High Temperature Superconductivity A Joint Feasibility Study for a Power Application with HTS Cable by Peco Energy Company

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REPORT SUMMARY

Practical realization of high temperature superconductivity (HTS) technology is within the electric power industry’s reach. This report documents a feasibility study conducted 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. AC HTS circuits, for example, can carry two to five times more current than conventional cables of comparable size. Although this phenomenon was discovered over 80 years ago, its potential has remained unfulfilled because, until recently, these 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 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. One participant in this process was PECO Energy Company (PECO), who viewed HTS applications as one way to replace multiple aging circuits within a limited space, while maintaining reliable service in an environmentally responsible manner.

Objective

To determine the technical and economic feasibility of using HTS system technology in the PECO network.

Approach

A search within PECO's system was initiated for a location that would utilize the full potential of HTS cables--a line with high load growth potential. This was identified as a circuit linking two substations in the downtown Philadelphia vicinity that had reached its maximum load capability. 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 meet the technical performance parameters the team established, the PWS design 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 to preclude HTS cable use in this application. They recommended, however, that thorough field trials and qualification tests be conducted before any long length commercial installation.

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-102779, TR-103631, and TR-110891). 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.

Subjects

Underground Construction, O&M
Underground System Alternatives

Topics

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 October of 1996, EPRI, Pirelli Cable Corporation, and PECO Energy Company performed a joint study to assess the technical and economic feasibility of installing a HTS cable system in downtown Philadelphia. The project team concluded that a HTS system could be designed to meet the requirements of a standard underground transmission cable at distribution voltages, and be more advantageous than a conventional system because of better utilization of the existing duct system.

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INTRODUCTION

PECO Energy Company is the electric power and natural gas provider in a service territory encompassing 2100 square miles in southeastern Pennsylvania. This includes the electric service encompassing the City of Philadelphia. One of PECO's main objectives is to optimize their asset utilization through maintenance, modification, and expansion of their infrastructure. These attributes are represented in PECO's interest in innovative technologies such as high temperature superconductivity (HTS).

It is well known that conventional cable systems are limited in their current carrying capabilities, represented by the fact that conventional cables have a temperature constraint that is directly related to the current that is applied to the cable. And in time, if the current values increase due to the increased load, then the cable must be paralleled with another cable or replaced with a higher voltage cable to meet the load demand. In addition, because of the temperature cycling performed on the cables from the cycling load, during its lifetime, degradation of the cables may hamper performance. Maintenance and repair costs will begin to increase as degradation eventually causes more failures. In many urban areas, cables installed in the past have reached their designed maximum current carrying capabilities and are beginning to fail at an increased rate. Along with these aging cables is the problem of installing new cables within these highly populated areas having congested duct banks. The increased capability of HTS cable systems creates an avenue for replacing multiple aging circuits within a limited space. Because of these benefits, PECO is interested in the application of HTS cables.

Growing demand for energy in the City of Philadelphia has caused PECO to consider the new HTS technology as a feasible solution to supplement the existing cable systems. A HTS system, with the inherent benefits not typical of conventional systems, may overcome the need of upgrading existing cable systems and installing new circuits.

Status of HTS Development

An investigation within the PECO power network was performed by engineers to ascertain the most advantageous application for a HTS system, noting that HTS cables have high current capability at any voltage level. In this respect, the application selected should be a highly loaded circuit to capture the real benefits of HTS cable systems. The application selected for the study was chosen because it could meet the growth potential in the urban area while overcoming the limitations of duct availability and the space for additional transformation capacity. The problem arises from the fact that the available space for a transformer or for a duct bank required by a high voltage cable or for medium voltage cables was extremely restricted. The resolution was to incorporate a 13.8 kV HTS cable at transmission power levels to eliminate the load problems without requiring additional space. By utilizing the existing ducts available, a proposed HTS cable at 13.8 kV would be installed in the existing ducts and supply the load needed in that region. The distance of the circuit would be 2.2 miles and would run through three existing 3.5-inch ducts. Upon identifying the specific application, the team members established the technical parameters required for the project.

Four HTS cable designs were evaluated by Pirelli engineers in an effort to find the most effective technical and economical solution. A HTS system was then designed around two carefully selected 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.

The 50-meter long HTS cable conductor was manufactured in two phases. This was done in order to confirm that the cabling operations were 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 in a helical fashion around a Teflon tube (the channel for the LN flow). The measurements performed on each individual tape have shown a critical current of 1800 DC amperes, which is in agreement with the engineering calculations performed at the time of designing the cable. The second phase consisted of the application of additional layers of tapes with a total critical current of approximately 3200 DC Amperes. This variation was not attributed to an over stress situation that might happen during the cabling of the conductor, but probably to the intrinsic effect of the magnetic field induced by the HTS tapes.

Feasibility Study

In August 1996, EPRI and Pirelli gave a presentation to update PECO management on HTS current status and potential applications in the transmission / distribution area. PECO showed their interest soon after this presentation with a scheduled meeting.

During the meeting on December 12, 1996, Pirelli engineers met with the PECO engineers to discuss and select a real application for a HTS system. A list of the tasks to be performed was formulated. At this meeting the team leaders were appointed along with a list of the team members from both Pirelli and PECO.

The group established the needed tasks and required data for a descriptive and thorough study. The group commenced upon the activities analyzing the several possibilities in both the transmission and distribution areas. Finding the most appropriate section of the power system at PECO that could utilize the benefits of the HTS cable system was the initial step in the process. And 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 load flow and fault current challenges. The system protection was analyzed, as well, to insure the security and reliability of the circuit. Where the circuit would terminate and by which routing plan the cable would travel was also essential for the study. Once this information had been acquired through PECO's team members, the specific design criteria for the HTS cable was formulated.

The cable designs that were made available by the Pirelli engineers depended upon the specific requirements of the cable system. The group analyzed four of the HTS cable designs that were initially considered for the installation, and eventually narrowed the choices down to two cable designs. These designs proved to be the most advantageous. From the cable designs and the system electrical parameters, the Pirelli team members were able to develop the cable constructions needed for the selected real installation in the distribution network.

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

Selecting a Potential Application

The PECO engineers had been interested in the benefits of a HTS system within the dense urban areas. These areas possess the challenges of potential load growth coupled with severe limitations of duct availability, the lack of space for additional transformation capacity, and the lack of equipment for upgrading. The upgrading of the existing oil-filled 69 kV circuits with conventional 230 kV or 69 kV cables would require extensive transformation investments. With the advantages of HTS, PECO could utilize 13 kV voltage levels to supply power directly from generation 13 kV or 230-13 kV buses to city center load centers along 230 kV corridors, overcoming all the problems generated by space restrictions and the investments of additional transformations. This would eventually enable a progressive retirement of the 69 kV circuits and 69-13 kV transformations.

To select a potential application, PECO engineers analyzed numerous possible areas where a HTS circuit would be beneficial and, in some cases, be the technical alternative. The engineers looked into various areas within PECO's power system, specifically in the downtown Philadelphia vicinity. For the selection process, several criteria were established: 1) urban growth, 2) load growth potential, 3) limited underground duct capacity (number and size of ducts), 4) limited space for additional substation equipment (transformers and switchgear), 5) ability to thoroughly test the cable without affecting customers, and 6) to provide an important function once testing is completed.

With this constraint, the Team members agreed upon a new circuit, between two substations, that could feed a desired load to an area where growth is expected. The two substations were named Substations A and B. Substation A is a large transmission / distribution substation with three 62 MVA 230-13 kV transformers to supply areas with 13 kV distribution load, and supply power to neighboring, smaller distribution stations. Substation B, at the other end of the circuit, is a large distribution substation that feeds an area that is growing, and is reaching its maximum load capability with the high voltage feeds supplying it. This substation has three 69 kV feeds that supply its six 40 MVA transformers. This substation had reached its maximum potential, as far as having room for additional transformers or high voltage cable feeds, unless an enormous economic undertaking was performed. An excellent HTS application opened up--to utilize the power from Substation A by connecting to the 13.8 kV bus-work and sending the power to Substation B via available ducts. The 13.8 kV circuit at one end of the circuit could be connected to and then distributed through the limited amount of ducts to the other substation. At Substation B the cable would terminate on the existing 13.8 kV bus-work and therefore not require a new transformer, avoiding the space constraints associated with a new transformer. The HTS cable would travel within the existing, limited duct space, which could not accommodate a 69 kV circuit or additional circuits of conventional cable at 13.8 kV without the installation of a new duct bank. In summary, after a thorough analysis, a conclusion was reached that the most viable alternative to conventional cables was the adoption of a HTS cable system at 13.8 kV that could be installed in the existing ducts, eliminating the requirement of a transformation step to 69 kV.

The main parameters of the project were defined as follows:

- Voltage: 13.8 kV
- Current: 2500 amps
- Circuit Length: 2.2 miles
- Fault Current: 40 kA, 13 cycles
- Duct Description: 3.5-inch square terracotta ducts
- Manholes along Route: 55

It is worth noting that many other venues were evaluated within PECO's system that would benefit from the capabilities of HTS cable systems. Areas where replacement or upgrading of existing 69 kV cables might be required in the near future were also analyzed. In these situations, a HTS cable system could utilize the existing pipes and significantly increase the power transfer, as well as avoid challenges and hurdles in urban areas where the "right of way" is a very critical factor. Another area where a future power flow increase would be required with conventional systems is in the upgrading to higher voltage levels to accommodate growth. The high cost associated with new transformers and new pipes identified the HTS system as a viable alternative to a conventional solution. Ties between major transmission substations, not existing today, were also considered because of expected load growth or for improved stability within the system. It was also anticipated that HTS connections could be used at lower voltages and higher currents than allowed by conventional cables.

Electrical Parameters

A few electrical parameters needed to be evaluated in detail because of the proposal that a low-impedance, high-capacity tie between two heavily-loaded substations had been chosen for the desired application. In fact, a distribution cable is normally used to distribute a limited amount of power to the various customers. Therefore, the HTS cable could be considered a transmission cable at distribution voltages because of the higher power transfer capability. In PECO's application, the HTS cable will perform as a bus connection between the two substations, therefore enabling more versatility and stabilization within their network. This connection, although beneficial in many respects, has some challenges that need to be evaluated and overcome. Listed below are various potential problems that needed some extra effort from the team members.

Fault Current

One area evaluated was the fault current that could be created by the addition of the HTS cable. The Pirelli team members verified that the cable could be designed to accommodate the fault current. They agreed that the limiting factor in the fault-current-withstanding-ability was mainly the transformer and switchgear ratings. The fault current was calculated to be approximately 40 kA from one source and approximately 33 kA from another source. The situation where the fault resides in one of the substations creates a total of 73 kA supplying the fault. This level of fault current was evaluated and the conclusion was that the transformers and switchgear at both substations could not handle this fault current.

Load Flow

The load flow between the substations was thoroughly considered. A load flow study was performed by PECO engineers, which determined the load current values. The load flow currents depend a great deal on the cable impedance and where the sources of power remain within certain vicinities of the PECO system. The overloading of existing transformers under normal and outage conditions, as well as over-stressing of equipment, especially at Substation B, were identified as the main limiting factors. Despite the fact that the cable ratings are designed to meet extremely high levels, a decision was made to ensure a load flow maximum of 2500 amps. Both substations' switchgear meets the 2500 amps criteria for the proposed circuit, and no problems were anticipated in designing and manufacturing a HTS cable with greater capabilities in the current carrying area.

Resolutions to the Fault Current and Load Flow Challenge

The first upgrade to reduce the fault current was to increase the impedance values of the cable. The pipe retrofit, warm dielectric, single phase elements (PWS) design actually offers higher impedance values than other HTS cable designs, and would lessen the fault current levels. However, the increased impedance value for the PWS cable design would not bring the fault current levels down to the values stipulated by the transformer and switchgear equipment.

The next alternative was to increase the reactive impedance through the implementation of current-limiting phase reactors. These reactors are simply a coil of wires/cables placed in series with the cable, which automatically induces a reactance, which in turn increases the impedance; this impedance will then limit the fault current. This technique is used quite extensively in the distribution network because of the high fault currents typical of the network. This technique would work well for the HTS application in question and would also be necessary if a link with conventional cables was considered. The high current being applied to this circuit was much greater than the one in a normal distribution line, therefore establishing more losses in the phase reactor banks than was desirable. Although this alternative could reduce the fault current levels, the team members agreed that additional work would be performed to eliminate the undesirable losses attributed to the reactor banks.

The final solution consisted of situating the switchgear at the two substations so that the fault levels would never be attained. That is, positioning open breakers or switches at various spots within the two substations to reduce the amount of feeds to a proposed fault, thereby eliminating the fault current levels. This separation within the substations is quite common in the power system to overcome various power flow or fault contingencies. The existing substations' switchgear could be easily disconnected or reconnected at any given time by a remote operation. This enables the HTS circuit to be implemented and utilized to its advantages yet still maintaining acceptable fault current levels for the limited ratings associated with the transformers and switchgear.

Routing

Verification of the route was imperative to a successful and economical study. The routing was within the congested duct banks of Philadelphia, therefore the work to be performed on locating the necessary ducts or pipes was crucial and time consuming. A careful evaluation of all the existing prints associated with the ducts and manholes was performed (Appendix A). After a thorough study the investigation uncovered at least three, 3.5-inch ducts throughout the entire cable run, except for the final 200 feet directly outside of Substation A. This section will require a new duct bank to be installed for the circuit implementation. The 2.2 miles of the cable route was painstakingly evaluated by the many prints available of the system in that vicinity. A physical duct bank check would need to be performed to verify the accuracy of the available ducts within the manholes. Since the duct banks were so important to the study, and in order to proceed with the cable design, a meeting at PECO was attended by Pirelli engineers to determine the exact condition, dimensions, bends, and malformations that these ducts might possess. During this visit, the Pirelli attendees were able to inspect a typical manhole to size the area for the bending, splicing, and pulling of the HTS cable. Through the investigation of the ducts and route, the number of manholes remains at approximately 55.

The specific dimensions of the duct banks are 3.5-inch or 4.5-inch square, usually in sets of 4 to 20 ducts in a bank (Appendix B). The ducts were all predominately smooth, but need to be checked before the cable is installed. The assessment of the ducts will include a mandrel run through the ducts to clear any collapsed ducts or imperfections within the duct bank, and will be performed prior to the installation of the cable.

HTS Cable Designs

From a general point of view, the following four HTS cable designs are possible:

- 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).

The team looked at all the design types, but because the application required the utilization of the existing ducts, the RCS and FCT designs were obviously eliminated.

Both the RCS and FCT designs involve either a rigid cryostat pipe or a flexible cryostat pipe that would not retrofit with the existing ducts.

In order to optimize the cable designs, the following assumptions were made:

1. The overall dimensions of the HTS cable should be compatible with the duct dimensions, allowing an acceptable clearance between the overall cable dimensions and the duct inner wall for installation reasons.

2. The refrigeration system should be designed as simply as possible, preferably with one refrigeration plant located in a substation (A or B).

After the electrical parameters were evaluated, the Pirelli engineers began the process of identifying the appropriate cable design for PWS and PCS using the iterative process.

The application greatly benefited from the idea that the existing ducts could be used for a transmission cable at distribution voltages. This resulted in the selection and evaluation of both the PCS and PWS designs, due to their ability to install into existing ducts. Both the PCS and PWS designs were specifically designed for pipe or duct retrofit applications, thereby filling the application's desired criteria.

The final dimensions of the PWS and PCS cables were determined to accommodate the various electrical parameters. The first concern was to design the cable to be installed in the existing ducts that measured 3.5 inches in width and height. This determined the cable diameter for the installation purposes. The team members agreed that a cable with a diameter of 3 inches would create sufficient clearance (0.5 inches) for a clean installation. It was also established that a clearance of 0.25 inches would be the minimum limit for an installation within those duct types.

From this discussion, Pirelli engineers designed both the PWS and PCS cable with the appropriate dimensions. It should be noted that the inner cable duct dimension determines 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. The team agreed that reducing the number of cooling plants has a much greater benefit then reducing the size of the cable inner duct dimension, which would result in a clearance greater than 0.5 inches, making the installation easier.

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 support, because this section of the cable will carry a large percentage of the fault current. The number and thickness of the HTS tapes are determined by the 2500 amp continuous current required for the application. The conductor shield, insulation, insulation shield, metallic sheath, and jacket are all determined by the necessity to minimize cable outer diameter.

The designs of the PWS and PCS cables are shown in Figures 1-1, 1-2, and 1-3.

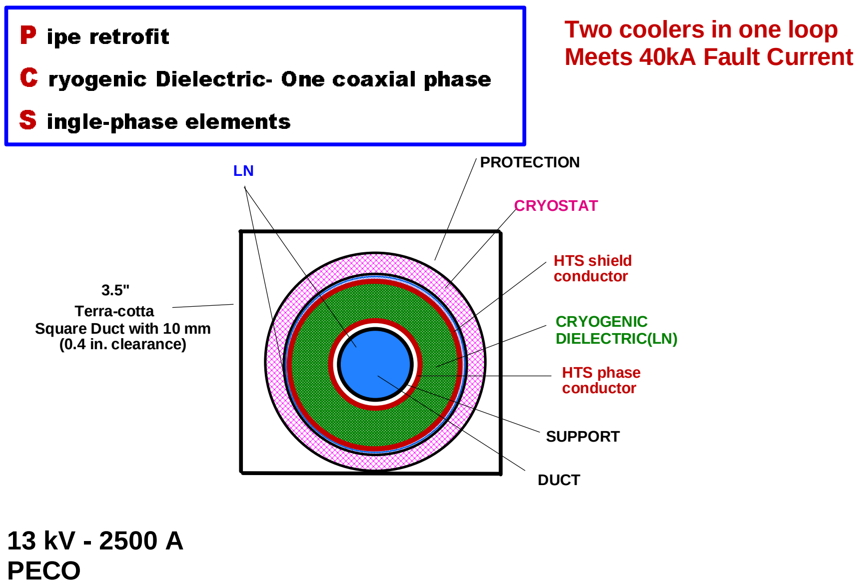


Figure 1-1
PCS Design

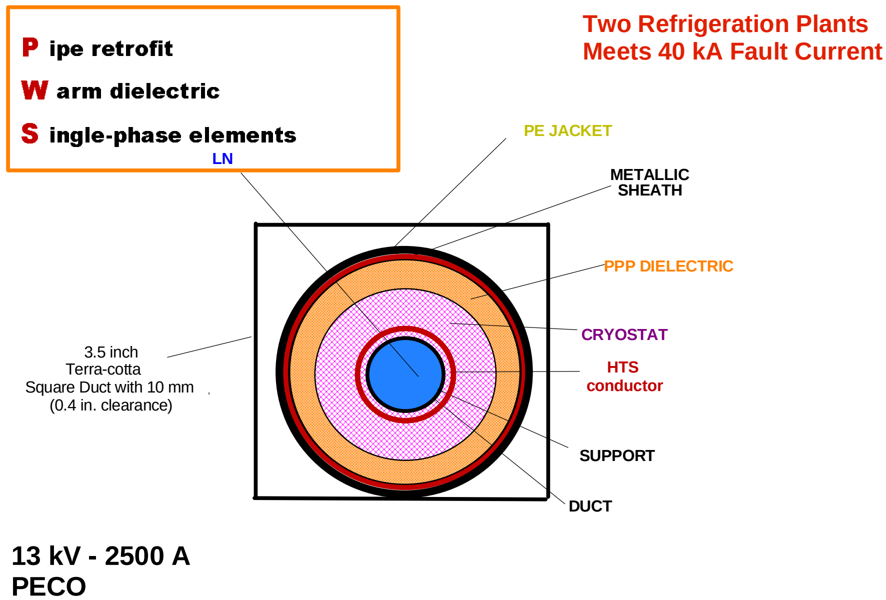


Figure 1-2
PWS Design with PPP Insulation

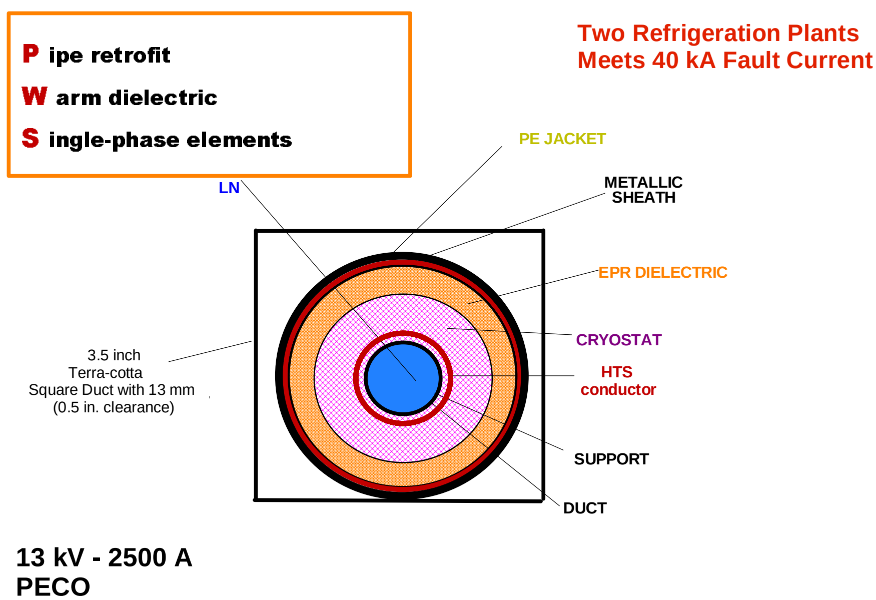


Figure 1-3
PWS Design with EPR Insulation

The PWS design is the warm dielectric arrangement that has an inner duct with HTS tapes applied in a helical fashion over the copper support. This section is kept cooled by the introduction of liquid nitrogen. Beyond this section is the cryostat section which eliminates any transfer of heat between the warm temperature dielectric and the cold temperature conductor. Applied over the outer section of the cryostat is the insulation. Two types of insulation were considered: the EPR dielectric insulation and the PPP insulation.

The PPP insulation required a lead sheath for the containment of the dielectric fluid.

In the case of the EPR dielectric, it can be exposed to water with no effects to the dielectric properties and therefore, a lead sheath is not needed. A copper shield capable of short circuit conditions and an external PE jacket will complete the cable construction. A positive result in the EPR dielectric design is the overall dimensions of the cable, which are reduced 0.13 inches, and the weight, which is cut by more than half. All of these details contribute to an easier installation and longer cable pulls between joints. The PWS cable does require two refrigeration plants due to the intrinsic design established in this application.

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 liquid nitrogen. The shield of the PCS design utilizes the HTS tapes, which contributes to highly reduced losses. In fact, the shield current will nearly match the conductor current although flowing in the opposite direction, thereby balancing the magnetic effects and derived losses typical of conventional cables. Beyond the HTS shield is a cryostat medium that acts as a thermal insulator. This eliminates the transfer of heat between the liquid nitrogen temperatures within the cable and the ambient conditions.

The cable design in the PCS case required one plant comprising of a refrigeration unit and a pumping section, and another plant requiring only a refrigeration unit. This reduction in refrigeration plants needed for the PCS design, as compared to the PWS design, is made possible due to the reduction of heat-generating losses in this design.

The main characteristics of the selected cables are summarized below:

	PWS		PCS
	EPR insulation	PPP insulation	
Inner duct diameter (mm)	27.6	27.6	32
Overall diameter (mm)	76.2	79.5	77.8
Weight (kg/m/phase)	6.7	14	8.7

HTS Cable System

PWS - Refrigeration System

The refrigeration system for the PWS design encompasses two separate systems. The refrigeration systems will start at both ends of the termination and send the liquid nitrogen through one of the phase's inner duct channels. Upon reaching the center of the circuit length, both ends will then be bypassed and returned through the remaining two phases, back to the associated refrigeration station. At this point, the refrigeration system will pressurize and cool the liquid nitrogen to the temperature at the starting point.

During a group meeting in Philadelphia, Pirelli representatives were able to visually identify the site and space available for the refrigeration system. In the case of the PWS cable design, two refrigeration plants would need to be utilized for appropriate cooling requirements and, therefore, space availability was determined by the team members.

PWS - Joints & Terminations

The joints and terminations pertaining to the PWS circuit design were evaluated by the team, as was the positioning of the terminations at the various substations. Since the joints and terminations are designed at the 13.8 kV voltage level, the size and complexity of the design is greatly reduced.

The joints involved in the PWS circuit prompted questions from the PECO representatives. Concerns about the size of the joints and the installation of these joints were discussed. The group from Pirelli foresees no installation problems in the joint installation. Layouts of the typical manholes within the PECO territory were presented, and the space available to create a joint within these manholes was established as appropriate. The amount of joints required still remains a question due to the fact that an accurate elevation and routing plan has not been compiled as yet. Therefore, the specific pulling tensions once determined will fix the number of cable sections and number of joints needed. It has been established that there are approximately 55 manholes along the circuit length. With this information, the length of each segment can be easily determined, and only the costing variable requires finalization.

Incidentally, 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

The refrigeration plant for the PCS cable was designed to consist of a pumping plant and cooling plant at one end of the circuit at Substation A. The other end of the circuit would entail only a cooling plant at Substation B. This system was designed to include the entire length of the circuit as one complete flow system. The design would initiate the liquid nitrogen flow in one of the phases from Substation A. Upon reaching the other end of the circuit the liquid nitrogen would be cooled and returned to the initial substation to close the loop.

PCS - Joints & Terminations

The joints and terminations associated with the PCS design was discussed by the team. The terminations would be located in the same location as determined by the PWS design termination. As mentioned before, the location of the termination was easily attained due to the fact that 13.8 kV designs would entail much less space utilization. The number of joints is still to be determined, but the team members foresee no difficulties in the installation of these joints.

Conventional Cables or Alternative Options

The group analyzed the conventional cables or alternate methods to achieve the challenges that PECO is facing within their infrastructure, specifically at the selected substations. Because the HTS circuit is able to utilize the existing ducts and no other cable or method could perform such a task, other methods were evaluated adding the cost of duct banks or pipes. The three conventional cable system alternatives are discussed below and detailed in Appendix C.

Conventional 15 kV rated solid dielectric cable was an alternative solution if there were the required amount of ducts. As discovered by the team, there were only 3 or 4 ducts available, enough for the HTS solution, but not nearly enough for the conventional cable. Depending upon the proximity of the circuits within the duct bank, the ambient temperature, and the soil resistivity value, four cables per phase were necessary for the ampacity rating (Appendix D). From this calculation, a 4x3 duct bank would need to be installed to accommodate the conventional solid dielectric cables required. A cost estimate for the cables was compiled by Pirelli's marketing group. PECO approximated the price of installing a duct bank within that section of the city. With these numbers, a total cost was estimated for a solid dielectric conventional cable rated at 15 kV with a 4x3 duct bank installed. This was the first conventional cable assessment for the application in question.

The other alternative conventional method was to install a 69 kV cable along the same route. This cable would be a pipe type cable either HPOF or solid dielectric, installed in a pipe or duct. This alternative would be the logical choice if there were not the stipulation that a transformer needs to be purchased for one of the substations. The cable cost was again estimated by the Pirelli organization, and the pipe cost was estimated at slightly less than the duct bank cost in the previous method. The cost of a 69 kV / 13.8 kV, 45 MVA transformer was also estimated for this case. Costs for the associated switches, relaying, and modification of the substation were accumulated in the total costs to represent the second alternative method.

The third alternative method was to actually build a substation within the proximity of the growing area to supply an additional outlet for power transfer. This alternative could have a broad range of expenditures, so certain assumptions were made to display cost comparisons. The dramatic aspect of this proposal is the cost of the real estate within this section of the city. The size of the substation was another decision that needed to be made to establish a cost. It was assumed that two 69 kV / 13.8 kV transformers would be installed within the substation to provide a firm capacity of 30 MVA. Along with the transformer, the substation would require all the switchgear and relaying that would comprise a typical two transformer, numerous feeder substation. Another assumption made was two 69 kV circuits would need to be directed to this substation from another substation. This circuit price was half the price of the 69 kV circuit in the previous example because the circuit was presumed to be approximately half the distance. It was assumed that the location of the substation would be chosen, if possible, to limit the length of the high voltage cable. The costs of the real estate, the transformer, the associate substation equipment, the high voltage feed, and the low voltage feeds leaving the substation were compiled to create an estimated cost for the third alternative method.

AC Losses of HTS Conductors

The AC losses of the HTS cable conductor are still under investigation by R&D organizations because of the unfamiliar aspects pertaining to the materials, the design, the manufacturing process and the testing technologies. 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 probable reasoning for the variance is 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 (mod. 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 works, is more conservative than model 1, resulting in higher AC losses.

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

AC Loss Measurements

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

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

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

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

c) Electric measurement technique - development performed by Furukawa Electric Company / TEPCO [ref. 3]

d) Electric measurement technique - development work carried out by Siemens AG

e) Electric measurement technique - development work performed by Furukawa Sumitomo Electric Industries / TEPCO [ref. 4]

The graphs shown in Appendix E 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 has been 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 were calculated using model 2 and shown in Appendix F. The operational costs of the conventional cable system compared to the HTS cable system were calculated by using a typical capitalization methodology adopted by utilities with a service life of 30 years. The parameters necessary to perform the calculations were provided by PECO.

From the previous discussion the three alternatives were priced according to certain assumptions, and therefore the costing is strictly an estimate. The prices below include all costs associated with the solutions to accommodate the loading problems foreseen in the PECO power system. A more detailed analysis is located in Appendix C.

Cable System	Cost
Conventional 15 kV cables and duct bank	$6.5-8 million
Conventional 69 kV pipe-type cable and transformer	$6-7 million
Conventional substation with two transformers, site cost, and assoc. equip.	$5.5-9.5 million

Conclusion

The team members evaluated the technical aspects of the study and surmised that the chosen application was more suited for a HTS cable system than a conventional cable system. Regarding the economic aspect of the evaluation, the uncertain cost accuracy of the conventional cable options, along with the uncertain conditions of the ducts required for the HTS cable, generates too many variables for an accurate economic comparison.

Since the application was chosen on the basis of future growth in the area, the urgency of the installation was not imperative. An additional concern was the overall circuit length of the newly developed HTS design adopted in this application. The Pirelli engineering department feels comfortable with the PWS design utilizing the EPR dielectric, but a thorough field trial and qualification test would need to be performed before any long length commercial installation is begun. At this point, progression toward the actual installation was halted, though PECO remains interested in HTS cable systems for the studied application, as well as for other potential applications as they 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 which 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.

1.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 is to be monitored and recorded.

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

2.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).

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

2.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

2.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.

3.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** that 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 N_2 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 person's 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

[2] J.W. Lue et al. - *Test of Two Prototype High Temperature Superconducting Transmission Cables* - presented at 1996 Applied Superconductivity Conference

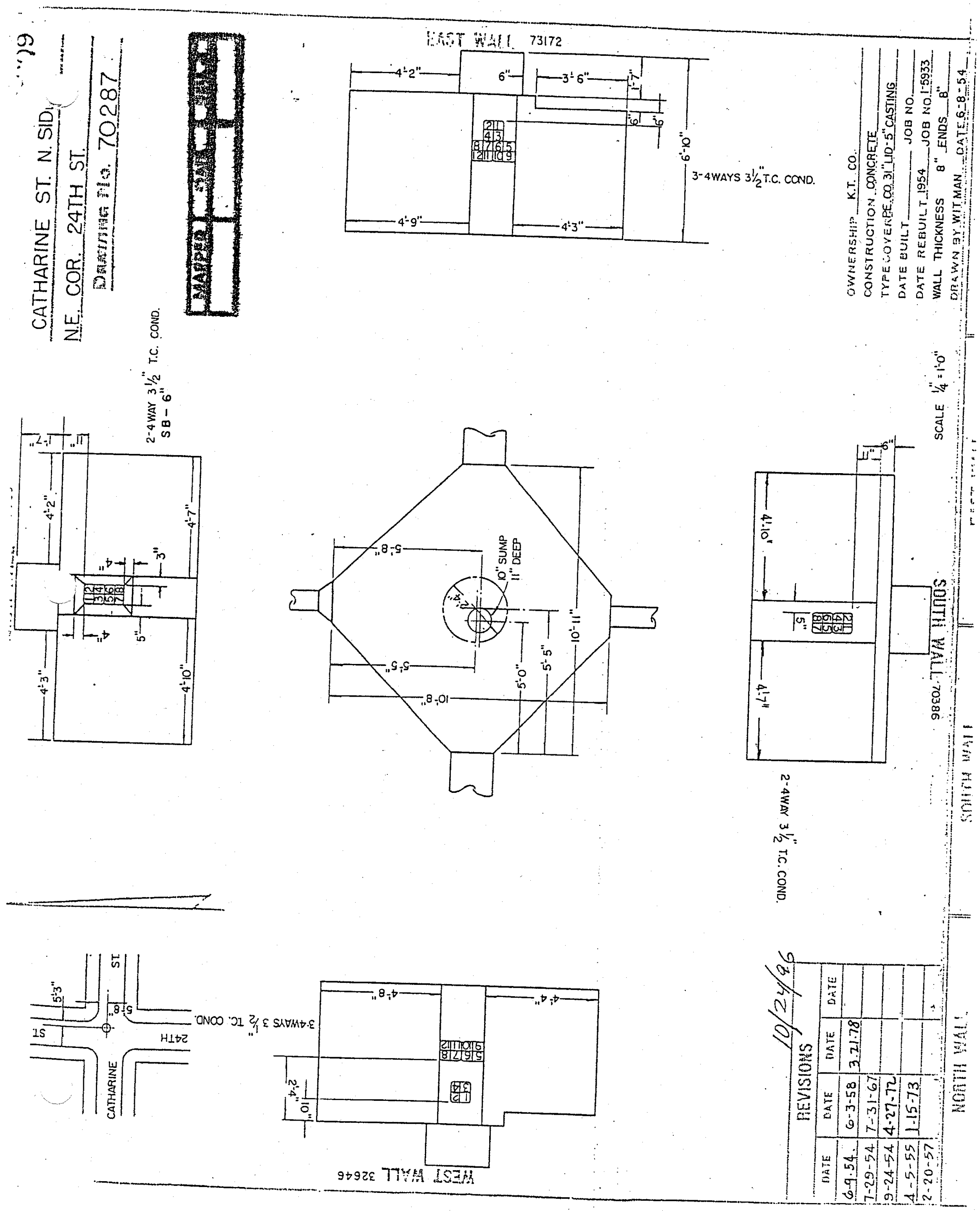
[3] S. Mukoyama et al. - *Research and Development of 50 m Long High Tc Superconductor for Power Cables* - presented at 1995 ISS

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

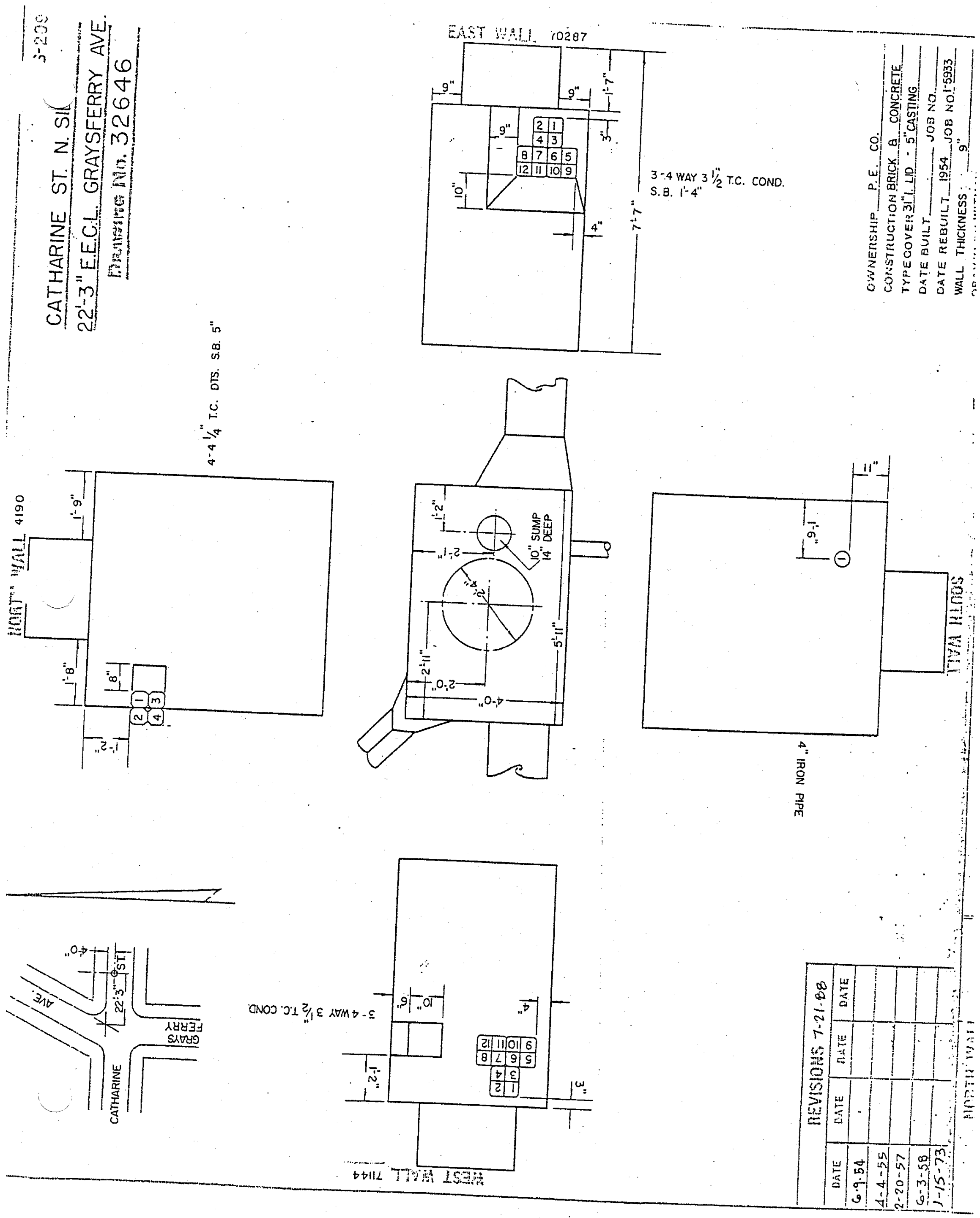
[5] K. Sato et al. - *HTS Large Scale Application Using BSCCO Conductor* - presented at 1996 Applied Superconductivity Conference

A

TYPICAL MANHOLE CONFIGURATIONS ALONG THE ROUTE



CATHARINE ST. N. SID.
N.E. COR. 24TH ST.
70287
MAPPED
EAST WALL 73172
3-4WAYS 3½" T.C. COND.
2-4 WAY 3½" T.C. COND.
SB - 6"
10" SUMP
11" DEEP
SOUTH WALL 70386
2-4WAY 3½" T.C. COND.
WEST WALL 32646
3-4WAYS 3½" TC. COND.
NORTH WALL
SCALE ¼" = 1'-0"
OWNERSHIP K.T. CO.
CONSTRUCTION CONCRETE
DATE REBUILT 1954
WALL THICKNESS 8" ENDS 8"
DATE 6-8-54
REVISIONS
CATHARINE
24TH
ST


CATHARINE ST. N. SI
22'-3" E.E.C.L. GRAYSFERRY AVE.
Drawing No. 32646
EAST WALL 70287
3-4 WAY 3 1/2" T.C. COND.
S.B. 1'-4"
4-4 1/4" T.C. DTS. S.B. 5"
NORTH WALL 4190
10" SUMP
14" DEEP
SOUTH WALL
4" IRON PIPE
WEST WALL 7144
OWNERSHIP P.E. CO.
CONSTRUCTION BRICK & CONCRETE
TYPE COVER 31" LID - 5" CASTING
DATE BUILT
DATE REBUILT 1954
WALL THICKNESS 9"
JOB NO. 1-5933
REVISIONS 7-21-88
DATE
6-9-54
4-4-55
2-20-57
6-3-58
1-15-73
CATHARINE
GRAYS FERRY
AVE.

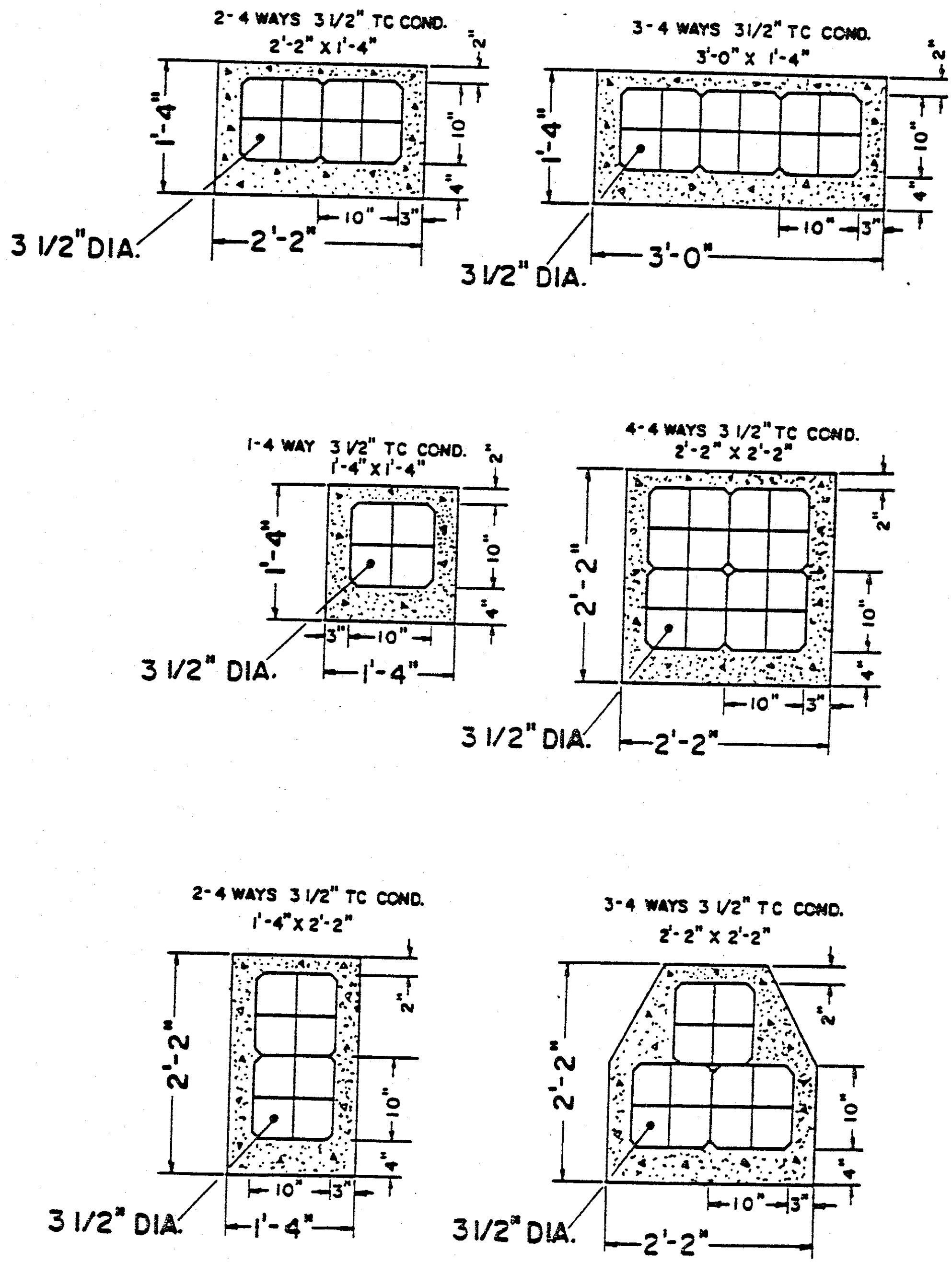
B

DUCT BANK CONFIGURATION DRAWINGS

K.T. CO. DUCTS CONCRETE JACKET

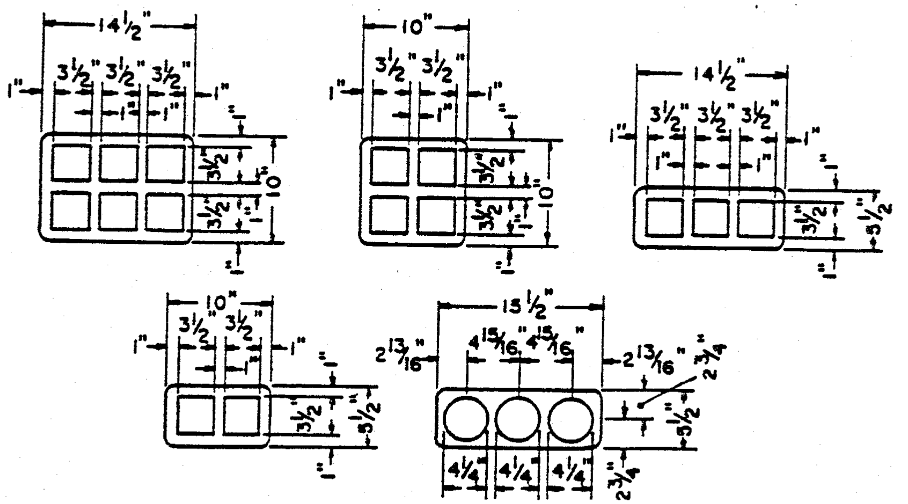
FOR CONDUIT MAP SECTIONS

ALL SECTIONS ARE TO BE 3/8" = 1'-0" SCALE.
EXAMPLES SHOWN OLD METHOD – NEW METHOD
SHOW CONC. JACKET AS DASH LINES.

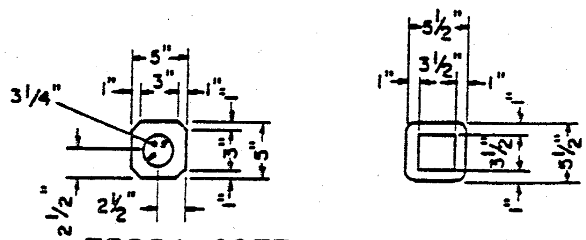


52

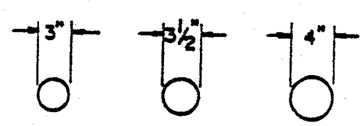
STANDARD K.T. CO. DUCTS



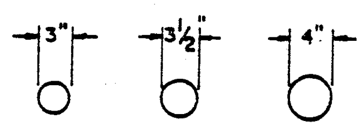
TERRA COTTA CONDUITS (MULTIPLE)



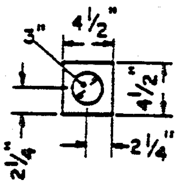
TERRA COTTA DUCTS (SINGLE)



FIBRE DUCTS



IRON PIPES



WOOD DUCT

C

COSTING MATRIX

Preliminary Conventional Cable Cost Estimates for PECO Installation

13.2 kV - 2500 Amps Continuous Rating

or

69 kV - 500 A Continuous Rating

Costs Including Installation	Solid Dielectric Cable 69 kV 1 circuit with 3 joints	Solid Dielectric Cable 13.2 kV 1000MCM 4 circuits with 4 joints each	Solid Dielectric Cable 13.2 kV 1500MCM 3 circuits with 4 joints each	Solid Dielectric Cable 13.2 kV 2500MCM 2 circuits with 4 joints each
Cable	805,000	1,267,000	1,391,000	1,405,000
Excavation and Conduit	2,324,000	4,412,000	4,412,000	3,486,000
Splices	39,000	10,000	10,000	10,000
Manholes	125,000	included in excavation	included in excavation	included in excavation
Potheads	26,000	15,000	15,000	15,000
Installation of Cable, Splices, and Terminals	700,000	1,400,000	1,200,000	1,000,000
Misc.	200,000	150,000	150,000	150,000
Immobilization/ demobilization	30,000	25,000	25,000	25,000
Termination structure	60,000	40,000	40,000	40,000
Relay	200,000	150,000	150,000	150,000
Switches and peripherals	(xfmr.needed) 2,000,000	300,000	300,000	300,000
Refrigeration plant and associated control and monitoring	-	-	-	-
Grandtotal	6,509,000	7,769,000	7,693,000	6,581,000

Using 13 kV Conventional Cables for the Application in Question	**Costs**	**Using 69 kV Conventional Pipe-Type Cables for the Application in Question**	**Costs**	**A New Substation with a 69kV/13kV - 28 MVA Transf., 5 - 13 kV feeders, and assuming a 1 mile long 69 kV feed**	**Costs**
New duct bank $400/foot for a 4 x 4 bank	$400 x 11,619 ft = 4.6 million	Pipe and cable $200/foot for 1-6" pipe	$300 x 11,619 ft = 3.5 million	Site for Substation	1 - 3 million
4 cables per phase at $10,000/1000ft per cable(solid diel. cable - 1000MCM)	$10,000 x 12 x 11.62 = 1.4 million	New pipe-type cables at $30,000/1000ft	$30,000 x 3 x 11.62 = 1.0 million	Associated Substation Equipment	1 - 2 million
		Add one 40MVA transf.	1 - 2 million	Add 5 cable runs throughout city	1 - 2 million
Additional costs - joints, terminations, etc.	$500,000	Additional costs - pumping plant, joints, terminations, etc.	$500,000	69 kV cable run and equipment	2.5 million
Total	6.5 million		6 - 7 million		5.5 - 9.5million

Note: All prices are including installation.

D

AMPACITY CALCULATIONS FOR CONVENTIONAL CABLES

DATA SET NO. 1

SINGLE CONDUCTOR EXTRUDED CABLE,XLPE OR EPR

PECO Study
15 KV EPR copper cable
APRIL 22/97
1000.0 MCM COMPRESSED COPPER CONDUCTOR
EPR INSULATION
THE INSULATION THICNESS IS SPECIFIED
LC TYPE COPPER SHEATH
SHEATH THICKNESS IS SPECIFIED
LLDPE JACKET
JACKET THICKNESS IS CALCULATED
DESIGN TO AEIC CS-6/96 SPECIFICATION

CABLE DIMENSIONS NET LEVEL

	IMPERIAL UNITS
CONDUCTOR SIZE	1000.0 MCM
CONDUCTOR DIAM	1.060 INS
SHIELD DIAM	1.130 INS
INSULATION DIAM	1.620 INS
INSULATION THIK	245.0 MILS
SHIELD DIAM	1.700 INS
LC SHEATH DIAM	1.801 INS
LC SHEATH THICK	30.0 MILS
LC SHEATH WIDTH	6.00 INS
LC SHEATH AREA	228.6 MCM
JACKET DIAM	1.961 INS
JACKET THICK.	80.0 MILS

CABLE ELECTRICAL PARAMETERS

AT 15. KV AC STRESS = 1. 6753 KV/MM
AT BIL OF 95. KV STRESS = 18.3775 KV/MM
CABLE CAPACITANCE = 0.141029 MICRO-F/FT
CHARACTERISTIC IMPEDANCE = 12. 5 OHMS
REFERENCE DC RESISTANCE AT 24 DEG C 10.848 UOHM/FT 35.589 UOHM/M
CONDUCTOR DC RESISTANCE AT 90 DEG C 13.612 UOHM/FT 44.657 UOHM/M
CONDUCTOR AC RESISTANCE AT 90 DEG C 14.445 UOHM/FT 47.392 UOHM/M
KS = 1.000 KP = 0.800 YCS = 0.057 YCP = 0.004 YC = 0.061
FREQUENCY = 60. CABLE SPACING = 6.00 INS

PAGE 2

CABLE PRODUCTION LENGTH AND WEIGHTS
___ _ __ _ __ _ __ _______ ____ ________ ____

TOTAL WEIGHT IN AIR	=	4.91 LB/FT	7.32 RG/M
AS EXTRUDED	=	3.78 LB/FT	5.64 KG/M
LENGTH (WEIGHT LIMITED)	=	4756.0 FT	1449.6 M
TEST LENGTH (BIDDLE)	=	1347. FT	411. M
TEST LENGTH (HYPO MAX)	=	2269. FT	692. M
TEST LENGTH (HYPO MIN)	=	85. FT	26. M

SHIPPING LENGTH INFORMATION
__ ____ __ ____ _______________

SHIPPING REEL DIMENSIONS:

MIN. DRUM DIAM. = 33 INS

FLANGE DIAMETER = 142. INS.
TRAVERSE = 126. INS.
DRUM DIAMETER = 80. INS.

SHIPPING LENGTHS:

LENGTH = 27070 FT 8250 M
CLEARANCE = 1.6 INS
LENGTH = 24812 FT 7562 M
CLEARANCE = 3.5 INS
N1 - 15 N2 - 14 M - 63

PAGE 1
ELASTOMERIC CABLE AMPACITY --- DATA SET NUMBER

PECO Study
I5 KV EPR Copper Cable 1000MCM
#95XXX APRIL 22,1997

INPUT DATA
****
THE COMDUCTOR TEMP. OF 90.0 DEG C GOVERNS
THE CABLE INSULATION IS EPR
THE CONDUCTOR IS COMPACT ROUND COPPER 507. MM SQ
FREQUENCY IS 60 HZ
THE CABLE HAS A COPPER LC SHEATH
THE CABLE HAS A PE JACKET
CABLE IN DUCTS
NUMBER OF DUCTS IS 12
CROSS-BONDED SHEATH SYSTEM
HOTTEST POSITION IS NUMBER 5
SYSTEM OPERATING VOLTAGE = 15KV
EXTERNAL CIRCULATING CURRENT LOSS FACTOR = 0.000 P.U.
CONDUCTOR DIAM. = 26.9 MM
INS. DIAM. = 41.1 MM
INS. THICKNESS = 6.2 MM
TAPE DIAM = 43.2 MM
BARRIER DIAM = 43.2 MM
NO OF WIRES = 0
WIRE DIAM. = 45.800 MM
SHEATH AREA = 109. MM2
PER-CENT TAPE OVER-LAP = 0%
COMD. TEMP. - 90.0 DEG C AMBIENT = 24 DEG C
SKIN EFFECT FACTOR = 1.000
PROXIMITY EFFECT FACTOR = 0.6
DUCT ID. = 104.0 MM DUCT OD. = 108 MM
THE REF. CABLE DEPTH H = 914 MM
THE CABLE SPACING = 152 MM
THE THERMAL BACKFILL ZONE OR DUCT BANK DIMENSIONS ARE
X - 760. MM Y - 760. MM DEPTH = 1380 MM
SOIL THERMAL RESISTIVITY ZONE 1 = 0.60 K-M/W
SOIL THERMAL RESISTIVITY ZONE 2 = 0.90 K-M/W
THE SYSTEM LOAD FACTOR IS 0.750 P.U.

THE CABLE OR CABLE GROUP CO-ORDINATES-ARE MM.:

X -	.000	.000	.000	152.000	152.000	152.000
X -	304.000	304.000	304.000	456.000	456.000	456.000
Y -	762.000	914.000	1066.000	1066.000	914.000	762.000
Y -	762.000	914.000	1066.000	1066.000	914.000	762.000

INSULATION THICKNESS = 6.2 MM

MAXIMUM STRESS	= 1.68 KV/MM
CABLE CAPACITANCE	= 0.46587 MICRO-FARRAD/KM
DIELECTRIC LOSS	= 0.03953 WATTS/M
CHARGING CURRENT	= 1.51642 AMPS/KM

PAGE 2
CALCULATION RESULTS
****

NUMBER OF ITERATIONS ' 2
AMPACITY = 648. AMPS
MVA RATING = 16.85 LOSS FACTOR = 0.6187 P.U.

THERMAL RESISTANCES IN K-M/W OR T.O.M. :
***** *********** ************************

INSULATION	=	.377			
1ST JACKET	=	.047			
MOIST. BARRIER	=	.000	DUCT WALL = .036		
DUCT SPACE	=	.559			
BEDDING	=	.000			
DIELECTRIC LOSS					
GROUND AT LF=1	=	3.669			
CONDUCTOR LOSS					
GROUND AT LF	=	2.295	TOTAL AT LF=1	=	4.500
TOTAL R2	=	.424	TOTAL R3	=	2.907

ELECTRICAL RESISTANCES MICRO-OHM/M
** ** * * * * *** * **** * ** * *** ** *** ** ** * *

CONDUCTOR	= 46.99			
SHEATH	= 301.17			
ARMOUR	= 0.00	EQUIVALENT 1	=	301.17
EQUIVALENT 2	= 301.17			

LOSS FACTORS PER UNIT
********** ******* ****

SKIN EFFECT	=	.0575	PROXIMITY	=	.0027
CONDUCTOR	=	.0602	SHIELD & SHEATH	=	.0057
ARMOUR	-	.0000	EQUIVALENT	=	.0057

EXTERNAL CIRCULATING CURRENT EFFECT - .0000

SYSTEM TEMPERATURES DEG. C.
**** ************ ********* **

CONDUCTOR = 90.00 SHIELD & SHEATH = 82.54
CABLE SURFACE = 81.61 DUCT SPACE = 76.04
AMBIENT = 24.00

CABLE LOSSES WATTS/M :
* *** * * * * ** * ******* *****

TOTAL	= 19.914	DIELECTRIC = .040
CONDUCTOR	= 19.761	SHEATH & SHIELD= 0.113
ARMOUR	= 0.000	

TEMP. DROP DUE TO DIELECTRIC LOSS = 0.1779 DEG C
DIELECTRIC POWER FACTOR = 0.0030 P.U.
GB= 1.86439 LN(F) = 23.70387

NEHER-MCGRATH METHOD

E

AC LOSSES

CONVENTIONAL CABLE SYSTEMS

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

Current-related

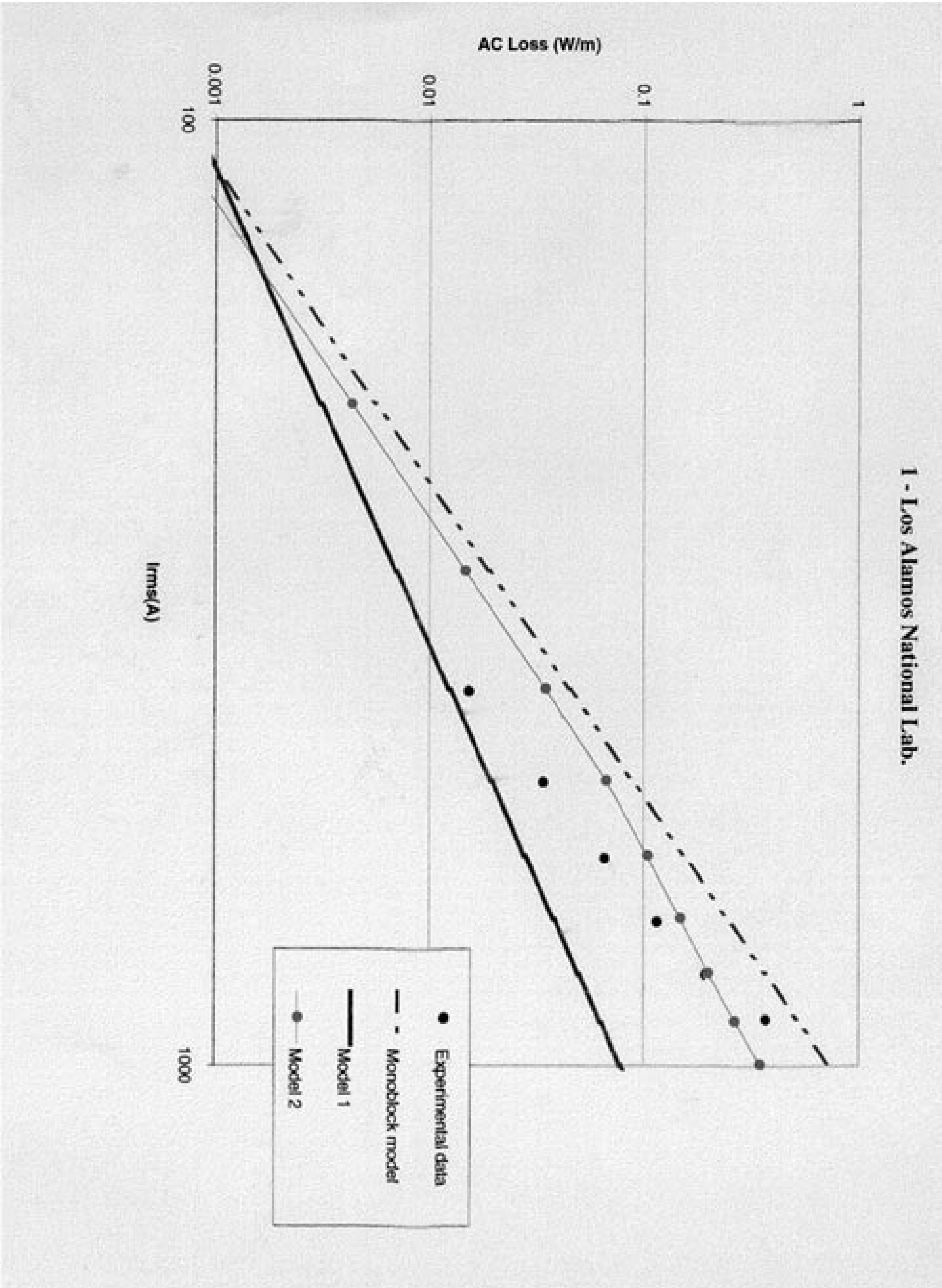
- conductor
- metal components (shield, skid wire, pipe)

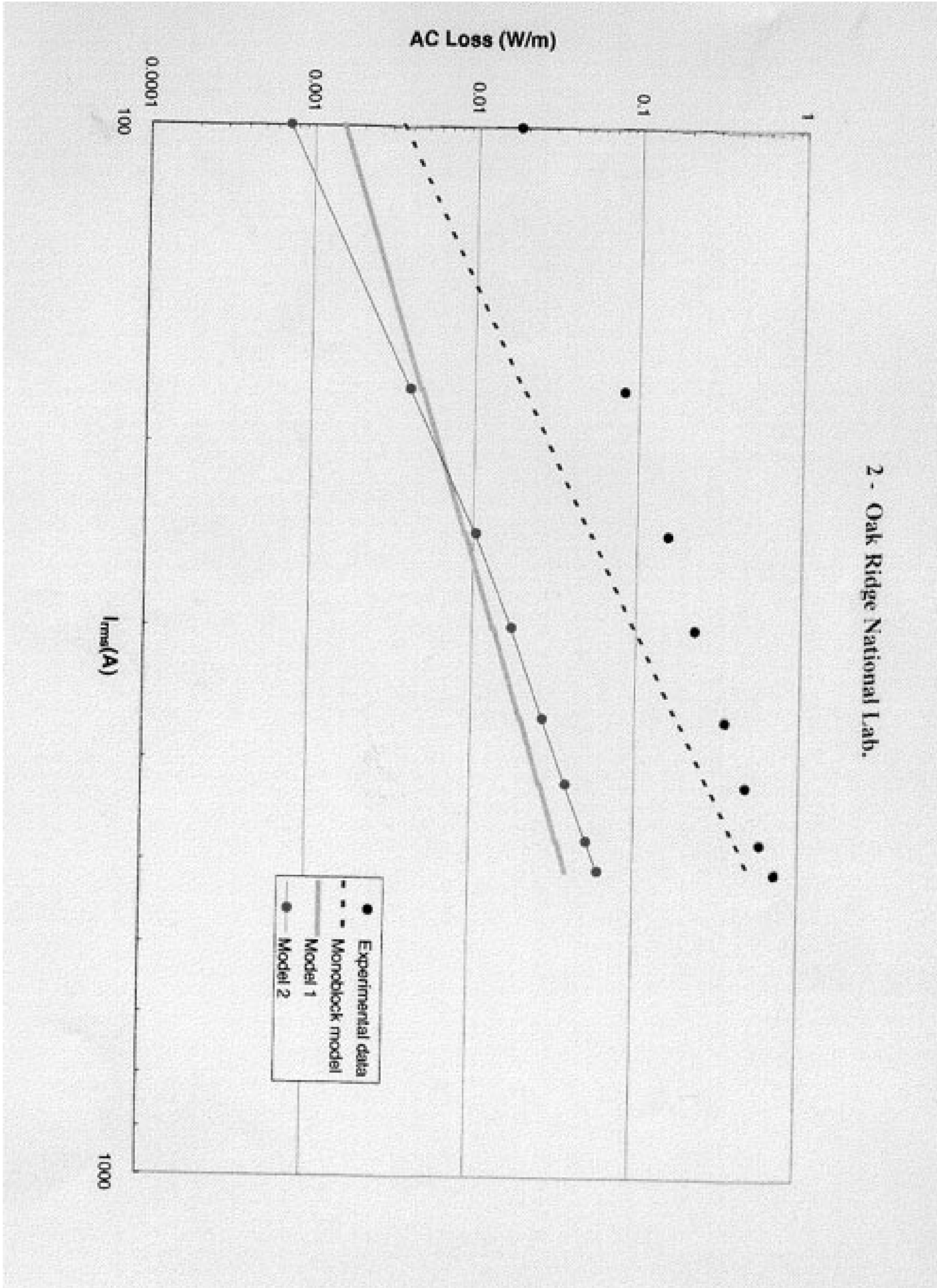
Voltage-related

- 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.


1 - Los Alamos National Lab.
AC Loss (W/m)
0.001
0.01
0.1
1
100
1000
Irms(A)
Experimental data
Monoblock model
Model 1
Model 2


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

F

COMPARISON OF TOTAL TRANSMISSION LOSSES BETWEEN HTS CABLES AND CONVENTIONAL CABLES

PECO
HTS POWER TRANSMISSION CABLE SYSTEM
VOLTAGE 13.8 kV - 2500 A