*Case Study on the US Superconducting
Power Transmission Program*

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*Edward F. Hammel**

**Consultant at Los Alamos.*

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LIST OF ABBREVIATIONS

A	amperes
AC	alternating current
AEC	Atomic Energy Commission
BNL	Brookhaven National Laboratory
CERL	Central Electricity Research Laboratory
CERN	Centre Européen de Recherche Nucléaire
CVD	chemical vapor deposition
DC	direct current
DOC	Department of Commerce
DOD	Department of Defense
DOE	Department of Energy
DOI	Department of the Interior
EEI	Edison Electric Institute
EES	Electric Energy Systems Division, DOE
EPA	Environmental Protection Agency
EPRI	Electric Power Research Institute
ERAB	Energy Research Advisory Board, DOE
ERC	Electric Research Council
ERDA	Energy Research and Development Administration
FPC	Federal Power Commission
GE	General Electric Company
GITL	gas insulated transmission line
GVA	gigavolt amperes (10^9 volt amperes)
GW	gigawatt (10^9 watts)
H _c H _{c1} H _{c2} }	critical magnetic fields (see footnotes pp. 3 and 21)
HVDC	
Hz	
IBM	International Business Machines Corporation
IRRPOS	Interdisciplinary Research Related to Problems of Our Society, NSF
J _c	critical current density (amperes/cm ²)

LIST OF ABBREVIATIONS (cont.)

K	kelvin (thermodynamic temperature)
kOe	kilooersted (10^3 oersteds)
kV	kilovolt (10^3 volts)
kWh	kilowatt hour (10^3 watt hours)
LASL	Los Alamos Scientific Laboratory (see footnote p. 26)
LTEP	Low Temperature and Electric Power Conference, London, 1969
MHD	magnetohydrodynamic
MVA	million volt ampere (10^6 volt amperes)
MIT	Massachusetts Institute of Technology
MW	megawatt (10^6 watts)
NSF	National Science Foundation
Oe	oersted
OPEC	Organization of Petroleum Exporting Countries
PECo	Philadelphia Electric Company
R&D	research and development
RANN	Research Applied to National Needs, NSF
RIF	reduction-in-force
SPTL	superconducting power transmission line
T_c	critical temperature
Type I	} superconductors (see footnote, p. 21)
Type II	
UC	Union Carbide Corporation
UHV	ultra high voltage
UPC	Underground Power Corporation

PREFACE

On June 6, 1984, the Secretary of Energy, Donald P. Hodel requested the Energy Research Advisory Board (ERAB) to "undertake a study that would examine the future energy needs of the Nation and develop judgements on the essential ingredients of a balanced energy R&D effort." In response to this charge the ERAB established a steering group and several technical panels, one of which, the Infrastructure Panel, was to deal with such issues as non-energy resources, externalities, environment and health, etc. At an ERAB meeting at the Los Alamos National Laboratory in August 1984, the Infrastructure Panel agreed that several energy technology case studies would be useful in enabling it to meet its responsibilities. At a subsequent meeting of the Infrastructure Panel, a format for these case studies was agreed upon. The present report is one of these case studies, organized according to the prescribed format.

The R&D described in this case study falls in the "infrastructure" category, i.e., it was not motivated by either energy "supply" or "demand" considerations but rather by energy "delivery," i.e. infrastructure, concerns. As noted in the 7/3/84 Draft ERAB Working Paper "Lessons from a Decade of Experience in Energy R&D" (p. 3), infrastructure energy initiatives are "the most tactical in nature and the most easily influenced by near-term attitudes in spite of the actual long-term nature of the problems."

Readers interested primarily in the policy aspects of this R&D program will find that PART I, section II. A & B and section III. A-D, F & G are the most informative and useful. PART II describes the technical and fiscal content of the program, but of that material, only section IV. A-E, G (especially Fig. 2), H and I.2.b include discussions of policy issues. Finally, PARTS III and IV are entirely devoted to policy matters.

EXECUTIVE SUMMARY

1. Superconductivity, the abrupt loss of resistance to the flow of an electric current that occurs in many materials at (and below) some very low temperature, was discovered in 1911. This transition from the normal to the superconducting state was completely unforeseen at the time and it remained a scientific puzzle until Bardeen, Cooper and Schrieffer,⁸⁵ almost half a century later in 1957, provided the correct theoretical explanation for the phenomenon.

It was also recognized shortly after the discovery of superconductivity that the ability to create a resistance-free conductor might have important practical applications. These expectations were not initially realized, however, because all attempts to pass usefully large currents through the superconductor caused it to revert to its normal resistant state.

During the five decades following the discovery of superconductivity a considerable amount of theoretical and experimental research was carried out in an effort to understand this phenomenon:

- many important properties associated with the superconducting transition were discovered, e.g. the behavior of superconductors in a magnetic field.
- many new types of superconductors were found and their properties determined,
- many significant theoretical advances were made.

Despite this effort, no practical applications of superconductivity occurred until 1961. In that year Kunzler and coworkers at the Bell Laboratories² discovered that certain carefully prepared high T_c Type II superconductors* were capable of maintaining phenomenally high currents without reverting to the normal (resistive) state.** At that point, superconductivity was ready to move out of the laboratory and into the world of practical application.⁸⁶

2. During the 1960s, the electric utility industry was becoming increasingly aware of the fact that, if its historical growth pattern was to continue, new advanced technologies would have to be developed and deployed.

*See Section II.B. p. 3 and footnote p. 21.

**These new Type II materials were also capable of maintaining the superconducting state in the presence of high magnetic fields.

But exponential growth always approaches a limit; and as that limit is approached, the next doubling period results in catastrophe unless fundamental changes in the traditional growth pattern are made. In the case of power transmission, growth-related problems were already being experienced in acquiring additional rights of way for overhead and underground cables, opposition to additional overhead lines was increasing on aesthetic (visual pollution) and environmental grounds and questions were constantly being raised regarding possible long term adverse health-related consequences of exposure to the ground level electrical and magnetic fields created by high voltage transmission lines. The answer to these problems appeared to be the development of new, advanced, very high capacity transmission systems for which the issues outlined above were either nonexistent or markedly reduced. Several such transmission technologies were already being considered by the industry and exploratory R&D had been initiated on some of them.²⁷ Of these, a power transmission line utilizing the new Type II superconductors looked promising and by the late 1960s one major research program was already being supported by the industry to explore that concept's technical feasibility.

3. With the advent of the energy crises of the early 1970s, public pressure as well as concerns about national security encouraged the federal government to undertake a substantial energy R&D effort. In the case of high capacity power transmission R&D, arguments were advanced that the private sector's efforts were inadequate and, in consequence, two additional federally supported superconducting power transmission R&D projects were begun. These activities were subsequently expanded to include a number of related supporting research activities.

By the mid seventies, a decision was made by the utility industry's Electric Power Research Institute (EPRI) to focus its attention primarily on short to intermediate term research. It was more or less simultaneously agreed that the most appropriate federal role in energy research was sponsorship of long-range, high risk, big potential pay off R&D programs and, in accord with this clarification of responsibilities, sponsorship and management of the industry-funded superconducting transmission project was transferred to the government. The subsequent course of the overall program, as reflected by its funding pattern, is shown in Fig. 2, p. 39.

4. At approximately the same time that the above-mentioned transfer was taking place and despite the fact that the nation's overall consumption of

energy was continuing to increase at near historical rates, planners in the electrical utility industry were projecting progressive decreases in the consumption of electrical energy in the US (see Fig. 6, p. 53). Given this situation, it is reasonable to conclude that, had the electrical utility industry's R&D organization been responsible for both the management and the funding of the nation's superconducting power transmission line program, a reassessment of the urgency for pressing forward with the development and demonstration phases of that program would have occurred and the program would probably have been slowed down. Within the federal R&D establishment, however, the institutional momentum for continuing R&D programs is difficult to decrease, regardless of changing external circumstances. Certainly the conclusions of the utility analysts regarding the probable decrease in urgency for developing and demonstrating advanced very high capacity transmission lines had virtually no impact upon the course of the federal program. What did occur was that, for a variety of reasons, the overall rate of increase of national energy R&D funding began to diminish and, in consequence, work on two of the three major superconducting transmission line projects was terminated as were most of the supporting research projects. The third major project (at the Brookhaven National Laboratory) was continued, however, until FY81 when its activities also began to be curtailed.

All three major programs, as well as the ancillary projects that were concurrently supported, can in retrospect be termed limited technical successes.^{34,42,87} But, and also in retrospect, since the urgency for continuing to develop and demonstrate a superconducting power transmission line (SPTL) at the originally agreed upon schedule had diminished by the late 1970s, adjustments should probably have been made in both the scope and content of the federal program at that time. This view is not universally held however.^{60,66}

The arrival of a new national Administration in 1981, with radically different ideas about who should be responsible for the latter phases of the energy R&D process will probably result in the termination of the US superconducting power transmission program by the end of FY86.

5. The conclusions that emerge from this case study are:

- a. Given the national energy crisis of the early 1970s, citizens expected the government to "do something." The government responded

by establishing new energy organizations and energy R&D programs to address the problem. The SPTL R&D effort was one such program.

- b. Within a few years of initiating the SPTL program, evidence began to accumulate suggesting that the development of very high capacity power transmission systems was not as urgent a problem as originally believed.
- c. Had the electrical utility industry been spending its own funds to support the SPTL R&D program, that program would probably have been slowed down by the mid 1970s. In particular, it seems unlikely that the industry would have proceeded with the relatively costly engineering development and demonstration phases until it had ascertained whether, and if so, when such an advanced technology, would be needed. The rate of development would then have been adjusted accordingly.
- d. Since the SPTL program was federally funded, managed, and, for most part, carried out in federal laboratories and since the national energy R&D policy in effect during the 1970s included federal involvement in the entire technology development spectrum (basic research through commercialization), it is not surprising that management emphasis was placed both initially and throughout the life of the program on reaching the engineering development and demonstration phases.

In retrospect, it can be (and has been) pointed out that many of the federally-sponsored energy R&D programs destined for ultimate use by the private sector were organized, and their continuance was "justified," by the participating R&D community itself. The establishment and maintenance of such programs were therefore based largely upon the R&D community's own evaluation of national energy needs. In this process, relatively little consideration was accorded economic and other practical private sector production and marketing requirements. Since these issues become increasingly important as the latter developmental phases of these technologies are embarked upon, their neglect by the federal R&D establishment frequently resulted in waste, excessive costs, poor technical judgements and counterproductive programmatic decisions. Sentiment is now developing in favor of eliminating involvement of the federal research

establishment from these latter developmental phases altogether or allowing it only under certain circumstances, for example, when a particular federal laboratory is clearly the best qualified performer.

- e. Accepting the fact that some bona-fide reasons do exist justifying involvement of the federal research establishment in the developmental and demonstration phases of energy R&D, the following question arises; How should the content, character, and especially the development rate of such programs be determined? The analysis of the SPTL R&D program carried out in this case study is capable of contributing some information and also one "action item" relevant to this question. Since this data is believed to be largely generic, it will be so formulated below:

- The development rate of an energy R&D program depends primarily upon the urgency and the need for the product or process under development. Since urgency and need are time dependent, it is essential that ongoing, independent and authoritative data on these two issues be provided the program management.
- If urgency and need have been established, it must then be determined whether alternative technologies are likely to be available when the decision to deploy must be made.
- If alternative technologies are expected to be available when needed, the relative technological complexities of all contenders must be determined. Those that are too complex and too unfamiliar are likely to be rejected by the potential user in favor of less satisfactory but more conventional alternatives.
- The successful new technology must "fit in" with the existing system, i.e., it must be capable of being added incrementally as needed. If the introduction of a new technology simultaneously requires wholesale replacement of an existing technology, including inventories, facilities, personnel, etc., the acceptance hurdle may be unleapable.
- The projected economic benefit of the successful new technology cannot be marginally superior to alternatives. By the time that the project is ready to embark upon its engineering development and demonstration phases, its potential economic advantages must

be substantial vis a vis those of its competitors. Otherwise, continuation of the effort to commercialize it is not warranted.

- Since it is essential that funding and management responsibility for an energy R&D program be progressively assumed by the potential private sector user as the activity enters its engineering development and demonstration phases (when the work itself is carried out in a federal laboratory), institutional changes, e.g., legislative, organizational, regulatory, fiscal, etc., may have to be made in certain industrial R&D areas (such as long-range, high-risk electrical utility R&D), in order to transfer these responsibilities to the private sector. Consequently, efforts must begin to determine what changes, if any, are required and how to accomplish them.

From an analysis and evaluation of information such as that noted above, (and implementation of the last-mentioned item) various options will emerge for energy R&D programs underway in federal laboratories, e.g., carry on, slow down, speed up, change thrust, change content, terminate, etc. Of these, the optimal option will presumably be selected and exercised by the project management. In consequence, the character, content, and developmental rate of energy R&D programs will become (and remain) more closely coupled to the projected needs of the eventual user.

Case Study on
THE US SUPERCONDUCTING POWER TRANSMISSION PROGRAM

by

Edward F. Hammel

ABSTRACT

After the 1911 discovery of superconductivity (the abrupt loss of electrical resistance in certain materials at very low temperatures), attempts were made to make practical use of this phenomenon. Initially these attempts failed, but in the early 1960s (after 50 years of research) they succeeded. By then, the projected growth in the production and consumption of electrical energy required much higher capacity power transmission capabilities than were available or likely to become available from incremental improvements in existing transmission technology. Since superconductors were capable in principle of transmitting huge amounts of power, research programs to develop and demonstrate superconducting transmission lines were initiated in the US and abroad.

The history of the US program, including the participants, their objectives, funding and progress made, is outlined. Since the R&D program was terminated before the technology was completely demonstrated, the reasons for and consequences of this action are discussed in a final section.

I. INTRODUCTION

The purpose of this study is to review the history of the US Superconducting Power Transmission program and to identify and assess the key ingredients relevant to a) the decision to initiate the program, b) its growth and expansion, c) problems that arose in the course of its development, d) its decline in terms of funding, scope and activity, e) its technological successes, f) remaining problem areas, and g) its inability to achieve industry acceptance and implementation. Finally, the "lessons learned" will be identified and examined.

PART I. BACKGROUND

II. THE SCIENTIFIC AND ENGINEERING STATUS OF SUPERCONDUCTING TECHNOLOGY PRIOR TO INITIATION OF THE PROGRAM

A. Early problems with applied superconductivity

By the beginning of the twentieth century, it had been established that the resistance of electrical conductors varied with temperature and that, for pure metals, the resistance decreased linearly with temperature. At low temperatures, however, the resistance decreased more rapidly than linearly and the reason for this change was not understood. The hope of discovering experimental clues to the origin of this particular phenomenon therefore provided an additional incentive to already ongoing efforts to achieve ever lower temperatures. Finally, in 1908, Kamerlingh Onnes liquefied helium in Leiden and, in consequence, the accessible temperature range for scientific investigation was extended to within about one degree of absolute zero.

In 1911 the Leiden group, while measuring the resistance of mercury as the temperature was progressively decreased, discovered that at 4.2 K the electrical voltage across the sample (which was carrying a small electric current) abruptly vanished. Clearly, an infinite electrical conductivity had suddenly and unexpectedly been established in the mercury. Thus was superconductivity discovered and shortly thereafter the same phenomenon was observed in lead at a critical temperature, T_c , of 7.2 K, and in a number of other metals at comparable T_c 's.

Since electric power technology was already well established in the industrialized nations at the turn of the century, the Dutch scientists immediately realized that this phenomenon might have important practical applications. By 1913, several attempts had been made to construct prototype electrical devices utilizing superconducting materials, but the results were disappointing; long before the currents through the superconductors increased to useful levels, resistance reappeared. For almost the next fifty years the phenomenon of superconductivity remained a laboratory curiosity, not even understood theoretically. During this period, however, investigations by a small group of low temperature physicists continued and the properties of superconductors were further elucidated. Efforts also continued to discover superconductors with higher critical temperatures. Transition metals, alloys, metallic carbides, nitrides, solid solutions, and ternary compounds were all

systematically investigated and many of them were found to be superconducting. An increased understanding of the criteria for high T_c superconductors gradually evolved and as the years passed several new superconducting materials with critical temperatures as high as 18 K were discovered. Inexplicably, however, the possibility that these new materials might also exhibit usefully high current densities was not investigated until the mid 1950s and even then progress was slow and halting.¹

B. The discovery of Type II superconductors

In 1960, a dramatic breakthrough was achieved by Kunzler² and coworkers at Bell Labs. In Kunzler's research it was demonstrated that a molybdenum-rhenium alloy wire at 1.5 K was capable of carrying more than 2×10^4 amps/cm² in magnetic fields as high as 14 kilooersted (kOe) without returning to the normal resistive state. In the years that followed, this limit was extended to critical current densities, J_c , in excess of 10^7 amps/cm² in magnetic fields, H_c ,* of several hundred kOe using other high T_c materials.

The discovery of these high T_c , J_c and H_c materials, called Type II superconductors, immediately revived (and extended) the ideas, generated half a century earlier by the Dutch investigators, for utilizing superconductors in electrical technology. Shortly after the announcement of Kunzler's results, papers began appearing and patent applications were filed for superconducting motors, generators, magnets, transmission lines, switches, etc. These proposals stimulated efforts by industry to develop sophisticated forms of these new superconducting materials, particularly wires, capable of being utilized in practical applications.

III. THE RATIONALE FOR INITIATING A PROGRAM TO DEVELOP AND DEMONSTRATE A SUPERCONDUCTING POWER TRANSMISSION LINE (SPTL)

A. Status of the technology for distributing electrical energy prior to the initiation of the SPTL program

Development of the technology required to generate, transmit and distribute electrical power to increasing numbers of customers began in the early 1880s. As the electrical utility industry grew, it became apparent that

*Superconductivity is also "quenched" when subjected to a magnetic field in excess of a critical field, H_c . This field is a function of temperature and can be either externally applied or self-generated by an electric current through the superconductor.

economies of scale, improvements in load factor, enhanced reliability, increased thermal efficiency and many other advantages all favored the establishment of large generating plants. Such plants, capable of serving many different load centers simultaneously, frequently could not be centrally located, e.g. because adequate supplies of cooling water were to be found only near a river or a large lake. Furthermore, the communities and cities being served were themselves often separated by large distances. Hence, realization of these large scale generation advantages required the simultaneous development of a reliable and efficient long distance power transmission system. Additional motivation for the development of such a long distance transmission technology arose from increasing interest in the construction of large hydro-electric installations, which usually had to be located far from load centers.

The first large central station plants were DC but the low voltage transmission of DC power over long distances was found to be hopelessly inefficient and all attempts to improve the efficiency proved unsuccessful.³ AC transmission was highly efficient, however, and since the advantages of large central station generation were so substantial, the US electrical utility industry quickly (but not without controversy) committed itself to the generation, transmission, and distribution of AC power. For the most part, the rest of the industrialized world followed suit.

During the next eighty-five years, the primary objective of the US electric utility industry was to satisfy the increasing consumer demand for reliable electric power at the lowest possible cost. And, as measured by the growth of installed generating capacity and kilowatt-hours (kWh) of electricity produced (which exceeded 7% per year except during the Great Depression) that objective was achieved.

B. Problem areas

This remarkable growth was not sustained without the appearance of new technical problems. For example, since the amount of power that can be transmitted over a given cable increases as the voltage is increased and since cable costs account for a substantial fraction of the capital costs of a transmission line, efforts have continually been made to increase line voltages. But increasing line voltages caused new problems relating to insulation, corona discharge, radio, telephone and TV interference, transformer design, cable design, circuit breaker design, biological effects of high voltages, etc. By mid-century, however, these particular problems had been

solved to the extent that AC transmission lines could be designed, built and operated satisfactorily up to about 345 kV.

When these transmission systems were interconnected in order to enhance the reliability of power delivery, additional problems relating to network stability and control arose. It was also found that, with these large interconnected transmission networks, increased line and load reactances limited the actual amount of power that could be delivered to customers. Again, solutions were eventually found to these problems and by 1960, it could be justly and proudly claimed that the US electrical utility industry was based upon a mature and successful technology capable of continued expansion in support of the expected further growth of US commerce and industry.

By the mid 1960s a new and different kind of problem, namely increasingly severe insults to the environment caused by the continued growth of many types of large scale industrial activity (including the electrical utility industry), had become apparent to a large segment of society. These insults eventually became so widespread and so severe that a national consensus was generated demanding that some corrective action be taken to ameliorate the problems that were being created: A recital of the litany of the many specific environmental insults to air, water, land, flora, fauna and humans that finally produced a Federal response is irrelevant to the present discussion, but by 1969 that response was substantial. It included passage of the National Environmental Policy Act, establishment of the Council on Environmental Quality, establishment of mandatory Environmental Impact Statement filing procedures and the establishment of the Environmental Protection Agency (EPA).

It was immediately recognized by the electrical utility industry that the probable impact of these environment-related actions upon the projected growth of the industry would be significant. The maintenance of a 7% growth rate to meet expected demand required a doubling of generating capacity and its associated transmission system every decade; and by 1970, with 1500 billion kWh of electricity being produced from 350 gigawatts (GW) of generating capacity and then distributed over 250,000 miles of transmission lines, serious public concern had already surfaced regarding air pollution from power plants, the safety of nuclear generating plants, the disposal of radioactive waste from reactors and adverse health, environmental and aesthetic impacts of transmission lines. The utilities themselves were simultaneously finding that

the acquisition of new transmission rights of way was becoming both difficult (either due to land use restrictions or the absolute unavailability of additional land) and costly. Under these circumstances, the prospects of obtaining the necessary approvals for the construction of new generating plants and new transmission lines to enable the industry to meet the projected 7% per annum increase in demand were dim.

Nevertheless, planning for further expansion continued and in 1973, the Federal Power Commission (FPC) in its annual National Power Survey⁴ estimated that by 1990 the average size of each generating unit in a power plant would be about 2.7 GW and each plant would be producing about 10 GW. The idea of grouping several such plants to form a so-called "power or energy park" was also much in vogue at the time. Combining this type of generation projection with the expected increase in demand, the FPC survey concluded that by 1990 single transmission lines with capacities up to 10 GW might be needed.

A related problem in the early 1970s was whether the commitment of several GW of power to a single line was a responsible operational procedure for meeting the projected overall growth in demand. The answer depends upon whether an interruption of the flow of electrical energy over the line in question would comprise a large fraction of the power being supplied the load center and upon whether alternative routes for power delivery would be readily available. This question was eventually answered in the affirmative, since, as load center demand continued to grow and as power networks were increasingly interconnected, so also could the amount of power per transmission line be safely permitted to increase.

C. Conventional solutions and their problems

The conventional solution to increasing overhead transmission line corridor capacities has been either to install additional lines in parallel with existing ones or to increase existing line voltages. Of these options the former has been effectively eliminated by both environmental (aesthetic) constraints and either the outright unavailability of, or the excessively high acquisition costs for, additional rights-of-way.

It is indeed true that exercising the latter option is an extremely effective method of increasing line capacity as shown in Table 1. These data are approximate because an overhead AC line's power carrying capability depends upon length as well as upon voltage and these particular entries refer to a line 300 miles in length. At 100 miles the power carrying capability is

greater by a factor of about two; at 600 miles the capacity is reduced by about 60%. Obviously, significant increases in load are obtainable by increasing line voltage.

TABLE 1
APPROXIMATE AC OVERHEAD LINE LOADING

Line Voltage (kV)	Approximate Surge Impedance Loadings* (GW)	Total Number/Percentage of US Transmission Line Miles†
22-131	<0.07	423,800/67.9
132-253	0.07-0.14	144,500/23.1
254-400	~0.37	35,500/5.7
401-600	~0.85	17,700/2.8
601-800	~2.2	3,100/0.5
1100	5.0	-0-
1400	8.0	-0-

*"Surge Impedance Loading" is a measure of a transmission line's power carrying capacity. Data from Ref. 4.

†Data from Statistical Yearbook of the Electrical Utility Industry/1980, Edison Electric Institute.

The US electrical utility industry, in pursuing this option for increasing transmission line corridor capacity, had by 1970 installed a few 765 kV transmission lines, but all of them provoked considerable opposition from environmental groups as well as from other citizen organizations concerned about adverse long-term health effects that might result from the high electromagnetic field gradients created by these lines at ground level. Although it was clearly possible to construct and operate 765 kV transmission lines, their public acceptance in the US was (and still is) far from assured.⁵

Another conventional option was the undergrounding of transmission lines, but there the situation was even worse. Undergrounding has always been in principle a desirable option, but its cost has commonly ranged between 3 and 20 times that for overhead systems of the same capacity and the highest

capacity underground cables available in the 1960s were capable of transmitting only a fraction of the power that could be carried in an overhead system. Furthermore, in addition to their high costs and limited power carrying capacity, these cables were characterized by high insulation losses, excessive charging currents (leading to length limitations), high resistive losses, and the need for complicated cooling systems to dissipate the resistive heat generated. It is therefore not surprising that underground transmission systems still comprise less than 1% of the nation's total power transmission network, and in general are utilized only when the use of overhead systems is barred by topography, by law or by prohibitively expensive right-of-way acquisition costs.

D. The response of the electrical utility industry and the federal government

The problems expected to be encountered in attempting to meet the nation's projected demand for electric power for the next several decades by either a straightforward multiplication of current overhead and underground technology or by continued incremental improvements in these systems prompted the electric utility industry in the mid 1960s to intensify its R&D efforts in power transmission. Although dramatic breakthroughs in conventional transmission technology were not expected, it was believed that a sufficient number of small improvements in power transmission capability could be achieved with a vigorous "product improvement" R&D program to permit the growth in electrical production to continue at approximately the projected levels for the near term. If, simultaneously, R&D support was provided for exploratory research in advanced power transmission concepts, there was reason to believe that one or more of these new ideas could be developed in time to permit an orderly and reliable transition when needed to much higher capacity, safe and environmentally acceptable transmission systems. This particular strategy was adopted by the industry, and it was further supported by those agencies of the federal government authorized to foster improvements in the delivery of electric power to the nation's consumers.

Beginning about two decades ago, the Electric Research Council (ERC) [initially through the Edison Electric Institute (EEI) and, after 1973, through the Electric Power Research Institute (EPRI)] in collaboration first with the Department of the Interior (DOI), then with the Energy Research and Development Administration (ERDA) and now with the Department of Energy (DOE) have carried out such an R&D program. In general, the federal program tended

to support long-term, high-risk advanced power transmission projects whereas industry support was concentrated on those more likely to have an impact in the near (10 yrs) or intermediate (10-25 yrs) term. There was, however, considerable overlap in support; for example, the industry elected to provide substantial support for R&D in advanced, but not particularly revolutionary or unfamiliar, concepts such as the compressed-gas-insulated transmission line. The federal government has, on the other hand, been the primary sponsor of the more unusual, less familiar, research proposals.

E. Alternative advanced transmission technologies

Although alternative advanced transmission technologies other than the superconducting one are not the subject of this case study, the fact that the research undertaken to develop them took place concurrently with that of the superconducting power transmission line is relevant to this discussion and it is therefore important to specify what these technologies were. In this concluding portion of section III these alternatives and the SPTL are briefly described.

1. Overhead transmission

a. Introduction. Some of the technical problems associated with, and the basis for public opposition to, increasing the power carrying capacity of existing overhead transmission line corridors by increasing line voltages have already been mentioned. Consequently, the electric utility industry and the federal government have continued to support a substantial R&D program in both AC and DC overhead transmission with the general objective of systematically overcoming these impediments.

b. The AC overhead power transmission R&D program. The components of this program were (and still are):

- determination of the effects of electromagnetic fields on human health.
- establishment and maintenance of a research program organized to identify and solve the technical problems (such as insulator design, transmission tower design, cable design, grounding, etc.) arising from overhead power transmission systems at voltages from 765 kV to 1,500 kV.

Of these two main R&D thrusts, the problems noted in the latter appear to be technically soluble, especially at the lower voltages and, as seen in Table 1, the increased use of such lines can provide marked increases in transmission

capability. Ambiguous and contradictory results from research in the first-mentioned R&D category are, however, still inhibiting the large scale exploitation of this technology at voltages in excess of 345-500 kV. In consequence, most of the transmission line mileage added in recent years has still been at 345 kV.

c. The DC overhead power transmission R&D program. A century ago the high voltage transmission of DC power was technically difficult and hopelessly inefficient over long distances. Recently, however, technological advances in AC→DC conversion technology at high voltages (and its inverse) as well as in DC circuit breaker design have made the long distance transmission of DC power technically feasible. This transmission mode has also turned out to be economically feasible for sufficiently long distances (although the cost per mile of a DC system is substantially less than that of an AC system, electric power is both generated and utilized in an AC mode. Hence, costly converter, AC→DC, and inverter, DC→AC, stations must be installed at the line terminals. An economic "crossover" distance favoring DC over AC therefore always exists for DC transmission systems.)

One advantage of DC systems is that the enhanced power carrying capacity obtainable by increasing the line voltage can be achieved at half the AC voltage penalty by the use of a bipolar system in which half the DC voltage difference is above ground potential and half below. Other advantages include narrower rights-of-way, lower line costs, enhanced firm power capability, etc.

A final important advantage of DC systems derives from the power flow instabilities inherent in large interconnected AC networks (mathematically these are highly nonlinear systems whose behavior, when perturbed, is difficult to predict or control). Such instabilities (power surges) cannot propagate in a DC system and in consequence, short DC transmission links are being increasingly used to interconnect large regional AC power grids. Under these circumstances the cost of the terminal equipment is justified by the protection afforded the interconnected networks.

Given these advantages, it is not surprising that a considerable amount of R&D has been underway for the past two decades on overhead high voltage DC (HVDC) transmission systems. Particular emphasis has been placed upon the development of ancillary equipment such as less costly and more efficient AC→DC converters, high-voltage, high-current DC circuit breakers, DC insulators, DC cables, ground electrodes, etc. and this research has been

remarkably successful. Unfortunately, DC field effects upon human health remains as much of a problem as in AC transmission although, as noted above, in DC systems the voltage magnitude is halved for the same power carrying capability of an AC system. Research on DC field effects upon human and animal health is therefore continuing.

The demonstrated advantages of DC transmission for both increased power carrying capability and system control together with the recent advances in the necessary supporting technology have encouraged many utilities to consider the increased use of this transmission mode. To date, however, its actual utilization has been small. In 1983, for example, no new transmission mileage added was DC. The reason for its unpopularity may lie in the fact that its use always involves high terminal costs and that it is still an overhead transmission mode with which all of the health, environmental and aesthetic problems of AC are associated. The fact that with DC these problems are diminished may not yet be sufficient to justify substantial utility commitment to its use.

2. Underground transmission

a. Introduction. In the case of conventional underground transmission cables, the power carrying capabilities of overhead lines shown in Table 1 as a function of line voltages are significantly reduced.⁶ Technologies for overcoming this limitation are being developed, however, and will be described below.

It is important, in introducing this section on underground transmission, to emphasize that, in general, the primary R&D problem to be solved is that of reducing underground transmission costs to levels roughly equivalent to those of overhead lines of comparable capacity. Comparable underground capacity can of course always be achieved by installing multiple underground lines and, in contrast to increasing overhead transmission power carrying capacity by the installation of multiple overhead lines, the use of multiple underground cables would eliminate the aesthetic, environmental, and electromagnetic field-related health and safety problems of overhead systems. But the use of multiple underground cables would involve multiple trenching, multiple cable splicing, multiple terminals, multiple reactive compensation and multiple rights-of-way as well as increased engineering related to avoiding existing underground utilities (water, sewer, telephone, etc.), increased problems with legal limits on the length of trench allowed to remain open in urban areas,

etc. Meeting such requirements would make this approach both operationally impractical and unacceptably costly. The rational way of reducing underground transmission costs therefore appears to be (as in the case of overhead transmission systems) that of increasing individual underground line capacities.

Given this general conclusion, it is essential to note that, in practice, the specialized technical characteristics of the different high capacity underground cable systems now under development may make one or another of them optimally appropriate for a particular application. Hence comparative cost is by no means the only criterion in choosing an underground cable system. The provision of different new, proven and cost-evaluated high capacity underground cable options designed to satisfy different operational requirements therefore appears to be the most useful objective of an underground cable R&D program and this strategy has, in general, been adopted by both the industry and the federal government.

b. Pipe-type cables: Most underground cable systems in the US are of this type. AC pipe-type cables consist of three conductors (one for each phase), each wrapped in kraft paper* and pulled through a steel pipe which has been laid in a trench. The pipe is then filled with an insulating oil and pressurized. The resistive and the dielectric heat generated by passage of the current is ordinarily dissipated in the surrounding soil, but for a high capacity cable the oil itself must be circulated and externally cooled.

R&D on this type of cable has been directed toward improving the quality of the paper insulation and that of the oil dielectric, developing extruded plastic insulation (to replace the more costly paper wrapping), improving the efficiency of the oil cooling systems, reducing the cost of trenching e.g., by developing effective tunneling systems, improving the thermal conductivity of the trench backfill material, etc.

Some improvement in the power carrying capacity of pipe-type cables has been achieved as a result of these R&D programs but the main consequences of these efforts have been improvements in reliability and reductions in cost.

c. Gas-insulated transmission lines (GITL). In this type of cable the insulation between a rigid axially located conductor and the solid metallic sheath is provided by a compressed gas with a high-dielectric strength such as SF₆. Its advantages are:

*A strong dark brown paper made from sulfate pulp.

- markedly increased power carrying capacity; for example, an increase by a factor of five over that of a conventional pipe-type cable at 500 kV,
- reduced charging currents leading to greatly increased critical lengths,
- negligible dielectric losses,
- improved thermal performance
- enhanced voltage insulating properties permitting substantially increased transmission line voltages.

Its primary disadvantage is:

- high cost (as noted above, although the power carrying capacity of a GITL can be many times that of a pipe-type cable, three of the former are ordinarily required, one for each phase).

R&D is now being directed toward GITL cost reduction. For example, cable manufacturers have developed a prototype gas insulated transmission line carrying three phase conductors and flexible gas-insulated cables capable of being dispensed from reels have also been developed. Other R&D directed toward reducing the cost of installing underground pipe-type cables mentioned in b. above will also impact upon GITL installation costs.

d. Cryoresistive cables. As noted in section II of this study, the resistance of pure metal conductors decreases with decreasing temperature. In the case of copper or aluminum conductors, their resistivities are reduced by a factor of about 10 when cooled to 77K, achievable by the use of liquid nitrogen as a refrigerant. Further decreases in resistivity occur at even lower temperatures and studies have been carried out investigating the technical and economic feasibility of cryoresistive cables operating at temperatures as low as 20K (achievable by using liquid hydrogen as the refrigerant). The rationale for pursuing the engineering aspects of cryoresistive cables is their large (2000-5000 MVA) power carrying capability per line. R&D programs have therefore been undertaken to develop cryoresistive cables with the objective of reducing the line's complexity, improving refrigerator performance, improving the dielectric performance of the cryogenic fluids that have to be used as refrigerants, etc.

e. Miscellaneous underground cable development.

1. Self-contained cables: this is a variety of pipe-type cable extensively used in Europe. Each phase is contained in its own

cable consisting of a hollow core filled with a pressurized oil, a hollow stranded conductor, insulation and a protective sheath. Heat transfer to the surrounding soil is much improved with this type cable and power carrying capacity is about twice that of a comparable pipe-type cable. To date these cables have not been used extensively in the US.

- ii. Microwave transmission through underground wave guides: Although this approach received some consideration several years ago, efficiency problems have so far delayed the initiation of a significant R&D program. The same problems apply to power transmission via laser radiation.
- iii. Charged particle transmission: This is an interesting, very high capacity transmission concept. To date, relatively little effort has been expended to explore either the technical or the economic feasibility of this idea.⁷

f. Superconducting power transmission lines. As we have already noted, the discovery of Type II superconductivity occurred at about the same time as the need for a much increased power transmission capability was recognized. It was apparent from the outset that, in principle at least, underground transmission lines utilizing Type II superconductors would be able to transmit large amounts of power

- without loss (except for that required for refrigeration)
- over long distances
- with zero external electromagnetic field,
- with negligible environmental and health-related problems and
- in right-of-ways only 8-10 ft. in width.

The problem seemed to be not whether such a technology could be developed, but only whether a superconducting transmission line could be made sufficiently reliable at a cost equal to or less than those of competing high capacity power transmission technologies, all of which appeared a priori to possess far fewer technical and societal advantages.

F. Summary

- the electrical generation, transmission, distribution and utilization system adopted in the United States is primarily AC.
- the growth rate of the US electrical energy system approximated 7% per year until 1974.

- by mid-century the adverse environmental impacts of industrial growth provoked public concern and eventually governmental action forcing US industry to achieve future economic growth in ways compatible with protection of the environment and preservation of the public health and safety.
- in order to satisfy the increasing demand requirements for electricity in ways compatible with preserving the quality of the environment, protecting the public health and ensuring the public safety, the electrical utility industry was obliged during the 1960s to focus attention on the development of 4-10 times higher capacity bulk power transmission systems (among other things). In 1971, the potential power transmission capabilities of several of the advanced systems then under development were summarized by Boesenberg and Zanona⁸ as shown in Fig. 1.

Fig. 1. Capabilities of new underground transmission systems.⁹²

G. Conclusion:

The substantial power carrying capability of a superconducting power transmission cable coupled with the expected need for very high capacity transmission systems in the future provided the rationale and the motivation for initiating a research and development program to explore the technical and economic feasibility of this new technology.

PART II. DATA: PROGRAMMATIC AND FISCAL

IV. THE US SUPERCONDUCTING TRANSMISSION LINE PROGRAM

The claim made near the end of the previous section that superconducting transmission lines were capable of transmitting "large amounts of power without loss" now has to be further qualified, but only slightly. The first part of that claim is rigorously correct, but the "without loss" part is true only for superconducting power transmission at constant DC current.* For AC transmission a small amount of energy dissipation in the superconductor always occurs and it also always occurs with DC transmission whenever the amperage is changed. Even with a "constant" DC current, the small superimposed ripple current introduced by the AC/DC conversion equipment at the terminals causes some slight dissipation. But in comparison with the resistive heat generated in conventional cables, the dissipation occurring in an AC superconducting cable is small and that produced in a DC cable is even less. Although, as previously noted, energy is also required to maintain the cable at low temperature, that refrigeration power amounts to only a few tenths of a percent of the transmission load envisaged for a SPTL. In any event, since the primary need of the industry was for an increased power transmission capability, and since SPTLs could clearly satisfy that need, a considerable amount of enthusiasm for an investigation of the practical problems associated with the development of both AC and DC SPTLs emerged during the 1960s.

A. Initial studies

What first occurred was the publication of a series of preliminary technical and economic feasibility studies for both AC and DC superconducting transmission systems.⁹⁻²³ Then, after reviewing the literature and carrying out thorough internal corporate analyses, three major low-temperature power transmission R&D projects were begun in the US; one by the General Electric Company (GE), one by the Underground Power Corporation (UPC) and the third by the Linde Division of the Union Carbide Corporation (UC). GE and UPC opted to develop resistive cryogenic cable,^{24,25} and UC opted for the development of an AC superconducting cable.²⁶

*But at current densities less than J_c .

B. A hesitant US response

It is of interest to note that, given the same amount of scientific and technical information, only three utility-related industrial organizations (out of perhaps a dozen) elected to become involved in the low temperature power transmission effort and of these three only one undertook the development of a superconducting transmission line. Why? The answer is not totally clear, but from the public record the following observations may be relevant:

- In 1970, the ERC appointed a Research and Development Goals Task Force to "establish R&D goals together with priorities, timetables and cost estimates." In its final report, "Electric Utilities Industry Research and Development Goals Through the Year 2000,"²⁷ the first "goal" listed was

"to produce, transmit and distribute electric energy in ways that are compatible with a healthy and pleasant environment."

The recommended R&D projects were assigned priorities 1-4, of which the Priority 1 projects were defined as "Critically Important: projects having an indispensable effect on all of our goals; which by their nature must receive first attention."

In the area of Bulk Power Transmission, one of only three Priority 1 projects was the development of Cryogenic Cables (including an AC Superconducting Cable) by the year 1990. There is therefore little doubt that the utility industry itself was, during the early 1970s, strongly supportive of research on superconducting power transmission.²⁸

- Electrical utilities have historically relied heavily on their manufacturers for performing the R&D required by the industry. Furthermore, consider the following quotation from an industry report: "Manufacturers generally do not invest tremendous sums of money in projects that will not produce a marketable product and return on their R&D investment for many years."²⁹ In the case of UPC, this reasoning probably played a role in their decision to concentrate on the cryoresistive cable.²⁵ In the case of GE, the superconducting option was carefully examined. Their expectation that a cryoresistive cable would be simpler to develop, would be

needed first* and, by using an appropriate design, could subsequently be adapted to the use of a superconductor, undoubtedly played a role in their choice. It was also expected that the development and deployment of a cryoresistive cable would provide valuable cryoengineering experience for moving on subsequently to an SPTL development.²⁴ UC on the other hand was totally comfortable with the cryoengineering aspects of the problem, and, in addition, had already been investigating the applied physics aspects of using superconductors for transmission line applications for several years.²⁶ Although UC was not then involved in the provision of equipment for the electrical utility industry, it was abundantly clear that if cryogenic cables were to be massively deployed by the industry, UC would be in a position to become a supplier.

- The two largest manufacturers for the US electrical utility industry, GE and Westinghouse, both possessed substantial expertise in low temperature physics in their research laboratories. There is no doubt that the management of each corporation had been made fully aware of the potential applications of Type II superconductivity in the electrical utility industry prior to their making a decision to either enter or defer corporate entry into an SPTL R&D project. The choice made by GE has already been discussed. Westinghouse elected to focus its R&D resources on the development of a superconducting generator.

C. A vigorous foreign response

During the late 1960s and early 1970s, there was no lack of interest in superconducting cable development abroad. By 1973, major SPTL R&D efforts were underway in the United Kingdom, West Germany, Austria, France, USSR, Japan, and Canada. These programs are described briefly in Appendix I. Although some of these foreign projects were government sponsored, many were privately funded.

It is perhaps appropriate to remark at this point that, since about 95% of the basic research that led to the discovery of Type II superconductivity was carried out in the US and funded by the US government, it was particularly galling to US researchers to observe the relative ease with which foreign

*See Fig. 1.

researchers were able to obtain funding for R&D designed to exploit the discovery of Type II superconductivity not only for power transmission but also for such projects as high speed rail transportation, motors, generators, transformers, switches, energy storage magnets, MHD magnets, etc. It may also not be coincidental that all of the foreign research centers carrying out SPTL projects were either well-established manufacturers for the electrical utility industry e.g., Siemens, Brown Boveri, Allgemeine Elektrizitäts Gesellschaft (AEG), Électricité de France, Compagnie Générale d'Électricité, etc. or governmental research institutes with responsibility for electric power research, e.g. the UK Central Electricity Research Laboratories, the USSR G. M. Krzhizhanovsky Power Engineering Institute, etc.³⁰

There is little doubt that the vigorous response made abroad to the possibility of utilizing the remarkable properties of Type II superconductors, not only in SPTLs but also in a variety of other practical applications, was forcefully brought to the attention of potential federal and industrial sponsors of R&D by US scientists. Although the scope of US applied superconductivity research never matched the total of that undertaken abroad, the existence of these foreign initiatives and the interest of US scientists and engineers in seeing a comparable effort underway in this country eventually led to the initiation of a moderately respectable US R&D program in this area.

D. The UC/Linde AC superconducting transmission line project

The UC program began in 1963 with investigations of the superconducting properties of electroplated niobium films. In particular, measurements of AC losses at power transmission frequencies showed that these losses were low enough to make practical the use of this material in an underground AC SPTL.³¹ By 1968 a research proposal to investigate the feasibility of this type of advanced power transmission technology was funded by the ERC through the EEI. The first phase of the project consisted of additional AC loss measurements using tubular niobium conductors similar to those envisioned for use in a power line.³² The second phase consisted of an economic analysis of a prototype cable design based upon the conductor loss measurements.³³

Additional support for the UC project was provided in 1974 by the DOI and, after the ERDA was established in 1975, federal funding for the UC project was provided by this agency.

Besides establishing the AC loss behavior of the superconductor chosen, the other components of an AC SPTL R&D program include the development of satisfactory low temperature dielectric materials, conductor design and development, the development of conductor joining processes, provision for thermal contraction, heat transfer and cycling, insulation development, development of the necessary refrigeration technology, studies of cryogenic fluid flow, development of cable terminations, personnel and equipment hazard analyses, etc. All of these components had to be appropriately designed and sized to meet the cable's projected utility use requirements in terms of emergency ampacity, fault current capability, accommodation to switching and lightning surges, etc.

The UC project's objectives, as finally formulated, consisted of the design, development, fabrication, and testing of a prototype 3,400 MVA 138-kV AC niobium superconducting cable system for high capacity underground power transmission. Essential elements of the design consisted of an 0.08 mm thick niobium conductor electroplated on an 0.8 mm thick copper substrate (to accommodate fault currents) with the copper itself being bonded to a 1.6 mm thick invar tube (to provide thermal dimensional stability). The cable itself consisted of three such conductors (one for each phase) each held coaxially in its own superconducting shield with insulating spacers. These three coaxial cables were to be assembled along with a helium return line within a single rigid 18-25 m long factory-fabricated, evacuated and sealed multishielded cryogenic envelope. The primary dielectric between the conductors and shields was to be pressurized helium at a temperature of about 4.7K. Installation of the factory assembled sections was to involve the field joining of the conductors, shields, helium return line, and the outer cryogenic envelope.

The funding history of the UC project is given in Table 2 and in Ref. 34 the title and National Technical Information Services (NTIS) number of the UC/Linde project's final report is listed.

It is important to note at this point that the 1968 decision to use niobium as the conductor was entirely reasonable. At that time it was generally believed that AC losses in Type II superconductors could only be

TABLE 2
FUNDING DATA FOR THE UC/LINDE AC SUPERCONDUCTING CABLE PROJECT

<u>FY</u>	<u>Funding(k\$)</u>	<u>Source</u>
63-71	536	EEI/EPRI/DOD
72	240	EPRI
73	300	EPRI
74	340	EPRI
	85	DOI
75	484	EPRI
	120	ERDA
76	475	ERDA
77	150	ERDA
Total funding	2730	----

kept low by operating below the first critical field, H_{c1} .^{*} Niobium has the highest H_{c1} of any Type II superconductor (approximately 1000 Oe at 4K), and it was this fact, together with its other properties (such as the relative ease of making superconducting joints in the field), that made it a strong candidate. On the other hand, its low transition temperature, $T_c = 9.5K$, required that the cable be operated between 4 and 5K and this, in turn, imposed high refrigeration costs. Finally, some critics have suggested that the decision to use helium as the primary dielectric imposed additional limitations on the design which ultimately led to increased overall costs.³⁵

E. The entry of the national laboratories into the superconducting power transmission line program

1. Introduction. Given the objective of this case study, it is appropriate to pause briefly before discussing the remaining components of the US

^{*}In contrast to Type I superconductors, which exhibit a single very low critical magnetic field, H_c , two critical fields, H_{c1} and H_{c2} , exist for Type II superconductors. At fields below H_c for a Type I or H_{c1} for a Type II superconductor, no losses should, in principle, occur when an AC current is made to flow through the superconductor. In practice, small hysteretic losses which depend upon the surface characteristics of the superconductor do occur. At fields in excess of H_{c1} for Type II superconductors it was expected theoretically, that substantial energy losses would occur with AC currents.

superconducting transmission line program to note that a change in the way a part of the R&D for the electrical utility industry was carried out occurred in the very early 1970s.

By the end of the decade of the 1960s, domestic production of oil and gas, which together accounted for more than three quarters of the nation's energy supply, began to decline. Furthermore, the oil experts were insisting that this decline stemmed from resource depletion and was likely to continue indefinitely. Demand, on the other hand, gave every indication of continuing to increase, but the gap was being closed without noticeable difficulty by imports. Nevertheless, serious problems were beginning to be discernable. Ever increasing balance of payment deficits for imported oil could be predicted with certainty.

In addition to the oil import problem, environmental pollution, which had been growing far faster than currently available corrective measures could counter, was being recognized in the early 1970s as having a major energy-related component. These and other issues contributed to an increasing public awareness of a long term national energy problem and an increasing public pressure on the federal government to "do something about it."

The Congress rose to the occasion. In 1971 the Atomic Energy Act of 1954 was amended to authorize the Atomic Energy Commission (AEC) and its laboratories to conduct R&D relating to "the preservation and enhancement of a viable environment by developing more efficient methods to meet the nation's energy needs" (Sect. 31a.6). And, in Sect. 33 relating to RESEARCH FOR OTHERS, the Act was further amended to authorize the AEC "when it finds private facilities or laboratories inadequate for the purpose to conduct for other persons through its own facilities those activities it deems appropriate to the development of energy." In this section, the Act previously read: "development of atomic energy."

At about the same time, other government agencies, noting that federal involvement in the energy business was likely to increase substantially, were staking out their own claims on future energy funding by internal reorganizations and by the initiation of new energy-related R&D programs. For example, the National Science Foundation (NSF), having in the late 1960s just established its Interdisciplinary Research Related to Problems of Our Society (IRRPOS) program, replaced it in the early 1970s by the Research Applied to National Needs (RANN) program, with specific attention being paid to the

energy area. Similar changes in emphasis were occurring in the DOI, The Department of Commerce (DOC), and the EPA.

Also, at about this same time, several of the major AEC laboratories were experiencing--in some cases for the first time in their history--substantial program reductions and personnel terminations. These programmatic changes arose from a variety of causes. At Los Alamos, cutbacks in the scope and funding of the space program led to the abandonment of research on the nuclear rocket and a reduction-in-force (RIF) of about 200 personnel. At Oak Ridge, major changes in their reactor development program provoked analogous personnel problems. Even Brookhaven, with the bulk of its program dedicated to basic research, experienced similar difficulties but on a smaller scale.

It was therefore not surprising that the management of each of the national laboratories welcomed the opportunity provided by the Congress to apply their collective talents toward helping to solve the nation's energy problems. In those days "preservation of the Laboratory" was indeed a mission!

Although the Congress had, in the Amendment to the 1954 Atomic Energy Act, authorized participation by the national laboratories in energy-related R&D, it failed to appropriate any funds for such activities in the FY72 budget. Consequently, there was a mildly mad scramble on the part of various national laboratory R&D entrepreneurs to head for where the money was; and at that time it resided, for the most part, with the NSF RANN program.

It would be incorrect, in this account of how the national laboratories became involved in energy R&D, to leave the impression that the proposals prepared and presented to the RANN program managers were without merit. In general, the research proposals prepared by the Laboratories coupled their particular areas of technical expertise to their perceptions of important national needs in the energy area. It is also fair to note that, in many respects, those energy-related R&D projects that were initiated at the national laboratories under the aegis of the NSF RANN program were subjected to a far more severe technical review process than comparable atomic energy projects funded under AEC auspices had ever received--in large measure because the two agencies had traditionally operated under different ground rules for project funding.

A final important consequence of the increase in attention being paid by the federal government to energy issues was a strengthening of the belief, long held by many in the federal funding agencies and in the R&D community, that the nation's energy-related problems had to be solved quickly. This sense of urgency was further enhanced by the 1973-1974 Oil Embargo. The federal response to the urgency issue was sharply increased funding for energy R&D--requested by the Administration and provided by the Congress. This action, in turn, enabled funding agencies to support multiple, parallel, alternative approaches to the solution of energy problems (to increase the probability of a successful outcome) and it simultaneously encouraged the R&D community to prepare and submit proposals to explore more alternative approaches than might otherwise have been justified.

2. The Brookhaven National Laboratory project. During the summer of 1968, the Brookhaven National Laboratory (BNL) hosted a major study on practical applications of superconductivity.³⁶ Among other things, the subject of AC losses in Type II superconductors was examined in detail,³⁷ and one important piece of information that emerged from that study was the realization that these losses, even when the superconductor was exposed to magnetic fields in excess of H_{c1} , could be made lower (than initially believed) by appropriate fabrication procedures.³⁸ Since BNL already had an established and highly capable materials science group with substantial experience in superconducting materials as well as expertise in practical AC superconductivity (from the development of superconducting pulsed magnets for future use in a very high energy synchrotron) and both power engineering and cryogenic engineering stemming from its accelerator program, it was not surprising that a proposal was submitted to the NSF RANN program in 1971 recommending that funding be provided the Laboratory for a detailed assessment of all existing programs for the transmission of electric power using cryogenic means.³⁹ The technical conclusions drawn from this study formed the basis of the BNL superconducting cable program.

Brookhaven concluded that by using Nb_3Sn (with a T_c of 18K) as the superconductor, a cable could be designed to operate in a higher temperature range with a considerable savings (over the UC design) in refrigeration costs. In its report, Brookhaven also made a strong case for an overall

systems approach to the problem of SPTL design.* Admittedly, high AC losses in the superconductor are undesirable, but the BNL argument was that the magnitude of these losses was (within limits) by no means the decisive factor in the cable design. The BNL study demonstrated that additional considerations such as the flow, heat transfer and other phase-related properties of the cryogenic fluid, its operating temperature and pressure, dielectric losses, overall system requirements (fault current capability and behavior, contingency power flow capability), economics (capital vs operating costs), etc. all contributed to the overall cable costs and all had to be appropriately integrated in reaching an optimal AC SPTL design.

In BNL's report to the NSF several conceptual transmission lines were studied. The two investigated most thoroughly were flexible cable designs. In the first, an interleaved Nb_3Sn ribbon conductor was examined and in the second a coaxial cable with the conductor of either Nb or Nb_3Sn was studied. The specific objective of the study was in each case to explore the influence of the superconductor selected upon the design of the refrigeration system and upon the cryogenic fluid circulatory system.

The outcome of the BNL study was a new proposal to develop a flexible coaxial Nb_3Sn superconducting cable, able to be fabricated in lengths of several thousand feet, transported to the installation site on reels and pulled in the conventional manner through an already installed and tested cryogenic envelope. It was also believed that such a cable could be operated over a temperature range of 6.5-8.0K using helium in its supercritical state as the refrigerant. The nominal power transmission capability of the BNL cable was to be 3000 MVA at 138 kV.

Brookhaven's proposal was deemed worthy of support by the NSF RANN program and work on the project began in 1972. NSF funding continued until 1975 when project management and support were transferred first to ERDA and then, after 1978, to its successor agency, the DOE. At present, the BNL

*It would be incorrect to conclude from this statement that the UC research team neglected this important aspect of the problem. They did not. It is true, however, that the BNL group, due in part to the new AC loss data and in part to their differing areas of expertise, was able to interest the NSF RANN program managers in their alternative approach to the development of an AC SPTL.

project is the only US SPTL project still underway, albeit at a much reduced funding level.

In Table 3, the funding history of the BNL project is presented and in Refs. 40 and 41 the titles and identification data for two recent reports on the BNL project are given.

TABLE 3
FUNDING DATA FOR THE BNL AC SUPERCONDUCTING POWER
TRANSMISSION CABLE DEVELOPMENT PROJECT

<u>FY</u>	<u>Funding (k\$)</u>	<u>Source</u>
72	120	NSF
73	800	NSF
74	800	NSF/AEC
75	1 400	ERDA
76	1 700	ERDA
77	1 950	ERDA
78	2 500	DOE
79	3 170	DOE
80	3 500	DOE
81	3 600	DOE
82	2 000	DOE
83	1 500	DOE
84	1 330	DOE
85	750	DOE
Total funding (to date)		----

3. The Los Alamos Scientific Laboratory project. The Los Alamos Scientific Laboratory (LASL)* SPTL proposal, also submitted early in 1972 to the NSF RANN program, differed considerably from those prepared by both UC and the BNL, not only because LASL was proposing the development of a DC SPTL, but also because the technical strengths, interests and motivation of the Los Alamos proponents differed from those of their colleagues at UC and BNL. All three groups could claim considerable experience in the well known phases of R&D: basic and applied research, exploratory development, technology

*Since 1980, the Los Alamos National Laboratory.

development, engineering development and production or operations. But the background of many of the LASL staff coopted to prepare the RANN proposal consisted primarily of low temperature physics research and cryoengineering. In consequence, LASL's proposal was relatively strong in its emphasis on the scientific and low temperature engineering aspects of an SPTL but relatively weak in its electric power engineering requirements as well as in the problems associated with the integration of such an advanced system into an already operational power transmission network.

It was the opinion of the Los Alamos group that, despite the fact that superconducting DC power transmission constituted, in principle, a simple, straightforward application of Type II superconductivity, a considerable amount of applied research still remained to be done before an optimal cable design could be formulated. A two phase R&D program was therefore proposed. In Phase I, a "test bed" would be constructed consisting of a 20m long highly instrumented cryogenic envelope, the interior of which would be easily accessible for installing, testing and monitoring the behavior of prototype superconducting conductors and dielectrics. From the information so obtained, a specific cable design would be developed with which the necessary power engineering and network requirements would be integrated some three years later with the commencement of Phase II of the project. Phase II would also include the construction and operation of a 300 m cable test and demonstration facility.

The LASL proposal was submitted to the NSF RANN program, was reviewed and, finally approved for RANN funding. At about the same time, however, the AEC decided to fund the project jointly and then, a few weeks later, informed the NSF that they would support the project entirely. In 1975 ERDA took over sponsorship of the LASL work and in 1977 responsibility for its funding and program management was transferred to the DOE.

The Los Alamos SPTL Project began in FY73 and was effectively terminated at the end of FY79 (during the period FY80-FY83, Los Alamos was funded at a much lower level in order to utilize some of its remaining SPTL facilities to carry out some supporting R&D for the BNL project, e.g. Nb_3Sn joint design and testing, pothead designs, etc.) In Table 4 the funding history of the Los Alamos National Laboratory SPTL project is given.

TABLE 4
FUNDING DATA FOR THE LOS ALAMOS DC SUPERCONDUCTING
POWER TRANSMISSION LINE PROJECT

<u>FY</u>	<u>Funding (k\$)</u>	<u>Source</u>
73	396	AEC
74	566	AEC
75	980	AEC/ERDA
76	1 165	ERDA
77	1 100	ERDA/DOE
78	1 220	DOE
79	717	DOE
80	425	DOE
81	393	DOE
82	24	DOE
83	30	DOE
Total Funding	7 016	----

Reference 42 provides the title and the NTIS number of the final report for the Los Alamos SPTL project.

4. The Oak Ridge National Laboratory project. Soon after the three US SPTL projects (as well as the two cryoresistive projects mentioned previously) got underway, it was recognized that very little engineering data and empirical design information existed on the AC, DC, impulse and surge behavior of dielectric liquids, solids and gases:

- a) at the temperatures encountered in cryogenic and superconducting systems,
- b) at voltage levels up to and including those required by bulk power transmission systems and
- c) under the environmental conditions expected for machinery, apparatus and transmission lines.

In 1972, therefore, the newly formed AEC Division of Applied Technology responded positively to a proposal from the Oak Ridge National Laboratory (ORNL) to carry out a study, in close collaboration with the three users, to obtain this information.

During the first year DC power supplies and measuring apparatus for 130 kV and 600 kV tests were set up, as well as AC supplies for 80 and for 350/700

kV rms testing. These limits were extended in subsequent years and the breakdown strengths of candidate dielectric materials were measured under expected operational as well as fault conditions. After initiation of the project, additional tasks were added to the contract scope. These included a study of methods of reducing losses in the niobium configurations used in superconducting cables and the development of a dispersion-strengthened, high conductivity aluminum for protecting superconducting cables during overload or fault conditions.

Funding for the ORNL project began in FY73 and the project was terminated in FY76. The funding history is given in Table 5.

TABLE 5
FUNDING DATA FOR THE ORNL CRYOGENIC DIELECTRICS PROGRAM FOR
THE US POWER TRANSMISSION PROJECT

<u>FY</u>	<u>Funding (k\$)</u>	<u>Source</u>
73	288	AEC
74	252	AEC
75	1 195	AEC/ERDA
76	500	ERDA
Total Funding	2 235	----

In Ref. 43 the title and the NTIS number for the final report of this project are listed.

F. Supporting SPTL projects

By 1975, after an approximately ten-fold increase in federal funding for SPTL projects in approximately two years, it was recognized that the overall progress of the program would benefit substantially by involving additional federal and industrial participants in the program, thereby broadening its resource base, supporting the technology development work of existing programs, and beginning the technology transfer process to the private sector. To this end the following new projects were initiated under ERDA auspices:

1. Dielectric materials

a. Measurements of Insulating Materials at Cryogenic Temperatures.
National Bureau of Standards (NBS), Institute for Basic Standards, Washington,

DC. The broad objective of this project was to contribute to the development of improved dielectric materials for use in electric power transmission lines operated at cryogenic temperatures; to facilitate the selection and utilization of existing materials; and to develop and/or improve the instrumentation for measurements on cryogenic insulation systems.

This project began in FY75, was concluded in FY78 and was funded by ERDA and the DOE. The funding history is given in Table 6.

TABLE 6
FUNDING DATA FOR THE NBS PROJECT: MEASUREMENTS OF INSULATING
MATERIALS AT CRYOGENIC TEMPERATURES

<u>FY</u>	<u>Funding (k\$)</u>	<u>Source</u>
75	60	ERDA
76	151	ERDA
77	167	ERDA
78	175	DOE
Total Funding	553	----

In Ref. 44 the title and the NTIS number for the final report of this project are listed.

b. The Characterization of the Structure and the Dielectric Properties of Polymer Tape Insulation for High Voltage AC Superconducting Cables. NBS, Polymers Division, Washington, DC. This project was initiated in FY76 and was funded by ERDA/DOE (through BNL) at an average of about \$80,000/yr. through FY80.

In Ref. 45 the title and the NTIS number of the final report on this project are given.

c. The ORNL project. (described previously in section IV.E.4) was the third of the dielectric materials development projects.

d. The Stanford project. (see item 3.g. below).

e. The BNL project. In FY75 BNL was funded by EPRI in the amount of \$85,000 (of which \$30,000 went directly to Phelps Dodge Cable and Wire Co.) for a study of lapped plastic insulation for SPTLs. In Ref. 46 the title and identifying number of the EPRI final report on this work is given.

f. The Cable Technology Laboratories (CTL) project. In 1978 CTL was funded by EPRI to investigate the potential of various dielectrics for cryogenic cables. Of the bulk solid dielectrics studied it was found that extruded cross linded polyethylene suitably applied to the conductor was capable of withstanding voltages approximately 1.5 times the rated voltage limit of comparable conventional cables. This project was concluded in 1984; approximately \$300,000 was expended on this work increasing more or less linearly from about \$20,000 in 1978-79 to about \$100,000 in 1983-84. In Ref. 47 the title and authors of two reports describing this work are given.

2. Helium Research.

a. Helium Research in Support of Superconducting Power Transmission, NBS, Cryogenics Division, Boulder, Colorado. This study was to provide supporting research on the dynamics of cryogenic helium flow and heat transfer for the superconducting power transmission development. The tasks involved theoretical studies of transmission line cooling systems dynamics and helium instrumentation development, such as flow meter evaluation, pressure transducer evaluation, thermometry in high AC electrical fields, and development of helium purity sensors.

The project at NBS (Boulder) began in FY75 and concluded in FY77. Its funding history is given in Table 7.

TABLE 7
FUNDING DATA FOR THE NBS PROJECT: HELIUM RESEARCH
IN SUPPORT OF SUPERCONDUCTING POWER TRANSMISSION

<u>FY</u>	<u>Funding (k\$)</u>	<u>Source</u>
75	150	AEC
	140	DOI
76	300	ERDA
77	250	ERDA
78	175	DOE
79	175	DOE
80	100	DOE
81	50	DOE
Total Funding	1 340	----

In Ref. 48, three reports on this project together with their NTIS numbers are given.

3. Superconducting materials development.

a. An Improved Superconductor for Transmission Line Applications Westinghouse Electric Corporation. The objective of this project was to develop an improved superconductor for transmission line applications. Clearly, refrigeration costs are substantially reduced as cable operating temperatures increase. Of all Type II superconductors, Nb_3Ge has the highest T_c , namely 23K. It is, however, difficult to fabricate as a wire or tape suitable for practical use. The Westinghouse project was intended to characterize Nb_3Ge for transmission line applications and to provide a data base for Nb_3Ge cable conductor fabrication. In addition, an assessment was carried out to determine the economic feasibility of using Nb_3Ge tapes (prepared by a chemical vapor deposition (CVD) technique) in SPTLs.

The experimental work to be carried out included optimization of the CVD parameters, i.e. temperature, delivery rates, carrier gas dilution, etc. to achieve improved purity, microstructure and surface topography. In addition, the doping of the Nb_3Ge with specific impurities to maximize flux pinning (thereby enhancing conductor current density) was to be investigated.

The Westinghouse project was begun by ERDA and the DOI in FY75 (at \$40,000 and \$110,000 respectively) and was terminated in FY76 (with the expenditure of an additional \$245,000). In Ref. 49 the title and the NTIS number for the final report on this project are given.

b. Hydrogen-cooled Superconducting Transmission Line. Westinghouse Electric Corporation. The title of this project is something of a misnomer, since it was primarily a materials development project. The Westinghouse Research Laboratory contracted with the DOE to investigate materials (that could be used in future superconducting transmission lines) with characteristics superior to those being used in the liquid helium-cooled SPTL being developed at BNL. The contract for this work amounted to about \$690,000 and was to be completed between FY80 and FY82. Lacking details of the sequential allocations, it will be assumed that the funding consisted of three equal \$230,000 payments.

The title and NTIS number of the final report for this project is given in Ref. 50.

c. Development of Niobium-Tin conductors for AC Superconducting Cables. Kawecki-Berylco Industries, Inc. The aim of this program was to improve the AC loss characteristics of Nb_3Sn superconducting ribbons. The primary effort was to be on the tin-diffusion production process, with a secondary effort on the bronze-diffusion technique.

A quality control program was also to be developed for producing long-length tapes.

This project was funded by ERDA in FY75 (at \$40,000) and was concluded in FY76 (with an additional \$59,000). In Ref. 51 the title and the NTIS number for the final report on this work is given.

d. A Research and Development Effort to Delineate and Optimize Nb_3Sn Conductor for AC Superconducting Transmission Cables. Intermagnetics General Corporation. This study was directed toward the optimization of Nb_3Sn conductors for use in superconducting AC cables, and toward the subsequent commercial production of long lengths of high quality composite conductor. Intermagnetics General Corporation's work was concentrated on the liquid diffusion process for producing superconducting tapes with low AC losses.

ERDA funded this study in FY75 (at \$20,000) and the project was terminated in FY76 (for an additional \$80,000). In Ref. 52 the title and the NTIS number of the final report on this work is given.

e. Research and Development Efforts Relative to Superconducting Materials. Airco, Inc. The technical effort of this project focused on three new approaches to provide low AC loss materials for transmission line applications. One was based on the techniques recently developed for multifilamentary Nb_3Sn ; the other two on the application of physical vapor deposition and sputtering techniques, which were well developed by Airco's Temescal Division. The potential payoff for each was low AC losses with known methods for economical scale-up. By February 1976 a number of tape samples of various configurations had been prepared and tested. Losses at 4.2K were of the order of $8W/cm^2$ at 500 A/cm (r.m.s.).

This project was initiated by ERDA in FY75 (at \$45,000) and concluded in FY76 (for an additional \$74,565). The title and NTIS number of the final report are given in Ref. 53.

f. Development of Nb₃Ge for Power Transmission Applications. Los Alamos National Laboratory. This project, initiated during FY75, was funded by EPRI. The objective of Phase I was to develop fabrication methods for producing (and produce) long lengths (~20m) of high quality Nb₃Ge tapes capable of supporting high AC current densities with low hysteretic losses at a temperature of about 14K (in order that a liquid or slush hydrogen refrigerant could be used to cool the cable).

Phase II of this project, initiated in January of 1979 and concluded in July of 1981, consisted of further material development, fabrication and cable performance testing of Nb₃Ge tapes.

The overall cost of the project was about \$1,000,000 over a five year period. In Ref. 54, the titles and identification numbers of the final reports for both the Phase I and the Phase II work are given.

g. The Stanford AC superconducting power transmission line project: materials research and conductor development. This project, begun in 1972, was directed toward investigating the properties of high T_c superconducting layered structures prepared using various advanced thin film techniques as well as measuring the AC losses in candidate dielectric insulating materials. The primary goal of the project was to develop fabrication techniques capable of supporting significantly higher current densities and significantly lower AC losses in Type II superconductors (particularly Nb₃Sn) at temperatures close to their transition temperatures. The fabrication methods to be investigated included electron beam evaporation, sputtering and plasma spraying.

Studies were also to be undertaken directed toward the development of layered configurations with low AC losses and high flexibility as well as the development of fabrication methods for multilayer composites. Eventually, prototype SPTL cable designs were to be developed consistent with the results of power system studies that would be carried out concurrently.

This project was funded initially by the NSF RANN program and subsequently by the EEI, the DOI, EPRI, and ERDA. Work began at Stanford during FY73 and concluded in FY77. The funding history of the project is give in Table 8.

TABLE 8
FUNDING DATA FOR THE STANFORD UNIVERSITY PROJECT: SUPERCONDUCTING
POWER TRANSMISSION LINE MATERIALS RESEARCH, CONDUCTOR DEVELOPMENT
AND AC SPTL INTEGRATION WITH EXISTING SYSTEMS

<u>FY</u>	<u>Funding (k\$)</u>	<u>Source</u>
72	2	Research Corp.
	11	EEI
73	33	EPRI
	11	DOI
	125	NSF
74	341	NSF
	77	EPRI
75	123	EPRI
	398	NSF
76	173	ERDA
77	195	ERDA
	100	DOD/AFOSR
78	97	ERDA
Total funding	1 686	----

In Ref. 55 the title and the NTIS and other reference numbers for the final reports of this project are listed.

4. Cryogenic refrigeration system development.

a. An Assessment and Study of Existing Concepts and Methods of Cryogenic Refrigeration for Superconducting Transmission Cables. Air Products and Chemicals, Inc. This study was to review the state-of-the-art of cryogenic refrigeration systems applicable to superconducting cables and to identify and discuss the tasks requiring research and development to obtain high reliability, low maintenance, low capital cost, and reasonable efficiency. The deliverable was performance data and R&D recommendations for cryogenic refrigeration processes for SPTLs.

This project was initiated by ERDA in FY75 (at \$30,000) and concluded in FY76 (for an additional \$62,000). In Ref. 56 the title and the NTIS number of the final report are given.

b. Methods of Refrigeration for Superconducting Transmission Cables. AiResearch Manufacturing Co. of California. The objective of this study was

to provide an open-minded study of helium refrigeration systems applied to superconducting power transmission cables. The tasks were to include

- a) an evaluation of the requirements of the various superconducting transmission cables under development,
- b) an assessment of the state-of-the-art of current systems composed of existing components or extrapolations of current designs,
- c) an evaluation of systems requiring R&D activity to establish suitable components not currently available.

This project was initiated by ERDA in FY75 (at \$42,000) and concluded in FY76 (for an additional \$72,000). The title and the NTIS number of the final report are given in Ref. 57.

5. System Studies.

a. PECO I. In FY76, ERDA contracted with the Philadelphia Electric Company (PECO) to evaluate several bulk power underground power transmission systems projected to become available for use in the 1990's and to determine their technical and economic suitability for inclusion in power networks. SPTL's were included in the study. The specific transmission scenario studied was a bulk power feed of 10,000 MW over a distance of 66 miles from a generation park to an urban distribution substation. The results of this study had a significant impact upon the course of the US SPTL program and will be discussed in detail in a subsequent section of this report. The cost of the study was \$330,000. In Ref. 58 the title and the identifying NTIS number of the final report of this study are given.

b. PECO II. Since the economic feasibility of most new technologies tends to be a function of the application scenario and since, in the case of electric power transmission lines, one important parameter is distance; a second PECO study was commissioned by the DOE in FY79 to compare the costs of several long underground, aerial and combined underground/aerial DC transmission line options. It was expected that the Los Alamos DC SPTL would be included in this study and for that reason the ratings of the transmission systems studied ranged from 4,000 - 12,000 MW. When R&D on the DC SPTL was terminated in 1979, this option was dropped from the PECO study. The study results are, nevertheless, relevant to the US SPTL development program and will be discussed subsequently in this case study. This study was completed in 1983. Its cost was \$640,000. In Ref. 59 the title and identifying data for this study's final report are given.

G. The U.S. SPTL funding history

In Table 9 the funding history of the US SPTL program is summarized and Fig. 2 the program's annual funding versus fiscal year is plotted for the last thirteen years. From FY63-FY72, approximately \$536,000 was expended by the ERC in support of the UC/Linde project. More will be said about this data in subsequent sections of this case study. It will be sufficient here to note firstly, that of the total amount (about \$45 million dollars) expended to date, approximately 56% was allocated to the BNL project; secondly, that the program funding increased dramatically in FY73 with the formal entry of the federal government into the energy R&D effort; thirdly, that after 1974, program funding leveled off to about \$4.5 million dollars annually for the next seven years; and finally, that it declined sharply in FY82 in consequence of the implementation of a different national policy toward federally-funded energy R&D by the new Administration.

H. The management and the sponsorship of the US superconducting transmission line program^{(60)*}

Informal cooperation between the electric utility industry and the federal government in energy-related R&D has existed for several decades. These shared interests were more formally coordinated in 1965 with the organization of the ERC which was established to provide a means by which the various components of the electric utility industry (including the electric power producing entities of the federal government) could cooperate in the support of R&D of general importance to the industry. Prior to the early 1970s, however, the focus of this effort (which was funded for the most part by the EEI) lay primarily within the industry--particularly, as has already been mentioned, with equipment manufacturers. Then, with the large scale entry of the federal government into energy R&D during the decade of the 1970s, and with the establishment of EPRI in 1973 (to which all of the ERC-managed research projects were transferred), it became necessary to formalize further the conditions under which cooperative efforts in electrical utility-related R&D were to be carried out. This was accomplished through a series of Memoranda of Understanding in 1974, 1976 and 1979 between EPRI and the AEC, ERDA, and the DOE respectively.^{61a}

*See the Introduction to NOTES AND REFERENCES.

Table 9
The Impact of the 1974
Superconducting Transition on the Program

Line	Superconducting Cable Description (see Table 1)	Q ₂₀	Q ₁₀	Q ₅	Q ₂	Q ₁	Q ₀	Q ₋₁	Q ₋₂	Q ₋₃	Q ₋₄	Q ₋₅	Q ₋₆	Q ₋₇	Q ₋₈	Q ₋₉	Q ₋₁₀	Q ₋₁₁	Q ₋₁₂	Q ₋₁₃	Q ₋₁₄	Q ₋₁₅	Q ₋₁₆	Q ₋₁₇	Q ₋₁₈	Q ₋₁₉	Q ₋₂₀	Q ₋₂₁	Q ₋₂₂	Q ₋₂₃	Q ₋₂₄	Q ₋₂₅	Q ₋₂₆	Q ₋₂₇	Q ₋₂₈	Q ₋₂₉	Q ₋₃₀	Q ₋₃₁	Q ₋₃₂	Q ₋₃₃	Q ₋₃₄	Q ₋₃₅	Q ₋₃₆	Q ₋₃₇	Q ₋₃₈	Q ₋₃₉	Q ₋₄₀	Q ₋₄₁	Q ₋₄₂	Q ₋₄₃	Q ₋₄₄	Q ₋₄₅	Q ₋₄₆	Q ₋₄₇	Q ₋₄₈	Q ₋₄₉	Q ₋₅₀	Q ₋₅₁	Q ₋₅₂	Q ₋₅₃	Q ₋₅₄	Q ₋₅₅	Q ₋₅₆	Q ₋₅₇	Q ₋₅₈	Q ₋₅₉	Q ₋₆₀	Q ₋₆₁	Q ₋₆₂	Q ₋₆₃	Q ₋₆₄	Q ₋₆₅	Q ₋₆₆	Q ₋₆₇	Q ₋₆₈	Q ₋₆₉	Q ₋₇₀	Q ₋₇₁	Q ₋₇₂	Q ₋₇₃	Q ₋₇₄	Q ₋₇₅	Q ₋₇₆	Q ₋₇₇	Q ₋₇₈	Q ₋₇₉	Q ₋₈₀	Q ₋₈₁	Q ₋₈₂	Q ₋₈₃	Q ₋₈₄	Q ₋₈₅	Q ₋₈₆	Q ₋₈₇	Q ₋₈₈	Q ₋₈₉	Q ₋₉₀	Q ₋₉₁	Q ₋₉₂	Q ₋₉₃	Q ₋₉₄	Q ₋₉₅	Q ₋₉₆	Q ₋₉₇	Q ₋₉₈	Q ₋₉₉	Q ₋₁₀₀	Q ₋₁₀₁	Q ₋₁₀₂	Q ₋₁₀₃	Q ₋₁₀₄	Q ₋₁₀₅	Q ₋₁₀₆	Q ₋₁₀₇	Q ₋₁₀₈	Q ₋₁₀₉	Q ₋₁₁₀	Q ₋₁₁₁	Q ₋₁₁₂	Q ₋₁₁₃	Q ₋₁₁₄	Q ₋₁₁₅	Q ₋₁₁₆	Q ₋₁₁₇	Q ₋₁₁₈	Q ₋₁₁₉	Q ₋₁₂₀	Q ₋₁₂₁	Q ₋₁₂₂	Q ₋₁₂₃	Q ₋₁₂₄	Q ₋₁₂₅	Q ₋₁₂₆	Q ₋₁₂₇	Q ₋₁₂₈	Q ₋₁₂₉	Q ₋₁₃₀	Q ₋₁₃₁	Q ₋₁₃₂	Q ₋₁₃₃	Q ₋₁₃₄	Q ₋₁₃₅	Q ₋₁₃₆	Q ₋₁₃₇	Q ₋₁₃₈	Q ₋₁₃₉	Q ₋₁₄₀	Q ₋₁₄₁	Q ₋₁₄₂	Q ₋₁₄₃	Q ₋₁₄₄	Q ₋₁₄₅	Q ₋₁₄₆	Q ₋₁₄₇	Q ₋₁₄₈	Q ₋₁₄₉	Q ₋₁₅₀	Q ₋₁₅₁	Q ₋₁₅₂	Q ₋₁₅₃	Q ₋₁₅₄	Q ₋₁₅₅	Q ₋₁₅₆	Q ₋₁₅₇	Q ₋₁₅₈	Q ₋₁₅₉	Q ₋₁₆₀	Q ₋₁₆₁	Q ₋₁₆₂	Q ₋₁₆₃	Q ₋₁₆₄	Q ₋₁₆₅	Q ₋₁₆₆	Q ₋₁₆₇	Q ₋₁₆₈	Q ₋₁₆₉	Q ₋₁₇₀	Q ₋₁₇₁	Q ₋₁₇₂	Q ₋₁₇₃	Q ₋₁₇₄	Q ₋₁₇₅	Q ₋₁₇₆	Q ₋₁₇₇	Q ₋₁₇₈	Q ₋₁₇₉	Q ₋₁₈₀	Q ₋₁₈₁	Q ₋₁₈₂	Q ₋₁₈₃	Q ₋₁₈₄	Q ₋₁₈₅	Q ₋₁₈₆	Q ₋₁₈₇	Q ₋₁₈₈	Q ₋₁₈₉	Q ₋₁₉₀	Q ₋₁₉₁	Q ₋₁₉₂	Q ₋₁₉₃	Q ₋₁₉₄	Q ₋₁₉₅	Q ₋₁₉₆	Q ₋₁₉₇	Q ₋₁₉₈	Q ₋₁₉₉	Q ₋₂₀₀	Q ₋₂₀₁	Q ₋₂₀₂	Q ₋₂₀₃	Q ₋₂₀₄	Q ₋₂₀₅	Q ₋₂₀₆	Q ₋₂₀₇	Q ₋₂₀₈	Q ₋₂₀₉	Q ₋₂₁₀	Q ₋₂₁₁	Q ₋₂₁₂	Q ₋₂₁₃	Q ₋₂₁₄	Q ₋₂₁₅	Q ₋₂₁₆	Q ₋₂₁₇	Q ₋₂₁₈	Q ₋₂₁₉	Q ₋₂₂₀	Q ₋₂₂₁	Q ₋₂₂₂	Q ₋₂₂₃	Q ₋₂₂₄	Q ₋₂₂₅	Q ₋₂₂₆	Q ₋₂₂₇	Q ₋₂₂₈	Q ₋₂₂₉	Q ₋₂₃₀	Q ₋₂₃₁	Q ₋₂₃₂	Q ₋₂₃₃	Q ₋₂₃₄	Q ₋₂₃₅	Q ₋₂₃₆	Q ₋₂₃₇	Q ₋₂₃₈	Q ₋₂₃₉	Q ₋₂₄₀	Q ₋₂₄₁	Q ₋₂₄₂	Q ₋₂₄₃	Q ₋₂₄₄	Q ₋₂₄₅	Q ₋₂₄₆	Q ₋₂₄₇	Q ₋₂₄₈	Q ₋₂₄₉	Q ₋₂₅₀	Q ₋₂₅₁	Q ₋₂₅₂	Q ₋₂₅₃	Q ₋₂₅₄	Q ₋₂₅₅	Q ₋₂₅₆	Q ₋₂₅₇	Q ₋₂₅₈	Q ₋₂₅₉	Q ₋₂₆₀	Q ₋₂₆₁	Q ₋₂₆₂	Q ₋₂₆₃	Q ₋₂₆₄	Q ₋₂₆₅	Q ₋₂₆₆	Q ₋₂₆₇	Q ₋₂₆₈	Q ₋₂₆₉	Q ₋₂₇₀	Q ₋₂₇₁	Q ₋₂₇₂	Q ₋₂₇₃	Q ₋₂₇₄	Q ₋₂₇₅	Q ₋₂₇₆	Q ₋₂₇₇	Q ₋₂₇₈	Q ₋₂₇₉	Q ₋₂₈₀	Q ₋₂₈₁	Q ₋₂₈₂	Q ₋₂₈₃	Q ₋₂₈₄	Q ₋₂₈₅	Q ₋₂₈₆	Q ₋₂₈₇	Q ₋₂₈₈	Q ₋₂₈₉	Q ₋₂₉₀	Q ₋₂₉₁	Q ₋₂₉₂	Q ₋₂₉₃	Q ₋₂₉₄	Q ₋₂₉₅	Q ₋₂₉₆	Q ₋₂₉₇	Q ₋₂₉₈	Q ₋₂₉₉	Q ₋₃₀₀	Q ₋₃₀₁	Q ₋₃₀₂	Q ₋₃₀₃	Q ₋₃₀₄	Q ₋₃₀₅	Q ₋₃₀₆	Q ₋₃₀₇	Q ₋₃₀₈	Q ₋₃₀₉	Q ₋₃₁₀	Q ₋₃₁₁	Q ₋₃₁₂	Q ₋₃₁₃	Q ₋₃₁₄	Q ₋₃₁₅	Q ₋₃₁₆	Q ₋₃₁₇	Q ₋₃₁₈	Q ₋₃₁₉	Q ₋₃₂₀	Q ₋₃₂₁	Q ₋₃₂₂	Q ₋₃₂₃	Q ₋₃₂₄	Q ₋₃₂₅	Q ₋₃₂₆	Q ₋₃₂₇	Q ₋₃₂₈	Q ₋₃₂₉	Q ₋₃₃₀	Q ₋₃₃₁	Q ₋₃₃₂	Q ₋₃₃₃	Q ₋₃₃₄	Q ₋₃₃₅	Q ₋₃₃₆	Q ₋₃₃₇	Q ₋₃₃₈	Q ₋₃₃₉	Q ₋₃₄₀	Q ₋₃₄₁	Q ₋₃₄₂	Q ₋₃₄₃	Q ₋₃₄₄	Q ₋₃₄₅	Q ₋₃₄₆	Q ₋₃₄₇	Q ₋₃₄₈	Q ₋₃₄₉	Q ₋₃₅₀	Q ₋₃₅₁	Q ₋₃₅₂	Q ₋₃₅₃	Q ₋₃₅₄	Q ₋₃₅₅	Q ₋₃₅₆	Q ₋₃₅₇	Q ₋₃₅₈	Q ₋₃₅₉	Q ₋₃₆₀	Q ₋₃₆₁	Q ₋₃₆₂	Q ₋₃₆₃	Q ₋₃₆₄	Q ₋₃₆₅	Q ₋₃₆₆	Q ₋₃₆₇	Q ₋₃₆₈	Q ₋₃₆₉	Q ₋₃₇₀	Q ₋₃₇₁	Q ₋₃₇₂	Q ₋₃₇₃	Q ₋₃₇₄	Q ₋₃₇₅	Q ₋₃₇₆	Q ₋₃₇₇	Q ₋₃₇₈	Q ₋₃₇₉	Q ₋₃₈₀	Q ₋₃₈₁	Q ₋₃₈₂	Q ₋₃₈₃	Q ₋₃₈₄	Q ₋₃₈₅	Q ₋₃₈₆	Q ₋₃₈₇	Q ₋₃₈₈	Q ₋₃₈₉	Q ₋₃₉₀	Q ₋₃₉₁	Q ₋₃₉₂	Q ₋₃₉₃	Q ₋₃₉₄	Q ₋₃₉₅	Q ₋₃₉₆	Q ₋₃₉₇	Q ₋₃₉₈	Q ₋₃₉₉	Q ₋₄₀₀	Q ₋₄₀₁	Q ₋₄₀₂	Q ₋₄₀₃	Q ₋₄₀₄	Q ₋₄₀₅	Q ₋₄₀₆	Q ₋₄₀₇	Q ₋₄₀₈	Q ₋₄₀₉	Q ₋₄₁₀	Q ₋₄₁₁	Q ₋₄₁₂	Q ₋₄₁₃	Q ₋₄₁₄	Q ₋₄₁₅	Q ₋₄₁₆	Q ₋₄₁₇	Q ₋₄₁₈	Q ₋₄₁₉	Q ₋₄₂₀	Q ₋₄₂₁	Q ₋₄₂₂	Q ₋₄₂₃	Q ₋₄₂₄	Q ₋₄₂₅	Q ₋₄₂₆	Q ₋₄₂₇	Q ₋₄₂₈	Q ₋₄₂₉	Q ₋₄₃₀	Q ₋₄₃₁	Q ₋₄₃₂	Q ₋₄₃₃	Q ₋₄₃₄	Q ₋₄₃₅	Q ₋₄₃₆	Q ₋₄₃₇	Q ₋₄₃₈	Q ₋₄₃₉	Q ₋₄₄₀	Q ₋₄₄₁	Q ₋₄₄₂	Q ₋₄₄₃	Q ₋₄₄₄	Q ₋₄₄₅	Q ₋₄₄₆	Q ₋₄₄₇	Q ₋₄₄₈	Q ₋₄₄₉	Q ₋₄₅₀	Q ₋₄₅₁	Q ₋₄₅₂	Q ₋₄₅₃	Q ₋₄₅₄	Q ₋₄₅₅	Q ₋₄₅₆	Q ₋₄₅₇	Q ₋₄₅₈	Q ₋₄₅₉	Q ₋₄₆₀	Q ₋₄₆₁	Q ₋₄₆₂	Q ₋₄₆₃	Q ₋₄₆₄	Q ₋₄₆₅	Q ₋₄₆₆	Q ₋₄₆₇	Q ₋₄₆₈	Q ₋₄₆₉	Q ₋₄₇₀	Q ₋₄₇₁	Q ₋₄₇₂	Q ₋₄₇₃	Q ₋₄₇₄	Q ₋₄₇₅	Q ₋₄₇₆	Q ₋₄₇₇	Q ₋₄₇₈	Q ₋₄₇₉	Q ₋₄₈₀	Q ₋₄₈₁	Q ₋₄₈₂	Q ₋₄₈₃	Q ₋₄₈₄	Q ₋₄₈₅	Q ₋₄₈₆	Q ₋₄₈₇	Q ₋₄₈₈	Q ₋₄₈₉	Q ₋₄₉₀	Q ₋₄₉₁	Q ₋₄₉₂	Q ₋₄₉₃	Q ₋₄₉₄	Q ₋₄₉₅	Q ₋₄₉₆	Q ₋₄₉₇	Q ₋₄₉₈	Q ₋₄₉₉	Q ₋₅₀₀	Q ₋₅₀₁	Q ₋₅₀₂	Q ₋₅₀₃	Q ₋₅₀₄	Q ₋₅₀₅	Q ₋₅₀₆	Q ₋₅₀₇	Q ₋₅₀₈	Q ₋₅₀₉	Q ₋₅₁₀	Q ₋₅₁₁	Q ₋₅₁₂	Q ₋₅₁₃	Q ₋₅₁₄	Q ₋₅₁₅	Q ₋₅₁₆	Q ₋₅₁₇	Q ₋₅₁₈	Q ₋₅₁₉	Q ₋₅₂₀	Q ₋₅₂₁	Q ₋₅₂₂	Q ₋₅₂₃	Q ₋₅₂₄	Q ₋₅₂₅	Q ₋₅₂₆	Q ₋₅₂₇	Q ₋₅₂₈	Q ₋₅₂₉	Q ₋₅₃₀	Q ₋₅₃₁	Q ₋₅₃₂	Q ₋₅₃₃	Q ₋₅₃₄	Q ₋₅₃₅	Q ₋₅₃₆	Q ₋₅₃₇	Q ₋₅₃₈	Q ₋₅₃₉	Q ₋₅₄₀	Q ₋₅₄₁	Q ₋₅₄₂	Q ₋₅₄₃	Q ₋₅₄₄	Q ₋₅₄₅	Q ₋₅₄₆	Q ₋₅₄₇	Q ₋₅₄₈	Q ₋₅₄₉	Q ₋₅₅₀	Q ₋₅₅₁	Q ₋₅₅₂	Q ₋₅₅₃	Q ₋₅₅₄	Q ₋₅₅₅	Q ₋₅₅₆	Q ₋₅₅₇	Q ₋₅₅₈	Q ₋₅₅₉	Q ₋₅₆₀	Q ₋₅₆₁	Q ₋₅₆₂	Q ₋₅₆₃	Q ₋₅₆₄	Q ₋₅₆₅	Q ₋₅₆₆	Q ₋₅₆₇	Q ₋₅₆₈	Q ₋₅₆₉	Q ₋₅₇₀	Q ₋₅₇₁	Q ₋₅₇₂	Q ₋₅₇₃	Q ₋₅₇₄	Q ₋₅₇₅	Q ₋₅₇₆	Q ₋₅₇₇	Q ₋₅₇₈	Q ₋₅₇₉	Q ₋₅₈₀	Q ₋₅₈₁	Q ₋₅₈₂	Q ₋₅₈₃	Q ₋₅₈₄	Q ₋₅₈₅	Q ₋₅₈₆	Q ₋₅₈₇	Q ₋₅₈₈	Q ₋₅₈₉	Q ₋₅₉₀	Q ₋₅₉₁	Q ₋₅₉₂	Q ₋₅₉₃	Q ₋₅₉₄	Q ₋₅₉₅	Q ₋₅₉₆	Q ₋₅₉₇	Q ₋₅₉₈	Q ₋₅₉₉	Q ₋₆₀₀	Q ₋₆₀₁	Q ₋₆₀₂	Q ₋₆₀₃	Q ₋₆₀₄	Q ₋₆₀₅	Q ₋₆₀₆	Q ₋₆₀₇	Q ₋₆₀₈	Q ₋₆₀₉	Q ₋₆₁₀	Q ₋₆₁₁	Q ₋₆₁₂	Q ₋₆₁₃	Q ₋₆₁₄	Q ₋₆₁₅	Q ₋₆₁₆	Q ₋₆₁₇	Q ₋₆₁₈	Q ₋₆₁₉	Q ₋₆₂₀	Q ₋₆₂₁	Q ₋₆₂₂	Q ₋₆₂₃	Q ₋₆₂₄	Q ₋₆₂₅	Q ₋₆₂₆	Q ₋₆₂₇	Q ₋₆₂₈	Q ₋₆₂₉	Q ₋₆₃₀	Q ₋₆₃₁	Q ₋₆₃₂	Q ₋₆₃₃	Q ₋₆₃₄	Q ₋₆₃₅	Q ₋₆₃₆	Q ₋₆₃₇	Q ₋₆₃₈	Q ₋₆₃₉	Q ₋₆₄₀	Q ₋₆₄₁	Q ₋₆₄₂	Q ₋₆₄₃	Q ₋₆₄₄	Q ₋₆₄₅	Q ₋₆₄₆	Q ₋₆₄₇	Q ₋₆₄₈	Q ₋₆₄₉	Q ₋₆₅₀	Q ₋₆₅₁	Q ₋₆₅₂	Q ₋₆₅₃	Q ₋₆₅₄	Q ₋₆₅₅	Q ₋₆₅₆	Q ₋₆₅₇	Q ₋₆₅₈	Q ₋₆₅₉	Q ₋₆₆₀	Q ₋₆₆₁	Q ₋₆₆₂	Q ₋₆₆₃	Q ₋₆₆₄	Q ₋₆₆₅	Q ₋₆₆₆	Q ₋₆₆₇	Q ₋₆₆₈	Q ₋₆₆₉	Q ₋₆₇₀	Q ₋₆₇₁	Q ₋₆₇₂	Q ₋₆₇₃	Q ₋₆₇₄	Q ₋₆₇₅	Q ₋₆₇₆	Q ₋₆₇₇	Q ₋₆₇₈	Q ₋₆₇₉	Q ₋₆₈₀	Q ₋₆₈₁	Q ₋₆₈₂	Q ₋₆₈₃	Q ₋₆₈₄	Q ₋₆₈₅	Q ₋₆₈₆	Q ₋₆₈₇	Q ₋₆₈₈	Q ₋₆₈₉	Q ₋₆₉₀	Q ₋₆₉₁	Q ₋₆₉₂	Q ₋₆₉₃	Q ₋₆₉₄	Q ₋₆₉₅	Q ₋₆₉₆	Q ₋₆₉₇	Q ₋₆₉₈	Q ₋₆₉₉	Q ₋₇₀₀	Q ₋₇₀₁	Q ₋₇₀₂	Q ₋₇₀₃	Q ₋₇₀₄	Q ₋₇₀₅	Q ₋₇₀₆	Q ₋₇₀₇	Q ₋₇₀₈	Q ₋₇₀₉	Q ₋₇₁₀	Q ₋₇₁₁	Q ₋₇₁₂	Q ₋₇₁₃	Q ₋₇₁₄	Q ₋₇₁₅	Q ₋₇₁₆	Q ₋₇₁₇	Q ₋₇₁₈	Q 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Fig. 2. US SPTL Program Funding vs Fiscal Year.

Initially, the industry managed and supported a wide-ranging R&D program focusing on near (10 year payoff), intermediate (10-25 year payoff) and long (>25 year payoff) term R&D programs. Beginning in the mid 1970s, however, EPRI's emphasis shifted more and more toward the support of near term R&D (which now accounts for more than 70% of the Institute's R&D budget).^{61b} This shift in emphasis was reflected in the financial sponsorship and the management of the US superconducting power transmission line program, as shown in Table 9. It is probably true that this transfer of responsibility for the future direction of the SPTL program (despite the fact that information exchange and a measure of cooperation in research planning continued between ERDA/DOE and EPRI) had a great deal to do with the future course of the program. This issue will be examined in more detail in Part III, the Conclusions portion of this case study.

I. The technical accomplishments of the US superconducting transmission line program

It is clearly impossible to recount the accomplishments of a twenty year, forty-five million dollar research program in a few paragraphs. What can be said is that the accomplishments were significant and substantial. Hundreds of progress reports, annual reports, final reports and research papers published in the archival literature support that statement. Furthermore, the scientists and engineers who participated in (some of whom are still participating in) this program were an able and dedicated group of individuals. Nevertheless, despite the number of dollars expended (as Table 9 and Fig. 2 clearly show), despite the number of published technical reports and papers (noted above) and despite the solid technical accomplishments of the program (which will be summarized briefly below), this effort has resulted neither in any commercial application of this technology nor in any industry-sponsored demonstration of its potential usefulness. It is therefore of importance to inquire into what was right about the conduct of this program as well as what, if anything, went wrong with it. This examination will be carried out in the concluding section of this case study. In the following paragraphs brief summaries of the actual accomplishments and the present status of the program will be presented.

1. The SPTL development program. One general comment on the program's accomplishments is the fact that three of the development projects (UC/Linde, BNL and Los Alamos) reached the point at which their cable designs were

sufficiently well formulated to permit inclusion in the PECO I study. Of these, the BNL design emerged not only as the lowest cost SPTL design but also as the lowest cost transmission option of the fifteen underground cable designs analyzed.

a. The UC/Linde project. The UC SPTL design turned out to be one of the two highest cost transmission systems examined in the PECO I study. In part, this result arose from the fact that a specific cable design choice was made in the very early phases of the project's history and for various reasons it became very difficult to make design changes during its final phases. Another contributor to the high cost of the UC project (as well as to several others) was the acceptance by the PECO engineers of component cost figures provided by the participants. Their differing assumptions on, for example, refrigerator efficiencies and system configurations yielded markedly different costs for satisfying similar performance requirements. It is, therefore, possible (and perhaps highly probable) that, had this project been continued and had other design options been explored, e.g. high T_c conductors, high electric strength insulators, etc. some of the very attractive UC design features, e.g. unitized factory fabrication, rigidity and dimensional stability, low AC losses, etc. could have resulted in both a technically and economically feasible high capacity AC superconducting transmission system option.

b. The BNL Project. The Brookhaven project has continued longer than any of its competitors and can, to the extent that it has been allowed to proceed, certainly be regarded as a success. Its proposal to develop and design a SPTL can in many respects be considered a paradigm of the research and effort that should precede the funding of any federally-sponsored R&D project. The BNL report to the NSF³⁹ upon which the BNL cable design ultimately selected for development was based, was a carefully prepared document which, among many other things, demonstrated that the Brookhaven group had:

- i. thoroughly investigated the electric utility industry's need for such a transmission system, and
- ii. persuaded key individuals in the industry that the BNL cable design was capable of being integrated into existing networks with relative ease, i.e. its installation involved fewer major changes in conventional underground cable technology (such as the use of flexible and

hence reelable cable, use of conventional cable winding machinery, etc.) than other designs.

Furthermore, during the entire course of the BNL project these critically important interactions with the ultimate users of their SPTL cable were maintained.⁴⁰ During the past year two 115 meter-long flexible single phase AC SPTLs rated for 138 kV and 1000 MVA three phase service have been tested at Brookhaven. All systems performed satisfactorily. The cables behaved as predicted. In October 1984, a 1 month run which included 4 days at 240 MVA per cable (80 kV and 3000 A) and 5 1/2 days at 333 MVA per cable (80 kV and 4100 A) was completed. The emergency test of 6000 A simultaneously with 80 kV to ground was also successfully accomplished and without reducing current the voltage was raised to 110 kV for about 20 mins. Operation for a total of 1 hour was then achieved at 6000 A with 20 minutes at 660 MVA per cable. There were no alarming thermal excursions and the current was reduced to 4100 A for another 24 hours thus demonstrating cryostability. The losses were larger than expected but not due to eddy currents. (The loss was strongly temperature dependent and the waveform was rich in harmonics--characteristics of super-conductor loss. In fact, the major source of the increased loss was due to current "crowding" at the edges of the outer conductor tapes. It is believed that this can be improved in a new design.)

Much engineering development remains to be done, e.g. development of cable splicing techniques, feeder joints and terminations, transfer of the BNL cable winding technology to industry, solution of problems related to integration of the cable into existing power networks, etc.

c. The Los Alamos project. The objective of the Los Alamos project was to address, during its first three years (Phase I), the unsolved physics and cryoengineering problems associated with the development of a prototype DC SPTL. This approach was, in fact, pursued for the first two years. But by the mid 1970's, many of the major federal-sponsored energy R&D projects then underway began to move into very costly development phases, and even a sympathetic Congress was beginning to insist upon more in-depth comparisons among alternatives before supporting additional project transitions from their research to their development phases. Concurrently, the high costs being incurred by those energy projects already embarked upon development phases were absorbing increasingly larger fractions of the funding allocated each energy technology category, with the result that pressure was being

continually increased on projects still in their research phases to "justify their continued existence". For the DOE's Division of Electric Energy Systems (EES), the decision to initiate the PECO I study was in large measure a consequence of the dilemma facing the SPTL program manager regarding the funding level appropriate for each of the three major SPTL projects then being supported, particularly since one of these was already in its development/demonstration phase and another was ready to enter upon it.

For Los Alamos, this decision forced a major shift in its project priorities from research to engineering in order to develop a DC superconducting transmission cable design sufficiently detailed and sufficiently justified to enter in the PECO I sweepstakes. Cable design decisions had to be made (and were made) on the basis of the best available data. Experiments were then conducted to confirm those decisions only when necessary. Increased attention was given to problems likely to be encountered in integrating the engineering characteristics of the selected SPTL design with existing transmission networks. Terminal equipment problems were investigated. Economic issues were addressed. Fault contingency situations were examined. The dielectric characteristics of the candidate insulating materials were measured, etc. Finally, and on schedule, the DC SPTL cable design and the electrical system studies were completed and submitted to the PECO engineers.

The Los Alamos design consisted of a coaxial 300 kV superconducting flexible cable utilizing copper stabilized Nb_3Sn superconducting wires. The cable was to be pulled (in lengths of about one half mile) through a rigid cryogenic enclosure. The associated refrigeration system was capable of maintaining the superconductor at a temperature of about 12K. The conductor was designed for a normal power load of 3.33 GW with contingency loading to 7.5 GW.

For the PECO I scenario, the Los Alamos entry costed out at 1.69 billion dollars, about 400 million dollars higher than the BNL AC SPTL design and the 10th most costly among the fifteen designs examined.

Despite this shift in project focus, substantial accomplishments were realized during the nine years of the project's history. Among these are the development of two conceptual cable designs capable of meeting economically most different load and contingency requirements. Optimal choices of both a superconductor (material and design) and an insulating dielectric were made after an extended development and testing program. Cable terminations were

designed and their components were independently tested. Effective and economical cable refrigeration systems were designed and tested, and extensive electrical network and system studies for DC SPTL's were carried out. In general, it can be claimed that a solid base has been laid for the construction of a prototype DC SPTL. On the other hand, there is also little doubt that an even stronger technological base for future development would have resulted from the more deliberate approach to this problem originally proposed. As with all such projects much research and much engineering development still remains to be done, most of which is discussed in detail in Ref. 42.

2. Supporting SPTL Projects.

a. Materials, cryogenic fluid flow and cryoengineering projects.

Eighteen major projects (more, if subcontracts from the three SPTL development projects are also included) were initiated and completed to support the US superconductive transmission line program. This support included:

- applied physics research, for example the Stanford project, which yielded both important advances in our basic understanding of the behavior of Type II superconductors under real SPTL operating conditions as well as significant advances in the technology of manufacturing sophisticated superconducting structures with highly specialized properties, such as low AC losses, high current densities, high fault current capabilities, low eddy current losses, high operating temperatures, etc. Basic and applied research on the behavior of candidate dielectrics was also carried out at Stanford.
- engineering research, for example the ORNL project, in which engineering data were obtained on the dielectric strength of helium (liquid and supercritical) and polymer dielectrics using projected SPTL geometries and operating conditions.
- cryogenic fluid flow research, such as was carried out at the NBS Cryogenics Division, Boulder, Colorado, in which the thermal-hydraulic behavior of helium circulated through kilometer-long channels was investigated.
- cryogenic refrigeration studies, in which the refrigeration requirements, (reliability, low cost, efficiency, etc.) were examined and assessments were made of additional developmental needs.

The final reports from these projects referenced in section IV. F. of this study provide detailed accounts of the results of this work. In general, it

was undertaken seriously, competently and effectively. It was also well conceived (although perhaps a bit redundant in certain areas) and certainly helped to enlarge and strengthen the technology base upon which the US SPTL program was carried out.

b. The PECO system studies. The moving of research ideas on to devices or technologies of practical use to society has historically been characterized by a high failure rate and, on the average, a long gestation period, e.g. 20-30 years. In an effort to speed up this process as well as make it more efficient, several extensive analyses of the research, development, demonstration and commercial deployment process have been carried out in recent years. One early consequence of these studies has been a detailed categorization of the so-called phases of the R&D process. The DOE has defined five major functional categories of the development process, namely:

- Basic and Applied Research
- Exploratory Development
- Technology Development
- Engineering Development
- Commercialization, Production, and Operations

Although the significance of these categories is more or less self evident, a detailed description of each is provided in Appendix II. For present purposes it is sufficient to note that the per project cost increases markedly when the technology development and, particularly, when the engineering development phases are embarked upon.

Since in the early 1970's the case had already been made for a considerable degree of urgency in the development of a practical SPTL in order to accommodate the very high power transmission loads expected in the 1990's, pressure was consistently exerted by sponsor program managers upon the SPTL research groups to move rapidly into the latter phases of the R&D process. The difficulty with this approach was that it was occurring simultaneously on practically all energy R&D fronts. Initially, the annual funding provided by the Congress tended to match this accelerated development program, but by the mid 1970s questions began to be raised, increasingly, regarding whether this sense of urgency had evaporated and hence whether the need for moving competing projects into their development phases in parallel still existed. In consequence, the rate of increase of energy R&D funding began to level off.

In advanced high-capacity underground power transmission, about a dozen or so R&D projects were by then underway and many of them were either already in, or about to enter, the high cost development or demonstration phases. Given the above-mentioned limit upon further increase in R&D funding together with both the current and the projected financial burden associated with the support of these projects into their development phases, the federal and the private sponsors of SPTL R&D were persuaded that some mechanism had to be developed to terminate those projects that could be shown least likely to be successful.

One contribution to the solution of this problem, initiated by the DOE in late 1975, was a comprehensive system planning exercise (identified in this case study as PECO I) in which the technical and the economic feasibility of fifteen different underground high capacity power transmission options currently under development were compared. The designs for the underground systems included in the study were supplied by the ERDA/EPRI--sponsored contractors.

In principle, such an assessment is not only a useful but also an essential aid to decision making. In practice, however, this procedure must be applied with care. Few, if any, decisions based upon a single such study can be justified. Arguments in support of this last assertion are collected in Appendix III. Most of them were formulated by PECO personnel and are included in the PECO reports as caveats and qualifications. Nevertheless, the PECO I study (including its preliminary findings), in which the BNL AC superconducting transmission cable was found to be the least costly of the options examined, is believed by many of the research groups involved to have contributed to the termination of support for the remaining US SPTL development projects.

As noted previously, the transmission distance is a critical parameter in any comparison of AC vs DC systems and at about the same time as the PECO I results were published, the DOE's EES division, which was at that time still supporting both the BNL and the Los Alamos projects, was well aware of the fact that, if a need for high-capacity transmission systems did continue to exist, the DC SPTL would be a strong competitor among alternatives once the distance to be traversed exceeded one or two hundred miles. To substantiate this conclusion quantitatively the PECO II study was commissioned. As noted

previously, the load levels considered ranged from 4-12 GW per system over distances from 30-200 miles.

Funding constraints led to the termination of the Los Alamos project before the PECO II study was completed, however. In consequence, no superconducting power transmission systems were considered in PECO II. This decision was, in retrospect, a most unfortunate one, but not because the results might have contributed to a decision to revive the Los Alamos project. Rather, the PECO II study, which was based upon operating parameters specifically chosen to compare the DC SPTL with alternatives, would have provided for future power engineers a carefully executed study of the potential contributions of a DC SPTL to high capacity (>5 GW) long distance (>150 miles) power transmission. Finally, since practically all of the necessary engineering data had already been provided PECO by Los Alamos to ensure inclusion of its DC SPTL in the PECO I study, it can scarcely be claimed that cost was a significant factor in that DOE decision. In effect, that decision significantly detracted from the overall value to the nation of the entire Los Alamos effort.

PART III. CONCLUSIONS

V. OVERVIEW

The several factors contributing to, and providing a rationale for, the initiation of the US SPTL program have already been outlined in section III of this case study. We therefore know why the SPTL R&D proposals were prepared, approved and funded. And given the same information, i.e. projections of needed transmission capability, the capability of existing transmission technology, the potential power carrying capacity of SPTLs, environmental constraints,⁶² and, not least, public pressure on the federal R&D establishment to "do something," it is reasonably certain that an almost identical set of actions and decisions would have been taken by analogous participants in such an enterprise today (there were at the time a few opposing "voices crying in the wilderness,"⁶³ but their objections and concerns went unheeded). Something apparently went wrong with this program, however, since all of the US SPTL programs were either terminated or sharply curtailed long before the R&D deemed necessary to demonstrate their technical and economic feasibility had been completed.

The commonly accepted reason for the demise of the SPTL R&D program is that the urgency for developing a new very high power transmission technology vanished. We shall explore subsequently the basis for this conclusion as well as whether the ultimate need for such a technology may also have evaporated (at least for the foreseeable future). The role of the federal government in this type of R&D will then be examined since changes in energy policy that accompany changes in national Administrations can also alter the definition of that role, the character of the R&D program and the speed with which any resulting changes are implemented. We shall also examine in passing whether earlier organizational and operational changes in the program could have resulted in a less costly R&D effort as well as in one more responsive to changing external conditions. Finally, some prescient thoughts from England on the inherent characteristics that a new technology must possess to ensure its acceptance by industry (as well as the conditions under which these requirements turn out to be invalid) will be presented and discussed.

VI. THE URGENCY/NEED/OPTIONS ISSUE

The energy use data upon which the belief that an urgent need for SPTLs existed in the early 1970s (when all of the major US SPTL programs were well underway) is shown in Fig. 3. This graph, in which the total annual US energy consumption has been plotted vs year on a semilogarithmic scale shows that from about 1850 until 1979 an average energy growth rate of about 2.7% per year was maintained in the United States. Positive growth rate deviations occurred from just before the turn of the century until the economic depressions of the early 1920s and particularly with that beginning in 1929. Higher than average growth rates were also maintained more recently, from the mid 1960s until the 1973 OPEC oil embargo. Then, after a sharp but short-lived drop in consumption, the old average growth rate of 2.7% per year was reestablished from 1976 to 1978.*

The specific conclusion that SPTLs were urgently needed when these R&D programs were initiated is confirmed by the data given in Fig. 4 in which the nation's growth in installed electrical generating capacity is plotted from

*A smooth curve through the points plotted in Fig. 3 defines the "envelope" of the annual US energy consumption data. The straight line is a least squares fit to the envelope data.

Fig. 3. US Energy Consumption (Quads/Yr) vs Year.

Fig. 4. US Installed Generating Capacity (GW) vs Year.

1902 through 1983. As noted previously, installed generating capacity, which is itself based upon projections of electrical energy consumption (Fig. 5), increased at a rate in excess of 7% per annum for about 70 years. So also did the nation's consumption of electrical energy (except during the Great Depression). Although it was obvious to everyone that this last mentioned rate of increase had to slow eventually (or the rate of total energy production had to increase substantially), there were few indications at the time at which the SPTL program was initiated that any such change was imminent.

By 1973, however, before the recent departures from the historical growth rates shown in Figs. 3, 4 and 5 occurred, reserve electrical capacity began to increase (in excess of the usual 20%) and, as the years passed, it showed no tendency to recover, as it had previously (see inset in Fig. 6). Estimates of future peak demand for electricity were therefore successively reduced by the industry itself beginning in 1975 as shown in Fig. 6.

The departure from the historic electrical energy consumption growth rate, which was already apparent to electrical utility planners in 1975, seems not to have become clear to the federal energy R&D establishment or to the public in general until the early 1980s. This was not surprising. The year 1979 began with the Iranian revolution and the flight of the Shah. This was followed in March with the Three Mile Island accident, and then by a succession of OPEC oil price increases. In May, gasoline shortages erupted on both coasts, and by midsummer, with almost every indicator seemingly pointing to more energy-related problems, President Carter (responding at least in part to concerns expressed by his new Department of Energy) called for additional legislation establishing a powerful new Energy Mobilization Board, a new Synthetic Fuels Corporation, and a host of other new energy conservation practices addressing the continuing energy crisis as perceived by the federal government.

Within the past few years, arguments have begun to be advanced suggesting that the downward trend in the rate of US energy consumption that began in 1979 (as shown in Figs. 3 and 5) is not a minor temporal perturbation. Instead, several well known analysts of the national energy scene have concluded that it is the beginning of a major discontinuity with all previous energy growth rate behavior. Since numerous books and articles have recently been published in support of this thesis,⁶⁴ it is necessary only to note here that the energy crises of the 1970s had the salutary effect of making the

Fig. 5. US Electrical Energy Consumption (billion kilowatt hours/yr) vs Year

Slower Growth in Demand for Electricity...

The New York Times / May 22, 1984

Fig. 6. Peak Demand for Electric Power (Actual and Projections) and Reserve Capacity vs Year. Copyright © 1984 by the New York Times Company. Reprinted by permission.⁸⁹

US public acutely aware of its dependence on energy and also of the fact that in the future it could no longer be assumed either that energy would be forever cheap or that its ready availability could be automatically taken for granted. One important consequence of that awareness and the trauma that accompanied it was that actions were taken--in some cases by the government and in others by the market place--which led to decreasing per capita energy consumption and decreasing amounts of energy consumed per dollar of GNP as shown in Figs. 7 and 8. These actions included: the 55 mph national speed limit, legislatively-imposed gas mileage improvements in the nation's automobile fleet, the adoption of improved industrial energy conservation practices (encouraged by the increased cost of energy), improved energy conservation practices in industrial, commercial and residential construction, increasing deployment of more efficient energy conversion technologies, e.g. cogeneration, and an increasing utilization of renewable energy sources (solar, wind, small hydro, etc.). Most of these changes have occurred without significant adverse impact upon quality of life and, in general, make good economic sense. On the other hand, it is not reasonable to assume that they can continue in the same direction indefinitely and, as may be seen from Figs. 3 and 7, it may well be that some minima have already been reached.

Fig. 7. US Per capita energy use vs year⁹⁰

Fig. 8. Energy/GNP Ratio vs Time and the GNP⁹¹

Although the long term growth data prior to 1974 and as well as the related information presented above contribute to and support the arguments already presented in section III (The rationale for initiating a program to develop and demonstrate a superconducting power transmission line), their inclusion here is only to focus attention on and to emphasize the fact that, during the last half of the decade of the 1970s, marked changes in historic energy and energy-related growth rates began to occur. The totality of this data provides considerable support for the propositions that:

- during the late 1960s and the early 1970s when the SPTL projects were initiated, there was every reason to believe, given the projected increases in generating capacity, that high capacity power transmission systems would be urgently needed by the 1990s,^{26,53}
- during the mid 1970s, this sense of urgency gradually evaporated due to successive decreases in electrical energy consumption, successive decreases in projected demand for electrical energy and successive reductions in projections for new generating capacity,
- this loss of urgency for the development of very high capacity transmission systems is likely to persist for the next several decades.

It is relatively common, when the urgency driving a particular human endeavor vanishes, to argue that the "need" still remains; all that has happened, it is said, is that the need has been postponed, and that the "show must still go on" albeit, perhaps, at a slower pace. It is worth noting that, although this reasoning may be correct, it is not necessarily correct. When urgency vanishes, need may also eventually vanish. The justification for this assertion is based upon the fact that given an urgent problem, the set of possible solutions selected for investigation is a function both of the problem itself and of the science and technology then available for solving the problem. Absent urgency, the passage of time is capable of changing both the problem and/or the potential solutions.*

*A hypothetical example of this vanishing of the "need" for SPTLs may be useful. Assume that one result of a decrease in urgency is that the SPTL development and demonstration phases are terminated. Assume, further, that the new US Strategic Defense Initiative proceeds at least through its R&D phases. It is not inconceivable that a spinoff from that undertaking might be a new charged particle high capacity power transmission technology with both technical and economic potentials superceding those of SPTLs. Should such a breakthrough occur, then when a high capacity power technology is required, there could well be no justification for reviving the SPTL approach.⁷

The historical and projected growth data presented above, together with the comments and interpretations made thereupon, seemingly provide considerable support for the proposition that both the urgency and the need for developing and, in particular, demonstrating a SPTL have vanished. However, the primary purpose of a "case study" is to provide accurate, relevant and complete data on the issue under consideration so that the reader can draw his or her own conclusions. We shall therefore pursue this subject only two steps further--firstly by exploring the various options available to the SPTL program sponsors and participants depending upon whether the urgency but not necessarily the need, both the urgency and the need, or neither the urgency nor the need have vanished. Secondly, we conclude this section by outlining one possible way of obtaining an answer to these questions.

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If only the urgency for developing a SPTL technology has, in fact, disappeared and the issue of need remains moot, the following options appear, in principle, to be available.

- a) reduce the size of the SPTL program,
- b) change the objectives of the SPTL program,
- c) change the overall thrust of the SPTL program,
- d) stretch out the SPTL program.

We now consider each of these options in turn.

- Reduce the size of the program. This is the action that was actually taken by the DOE beginning in 1976 when the UC/Linde project was terminated. It was taken again in 1978 when most of the supporting projects were concluded, and yet again in 1979 when the Los Alamos project was terminated. In some respects it can be argued that, although these actions were the right ones to have taken, they were taken for the wrong reason, i.e. they resulted primarily from the imposition of limits on the continued growth of energy R&D funding.* Fig. 9 clearly shows that the growth rate for national energy R&D funding decreased to approximately zero after FY79. This funding then remained essentially constant for the next three years, after

*Additional reasons for having reduced the size of the program are given in Ref. (60).

Fig. 9. The US Energy R&D Budget vs Fiscal Year (the difference between the points and the solid line arises from different methods of counting Energy R&D funding. Sources: Federal R&D Funding for Energy: Fiscal Years 1971-1984, National Science Foundation, NSF 83-301 and DOE Budget Reports).

which it sharply declined. Since it became impossible for the DOE to support more than one SPTL demonstration phase and since the DOE project management was convinced that the development and the demonstration of an SPTL remained an essential element of the DOE mission (as is apparent from the fact that funding for the BNL project continued to increase through FY81), the "winnowing" actions taken by the DOE were, from this viewpoint, appropriate. But, clearly, these actions were not taken in response to an increasing awareness on the part of the DOE management that the SPTL development effort had begun to lose its sense of urgency. It is, of course, of some academic interest to speculate on what those actions might have been had the DOE accepted the proposition that the urgency for developing a SPTL had evaporated. At present, however, the size of the national SPTL program, i.e., that of the remaining BNL project, has already been reduced to the minimum feasible level. Hence, little can be gained from further discussion of this particular option.

- Change the objective of the program. This is an option that has also already been taken. After the 1981 budget cuts and probably even earlier, both the DOE and the BNL program managers were persuaded that the BNL SPTL program, as originally conceived, was facing serious problems. In consequence, partly in recognition of the fact that the previously assumed need for multigigawatt transmission systems in the 1990s had, at the very least, been postponed and partly in recognition of the fact that SPTL development work abroad had almost totally collapsed, the immediate capacity goals of the BNL SPTL project were reduced from 3000-4000 MVA to 500-1000 MVA (a level more consistent with the shorter term projected needs of the electrical utility industry but totally consistent with BNL's original high capacity testing schedules). This approach therefore does preserve the capability of continuing, at some appropriate future time, with the development of high capacity SPTLs.

On the other hand, by reducing the load level, the overall justification for continuing to support the Brookhaven SPTL project may have been weakened. As noted previously in this report, the rationale for initiating all SPTL projects and in many ways their sole raison d'être (Fig. 1) was their high capacity power transmission potential. It remains to be seen whether low capacity SPTLs can compete economically, and in terms of reliability as well, with more conventional alternatives.*

- Change the thrust of the program. Instead of pressing forward to develop and demonstrate a particular SPTL (the design of which was "frozen" a decade ago because at that time responsiveness to the urgency issue required that applied research directed toward optimizing the design of an SPTL not be allowed to continue indefinitely), an alternative is to support an R&D program emphasizing only the

*A related development at Brookhaven was the initiation of a project in FY79 to develop an advanced ambient temperature cable utilizing synthetic polymer tape insulation. The technology upon which this new project was based was a direct consequence of BNL's program to design and develop a flexible AC superconducting power transmission cable. This project was also directed toward satisfying the short term needs of the utility industry. By FY85 more than half of the total BNL funding from EES was being allocated to this new spin-off activity.

applied research aspects of the SPTLs. This is the approach that seems to have been taken by EPRI. Since the electrical utility industry was well aware of the decrease in urgency for the development of high capacity power transmission systems by the mid 1970s, EPRI terminated its support of SPTL demonstration projects in 1975. But rather than abandoning the concept entirely, EPRI continued to support applied research in those areas considered to be critical impediments to the future development of economic and reliable SPTLs. These were studies relating to the feasibility of using higher T_c superconductors (which if successful would reduce refrigeration costs), studies of advanced and innovative refrigeration processes (which if successful would enhance reliability) and studies of low temperature dielectrics (which if successful would enhance reliability and also make possible cable operation at higher voltages).⁴⁷

This approach constitutes a relatively low cost response to the decrease-in-urgency issue. It also tends to keep experienced research teams together, preserves in a viable manner previous programmatic accomplishments, maintains the benefits inherent in supporting diverse approaches to a basic technological problem, produces results of general utility, and finally, gains time for further assessing the long term implications and the permanency of the apparent urgency changes.

- Stretch out the program. Despite the evidence presented at the outset of this section, respected advocates of the SPTL concept continue to argue that neither the urgency nor the need for SPTL development has evaporated [see Refs. 65, (60), and (66)]. Consequently, serious consideration should be given to stretching out the US SPTL development program, thereby preserving the technology, equipment and experience that has been assembled at Brookhaven during the past dozen years. A "level of effort" SPTL program could be continued, presumably at Brookhaven, until the urgency/need issue is resolved.

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If both the urgency and the need for continued SPTL development have evaporated, (and a case can be made for that conclusion based on the data given at the beginning of this section and on the specific arguments listed below), then the only remaining option is to:

- Terminate the program. In large measure, this was the action taken throughout Europe because it had become increasingly clear to the sponsors of SPTL projects that the need for multigigawatt cables was decades in the future. In the US, the case for abandoning further SPTL development and demonstration efforts is based upon the following arguments:
 - a) power parks (both nuclear and coal-fired) have been more or less forgotten; in contrast, dispersed, small modular power plants are now being given considerable attention.⁶⁷ If this trend continues, the market demand for multi GW transmission systems may be so limited that little or no incentive will ever exist to commercialize it.
 - b) with the 7% growth rate in generating capacity sharply reduced, broadly based concern about multiple high capacity overhead transmission lines blanketing the countryside is also much reduced. Society reacts vigorously and effectively when a proposed or projected development threatens to impair some aspect of the life style, the health, the safety or the quality of the environment for large segments of the population almost simultaneously. Such threats clearly occur more frequently with rapid growth situations. With much slower growth, the same adverse impacts occur successively, instead of simultaneously, and they occur in widely dispersed regions affecting relatively few individuals at any one time. Under these conditions it becomes exceedingly difficult to generate the large scale, coherent and vigorous public outcries and objections necessary to initiate new legislative or regulatory actions to counter or ameliorate the adverse effects of such developments.
 - c) normal continuing improvements in the capacities of conventional overhead and underground transmission systems appear likely to accommodate almost all power transmission needs for many more decades.

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If neither the urgency for developing SPTLs nor their need by electrical utilities has evaporated, then further development and demonstration efforts should be continued.

The arguments in favor of continuing with this work are forcefully presented by the advocates of this position. They are reproduced in full in Refs. 65, (60), and (66). Central to their position is the conviction that:

- the BNL project, despite suffering a sharp curtailment in funding which began in FY81, has been a success, i.e., it has clearly demonstrated the technological feasibility of AC superconducting transmission.
- the electrical utility industry continues to support the development of SPTLs.
- the decrease in demand for electrical energy is a short term phenomenon
- 500-1000 MVA SPTLs can compete economically with existing alternative underground power transmission systems.
- the need for very high capacity network interties remains. An SPTL is clearly the optimum transmission system for such service, and proceeding with the development of much lower capacity systems will make possible the necessary capacity upgrading whenever it is needed.

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Which of the options outlined above (or some combination thereof) is the optimal choice clearly hinges on a resolution of the urgency/need issue and also upon whether a lower capacity SPTL can become a viable competitor with alternatives. The standard procedure for resolving this issue is for the responsible management entity to obtain authoritative, objective, unbiased analysis and opinion. One way of obtaining this information is via system studies and advisory committees. Both of the above approaches have been employed previously, e.g. the PECO studies, but in these cases the entity or individual being provided this information had a considerable stake in the outcome. Under these conditions, the appearance of a conflict of interest exists and hence the outcome or the interpretation thereof is suspect. An alternative approach is to consider an enlargement of the ERAB concept. The operational element could be a specialized energy research advisory committee

(SPERAB?), knowledgeable, in this particular instance, about the electrical utility industry but including generalists as well. It could report to ERAB, to the appropriate DOE Assistant Secretary or to both. It would be responsible not only for providing advice but also for commissioning system studies and for setting the terms of such studies (including the scope and the frequency with which they should be updated since the problems being dealt with are obviously dynamic). A final responsibility of the committee might be to determine that point in the sequence of R&D phases that the activity should be transferred to industry (or the point at which the transition process should be initiated) as well as the point at which significant cost sharing with the ultimate user should begin. Inherent in this last-mentioned responsibility is a recommendation by the committee of a federal laboratory development schedule such that the transition to industry will be timely.

VII. THE ROLE OF THE FEDERAL GOVERNMENT ISSUE

So much has already been written on this subject, that it would seem superfluous to belabor the issue again. Furthermore, the question of whether the federal government should have become involved during the early 1970s in the SPTL program has already been discussed and answered affirmatively in section IV.E. Nevertheless, the issue of what that involvement was initially, how it evolved in response to policy and other changes, and where it stands at the present time is relevant to this case study.

The classical criterion for federal involvement in energy R&D has, in principle, been a determination* that the private sector R&D effort in a given nationally important energy-related area was inadequate (for a variety of reasons, practically all of which have been discussed in previous ERAB reports⁶⁸ as well as in other recent publications⁶⁹). In the case of the BNL and the Los Alamos SPTL programs, however, this criterion was not applied. By 1972, when the federal SPTL programs were initiated, the electrical utility industry was well aware of the contribution SPTLs might be able to make to solving its expected high capacity transmission problems,²⁷ it had already sponsored numerous technical studies, assessments and applied research projects and it was currently funding the UC/Linde SPTL development

*In practice, that "determination" was often replaced by an assumption, a political decision or a history of substantial federal involvement.

project.^{11,15,18,23-26,31-33,38} In retrospect, the question of whether it was wise for the UC/Linde group to settle on a design and move into the big hardware stage so early should probably have received more consideration. But since the UC research group had already been studying AC losses in niobium for several years and the urgency for getting something underway seemed high, it would have been unreasonable not to have supported the actions then taken. It is also conceivable that, had the private sector continued to fund and manage the UC project, pressure would eventually have been applied by the funding agency to correct perceived deficiencies, experiment with higher T_c superconductors, and investigate different cable designs. Alternatively competing SPTL proposals might have been funded by the industry.

Additional evidence of industry's early interest in superconducting transmission line technology may be found in the fact that, at about the same time that Brookhaven was preparing its SPTL proposal for the NSF RANN program, General Atomic was independently pursuing its own ideas of using high T_c superconductors for AC power transmission. In Ref. 38 a chronology of the research undertaken by General Atomic to develop low AC loss Nb_3Sn conductors is given. This work formed the basis for the Stanford University SPTL program.

Regardless of the justification (or lack thereof) for the government's entry into the SPTL development program, the national energy policy in effect at that time included federal involvement in all five phases of the R&D process. In consequence, both the BNL and the LASL SPTL proposals included a demonstration phase (as did the UC/Linde project).

Through FY74, the three SPTL development projects underway in the US were funded by both the electrical utility industry (the UC/Linde project) and the government (the BNL and the LASL projects). In FY75, however, funding and management responsibility for the UC/Linde project was transferred to the government. The reason for this shift can be traced to: a) a 1971 threat by the Congress to establish a federal version of EPRI,⁷⁰ b) the response of the industry to that threat by creating EPRI in 1973, c) the assumption by EPRI of management and funding responsibility for the ERC's R&D programs, including a number of long term, high risk projects (many of which were undertaken in response to the industry's 1971 R&D goals study²⁷), d) the limited financial resources for R&D made available to EPRI, e) the high cost of supporting the demonstration phase of long term, high risk projects, f) the

short and intermediate term R&D needs of EPRI's constituency, and g) the necessity on the part of EPRI of demonstrating to that constituency its responsiveness to those needs. Given

- a) these pressures to concentrate on utility-related short and intermediate term R&D,
- b) the way in which these pressures developed and
- c) the fact that the energy R&D charter assigned the federal research establishment by the Congress in the early 1970s included a substantial federal commitment to the development and demonstration of renewable and "inexhaustible" sources of energy, e.g. solar, fusion, the breeder reactor, etc. as well as to that of the necessary infrastructure technologies, e.g. advanced power transmission technologies, energy storage systems, etc.,

EPRI very early in its institutional history decided to allocate almost all of its R&D resources to near and intermediate term projects. During the same period (1973-1975), the federal government assumed responsibility for continuing several of the long term, high risk R&D projects initiated by the industry.

As has already been noted, both the UC/Linde and the Los Alamos projects were eventually terminated and BNL continued with its AC SPTL demonstration and testing program. In 1981, however, the new Reagan Administration introduced major policy changes in the objectives, strategies, and allocations of energy R&D funding. Specifically, as formulated in the 1983 National Energy Policy Plan, the energy R&D policy of the federal government will emphasize energy-related basic and applied research and development such that "Once basic and applied R&D have been accomplished, the pace at which new or alternative technologies are commercialized and marketed will be determined not by the federal government, but by entrepreneurs and consumers."⁷¹ This general policy statement was then further elaborated in a subsequent section of the Plan as follows: "... federal energy research and development has been redirected to emphasize basic and applied research and development and to move away from the demonstration and commercial efforts that dominated previous energy research and development policy."⁷² Implementation of this policy by

the DOE accounts for the sharp decrease in funding for the SPTL program shown in Table 9 and Fig. 2.*

On August 31, 1981, the Deputy Secretary of the DOE requested ERAB to refine this policy, since demonstration projects as well as other situations do exist in which policy exceptions or modifications may be justified.⁷³ This effort^{68a} eventually led to a follow-up study on the Federal Role in Energy R&D^{68c} in which ERAB recommended to the DOE that, in general, the following guidelines be applied to Federal energy-related R&D:

- "Beyond the basic or exploratory research phase, DOE should insist on a significant level of co-funding by the private sponsor to assure that the technology is viewed as truly worthy of funding. This must be more than a 'token' private contribution. Projects should be judged by the willingness of the sponsor to put private R&D dollars at risk. This is a far more reliable criterion than the often quite inaccurate and unreliable 'appraisals' commissioned by DOE or private sponsors to justify projects where many of the resulting economic estimates are suspect.
- To provide further incentive for industry R&D, DOE should allow the resulting information to remain proprietary, with due regard to free rights for the government's own use and willingness of the private sponsor(s) to license others at reasonable rates.
- Whenever private co-funding is substantial, guidelines should be established which allow the private sector participant(s) to manage the project without undue involvement from DOE. Unwillingness to do so has resulted in excessive costs and often very poor judgement regarding program selection and objectives."⁷⁴

In both of these reports,^{68a,68c} however, it was emphasized that circumstances exist "in which it would be unrealistic to expect timely and effective assumption by industry of R&D responsibilities abdicated by the government."⁷⁵ The electrical utility industry was one such industry.

*Had the electrical utility industry (EPRI) continued to be responsible for both the funding and the management of not only the UC but for the entire US SPTL R&D program, it is conceivable, in view of their less optimistic growth projections, that this decrease would have occurred much earlier, as it did abroad.

The reason for including the discussions and quotations reproduced above in this case study is to call attention to a policy dilemma that still requires resolution. Specifically:

- implementation of the first of ERAB's recommended guidelines (co-funding of the demo phase) is, at present, not possible for the SPTL program, neither by EPRI nor by the equipment manufacturers (because of the unresolved urgency/need issue, limited funds for long term R&D and uncertainties regarding the market for such systems). ERAB has concurred in the conclusion that this type of R&D cannot feasibly be funded by the utilities.⁷⁶ Hence if this program is to continue it will require either substantial federal funding or the assumption by EPRI of responsibility for funding an increasing proportion of long range, high risk R&D relevant to the long term health of the utility industry. At the moment, the latter option is unlikely to be adopted.
- but the DOE has sharply curtailed the US SPTL project.
- should it turn out that federal funding (for the BNL project) is approved pending a resolution of the urgency/need issue and should such a study confirm both the continued urgency and need for developing a SPTL, another problem arises regarding the third ERAB recommended guideline, namely that, for the remaining demonstration phases of the project, it be managed by the electrical utility industry or its representative, e.g. EPRI. Optimal benefits will probably be obtained from the moneys expended for such work if the project management is controlled by the private sector but it is far from clear, if fiscal responsibility remains with the federal government, how public funding and private management can each be substantial simultaneously.

Before concluding this section it is worth calling attention to one assumption that pervades the above discussion, namely that the urgency/need issue will be settled in favor of proceeding with the SPTL development. Obviously, if either the urgency or the need has vanished, the entire issue of cost sharing during the development and demonstration phases is irrelevant! This fact, introduced at this point in the discussion, is intended to emphasize the hierarchy among the criteria usually employed in evaluating R&D

programs and establishing priorities. Often, in fact, "need" is taken for granted, merely because the program already exists! In the case of the SPTL, and probably quite generally as well, it is essential to settle the urgency/need issue before addressing such other criteria as technical and economic feasibility, role of the federal government, cost/benefit evaluations, etc.

VIII. OTHER ISSUES

A. Introduction

Assuming that the urgency/need issue is resolved in favor of proceeding with the development of a SPTL and that a satisfactory funding/management modus operandi can be worked out between the electric utility industry and the government, it might seem reasonable to conclude that the US SPTL development program should and will be continued. The point of this final section of the SPTL case study is to suggest that "it ain't necessarily so." It is true that a favorable resolution of the above two issues is a necessary condition for continuing this R&D program but it may not be a sufficient condition.

B. The complexity issue

Few scientists and engineers familiar with the details of a SPTL would argue that it is other than an advanced, highly sophisticated technology. In the words of B. J. Maddock and W. T. Norris:* "Superconducting technology is complex: there is quite a lot to go wrong."

At this point it is important to interrupt this discussion with a caveat. The history of technology is littered with examples of important new ideas which have been rejected by the "establishment," often to its regret. It is so much easier to say "no" and not to stick your neck out. But society needs its visionaries, its advocates, its evangelists, its enthusiasts and often even a bit of snake oil salesmanship to overcome social and bureaucratic inertia or timidity. Although it may appear arrogant for outsiders to tell the "experts" what it is that the experts need, history has occasionally proved the outsiders right.

Of the following comments, those in quotes have been taken directly from the Maddock and Norris paper⁷⁷ and many of the remaining ones are theirs

*Maddock and Norris were themselves deeply involved in the superconducting transmission R&D program at the Central Electricity Research Laboratories (CERL) at Leatherhead, England. Much of this section is based upon their review article: Superconductivity in Electricity Supply.⁷⁷

paraphrased. Although these remarks may sound anti-progress, anti-innovation and anti-advanced technology, Maddock and Norris did not advocate such a philosophy nor does the author. The only objective of this section is to examine and discuss the situations in which and the conditions under which a new highly sophisticated, advanced technology such as a SPTL is likely to be successfully developed and deployed on a large or moderately large scale.

We begin with a series of statements, some of which will be further discussed in Part IV.

1. For very large and constantly growing technologies, e.g. the electrical utility system, in which the capital investment already comprises a substantial fraction of the gross national product, strong institutional pressures exist to require that new plant items fit into existing subsystems without a major disruption of processes and procedures. The normal response to growth situations is therefore a tendency to make incremental technological improvements, thereby making maximum use of plant, existing inventories, experienced personnel, etc. Given such enormous investments, wholesale replacement of plant components is unthinkable and "some utilities find replacement of even superannuated plant a scarcely tolerable burden."
2. Existing technologies turn to new, different, unfamiliar highly advanced component technologies only when normal incremental technological advances are perceived to be approaching a limit of some sort. [This limit could be one of transportability (as the size or weight of some component such as a transformer or a generator increases), transmission line capacity, etc. Given such problems, the industry involved usually begins to consider the use of new advanced technologies. However it concurrently attempts to solve these limit problems using conventional approaches (such as developing better transport methods, subdividing conventional units into smaller parts, etc.). This is the moving target phenomenon faced by many developing technologies and when these attempts to solve perceived problems by the use of unusual or ingenious conventional techniques are successful, the urgency for developing new advanced technologies is diminished.]

3. "The absence of growth is a certain curb on innovation--the economic ambience is not sympathetic." "Only if a [new] development proposes to be the salvation of [ones] business [does one] get really interested in novelty in times of austerity." "Almost everything that can be done with superconductors in electric power systems can be done with copper quite satisfactorily at present."
4. "The final [CERL's SPTL] design looked highly practicable with savings in cost achievable, but these savings were not enormous--there was no competition, cost wise, with an overhead line. The benefits over conventional cables were only available if you wanted to move several GVA. Furthermore if you insisted on an additional cable to provide a secure connection, a large single cable duplicated is maybe more expensive than $(n + 1)$ smaller cables where $n > 1$. Furthermore, bearing in mind that power station sites are often expanded gradually, the possibility of staged installation of lower powered cables allows a deferment of expenditure which is not available if large cables, each capable of carrying the power of the fully developed site, have to be installed initially."
5. "Fabre⁷⁸ warned us in 1969 at the Low Temperatures and Electric Power (LTEP) conference in London of the dangers of "gigantisme"--which he saw as the end of a line of evolution but which appears quite early as a danger too. If a new development is excessively encumbered--be it by the necessity to be large, be it by the need (real or apparent) for elaborate associated technology--in the case of superconductors high vacuum and helium handling--then the initial hurdle may be unleapable."

C. The economic issue

Another quotation from the Maddock and Norris paper is useful to introduce this subject: "We mentioned earlier the hurdle that superconductor developers must leap--the benefit offered must amply exceed the anticipated cost of acquiring it. And even then the administrators of the finances prefer cash now to cash later--their discount rates are high." This same conclusion has surfaced in numerous other analyses of the viability of other developing (and even developed) new technologies. A marginal economic benefit over existing alternative technologies should by no means be considered sufficient to justify continued R&D.⁷⁹ This was one of the problems with the PECO I

study. As noted previously the BNL SPTL design emerged as the winner from a field of 15 entries, but it is less frequently noted that the estimated costs of the lowest five cable systems differed by less than 10%. Given the currently common cost overruns of several hundred percent when new technologies are actually implemented, it is clear that substantial projected cost differences, between a new advanced technology and its competitors will probably have to exist in the future in order to justify the expenditure of either public or private funds in support of demonstrations.

PART IV. FINAL COMMENTS, QUESTIONS AND SOME LESSONS LEARNED

The final sentence of the Abstract to the Maddock and Norris paper⁷⁷ reads: "Any economic advantages of using superconductors [in the electrical utility industry] appear for the most part marginal." This remark was made in 1978, at which point most of the European SPTL projects either had been terminated or their funding had been sharply curtailed. Further evidence of the diminution of interest in SPTL R&D is provided by the number of major papers on SPTLs presented at the biennial Applied Superconducting Conferences over a 12 year period: 1972 (7), 1978 (11), 1984 (1).⁸⁰ In 1983 EPRI and Westinghouse terminated their joint six year \$19 million 300 MVA superconducting generator development program which was originally scheduled for service in 1985. And in the President's FY86 Budget, funding for a fifteen year superconducting generator R&D program at The Massachusetts Institute of Technology (MIT) was reduced to \$400,000 to "complete analysis and finalize documentation of the superconducting generator." Similar funding and closeout activities were included for the BNL SPTL project. Finally, in a related development, The International Business Machines Corporation (IBM) announced in September 1983 that it was terminating its superconducting computer project which began in the mid 1960s and had by 1983 become a \$20 million per year effort involving about 115 researchers.⁸¹

Despite all of these grim statistics, applied superconductivity is still alive and well and living in CERN, Batavia, Stanford, Boston, and, indeed, wherever very high field magnets are being manufactured and used!^{80c}

The explanation of this apparent contradiction lies firstly in the fact that, for the high energy physics community (and more recently for the medical

diagnostic community which is now using to an increasing extent the new Full Body Nuclear Magnetic Resonance Diagnostic Machines), no other way exists of achieving the desired result. Secondly, and almost equally important, these applications are taking place within a highly sophisticated technological environment populated with highly trained technical personnel who are themselves well supported by an advanced and broadly based scientific and engineering infrastructure. These conditions are scarcely duplicated in the electrical utility industry which is best characterized as a heterogeneous collection of some 3500 entities divided by geography, tradition, vast differences in size, technical resources and philosophy of ownership.

Another analog of a situation in which an advanced technology development program works under one set of conditions but fails under another set is provided by the history of the national laboratories themselves. Most of them were established to do one advanced technological development job for only one customer and, in large measure, the objective was "to solve the problem". In general, these problems were successfully solved. Furthermore, the ultimate use of the "product" was frequently carried out by the same highly trained group of technicians that had designed, built and tested it. Those national laboratories that were established after the World War II, either continued in the same tradition or were chartered to carry out research projects under circumstances analogous to those in which superconducting magnets are currently being successfully applied. In contrast, the federal laboratories have not been notably successful in solving the nation's energy-related problems, largely because the conditions under which energy R&D must be carried out are in many ways the inverse of those outlined above.

In summary, the federal research establishment, and the national laboratories in particular, excel in problem solving. If the military, NASA, or some other federal agency can define a technical problem, then if it's possible to solve it, it will get solved. For example, if the DOD had need of transmitting 10 GW of electrical energy from point A to point B, one can be reasonably sure that within a year or two a SPTL would have been designed, built, tested, installed and would be operating as required (in that short a time the design would not have been optimized but the line itself would almost certainly have worked). Furthermore, the researchers charged with doing the work would not have had to worry about whether or not it was needed, whether or not it was urgent, whether or not it was economic, whether or not it would

"fit in," whether or not there would be enough trained people to run it, whether or not there were environmental problems, whether or not it was too risky, etc.

These differences between how the federal R&D establishment is able to work successfully for the government and how it must enlarge its concerns and outlook when it works for the private sector, lead directly to the most important lesson to be learned from this exercise. This lesson is applicable whenever the federal research establishment undertakes R&D in support of private sector problems. Not surprisingly, it has already been formulated by ERAB as the second of its General Conclusions and Recommendations to the November 1981 report "Federal Energy R&D Priorities,"^{68a} namely: "Our energy system is a web of machines and people; the current budget is focused on machines. Consideration should be given to research in social areas, to prepare for rapid energy development in certain portions of the country and to help transfer conservation [as well as other advanced] technologies for the industrial and residential sectors." To this the present author would only urge that the suggested social research include economic analyses of the urgency and need for the research under consideration and that it be carried out not only prior to initiating the R&D program but also during the entire existence of the program.

A second "lesson" or question emerging from this study originates from the assertion, or perhaps from the assumption, that major energy-related industries exist in this country that are incapable (for a variety of reasons) of assuming financial and management responsibility for carrying out their own long range, high risk R&D programs and that the federal government is therefore obligated to sponsor and manage this R&D for them. The core issue here is whether it is more desirable to remove the impediments preventing these industries from assuming responsibility for their own long range R&D (particularly the engineering development and demonstration phases) than to continue to suffer the well known problems of federal management of such R&D, namely the "excessive costs and often very poor judgement regarding program selection and objectives."⁷⁴ Clearly, a closer coupling between the performer of the R&D and the ultimate user must somehow be established.

The third lesson to be learned from this study is the fact that new, advanced, unfamiliar, complex technologies are likely to be accepted by the industries for which they are being developed when:

- a. a clear and unambiguous need exists which only the new technology can satisfy, and
- b. the need is urgent.

Conversely, such new technologies are unlikely to be accepted when:

- a. less complex, more familiar alternative technologies are already under development,
- b. these alternative technologies will "fit in" with existing systems,
- c. the new advanced, unfamiliar, complex technology is likely to provide the industry with only marginal economic benefits over its more conventional competitors.

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APPENDIX I

FOREIGN SUPERCONDUCTING POWER TRANSMISSION LINE PROJECTS

In 1973, the SPTL programs underway abroad were summarized in the review paper "Superconducting and Resistive Cryogenic Power Transmission Research in the US--An Opportunity for Cryogenic Innovation" by B. C. Belanger.⁸² In an Appendix to that paper reproduced below, Belanger summarized the world-wide activity in this field as of that date.

Appendix, World-Wide Activity in Superconducting And Resistive Cryogenic Power Transmission

United Kingdom

The Central Electricity Research Laboratory (Leatherhead, Surrey) has been investigating superconducting cables since the early 1960's. The CERL has at times worked closely with British Insulated Callender's Cables Ltd. The CERL has tended to favor rigid tube niobium cable designs, with 33 kV, 750 MVA being a frequently quoted specification. The CERL, BICC, and various universities in the U.K. have produced a large number of excellent papers on cryogenic dielectrics and ac losses in superconducting materials for transmission applications.

West Germany

The Siemens Co. (Erlangen) is investigating ac superconducting cables employing niobium conductors and has given some consideration to flexible Nb_3Sn cables. The level of effort has decreased recently because Siemens is concentrating its efforts on magnetically levitated trains.

Allgemeine Elektrizitäts Gesellschaft (AEG) in Frankfurt has concentrated on flexible self-contained dc superconducting cables employing Nb_3Sn conductors and a flexible dewar (from the Kabelmetal Co.). The German Linde Company is also participating in this project.

A joint study of liquid nitrogen cooled cryoresistive cables is underway involving Kernforschungsanlage (Jülich), Felten and Guillaume Kabelwerke A. G. (Cologne), and the Brown Boveri Company (Mannheim), KFA will emphasize the more basic research aspects, while Brown Boveri and Felten and Guillaume will be concerned with the more hardware-oriented aspects of the project.

Austria

Professor Klaudy's work at the Institute for Low Temperature Research at Graz has emphasized ac niobium cables. This project has received financial support from German firms, in particular from AEG.

France

Électricité de France (Clamart) and Compagnie Generale d'Électricité (Marcoussis) have worked closely to produce comprehensive studies of both cryoresistive and superconducting cables. The French effort in dielectrics is particularly noteworthy.

USSR

A technical exchange agreement covering, among other items, superconducting transmission was recently signed between the US and the USSR.⁸⁸ Superconducting power transmission research in the Soviet Union is being done at the G. M. Krzhizhanovsky Power Engineering Institute in Moscow. This group has a 12-m-long, three-phase model with supercritical helium cooling in operation. Their model uses Nb_3Sn conductors. They have also explored niobium designs. Cryoresistive cables apparently have not received as much attention as superconducting cables in the USSR.

Japan

The Central Research Institute of the Electric Power Industry has recently proposed a major development effort for superconducting transmission. The Ministry of Industry and Trade has approved the proposal and at the time of this writing the proposal is being considered by the Ministry of Finance. The principal companies which would be involved are Furukawa, Sumitomo, Hitachi, and Fujikura. Hitachi and Furukawa have already built large cryoresistive models. Furukawa has also built a smaller superconducting cable model (copper, $NbTi$, Nb layers).

Canada

The Hydro Quebec Research Institute (I.R.E.Q.) in Varennes, Quebec, near Montreal, is studying superconducting cable systems but has not as yet chosen a particular concept for development.

In 1979, the status of SPTL projects abroad was updated in a paper by E. B. Forsyth⁸³ as follows:

"Summary of Major Development Projects"

Table 2 gives a summary of the active projects throughout the world in 1976. After tests on a 5 m cable (6) the CERL project was phased out. Similarly the program in Germany was run down after tests on a 15 m cable at AEG and a 35 m cable at Siemens (7). In contrast the project at the Institute for Low Temperature Research in Graz, Austria, is still very active. This is probably the oldest project, having started in 1965. At present a single-phase test cable is being fabricated for incorporation into a 60 kV system at the Arnstein power plant. When completed this will be the first test of a superconducting cable in actual utility service.

At the Kzhizhanovsky Power Engineering Institute in Moscow tests have been performed on 8 m cables for several years. Construction has started on an outdoor test at the Mosenergo substation which will initially comprise a 3-phase rigid cable operating at 15 kV about 100 m long with the capability of extension to 1000 m. The lexible cable under development at Podolsk has been evaluated for thermal performance at low temperature in a length of 50 m; current tests are imminent.

In the US the projects at Los Alamos Scientific Laboratory and at Brookhaven National Laboratory are still very active although the competitive position of dc systems is a complex problem. There is no doubt that conventional cables can handles substantial power levels using dc transmission, this may lead to a de-emphasis of superconducting dc systems. It is not improbable that successful trials of the 138 kV cable at Brookhaven described above may lead to utility interest as the room-temperature components for this rating could be designed without great difficulty, i.e., transformers and circuit breakers. It has been decided not to continue to rigid cable design under development by the Union Carbide Corporation. This step was taken in the light of unfavorable projections of the future economic viability of this particular approach. It should be emphasized that the decision to close down a project based on economic forecasts must be made with great care. Generally speaking, analysis of the forecast indicates what programmatic changes are necessary to optimize the design, although even with these changes the general design may not be viable. This judgement is a great art which must be

TABLE 2
SUPERCONDUCTING POWER TRANSMISSION PROJECTS

<u>Institution</u>	<u>Location</u>	<u>Type of System</u>
<u>Europe</u>		
Central Electricity Research Research Laboratories	Leatherhead, England	Flexible ac cable, NbZr conductor
Siemens	Erlangen, Germany	Flexible ac cable Nb conductor
Allgemeine Eletrizitats Gesellschaft (AEG)	Frankfort, Germany	Flexible dc cable, Nb ₃ Sn conductor
Institute for Low Temperature Research	Graz, Austria	Flexible ac cable, Nb conductor
<u>Soviet Union</u>		
Kzhizhanovsky Power Engineering Institute	Moscow	Rigid ac cable, Nb ₃ Sn conductor
All-Union Scientific Research Institute of Direct Current	Leningrad	DC superconducting cable
All-Union Research Institute of the Cable Industry	Podolsk	Flexible ac cable, Nb ₃ Sn conductor
<u>United States</u>		
Brookhaven National Laboratory	Upton, New York	Flexible ac cable, Nb ₃ Sn conductor
Linde Division of Union Carbide	Tarrytown, New York	Rigid ac cable, Nb conductor
Los Alamos Scientific Laboratory	Los Alamos New Mexico	Flexible dc cable, Nb ₃ Sn or Nb ₃ Ge conductor

frequently exercised by responsible officials in funding agencies. The problems involved have received some attention (8).

The major reason cited for the discontinuance of superconducting power transmission projects in Europe is that the power level at which these systems become economically attractive is higher than anticipated circuit needs. At the same time most projects complete the demonstration phases with some unresolved technical problems. Although these problems have not received much public discussion they probably reinforce the decisions made officially on economic grounds. Neither reason is completely justified at this stage of development: it would be more logical to refine the project goals in the light of the analysis rather than shut down completely."

APPENDIX II
DEFINITIONS OF THE PHASES OF R&D FROM 1960, 1980 AND 1983

1. From THE FUTURE ROLE OF THE ATOMIC ENERGY COMMISSION LABORATORIES. Joint Committee on Atomic Energy, 1960:2, p.7.

DEFINITIONS

Basic research is used in this report, as it is by the National Science Foundation, to mean research which is directed toward increase of knowledge in science. It is research where the primary aim of the investigator is a fuller knowledge or understanding of the subject under study rather than a practical application. This type of research is distinguished from all other research and development work by the fact that it alone has no immediately useful goal. It is not undertaken to answer an engineering question or to find a cure for a disease or to identify a material which will meet a specific structural requirement. Whether ultimately it will be of practical value often cannot be predicted by the researcher at the time he is working on the problem. An example is Enrico Fermi's work in Italy in 1934 when, in attempting to find some explanation for the peculiar results experienced in inducing artificial radioactivity in silver, he discovered that certain substances will slow down, or moderate, neutrons. This discovery was later to become an essential principle in the construction of atomic reactors.

Applied research and general development categorizes work undertaken or carried out because of the clear probability that it will have a useful end result. It is applied to work of a general nature as distinguished from a specific development project. An example is the work of Argonne National Laboratory in the development of the fluidized bed. In traditional chemical processing, materials are frequently dissolved in order to react one with another. In the fluidized bed method, a solid is powdered. Instead of being dissolved, and the gas to be reacted with it is bubbled through the bed of powder as through it was a liquid. This work was undertaken to develop a technique which offered hope of eliminating the use of large volumes of liquid in chemical work. At the time it was started it was not directed toward the solution of any specific engineering or production problem, through its general potentialities were recognized. Subsequently, the technique was

adopted by private industry for the supply of feed materials to the Commission's production plants.

Project development includes all effort devoted to the solution of specific problems encountered in producing an end product, such as a pressurized water powerplant, or a recovery system for a specific reactor fuel. A good example is the Shippingport pressurized water reactor. The project development of this plant was undertaken after the feasibility of the construction and operation of pressurized water reactors for power production already had been demonstrated at the Nautilus prototype in Idaho. There remain, however, a great number of difficult problems to be solved in order to produce a large reactor that would meet the requirements of an operating utility. These problems included such matters as pumps, control systems, fabrication of maximum-life fuel, and shutdown systems necessary to assure the safety of the large population in the area.

Process and product improvement is concerned with lowering costs and increasing the efficiency of products or systems which already have been developed and put into production or operation. In the Commission, the effectiveness of this work is evidenced by the great increases in production and reductions in operating cost per unit of product that have been achieved at the production facilities.

The range of research and development work, from the basic research category to the process and product improvement category, actually is made up of indistinguishable gradations; each category shades into another. The application of the terms as defined here is subject to degrees of interpretation, and their use will always be somewhat arbitrary. Nevertheless, the general categories are valid and aid in generalizing about related kinds of work.

2. DEFINITIONS OF FUNCTIONAL CATEGORIES OF R&D from ASPE "Program Preparation Instructions for FY82-86," 12/2/79, pp. 26-27, Department of Energy, 1980.

The Technology Base is defined to include the level of effort allocated to basic and applied research and exploratory development.

BASIC AND APPLIED RESEARCH

1. Basic Research. Systematic, fundamental study directed toward fuller scientific knowledge or understanding of subjects bearing on National energy needs.

2. Applied Research. Systematic study directed toward fuller scientific knowledge for direct use in fulfilling specific energy requirements.

These efforts are directed toward the solution of problems in the physical, biological, behavioral, social, and engineering sciences some of which do have a clear-cut applicability to specific projects. This includes the technical means of obtaining the knowledge, understanding, and solution. Other kinds of applied research are more generic in nature.

EXPLORATORY DEVELOPMENT. Efforts guided by the principle that the work should lead ultimately to a particular application or product. Even so, the techniques and intrinsic intellectual value of the work may compare favorably with that of basic research activity. Exploratory development can cut across several scientific disciplines and is intended to explore possible innovation in a particular area of one or more energy technologies.

TECHNOLOGY DEVELOPMENT. Systematic use of the knowledge and understanding gained from research to achieve technical feasibility and to gauge economic and environmental potential of energy concepts, process, materials, devices, methods and subsystems.

Comprises development of engineering technologies, subsystems, planning and analysis studies, energy system concept formulation, comparison of alternative concepts, and development and test of laboratory-scale engineering feasibility models. This includes demonstration by experiment of alternative system concepts as well as preliminary studies encompassing system analysis, trade-offs, preliminary cost benefit studies, planning, programming environmental studies.

ENGINEERING DEVELOPMENT. Systematic use of the knowledge and understanding gained from research and technology development to achieve the detailed design, construction, and test for performance, producibility, and reliability of energy system prototypes and pilot plants.

Detailed design, development and test of energy system prototypes and pilot plants judged to be technically and economically desirable as a means of achieving the principal energy goals. Engineering development may concern itself with processes, preproduction components, equipment, subsystems or

systems. This capacity also includes major system test facilities directed toward specific project development and the preparation of appropriate environmental impact statements.

DEMONSTRATION. Verification of economic and environmental viability for commercial application, through design, construction, test and evaluation, of large-scale energy systems in operational circumstances.

Final engineering design, assembly, test and evaluation of full-scale energy systems aimed at providing directly applicable experience in an operational environment so as to demonstrate economic viability for commercial application. Demonstration projects are intended to: a) overcome "scale-up" problems; b) contribute to the understanding of the economics of fabrication and operation; and c) resolve other questions such as public assistance, institutional and environmental issues. Preparation of suitable environmental impact statements is included in this category.

COMMERCIALIZATION, PRODUCTION, AND OPERATIONS.

1. Commercialization. When the predominant problems become those of bringing the system or project commercial reality rather than demonstrating technical feasibility such as:

- a) "scale-up" problems are overcome;
- b) economics of fabrication and operation are understood;
- c) public acceptance, institutional and environmental issues resolved;
- d) commercial interest in project.

2. Production. When the predominant problems became those of producing the item in quantity, bulk, or other parameters which meet specifically stated requirements.

3. Operations. When the predominant problems became those of bringing the system or project from prototype or pilot plant operational testing status, to full-scale operational condition to meet stated objectives.

3. From the 1983 National Energy Policy Plan the phases of R&D were redefined on p. 14 as follows:

Energy Research and Development

To a large extent, research and development activity can be described in terms of the path of technology development and the stages through which new technologies pass until they reach the market as competitive energy investment

options. Stated simply, the technology development path consists of five stages. Basic research involves the development of scientific knowledge, including a fundamental understanding of the physical and chemical properties of new unconventional fuel sources or energy systems. Applied research includes the broad engineering and physical science aspects of specific energy technologies. Proof-of-concept is where enough is learned to establish the technical viability and basic engineering feasibility of concept and to forecast its expected economic and environmental performance standards, permitting industry to make decisions concerning whether the concept merits further development. Process development involves increasingly larger scale systems where the objective is to reduce technical risks and to improve process operability, reliability, economics, and environmental impacts. Commercialization enables a new energy technology to gain acceptance in the marketplace.

APPENDIX III

In reading the PECO reports, one gets the impression that PECO itself was not entirely comfortable with the results. It is probably fair to say that the PECO results were professional, reliable and probably the best that could have been produced given the time and funding available. Nevertheless, PECO concerns about the conclusions that might be drawn from their report surface frequently. For example, the SUMMARY to PECO I consists of seven short paragraphs. The first paragraph refers the reader to a table summarizing the costs of the underground transmission systems studied. The subsequent paragraphs consist of "several notes of caution that must be considered." Two examples of these "cautions" (the second and third) will suffice.

- "several of the systems studies have never been installed on a utility system. Consequently, the cost of these cables as well as their installation costs are not known as accurately as those systems which are commercially available. However, every attempt was made to project probable developments in technology and commercial availability as fairly and uniformly as possible."
- "some systems which do not appear to have the lowest cost in the problem specified in this study would be the economical choice for a lower ampacity application or for a shorter length."

Cautions in the use of studies such as these also figured prominently in the PECO II study. On page 1 of this report the PECO study team points out that "Users of this report are cautioned that these results can not be directly applied to other applications." Subsequently, it is emphasized that "Any study of transmission economics is, by nature, site specific."

In section 2.6, Recommendations for Future Work, the PECO engineers also recommended that "any future studies of transmission economics [should] use lower transmission ratings, for example 2000 MW, since most applications will be closer to that rating." The implication here is, of course, that utility needs for multi gigawatt transmission systems lies far in the future.

NOTES AND REFERENCES

Introduction

It has been found, in the course of preparing this case study, that the recollections of participants, exparticipants and more or less disinterested observers differ significantly. Different perceptions of the same events served to paint these occurrences and the decisions they engendered not only with quite different hues but, on occasion, in starkly different colors. Participants tend to remember most clearly what they did and why; in contrast, the reporter usually writes from the perspective of history and with 20-20 hindsight.

The author of this case study has attempted to be neutral in his reporting, but he too was an early participant in the SPTL program and subsequently followed its development with more than casual interest. Consequently, in an effort to include all relevant divergent viewpoints, early drafts of Parts I and II of this case study were sent to most of the participants in the SPTL program for comment. In several instances, differing interpretations of events have surfaced. These opposing views, identified by a reference number in parenthesis in the text, are included in the notes that follow.

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6. The reduced power transmission capability of a conventional AC underground cable arises from a) the much higher capacitance per unit length of an underground cable compared with that of an overhead system of the same conductor diameter and b) the reduced capability of the cable to dissipate the internal heat produced.

The higher capacitance of an underground cable (between the conductor and the cable sheath and further enhanced by the high dielectric constant of the insulator) results in charging currents (when the cable is energized by a 60 Hz voltage) 20-80 times those for overhead systems.

The Joule heating of the conductor plus the dielectric heat generated in the cable insulation must be dissipated through the cable insulation into the surrounding earth or removed by a circulating refrigerated fluid. In either case the power carrying capability of a given cable is limited by its ability to dissipate the heat generated and this capability is termed the cable's thermal rating, the current output of the cable (and hence its power output) is reduced to zero. This length is designated the uncompensated critical length of the cable

This zero power transmission situation can be rectified by installing inductances (shunt reactor compensation) at appropriate locations along the length of the cable. For underground cables currently in use, the uncompensated critical lengths range from 25-50 miles. See Ref. 84 for further information.

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 - First publication: Brief version published in Physics Today, Dec. 1970 issue (statement that loss in Nb_3 at 10-12°K as low as Nb at 4.2° K)
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a. re Management

The inferences of this section (IV.H., pg. 38) are without merit. While EPRI, under pressure from her sponsors, has moved away from support of long term projects, the fundamental management decisions with respect to superconducting transmission R&D were not influenced to any degree by this action. Throughout my stewardship of the Electric Energy Systems R&D Program (1970-81) particularly close coordination was established and maintained with the pertinent industrial advisory committees. These were the ERC Underground Transmission Steering Committee (of which I was a member) from 1970-73, the EPRI Underground Transmission Task Force of which EES was a member from 1973-75 and with which EES continued to participate on a partnership basis from 1975-81. Not only was advice sought on project support decisions (initiation, expansion, contraction, termination) but, to my knowledge, all major decisions were concurred in. These included termination of superconducting transmission R&D efforts at Stanford and Union Carbide, abandonment of cryo-resistive cable development work (GE and UPC) and shutting down of such other long shot competitors as the glass-insulated cable project (PTI).

Besides this advice, a US-USSR Superconducting Transmission Exchange Advisory Committee was established with representation from all major participants in R&D (BNL, LASL, UC, Bureau of Standards, etc.), utility representatives and manufacturers. The decision to reduce and eventually terminate this exchange was fully supported by this committee. In addition to these committees, efforts were continually made to maintain industry participation and interest in all phases of the superconducting transmission R&D program; an effort which has been notably successful in the BNL project from its beginning right on through until today.

Of course, there was unrelenting pressure on EES program management from early 1975 (advent of ERDA) to reduce this program which had little relevance to the primary missions of the groups in which EES was an organizational entity--Conservation 1975-77; Solar 1977-79. Nonetheless, the superconducting transmission R&D program was consolidated in an orderly fashion, with the decision to support only the BNL project to fruition fully supported by industry.

To infer that the PECO Study provided the vehicle for cutting back other projects is naive. The results of the study had been anticipated, with the basic decisions on such issues as cryo-resistive cable and UC project support long since made. The basic PECO Study, widely acclaimed by industry and a landmark as such studies go, did document the validity of these decision. (As to the LASL dc cable not being included in the PECO II Study, I plead ignorance since this decision was made after my departure from DOE).

b. re Conclusions

Any conclusion which suggests that the superconducting transmission R&D program has not been a notable success is baseless. That the BNL cable is technically and economically ready to move into the industrial test stage has been amply demonstrated. That it has met the goals which industry formulated in 1970--a commercially viable cable ready by the mid-80's for commercial application in the mid-90's--is manifest. That, in the meantime, electric load growth has slowed and this capacity may not be needed so soon is no fault of the project. How many major government-sponsored R&D projects have overcome so many difficulties, including inconsistent funding support, and achieved such success in so short a time? This is the sole success story among many comparable international projects because there are always funding restraints. The BNL project was the most advanced technically, exhibited the most potential for industry acceptance and early need. It still does. When the prospects for dc superconducting transmission brighten, the trail blazed by the BNL ac cable will be most helpful, as will LASL's fundamental research. To label the overall program a failure because all technical avenues were not pursued through technical feasibility is not supportable.

In short, the thirty odd missions which have been expended on this program is a mere pittance when judged against other comparable government and industry R&D programs. More importantly, it provides a promising answer to many of the needs which confront industry in the all-too-imminent future.

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re Urgency and need

"The development of an ac superconducting system was based not so much on total electrical energy consumption but on growth in the capacity of interties, which is linked to total growth. Although growth has slackened off, other factors have made transmission interties just as likely to grow as the earlier reasons. In the

North East there is a growing demand for Canadian hydroelectric power. Throughout the country environmental concerns and fear of nuclear plants will drive generating plants further from population centers. This trend will require strengthened transmission back to the load center; near the population areas, overhead lines will be difficult to install. There are power transmission problems facing the utility industry today for which superconducting power transmission lines offer a potential solution that is either competitive with or superior to other solutions.

I must emphasize the long-range nature of this type of R&D; the BNL development time to the start of 1000 MVA system operation was 10 years. Another 10 will be required to foster industrial expertise and build the first commercial system. The R&D impetus should not, and can not, vary constantly to reflect short-term concerns. Finally, the major institutional failure at DOE has been what to do with a high risk, long-range program which actually succeeded. It must be borne in mind that expenditures shown in Table 9 are miniscule compared to the annual capital investment in transmission facilities, which runs in the 1-2 billion dollar range. The present stage of development indicates that using superconducting cables to transmit power appears technically feasible and, for specific applications, economic. But in order to be reasonably confident that this is the case, an intermediate stage of development is required where a system of some realistic length is installed in an actual utility power transmission network. Until this stage of development has been completed, the research is still high-risk and too expensive to be funded primarily by private industry, even though its potential for solving some of our nations most difficult power transmission problems is high. We have written a five year plan to get the Brookhaven expertise transferred to industry and an engineering firm has indicated willingness to participate. The only way to do this is to build a long system, obviously an expensive proposition and likely to cost more than the original development at Brookhaven. Of course, the usual dilemma exists; at this stage there can be no guarantee of customers because a utility company requires the following before investing its own money:

- 1) A commercial source to install and maintain the system.
- 2) Reliability data.
- 3) Demonstration of performance somewhere else first.

It was to these concerns we addressed the five year plan, which has yet to be approved."

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