High Temperature Superconductivity

A Joint Feasibility Study for a Power Application with HTS Cable by South Carolina Electric and Gas

TR-110891

Final Report, November 1998

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CITATION

This report was prepared by

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This report describes research sponsored by EPRI, South Carolina Electric & Gas Company and Pirelli Cable Corporation.

The report is a corporate document that should be cited in the literature in the following manner:

High Temperature Superconductivity A Joint Feasibility Study for a Power Application with HTS Cable by South Carolina Electric and Gas, EPRI, Palo Alto, CA; South Carolina Electric & Gas, Columbia, SC: 1998. Report TR-110891.

REPORT SUMMARY

Practical realization of high temperature superconductivity (HTS) technology is within the reach of the electric power industry. This report documents a feasibility study co-sponsored by South Carolina Electric and Gas Company (SCE&G) to assess a real-world underground transmission application of this technology.

Background

Superconductors are materials that can, under certain conditions, carry dc electricity without resistance. Alternating current HTS cables can carry two to five times more current than conventional cables of comparable size. Although superconductivity was discovered over 80 years ago, its potential has remained unfulfilled because, until recently, materials needed to be cooled to near zero for superconductivity to occur. In 1986 researchers discovered HTS materials that superconduct at the temperature of liquid nitrogen, an inexpensive, abundant, and environmentally benign refrigerant. For the past decade, EPRI has led basic and applied research to put HTS materials to practical use in the electric power industry. In March 1996, EPRI and its co-sponsors announced a world record-length HTS assembly for high voltage cable. In addition to further testing of this system, the next step was to evaluate potential power system applications of this technology. Motivated by the restrictions on putting in an overhead line, South Carolina Electric and Gas Company (SCE&G) viewed HTS applications as one way to meet potential load growth while maintaining reliable service in an environmentally responsible manner.

Objective

To determine the technical and economic feasibility of using HTS technology in the SCE&G network.

Approach

The project team conducted a search within SCE&G's system for a location that would utilize the full potential of HTS cables with a line with high load growth potential. The team identified a circuit with limited rights-of-way in a downtown area of Charleston, South Carolina. The link was needed to provide more efficient load flow and to meet possible contingencies. After the utility provided project specifications, the team then evaluated four alternative HTS cable designs to establish the most effective technical

and economic solution. Engineers completed preliminary designs, including the HTS conductor, cryostat, and refrigeration system, for each of the two most favorable preliminary cable systems: a pipe-type, warm dielectric, single phase system (PWS), and a pipe-type, cold dielectric, single phase system (PCS). The team conducted an economic comparison between HTS and conventional designs and documented all findings in a report.

Results

While both preliminary cable systems met the technical performance parameters, the PWS design and associated refrigeration system was deemed the optimal solution. The report concludes that the HTS cable system could be designed to greatly exceed the requirements of standard underground transmission cable. The team uncovered no technical obstacles that would preclude HTS cable use in this application. For the HTS system to compete economically with conventional systems, however, the new system would need to replace two or more conventional cable systems; or the current requirement should be above 2000 amps.

EPRI Perspective

HTS cables have the potential to revolutionize the power delivery industry by reducing costs and maximizing the use of existing conduits for electric power transmission. Projects like these move the industry closer to practical realization of this technology (see also EPRI reports TR-103631 and TR-110892). Wires made of HTS materials are expected to be widely used for electric power and utility applications such as underground transmission and distribution cables, large generators, transformers, and current limiters. In addition, end-use applications will employ powerful electric motors and power conditioning equipment involving superconducting magnetic energy storage.

TR-110891

Interest Categories

Underground Construction, O&M
Underground System Alternatives

Keywords

Superconducting Cables
Pipe-Type Cables
Underground Transmission

ABSTRACT

High temperature superconductivity (HTS) cables have the potential to revolutionize the power delivery industry by reducing costs and maximizing the use of existing conduits for underground transmission. In 1986 a class of ceramic materials showing superconductivity slightly below the temperature of liquid nitrogen was discovered and, when used in cables, can carry two to five times more current than conventional cables of comparable size. In June 1996, EPRI, Pirelli Cable Corporation, and South Carolina Electric and Gas (SCE&G) performed a joint study to assess the technical and economic feasibility of installing a HTS cable system on a highly loaded SCE&G underground circuit. It was concluded that a HTS system could be designed to greatly exceed the requirements of a standard underground transmission cable.

CONTENTS

LIST OF FIGURES

1

INTRODUCTION

South Carolina Electric & Gas Company (SCE&G), headquartered in Columbia, South Carolina, is a regulated public utility serving approximately 494,000 electric customers in a 15,000 square-mile territory in central and southern South Carolina.

Motivated by potential load growth in Charleston, keeping and maintaining reliable service even through severe contingencies, and pursuing the elimination of environmentally sensitive concerns, EPRI, Pirelli Cable Corporation, and SCE&G have found an application where high temperature superconductivity (HTS) can resolve all these important issues. The load growth in Charleston is an important issue, and the technology of HTS will continue to show its real benefits with growth expansion. Reliable service has been given a lot of consideration due to proposed legislative changes and a catastrophic power outage in the U.S. west. SCE&G realizes that utilities that establish a strong yet efficient system through severe contingencies will position themselves for the future. The aesthetics of overhead lines, along with environmental concerns associated with electromagnetic fields, have dictated that cities, such as Charleston, require utilities to underground circuits, which would eliminate the above concerns. HTS employs all the advantages of underground circuits and has no disadvantages typical of conventional underground cables, giving the utility the capability to send much greater power through one circuit.

Status of HTS Development

In 1986 a class of ceramic materials showing superconductivity above the temperature of liquid nitrogen (LN) was discovered. Before this breakthrough any power cable applications with low temperature superconducting material were proven to be technically viable but not economically feasible. The reason for the economic hindrance was that the liquid helium required to sustain the temperature of a power cable application in the superconductivity state is very expensive. Now, because of the breakthrough with ceramic materials, the temperature values for a superconductive state can be accomplished through the plentiful and inexpensive cooling medium of LN.

In 1994, EPRI contracted with Pirelli to design, develop, and test a prototype HTS, 115 kV, 400 MVA cable system. This project will finalize a HTS cable design capable of being installed within existing pipes as a means to replace existing cables due to age and / or load upgrades. This project received financial support from the U.S. Department of Energy's SPI.

The 50-meter long HTS cable conductor was manufactured in two phases. This was done in order to confirm that the cabling operation was not introducing an unexpected degradation of the electrical characteristics of the HTS tapes supplied by American Superconductor Corporation (ASC). During the first manufacturing phase, layers of tapes were applied helically around a central channel, the path for the LN flow. The measurements performed on the conductor assembly have shown a total critical current of 1800 dc amperes, a value in agreement with the engineering calculations performed at the time of designing the cable. The second phase consisted of the application of another layer of tapes with a total critical current of approximately 3300 dc amperes. The total critical current measured on the prototype cable has permitted our engineering departments to evaluate the intrinsic effects of the magnetic fields induced by the HTS tapes and, thereby, design the cables correctly for real applications.

Feasibility Study

In November 1996, Pirelli gave a presentation to update SCE&G management on HTS's current status and potential applications in the transmission area. SCE&G voiced their interest soon after this presentation with a scheduled meeting.

During that meeting, Pirelli engineers met with the SCE&G engineers to discuss and select a real application for a HTS system. The team leaders and members were appointed from Pirelli and SCE&G. A list of the tasks to be performed and the proposed agenda was distributed to all team members.

A search within SCE&G's power system was initiated for a location where a HTS cable system would be beneficial. The chosen application must require high current levels. One criteria that helped create the application for a HTS system was to find an area where there is load growth potential, as foreseen in the next 20-40 years, utilizing the full potential of superconductivity cables. The SCE&G team members found a potential application in the Charleston transmission network. A high voltage transmission overhead line initially designed to surround the city was still not complete, and two substations needed to be tied together for a more efficient load flow and for possible contingency concerns. The adoption of a highly loaded underground circuit was the final solution creating the justification for the deployment of a HTS cable system.

Four HTS cable designs were evaluated by Pirelli engineers to establish the most effective technical and economic solution. A HTS system was then designed around two preliminary cable designs: the pipe-type, warm dielectric, single phase (PWS), and the pipe-type, cold dielectric, single phase (PCS). These designs specifically met the technical performance parameters established for the chosen application, and the decision was made to finalize on the two designs and their associated refrigeration system.

The group established the needed tasks and required data for a descriptive and thorough study, and began work on analyzing the several possibilities in the transmission areas. Finding the most appropriate section of the power system at SCE&G that could utilize the benefits of the HTS cable system was the initial step in the process. With the selected application, an in-depth analysis of the electrical parameters concerning the application was begun. Some of the issues investigated in the electrical section were the installation techniques, the constraints on pulling tensions and pipe dimensions, and creating a suitable HTS design to meet all the electrical parameters. Once the techniques for the installation were established, a careful evaluation of the HTS cable designs was undertaken. A costing analysis was performed to verify the costs associated with all aspects of a cable system for an accurate comparison between the conventional cable systems and HTS cable system.

The cable designs made available by the Pirelli engineers depended upon the specific requirements of the cable system. The group analyzed four of the HTS cable designs, and from there narrowed the choices down to two cable designs. These two designs proved to be the most adequate and advantageous. From the cable designs and the system electrical parameters, the Pirelli engineers were able to develop the various cable construction parameters needed for the selected installation in the transmission network. Finally, the most economically feasible design was chosen.

The feasibility study was completed with guidelines concerning the specifications, procedures, operating conditions, and maintenance.

Selecting a Potential Application

After having analyzed the typical benefits of a HTS system as opposed to a conventional system, and taking into consideration that this would be the first long installation exposed to real operating conditions, both Pirelli and SCE&G agreed to limit the possible applications by adopting the following guidelines:

1. The application should require higher current (at least 1200 amperes) than permissible with a single circuit conventional system. The expected load growth should be evaluated for a period of at least 30 years.

2. The circuit should possess the ability for the HTS system to cover long distances, up to 10,000 feet, with one refrigeration plant positioned at one end of the circuit and without intermediate cooling stations.

3. The application should have the minimum amount of joints for the HTS cable, preferably one splice per phase for the entire circuit length.

4. Initially, the system should be capable of operating at a reduced load, and de-energized for certain periods of time without causing any major disturbances to the SCE&G network. This condition would allow the necessary evaluation of the system, and the training of the SCE&G engineers before operating the system at full load.

With all the above constraints, the SCE&G team members conducted a thorough analysis of the transmission network. Several potential applications were found, but the one application that encompassed all the above conditions was found in the Charleston area. This application was a tie line at 115 kV between two substations.

Connecting the two substations to distinct power regions of Charleston would enable an improved power flow situation on a daily basis and a needed stabilizing effect from contingencies.

The main parameters of the project were defined as follows:

Voltage: 115 kV
Current: 1500 amps
Circuit Length: 7130 feet
Fault Current: 22 kA, 15 cycles

The tie line required the installation of an underground cable system. The cable designers, who were not restricted to matching an existing pipe installation but were able to pursue an "optimal" cable design, were offered another "ideal" situation with this application.

By general consensus between the two teams, the "Charleston Project" was adopted as a potential application for a HTS system.

Electrical Parameters

Analysis of various electrical parameters was performed to verify the criteria needed for the design of the cable and the system. In the "Charleston Project" application a few areas required additional evaluation. Some of these areas included the required ampacity for the circuit, the fault current, and the impedance of the HTS cable for compatibility with the network. Other important parameters necessary to proceed with the design of the HTS cable included the methods of installation for the new circuit, the dimensions of the pipe to be used for the installation, and the number of joints acceptable for the application.

Ampacity Requirements

Ampacity levels were investigated by the team members of SCE&G to insure that the circuit could withstand various contingencies and fault conditions. These contingencies would enable one region of the Charleston area to feed a second region, and vice versa, without outages. Creating the ability to overcome these contingencies, and thereby stabilizing the service reliability was considered extremely important. The ampacities were 1500 amps, for the worst case scenario, and the time associated with this current level was four hours. In conventional systems, the cable would be designed to meet this emergency condition for the desired time frame. In HTS cable systems, since temperature increases due to current is nonexistent, the design criteria for the current is 1500 amps for continuous operation. In this respect, the HTS is over-designed but the difference between a HTS cable capable of 1200 amps compared to 1500 amps is a very slight design adjustment. Conventional systems would require a much larger conductor to accommodate the 1200 to 1500 amps change. In comparing the conventional versus HTS cable systems it was agreed that HTS would be rated at 1500 amps continuous, and the conventional system would be rated at 1200 amps continuous with a 1500-amps, four-hour emergency condition.

Fault Current Conditions

The fault levels were also analyzed for the two substations resulting in a worst- case fault condition of 22 kA for 15 cycles. Analysis of the HTS cable designs as subjected by the fault conditions showed good performance.

Installation

The team discussed the installation techniques in detail to accommodate the current, normal utility practices. SCE&G was concerned that the City of Charleston might impose their procedures/regulations concerning the installation of the circuit. The two types of installation were either direct-buried or open- trench methods. Subsequently, SCE&G ascertained that both installation techniques were acceptable. Because the cable designs were sensitive to the installation techniques, the evaluation continued for all the cable designs, with no restrictions resulting from the procedures established. The use of one joint per phase was found necessary for the PWS design along the cable route.

Pipe Dimensions and Joint Requirements

Upon evaluation of the installation technique for the various cable designs, the length of the cables and the pulling forces to install the cables were determined. The lengths of the cables, as determined by the pulling forces, established the number of joints necessary for the various cable designs. The size of the pipe and the required duct dimensions for adequate LN flow were determined. The pipe size was specified by SCE&G in the beginning to be eight inches. In order to accommodate the one-joint-only requirement, it was necessary to design a larger and more robust HTS cable due to the pulling forces, and a 10-inch pipe was the result of that design change. The team felt that the additional cost of a 10-inch pipe was not significant, and the best engineering solution was adopted.

HTS Cable Designs

After the electrical and the installation parameters were evaluated and determined, the Pirelli members began the identification of the appropriate cable design. Initially, four different cable designs were considered and analyzed for their adaptability into this project. The four cable designs were:

- Rigid cryostat, cryogenic dielectric, single-phase elements(RCS)
- Flexible cryostat, cryogenic dielectric,three-phase elements(FCT)
- Pipe retrofit, cryogenic dielectric, single-phase elements(PCS)
- Pipe retrofit, warm dielectric, single-phase elements(PWS).

To optimize the cable designs, the previously established, main design parameters were taken into consideration, and the additional restriction of an acceptable clearance between the overall cable dimensions and the 10-inch pipe's inner wall was made for installation purposes.

As a result of the above-mentioned parameters, the FCT design was eliminated because of transportation limitations. The RCS design was also eliminated because of SCE&G's desire to install the cable system in a conventional pipe. Both the remaining designs, PCS and PWS, were specifically designed for pipe retrofit applications or new conventional pipe installations, thereby making these designs suitable for this application with further optimization. The dimensions of the PWS and PCS cables were finalized by the Pirelli engineers.

For the PWS design, the finishing touches took into account the various criteria developed in the electrical parameters section of this report. The inner duct dimension creates the number of refrigeration plants necessary for the circuit length but also adds to the overall diameter of the cable. The larger the inner duct, the greater the cooling abilities for a given length. These two criteria are a strong determinate of the capable cooling lengths and overall cable dimensions. For both the PWS and PCS designs, one cooling section for the circuit was the selected criteria.

The other criteria for the cable dimensions was determined by the fault current levels on the conductor and the shield. These fault current values created the cross-sectional area needed for the copper duct because this section of the cable carries a large percentage of the fault current. The number of HTS tapes is determined by the critical current for each tape and the ampacity level (1500 amps in this case). The conductor shield, insulation, insulation shield, metallic sheath, and jacket are all determined by the appropriate specifications for the voltage class utilized in this application. The metallic sheath must also meet all the fault current levels. The design of the PWS and PCS cable was finalized in accordance with the criteria mentioned above and shown in Figures 1-1 and 1-2.

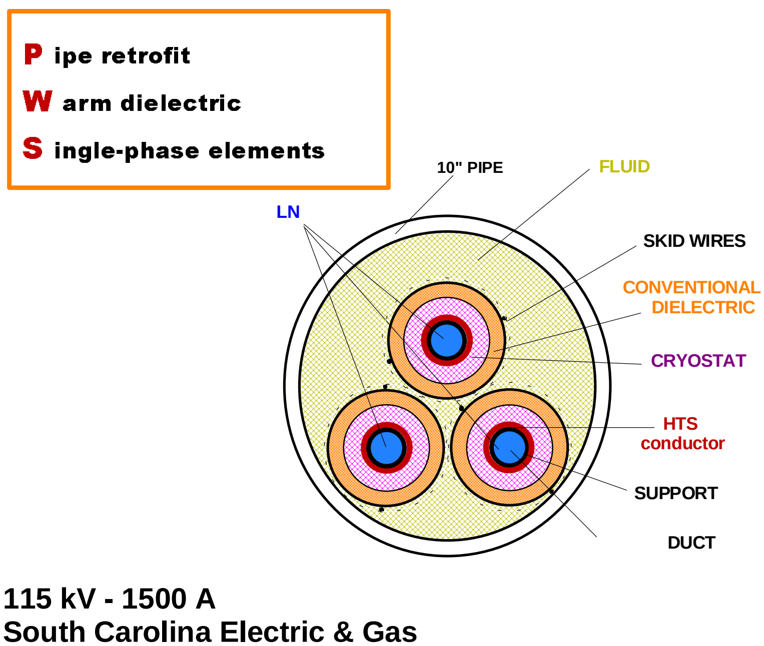

Figure 1-1
PWS Cable Design

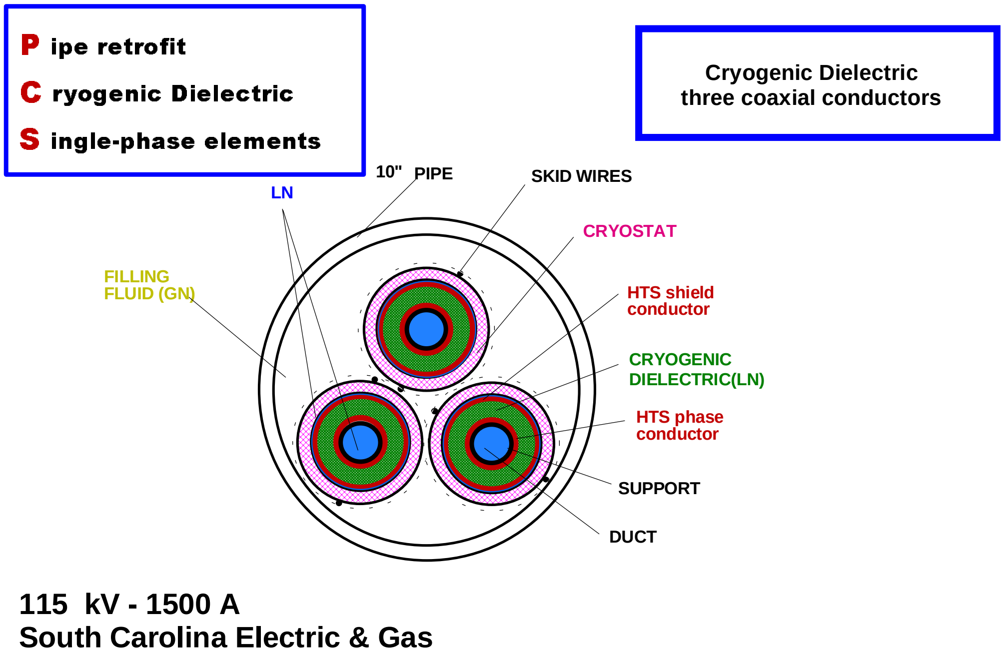

Figure 1-2
PCS Cable Design

The PWS design has the HTS tapes applied over a central channel necessary for the LN flow. The cryostat consists of an inner and outer corrugated pipe with a vacuum applied, as well as interposed spacers to maintain the temperature insulation. The conventional insulation is applied helically over the outer pipe, and is classified as “warm” dielectric because of its separation from the cold temperature.

For the PCS cable design, the same predetermined electrical parameters were assumed. The cable design has the same criteria as described for the PWS design except that the dielectric insulation is immersed in LN. The PCS design has a HTS shield that eliminates the magnetically induced currents, thereby tremendously reducing the ac losses (Appendix A). In the PCS design, the inner section resembles the construction of the PWS except that there is no cryostat section between the conductor and insulation. The entire HTS conductor, insulation, and HTS shield are immersed in LN. In fact, the peculiarity of the PCS coaxial design is that the shield current will match the conductor current, although flowing in the opposite direction, thereby canceling the magnetic effects and the derived losses typical of conventional cables. The cryostat medium acts as a perfect insulator, thus preventing any transfer of temperature between the LN temperatures within the cable and the heat outside the cable.

Final Selection

From the two HTS cable designs, PWS and PCS, the team members had to make a final, single design selection. Even though both designs could have been utilized in the application, a choice had to be made. The PCS design possessed many beneficial attributes in the ac losses due to the HTS shield configuration over the PWS design, but the overall evaluation determined PWS as the optimum solution. Pirelli will establish the techniques and procedures of terminating and creating joints for the PWS design, as well as the specific refrigeration design within the next year as part of EPRI's project. However, the decision was made to continue the feasibility study for the PCS design as well, for comparison purposes.

HTS Cable System

A tentative and conceptual design of the refrigeration system has been developed according to the following guidelines (Appendix B).

PWS—Refrigeration System

As established before, the refrigeration system will be located within one substation. The LN will flow through one of the phase's inner duct channels. Upon reaching the end of the circuit length, the LN will then be bypassed and returned through the remaining two phases to the refrigeration station. The LN will circulate at a calculated rate to insure that it will remain in a predetermined zone on the nitrogen vapor curve. The initial temperature and pressure of the LN will be set. Upon returning to the starting point, the final temperature and pressure, in correlation to a full 1500 ampere level, will be pressurized and cooled by the refrigeration system to the initial pressure and temperature values.

PWS—Joints & Terminations

For the joints and terminations, the same designs pertaining to the EPRI project will be adopted. The positioning of the terminations at the various substations was determined by the team. By the time the Charleston project is implemented, both the terminations and the joints will be fully evaluated and qualified. The termination will be similar to conventional pipe type terminations yet with slightly higher dimensions to accommodate the LN feeds, vacuum system feeds, and monitoring apparatus.

For the joint, no installation problems are anticipated at this time. The number of joints will be one, as was agreed during the previous phases of the study. A typical manhole at approximately the center of the circuit will comprise the location of the joint.

PWS—Installation

The cable pulling will be done in a conventional manner feeding through the riser pipes, the trifurcator, and reaching the center of the circuit at the manhole location. This technique will be done from both ends of the circuit, and the cables will be spliced at the manhole.

The technical qualification of PWS terminations and joints is progressing under a separate project (EPRI, 115 kV HTS cable system) and will be made available for this specific application.

PCS—Refrigeration System

As established before, the refrigeration system will be located within one substation. The LN will flow through one of the phase’s inner duct channels. Upon reaching the end of the circuit length, the LN will then be bypassed and returned through the remaining two phases to the refrigeration station. The LN will circulate at a calculated rate to insure that it will remain in a predetermined zone on the nitrogen vapor curve. The initial temperature and pressure of the LN will be set. Upon returning to the starting point, the final temperature and pressure, in correlation to a full 1500 ampere level, will be pressurized and cooled by the refrigeration system to the initial pressure and temperature values. The location of the refrigeration system would be positioned at one end of the cable circuit.

PCS—Joints & Terminations

The joints and terminations associated with the PCS design were discussed by the team. The terminations would be situated in the same location as determined by the PWS termination design. The number of joints would also remain at one for the PCS design. Installation techniques for the PWS design are applicable to the PCS design as well.

Conventional Cables

The decision was made at the very beginning of the study to analyze the conventional cables in the event that the HTS system would prove an impractical solution. The required current levels were theoretically achievable by various conventional cables, and the cable designs were evaluated by the team. Pirelli engineers performed calculations on conventional cable designs to insure that ampacity levels were accurate for various conductor sizes. The technical analysis performed by the team is summarized below.

Extruded Insulation

Conventional 115 kV rated, solid dielectric cable was an alternative solution for the SCE&G application. During the evaluation it was determined that the XLP cables, in a single configuration, would be appropriate for an emergency rating of 1500 amperes for four hours. Should the contingency last longer than four hours, a double circuit would be more appropriate. However, the decision was made to proceed with the single circuit configuration. Three vendors were approached by SCE&G to supply cable designs for the application to meet all the necessary continuous and emergency current levels. Various constructions with conductor sizes ranging from 2000 MCM to 2500 MCM were provided, all of which required two joints for the circuit length. Some of the cable designs offered were questionable with regard to the required current levels.

Paper/Oil Insulation

Another conventional cable solution for the application is HPGF 115 kV cables installed in an eight-inch pipe. This type of cable is the most common design for SCE&G in their high voltage underground circuits. A conductor size of 2250 MCM with one joint was found adequate for the project.

AC Losses of HTS Conductors

Because of the unfamiliar aspects pertaining to the materials, design, manufacturing process, and testing technologies, the ac losses of the HTS cable conductor are still under investigation by R&D organizations. A few theoretical models have been developed and used to evaluate actual ac loss measurements on samples of HTS conductors. Unfortunately, the values of the ac losses measured during the experimental trials do not correlate with the proposed theoretical models. The variance is probably due to the inadequacy of the theory and / or the extreme difficulty in the execution of the measurements.

Theoretical Models

The models most commonly used by Pirelli in the design of a HTS cable system are the following:

- the well known monoblock model (“Norris” model) where the conductor is schematized as a superconducting tube
- a model developed internally by Pirelli (model 1) in which the losses are calculated according to an exponential law

- a model jointly developed by Pirelli and external consultants (model 2) in which the losses are calculated according to an exponential law and to actual construction data of the superconductor. This model, still to be confirmed by extensive experimental work, is more conservative than model 1, resulting in higher ac losses.

Model 2 was selected to perform the necessary calculations for the operating costs for this study (Appendix A).

AC Loss Measurements

The available data relevant to ac loss measurements on HTS cable conductors are summarized below.

Typically, two different techniques have been used to measure the superconductor losses: the calorimetric technique and the electric measurement technique.

1. Calorimetric technique—measurements carried out as the Los Alamos National Laboratory on a sample manufactured by American Superconductor Corporation (ASC) [ref. 1]

2. Calorimetric technique—measurements carried out at the Oak Ridge National Laboratory on a sample provided by Southwire Company [ref. 2]

3. Electric measurement technique—development performed by Furukawa Electric Company / TEPCO [ref. 3]

4. Electric measurement technique—development work carried out by Siemens AG

5. Electric measurement technique—development work performed by Furukawa Sumitomo Electric Industries / TEPCO [ref. 4]

The graphs shown in Appendix A show the above experimental data as compared with the results of the theoretical models [ref. 5].

Approach to the Design of a HTS Cable System

The use of a particular model and the associated value of the ac losses have an impact on both the cable design and refrigeration design, therefore a preliminary parametric study with the above three models was carried out. The analysis of the results, in terms of conductor losses, total cable losses, critical cooling lengths, etc., confirmed the suitability of adopting model 2 in the design of the cable and refrigeration system. In fact, should the superconductor losses be lower than those assumed, the complete cable system will be more than adequate. In the event that the superconductor losses are higher, only a slight adjustment to the refrigeration system will be required, ensuring a proper functionality of the HTS system.

Costing and Economic Evaluation

The total transmission losses (kW) for the HTS system and the conventional cable systems was calculated for three different current ratings in order to understand the system cost: 1000 amps, 1200 amps, and 1500 amps.

The operational costs of the conventional cable systems versus the HTS cable system were calculated by using a typical capitalization methodology adopted by utilities with a service life of 30 years (Appendix C). The parameters necessary to perform the calculations were provided by SCE&G.

It should be noted that the actual operating current for the system is approximately 800 amps.

The total cost of the HTS cable system was higher than the conventional cable system. The main reason was because the HTS tapes are currently manufactured under a semi-industrial mode, and not yet implemented in the necessary economy of scale required by a full commercialization of the HTS system. Large capital investments to allow a large production volume on an annual basis are being considered by ASC. When implemented, the HTS cable system will become more competitive with a conventional cable system when high power ratings are required.

Conclusion

The team members carefully evaluated the technical merits of the study and determined that the HTS system was viable for the chosen application. In contrast, the economic assessment proved that the HTS system was not yet competitive with the conventional system. Compared to a conventional system, the HTS system needed a greater capital investment, and since the power requirements needed for the chosen application is very low, the conventional cable was a better choice. For the HTS system to meet the investment cost of a conventional system, according to the present day costs of HTS cable systems, the HTS cable application should replace two or more conventional cable systems, or the current requirement should be above 2000 amps.

The current high cost of the manufacturing of HTS tapes, the refrigeration system, and the low power requirements for which one single circuit of a conventional system was suitable, were the determining factors resulting in HTS being non-competitive. Additionally, SCE&G requires delivery of the installed circuit in 1998, and this is not achievable by Pirelli because of the time associated with the manufacturing of a large quantity of HTS tapes. The decision was made not to proceed with the HTS system at this time.

However, Pirelli and ASC are reviewing the feasibility of reducing significantly the lead time involved in the manufacturing of large volumes of tapes. SCE&G has maintained their interest in HTS systems for other potential applications within their area, and Pirelli has agreed to undertake the work as these applications become available.

2

SPECIFICATIONS, PROCEDURES, OPERATING CONDITIONS, AND MAINTENANCE

Specifications, Procedures and Operating Conditions

Introduction

This section will cover only the principles and engineering concepts concerning the refrigeration system. Also included is the preliminary testing to be carried out before the energization of the cable system. The detailed specifications procedures and operating conditions will be prepared in cooperation with the customer's engineering departments to meet their specific and individual needs. The system will be equipped with back-up components to ensure reliability and safety as necessary.

Operating Conditions

There are **four** distinct operational modes of the cooling system, defined by various conditions as follows:

1. Maintenance of the cable system in a completely non-operational condition, at ambient temperature, and in "safe conditions".

2. "Cool down" and stabilization of the cable system at ~ 70° K preparatory to energization.

3. Normal operation of the cable system at ~ 70° K, while energized and in service.

4. Emergency operation of the cable system (i.e., during the loss of normal electrical power failure of the primary refrigeration system equipment, etc.) at ~ 70° K for a prescribed time period, followed by either a return to normal operational mode or, if necessary, an automatic de-energization of the cable system.

General Specification for the Refrigeration Plant

Cryogenic System

The system is made up of five distinct sections.

1. cooling system
2. pressurization system
3. pumping system
4. transfer lines
5. vacuum system

1) The cooling system is comprised of a heat exchanger of either liquid helium or liquid nitrogen depending upon the design. The heat exchanger maintains the temperature of the flowing liquid nitrogen within a predetermined region of the nitrogen liquid / vapor curve for a given application.

2) The pressurization system maintains the required pressures for the liquid nitrogen to also reside inside the defined region of the nitrogen liquid / vapor curve for a given application.

3) The pumping system controls the mass flow rate in correlation with the predetermined region of the nitrogen liquid / vapor curve. The flow rate influences the heat transfer from the nitrogen to the cable system and vice versa.

4) The transfer lines deliver high-pressure liquid nitrogen to the cable from the refrigeration system and vice versa. There are also lines that deliver low pressure liquid nitrogen to the termination assembly to accommodate the transition from cryogenic temperature to ambient temperature.

5) The vacuum system is made up of a passive chemical material that maintains the vacuum integrity of the cryostat while the system is energized.

Control and Protection System

A Control and Protection System will verify the entire system’s operation and will react accordingly. The system will be divided into three functioning levels:

- Control Function—automatic control or manual control by an operator

- Alarm Function—alarms the operator of a malfunction and a corrective action is performed if possible, otherwise shut down is eventually required.
- Protective Function—a complete shut down to avoid serious damage

Refrigeration System

The “basic” specifications for the refrigeration system include the following:

1. The refrigeration system shall be constructed to operate under normal conditions, in a completely unattended fashion. Only periodic maintenance and inspection visits shall be required in order to ensure that proper condition of the equipment is being maintained. Such independent function shall be accomplished by the provision of a control and monitoring system adequate to permit completely automatic operation of the equipment under normal conditions. The inclusion of automatic emergency functions will be required to optimize and / or shut down the system in response to a variety of contingency scenarios.

2. The refrigeration plant’s control and monitoring system shall also provide the means by which both real-time and historical operational and performance data are collected, processed, and stored for subsequent analysis. This data will be used to optimize future performance of the refrigeration plant and the associated HTS cable system, as well as to diagnose the behavior of the system in response to emergency conditions. This data shall be transferred to a remote, attended location by means of the same control and monitoring system; uploading information in a format and on a schedule to be finalized at the time of project implementation.

3. The refrigeration plant shall include provisions to operate accordingly during cable system start-up and repair situations. Also, the system will maintain a pre-designed operating condition during outage situations that will comply with utility practices.

Cable Installation

Taking into account the size and condition of the pipe, the following preliminary activities should be carried out.

1. An accurate site survey should be carried out to determine:

   — the final routing of the HTS system with distance, bends, etc.

   — the real conditions of the pipe

2. The pipe will be checked for the presence of obstacles or irregularities as customary for conventional cables.

3. A suitable pulling eye and other equipment that may be deemed necessary, will be developed for subsequent pulling operations, and detailed instructions will be provided.

Thermo-Mechanical Evaluation of the Cryogenic System

The thermo-mechanical evaluation of the cryogenic system consists of two phases. The first phase, coming directly after pulling the cables within the pipe, is to verify the correctness of the installation and check the cables against possible damages incurred during pulling. The second phase is to verify the operation of the refrigeration system.

Preliminary thermo-mechanical evaluation of the cryogenic section

1. a. After completion of the cable installation, the following pressure withstand test shall be performed: the inner corrugated pipe will be filled with dry nitrogen and pressurized for a specific duration.

   b. The integrity of the outer corrugated pipe will be checked by evaluating the vacuum grade inside the cryostat.

The cables will be cooled down from the ambient temperature to the boiling temperature of LN, controlling the temperature transient. Either feeding from the refrigeration plant or from an external LN supply should be considered as a possible option, and if feasible, both tested for comparison purposes. Time for cool down and nitrogen use are to be monitored and recorded.

2. Verification of the installed system for thermal, pumping, and refrigeration losses.

   a. After the installation of the accessories and the connection to the refrigeration system, the system will be cooled down to the operating temperature using the best pressure (transient time and nitrogen consumption to be monitored).

   b. The refrigeration system will be operated in its nominal conditions and all parameters monitored until a stable condition is set.

   c. While maintaining the above steady condition, the salient parameters will be monitored and recorded for a subsequent analysis:

   — temperature , flow rate, and pressure at the interface of the main elements of the system (cable go / return, terminations, joints, pumps, refrigeration, etc.)

— level of LN in storage

— electrical power supplied to pumps and refrigerator

d. From the data obtained in 2c, the thermal losses relevant to each component of the system, the pumping losses, and the electrical (refrigerator) losses will be calculated for the no-load, no-voltage condition and compared to the design data. A high value of thermal losses relevant to the cable circuit should indicate possible damage to a section of the cable's cryostat section (see Maintenance and Repair).

Electrical Testing and Evaluation of Thermal and Electrical Losses

Following the cable installation, the assembly of the terminations, and the completion of all the necessary checks to ensure the correct performance of the system per 2c and 2d, the evaluation of the thermal and pumping losses will be undertaken according to the following steps:

3. a. The customer's standard testing (or Superconductive equivalent) for pre-energizing cable systems. Some of these tests would include meggering tests, relay trip tests, phasing verification, etc.

   b. The system will be energized at the phase-to-ground voltage applied to each phase conductor, with no load. After having reached a steady condition, the system losses will be evaluated.

Electrical Testing with the System Connected to the Grid

In this phase of the electrical testing, the system will be connected to the grid to evaluate all of the parameters under actual conditions. Refrigeration and control systems will be kept in their standard operating mode, and all the relevant parameters will be monitored and recorded.

3

MAINTENANCE AND REPAIR

Introduction

It should be noted that the development of the maintenance and repair techniques for the HTS system will be refined when the first system implementation takes place. In this application, the dielectric portion of the maintenance program should match an oil-filled cable system. The impregnation of the paper in the PCS design uses liquid nitrogen in comparison to the oil impregnation in the self-contained, oil-filled cable systems. The PWS design is similar to the conventional pipe-type cable design using paper-oil insulation with a flowing liquid nitrogen center.

Repair to Cryogenic System

In the event of failure of the cryogenic system the HTS cable has to be de-energized immediately to avoid major damages. Service conditions can be resumed only after repair, when it is certain that the cable system is at required temperature range, and all components of the HTS systems are in correct working condition.

The cause of the failure has to be identified and repairs carried out as rapidly as possible. There could be several reasons for a possible fault and, although it is not possible to make any prediction in this area, the faults can be classified into three categories:

For the PWS and PCS design

1. loss of thermal insulation in some part of the cryostat
2. dielectric breakdown (cable or terminations)
3. breakdown of the cryogenic system.

In the following we will comment on each category.

1. **Thermal insulation fault**. Because the cryostat consists of two pipes with a vacuum in between it is possible to have:

a. damage and puncture of the external pipe only

b. damage and puncture of both pipes leading to loss of pressure and loss of liquid nitrogen

c. damage to the thermal insulation in the PWS design that could indicate extensive insulation damage.

2. **Dielectric breakdown**. The following two situations should be investigated:

a. Dielectric breakdown only—An internal electrical breakdown without subsequent damage outside the insulation.

b. Dielectric breakdown—This can either follow mechanical damage to the pipe system or initiate damage to the pipe system.

A. Pothead Failure can be due to an internal breakdown or to external agents.

3. **Cryogenic Pumping System.** This event must be detected quickly and a disconnection of the cable from the power system is imperative. In some cases if supplying power service is important then a continuation of the circuit could be maintained for a calculated time period. But all pertinent information regarding the system operation must be consistently monitored for a secure cable circuit.

The following are very preliminary **repair guidelines,** which are pertinent to the previously mentioned possible faults:

Loss of Thermal Insulation: (1)

This would entail a leak in the cryostat material either from the inside section leaking LN into the thermally insulating area or the outside member letting heat into the thermally insulated area. The circuit would need to be shut down immediately especially if the leak was substantial as evaluated by the monitoring system. Damages to the outside pipe or inside pipe would entail replacing that section of the circuit with a new section. In either case the system would need to be void of any LN so as to perform the required splices. The following would be the progression of tasks:

a. warm the system to ambient temperature

b. cut the cable

c. execute a cable repair joint

d. cool down the system and restore the N2 pressure

e. restore to service

In the case of a PCS design a thermal leak could be fixed outside of the duct by welding the damaged cryostat sections. Whereas, in the PWS design the cryostat is apart of the conductor area and within the insulated area, a damaged cryostat would need to be discarded.

Loss of Electrical Insulation:

The procedure entails locating the faulted area and replacing the damaged section.

a. repair by inserting a short section of cable by means of two repair splices.

Potheads Failure:

This type of damage requires the replacement of a complete termination which entails:

a. a system pressure shut down

b. a system warm-up procedure

c. isolation of the pothead from the cryogenic pipe system

d. replacement of the pothead

e. restoration of the complete system to service.

Repair to Cable

The repair to the cable should be carried out as per procedures recommended by Pirelli and based, as appropriate, on practices followed for conventional cables.

Several techniques are presently being evaluated in Pirelli R & D organizations keeping in mind the several aspects of the HTS elements (geometry, number of HTS tapes, etc.).

The recommended repair technique will be part of the demonstration program to be evaluated by the customer’s personnel.

Maintenance to Cryogenic System

The Cryogenic System is the most important part because the cable mentioned in other paragraphs must be kept within the assigned temperature range. The refrigeration station will be designed to be completely unattended during normal operation of the cable system. Only routine pre-scheduled inspection visits, intended to ensure cleanliness, absence of vandalism, visible inspection of rotating equipment, etc. should be required.

Specific information will be given on preventive maintenance if required.

Hazards of Nitrogen

The use of liquid nitrogen is largely accepted within U.S. industries and is environmentally friendly yet there are hazards that need to be stated.

There are a few areas where the liquid nitrogen can create hazardous conditions. Since most power companies are new on the safety issues concerning nitrogen, this section has been added for clarity on those issues. The possible harmful effects could be asphyxiation and frostbite.

Asphyxiation is caused by a person being exposed to an atmosphere containing more nitrogen than typically normal (78%), thereby reducing the oxygen content. This harmful condition can cause loss of consciousness or death without any warning symptoms or distress. It is recommended to maintain a level of oxygen over 14% within enclosures for a safe working environment. It should be noted that since nitrogen in the liquid state is more dense than air, the cold nitrogen vapor can accumulate in low lying areas. If the system is malfunctioning this can prove dangerous particularly within the manhole enclosures. An atmospheric evaluation of the area needs to be checked for nitrogen and / or oxygen content.

The low temperatures of liquid nitrogen, if contact is made with a persons skin, will result in a “cryogenic burn”. The cold vapors can also result in frostbite or hypothermia and inhalation can damage the lungs. The condensation of air in proximity to the liquid nitrogen, where insulation is lacking, can result in oxygen enrichment from the liquid air. This extra oxygen content can present an increased fire hazard if this situation takes place inside a confined area.

Finally, it is worth noting that as a result of heat-in-leak vaporizing liquid nitrogen can develop over-pressurization. With the adoption of inexpensive relief valves, this problem is avoided.

4

REFERENCES

1. D.E. Daney et al.—*AC Loss Calorimeter For Three-Phase Cable*—presented at 1996 Applied Superconductivity Conference

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3. S. Mukoyama et al.—Research and Development of 50 m Long High Tc Superconductor for Power Cables—presented at 1995 ISS

4. M. Leghissa et al.—Bi-2223 Multifilament Tapes and Multistrand Conductors for HTS Power Transmission Cables—presented at 1996 Applied Superconductivity Conference

5. K. Sato et al.—*HTS Large Scale Application Using BSCCO Conductor*—presented at 1996 Applied Superconductivity Conference

A

APPENDIX A

HTS AC Losses Data

Conventional Cable Systems

The AC losses in conventional cable systems are well known, and formulas supported by the field data are used.

Current-related

- conductor
- metal components (shield, skid wire, pipe)

Voltage-related

- polarization of insulating materials/fluid

HTS Cable Systems

- As in conventional systems, the AC. losses are current and voltage related. In addition there are the refrigeration losses.
- Whereas the voltage related losses can be determined by using the conventional calculations, the current-related losses are still the subject of understanding and interpretation of the few experimental data available. They depend on the ceramic materials used for the Superconductor element, the manufacturing technology, and the testing methodology used.
- For the necessary engineering calculations, several models are being used by researchers and engineers. Pirelli has chosen the “Model 2”, and the theoretical results are tentatively shown.

- Only a long and real installation will tell us what are the real AC losses simply measuring the input/output power.
- In this way the refrigeration and I-related losses can be correctly determined.

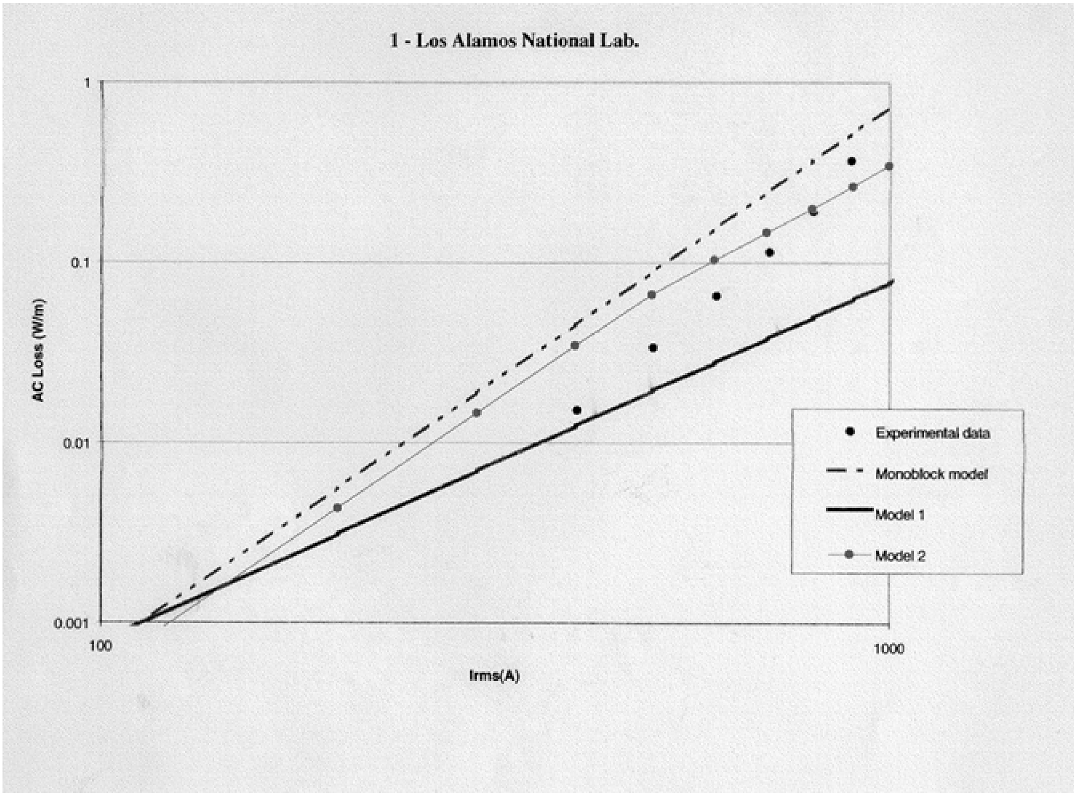


Figure A-1

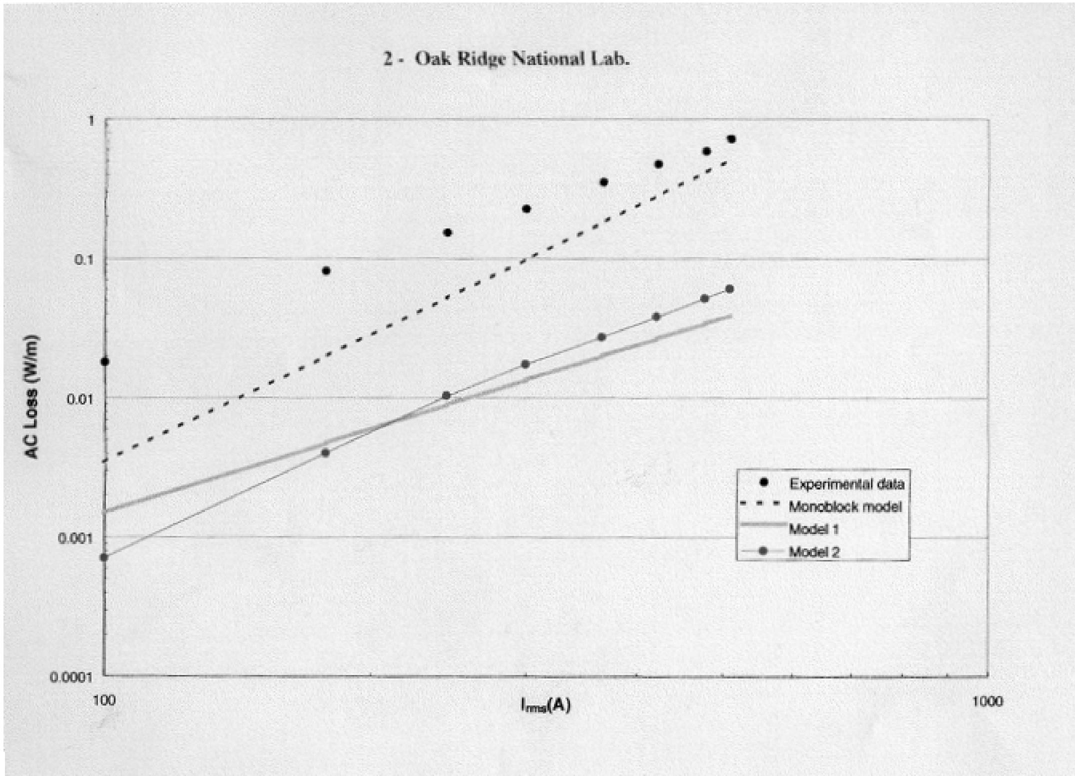

2 - Oak Ridge National Lab.
AC Loss (W/m)
1
0.1
0.01
0.001
0.0001
100
1000
I_{rms}(A)
Experimental data
Monoblock model
Model 1
Model 2

Figure A-2

B

APPENDIX B

Refrigeration System Basics

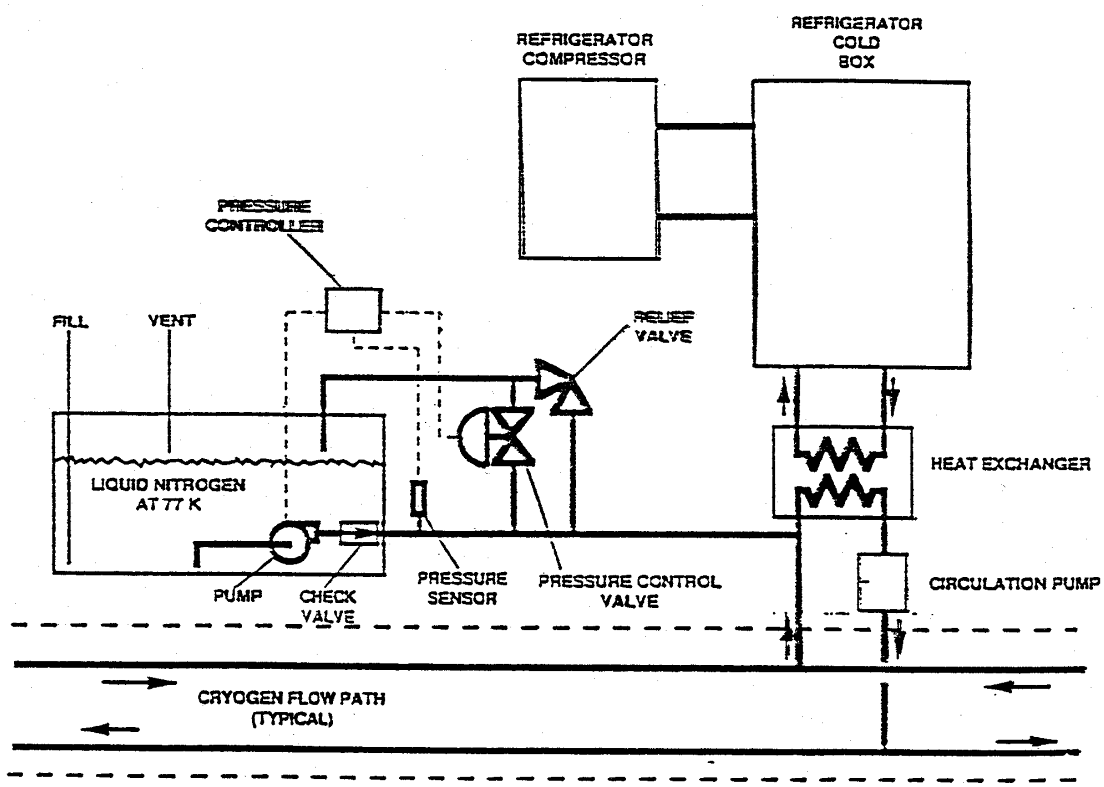
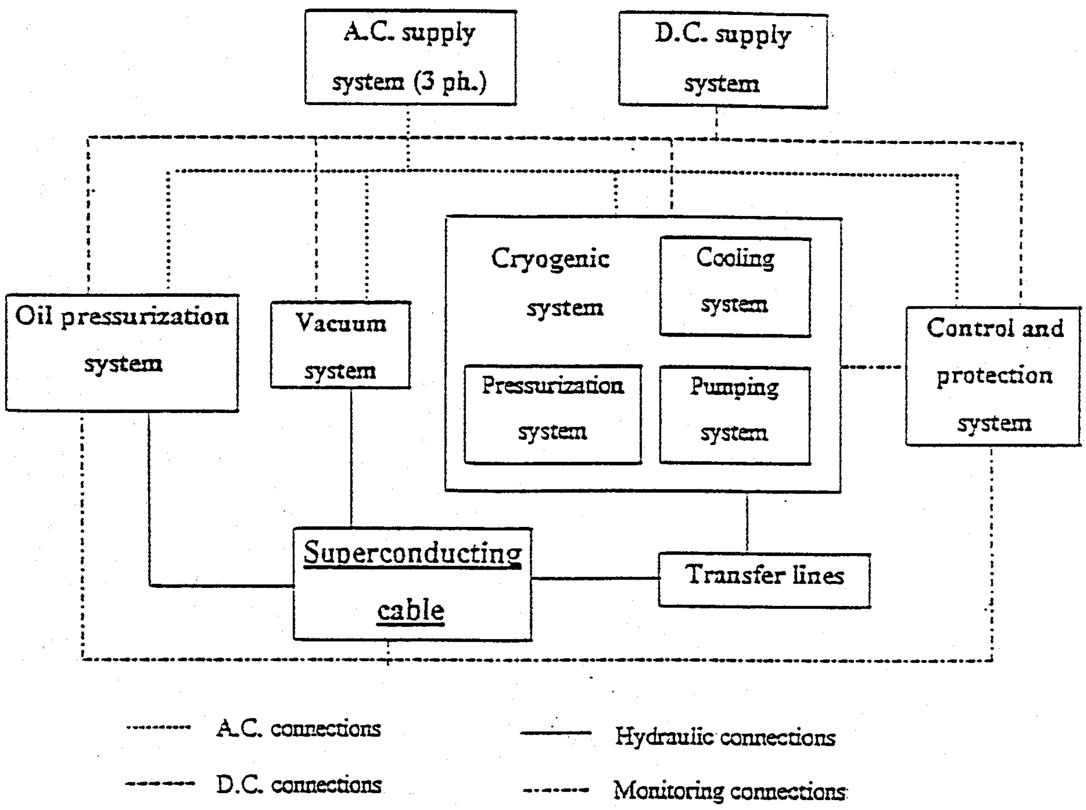


Figure B-1

Cryogenic System Block Diagram



Systems connections

Figure B-2

C

APPENDIX C

Capitalized Operation Diagrams for Conventional and HTS Cable Systems

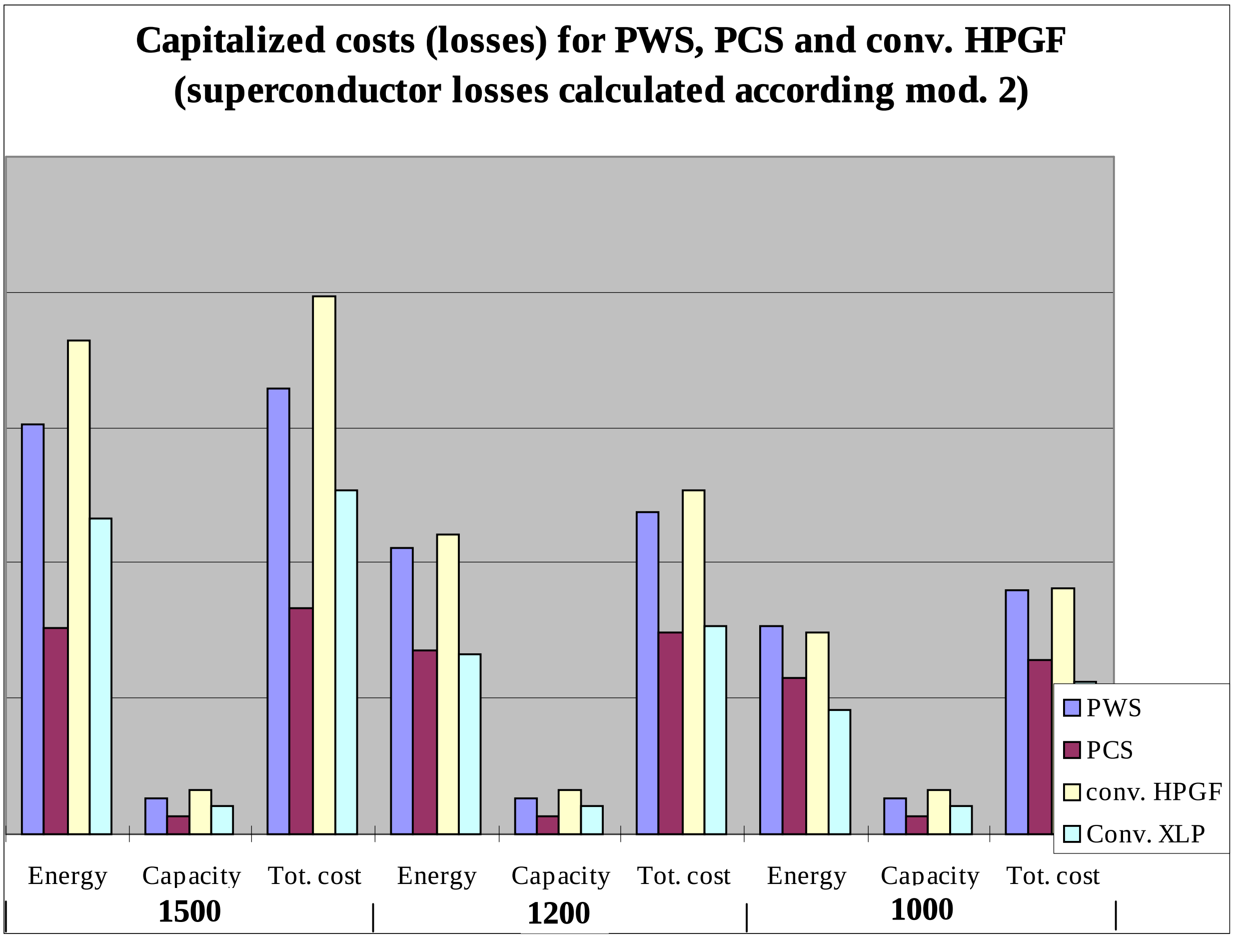


Figure C-1

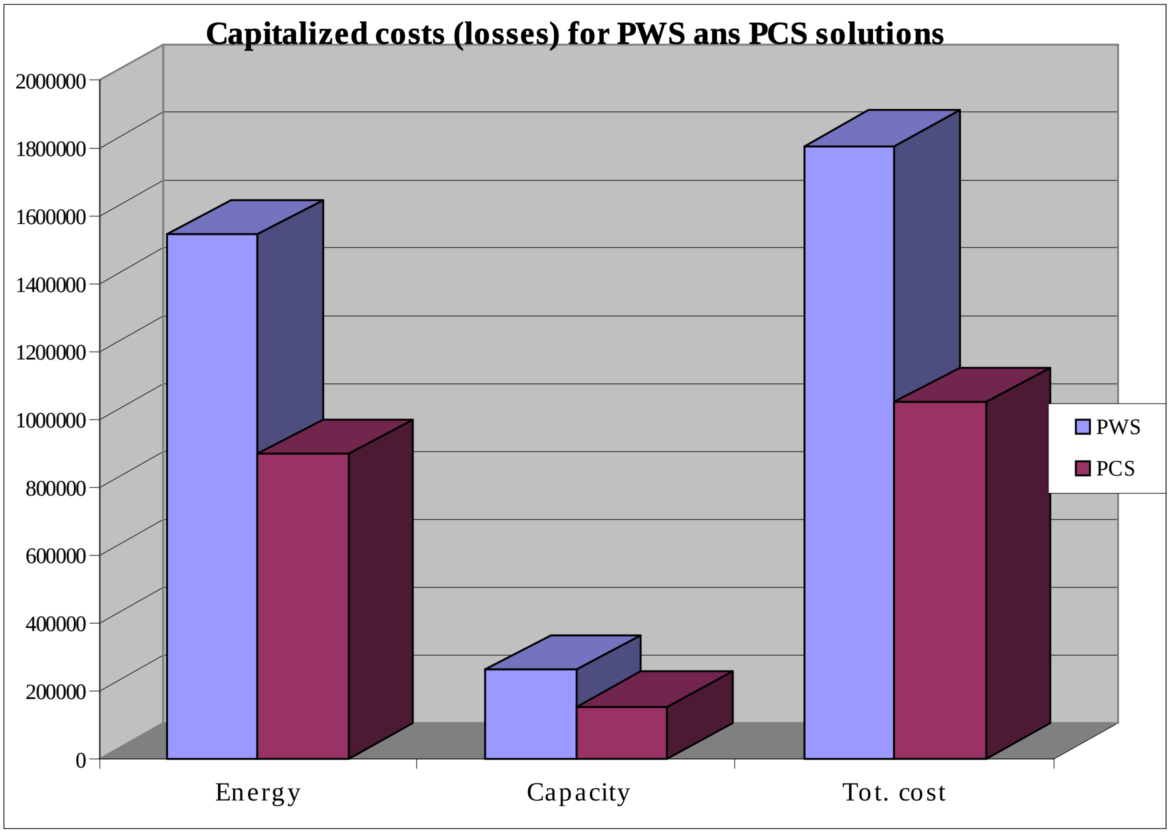

Capitalized costs (losses) for PWS ans PCS solutions
2000000
1800000
1600000
1400000
1200000
1000000
800000
600000
400000
200000
0
Energy
Capacity
Tot. cost
PWS
PCS

Figure C-2