kV and using Nb_3Sn as the superconductor would cost, including the converters, $806 million (∿ $13 per mVA-mile).

Because of the uncertainty about the magnitude of the ac losses in superconductors, the studies by Gauster, Freeman, and Long[13] and by Garwin and Matisoo[14] were restricted to economic analysis of dc lines. While the costs of these lines were attractive, the lines were of extremely high capacity and considerable length. Since over 25% of the cost of these dc lines was in the conversion equipment, the cost per unit length would increase very rapidly as the line lengths were reduced.

More recent studies of dc power transmission by both Voigt[15] and Delile[16] have shown superconducting dc lines to be competitive at much lower power levels than those considered by Gauster et al[13] and Garwin and Matisoo.[14] Voigt predicts a break-even point to be in the range 2-3 GW while Delile finds the superconducting line may be competitive at power levels as low as 1 GW. While these power levels are reasonable, these cost estimates did not include the conversion equipment. Thus, in the absence of a marked decrease in the cost of conversion equipment, for most power systems, the dc superconducting line cannot compete with an ac line except for very long lines. This assumes, as is discussed in the following section, that the ac losses in pure niobium do not prohibit the use of this type II superconductor for ac power transmission.

In many areas of the world, the transmission of very large blocks of power over distances of several hundred miles is increasing. As both the size of these blocks of power and the transmission distances increase, the use of dc superconducting transmission lines may be required. Nevertheless, a much more immediate problem for the electric utilities is the development of underground transmission lines to transmit large blocks of power to major urban areas from central power plants located up to 50 miles away. For this reason, I have concentrated primarily on summarizing the present status of research in ac superconducting power transmission. However, the information presented relating to the refrigerators and the cryogenic enclosures is equally applicable to superconducting dc transmission lines. In fact, these two components plus the installation costs are expected to represent over 50% of the total cost, not including right-of-way, of either dc or ac superconducting lines of comparable capacity.

CURRENT STUDIES

At the present time, there is considerable interest in superconducting power transmission in a number of countries. The major experimental studies thus far have been in the United States and Great Britain, while studies in France, Japan, Germany, and Russia have been devoted primarily to economic analyses of a number of superconducting systems. Although there is considerable amount of overlap between these various programs, they do tend in many ways to complement each other since there has been a difference in their major emphasis. For example, the study in the United States has concentrated heavily on the ac losses in superconducting niobium, the design of the cryogenic system, and a detailed economic analysis of an ac superconducting transmission line. The English studies, on the other hand, have concentrated most heavily on problems related to the electrical characteristics of a superconducting transmission line with particular emphasis being placed on problems related to line terminations and means of protecting against fault conditions.

While all current programs have a considerable way to go before the engineering development of a superconducting transmission line will be completed, the results to date are in agreement on a number of important points, the most significant of which are the following. 1. At power levels above 1 GW, the capital plus operating cost of a superconducting power transmission line will be below that of either conventional or resistive cryogenic lines. 2. Although additional engineering development is needed, there are no known fundamental obstacles which would preclude the development of superconducting transmission lines. 3. Niobium is the best choice of a superconductor for an ac superconducting transmission line.

The programs with which I am the most familiar and which, I believe, have included the most complete economic analyses are the programs carried out in the United States and Great Britain. In the United States, the largest program has been that of the Union Carbide Corporation, Linde Division, which was funded by the Edison Electric Institute while the work in Great Britain was conducted by BICC (British Insulated Callender's Cables Ltd.) on behalf of the CEGB (Central Electric Generating Board). Since there are more similarities than significant differences between all of the programs on superconducting power transmission, I will not attempt to review and compare all of these programs. Instead, I will first discuss the development and present status of the Union Carbide work. Following this, I shall review the present status of the BICC program on superconducting power transmission lines.

UNITED STATES

The most advanced program on underground superconducting power transmission in the United States is that of the Union Carbide Corporation. This program had its start in 1963 when we first began to investigate the superconducting properties of niobium prepared by an electroplating process developed by Mellors and Senderoff.[17] Measurements of both the ac losses and their relation to dc magnetization curves for this material, by Beall and Meyerhoff,[18] showed that the ac losses were low enough to make practical the use of this material in an underground ac superconducting power transmission line. In fact, Freeman,[19] in 1966, using some preliminary results of this study of ac loss in electroplated niobium wires, reported that the measured losses were only about 10% of those expected for a good cryogenic envelope of power cable dimensions. On the basis of these results, a program funded by the Edison Electric Institute was instituted in April 1968. This program consisted of two principal phases. The first was an experimental program to measure the magnetic field and temperature dependence of the ac losses in tubular niobium conductors carrying electric currents comparable to those envisioned for a superconducting power line. The second phase of the program was an economic analysis of a conceptual cable design based on the results of the ac loss measurements. This work, the details of which have been reported elsewhere,[20-24] is summarized below.

A photograph of the experimental set-up used for the ac loss measurements is shown in Figure 3. The dewar was 7 m.long and had an ID of 40 cm. One end was removable to provide horizontal access. A 40 cm. ID riser at the removable end was used for the installation of the 10,000 A current leads and a cryogen fill and withdrawal tube assembly; a second smaller riser at the opposite end was used for the electrical instrumentation. For the measurement of the ac power losses at temperatures above 4.2°K, the liquid helium

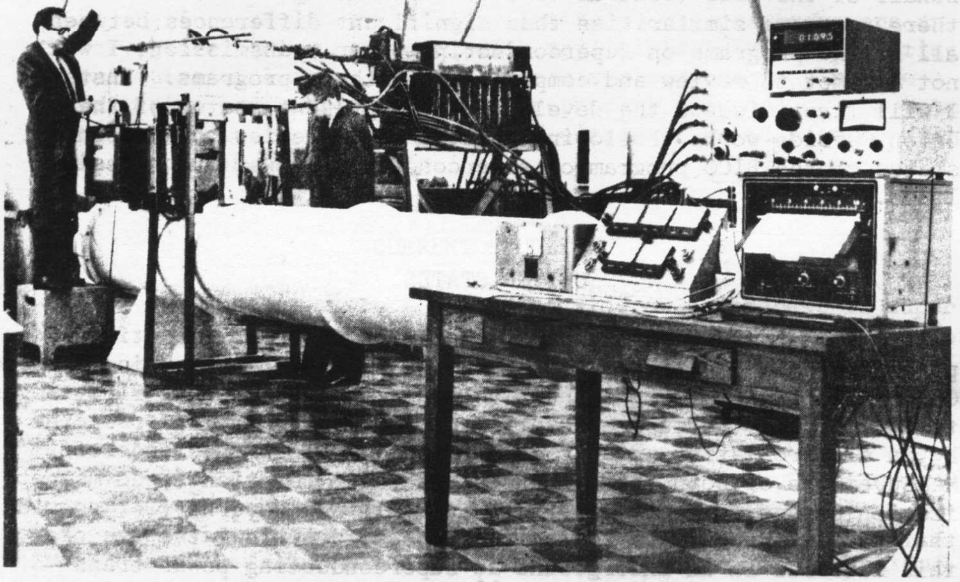

Figure 3. The ac superconducting power line test installation at Union Carbide. The transfer of liquid helium from the container on the left is being started.

temperature was controlled by maintaining a fixed pressure within the dewar appropriate for the temperature desired.

The ac loss measurements were made at 60 Hz on 6 m. lengths of 1 and 3 cm. diameter niobium tubes used as the inner conductor of a coaxial line shorted at one end. In all casès, the diameter of the outer conductor was nine times the diameter of the inner conductor. Two different 1 cm. diameter niobium tubes were tested. One of these was fabricated by electroplating, using the process developed by Mellors and Senderoff,[17] 0.005 cm. of niobium onto the outside of a 1 cm. OD, 0.85 cm. ID copper tube. A second 1 cm. OD conductor as well as the 3 cm. conductor and the 9 and 27 cm. diameter outer conductors were roll formed from 0.063 cm. thick annealed niobium sheet and longitudinally seam welded.

In Figure 4, measured values of the 60 Hz power losses are plotted as a function of the peak value of the surface magnetic field. These data were found to fit the previously observed

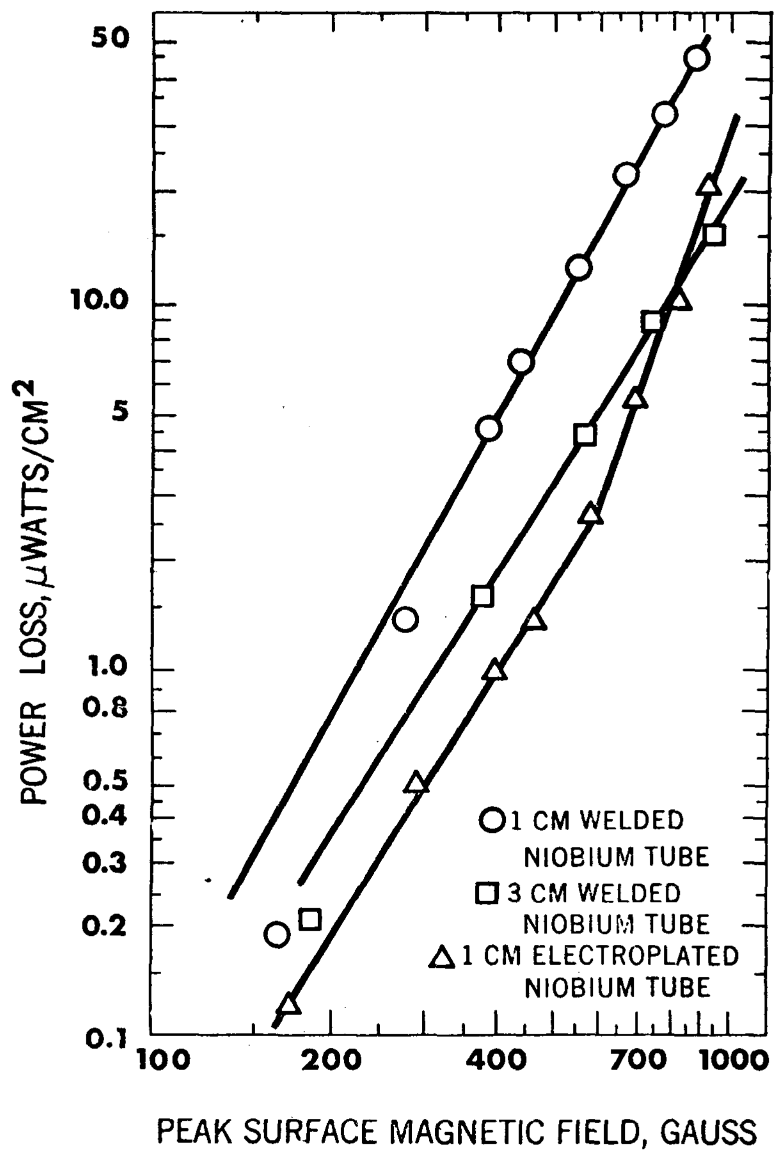

Figure 4. Power loss per unit surface area versus peak surface magnetic field for the 1 cm. electroplated and 1 and 3 cm. welded conductors