Final Report

Commercialization of Medium Voltage HTS Triax^{TM} Cable Systems

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1 EXECUTIVE SUMMARY

This report summarizes the work completed under the project "Commercialization of Medium Voltage HTS Triax^{TM} Cable Systems" which was an effort to commercialize HTS Triax^{TM} cable systems.

The project was competitively bid to the Department of Energy under the funding opportunity number DE-PS26-06NT42870-00 "Superconducting Power Equipment".

The contract award to Southwire Company began on August 27, 2007.

The original project scope that was established in 2007 aimed to install a 1,700 meter (1.1 mile) medium voltage HTS Triax^{TM} cable system into the utility grid in New Orleans, LA. In 2010, however, the utility partner withdrew from the project, so the 1,700 meter cable installation was cancelled and the scope of work was reduced. The work then concentrated on the specific barriers to commercialization of HTS cable technology. The modified scope included long-length HTS cable design and testing, high voltage factory test development, optimized cooling system development, and HTS cable life-cycle analysis.

In 2012, Southwire again analyzed the market for HTS cables and deemed the near term market acceptance to be low. The scope of work was further reduced to the completion of tasks already started and to testing of the existing HTS cable system in Columbus, OH.

The work completed under the project included:

- Long-length cable modeling and analysis
- HTS wire evaluation and testing
- Cable testing for AC losses
- Optimized cooling system design
- Life cycle testing of the HTS cable in Columbus, OH
- Project management

The 200 meter long HTS Triax^{TM} cable in Columbus, OH was incorporated into the project under the initial scope changes as a test bed for life cycle testing as well as the site for an optimized HTS cable cooling system. The Columbus cable utilizes the HTS Triax^{TM} design, so it provided an economical tool for these of the project tasks.

2 BACKGROUND

In recent years, the DOE has funded successful missions that developed and proved the technical capabilities of High Temperature Superconducting (HTS) cable systems. Such cable projects include two by Southwire Company:

1. A 30 meter, medium voltage HTS cable system installed and operated in Carrollton, GA.
2. A 200 meter, medium voltage HTS Triax^{TM} cable system installed and operated in Columbus, OH.

The goal of this project "Commercialization of Medium Voltage HTS Triax^{TM} Cable Systems" was to build on the past successes and deploy an optimized HTS Triax^{TM} cable system that would present a commercial solution to grid congestion and certain reliability problems experienced by electric utilities.

During 2007 and 2008, areas around New Orleans were experiencing rapid electric load growth due to tear-down and rebuild of home sites following hurricane Katrina. In a neighborhood just outside of the city, the electric load growth projections would have saturated the existing medium voltage power distribution system. The traditional solution to such conditions is the extension of new high voltage transmission facilities to the area. Overhead transmission, however, carried its own challenges including right-of-way constraints, public opposition to new overhead power lines and towers, and the construction of a new substation within the neighborhood. The HTS Triax$^{\text{TM}}$ cable offered a medium voltage (13.8kV) underground alternative by utilizing existing capacity at a neighboring substation, thus avoiding the need for new right of way, overhead transmission lines and a large substation. The HTS cable would be 1,700 meters long and used to extend the medium voltage bus of the substation, while maintaining power quality that would not have been possible with conventional medium voltage cables. Further, this project enabled the development of a commercial HTS Triax$^{\text{TM}}$ cable system by addressing the outstanding technical issues of long-length HTS cable operation, lack of an optimized cooling system and lack of high voltage factory test capability.

In 2010, the fall of the housing market negatively affected electrical load projections in the New Orleans area to the point that the existing utility infrastructure could maintain reliable operation for at least another 10 years. For this reason, the partner utility cancelled the system upgrade. In response, Southwire and DOE reduced the scope of the project to only address the commercial barriers and eliminated the installation of a long-length HTS Triax$^{\text{TM}}$ cable system. The reduced scope still addressed the activity needed to enable commercialization of the technology. The tasks of the project are categorized below. Some tasks specific to the 1,700 meter cable installation were cancelled, some were modified, and new tasks were added.

Long-Length Cable Analysis	
Task 1	2G Wire Evaluations
Task 2	Thermal *Analysis for Long-Length Cable*
Task 3	*Fluid Flow Analysis*
Task 5	Detailed Cable Design and Evaluation
Optimized Liquid Nitrogen Refrigeration System	
Task 4	Cryogenic System Specification, RFQ, Bid Evaluation
Task 13	Cryogenic System Build, Install & Commissioning
Task 19	Cable Cool-Down
Task 20	Cable Off-line Testing
Task 21	Integration with Utility Control Systems
Task 22	Energize Cable System
Task 23	Monitor and Characterize Cable System Performance
Factory Test Development	
Task 11	Cable Manufacturing and Transport
Task 25	HTS Cable Factory Test Capability
HTS Cable System Life Cycle Optimization	
Task 6	HTS Triax$^{\text{TM}}$ Termination Design Optimization
Task 26	HTS Cable Life Cycle Optimization
Technology Outreach	
Task 10	Conduct Technology Transfer Outreach to Broad Utility Industry
Project Management	
Task 24	Project Management Activities

From 2010 through 2011 Southwire continued to analyze the HTS cable markets. It was estimated that market acceptance for HTS cable technology was more than 5 years out due to the high cost of HTS cable technology and due to the perceived immaturity of the technology by the electric industry. In April of 2012, Southwire decided to further limit development activity associated with the project to work already complete and to testing of the HTS cable system in Columbus, OH.

The report will present results for the work performed.

3 HTS TRIAX^{TM} CABLE TECHNOLOGY

HTS Triax^{TM} cable systems were developed during 2002 – 2006 under a previous DOE funded project. The project was successful in developing and demonstrating the HTS Triax^{TM} cable, termination and splice. A 200 meter cable system was manufactured and installed into the utility grid in Columbus, OH where it operated for 6 years before being de-commissioned in October 2012. Figures 1, 2, and 3 show the current state of the technology for the HTS Triax^{TM} cable, termination and splice, respectively. HTS Triax^{TM} incorporates three electrical phases that are concentrically wound onto a common cable core. The concentric design allows for the most compact and cost efficient superconducting cable system design. Details of the HTS Triax^{TM} technology can be found in the reporting for the previous DOE funded project.

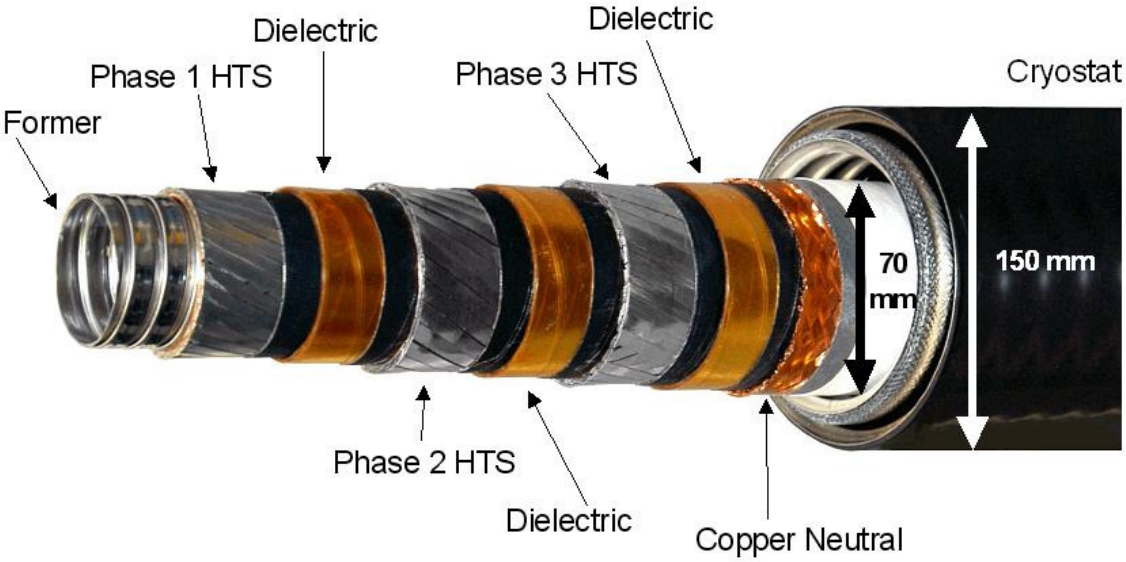


Figure 1. Southwire Triax^{TM} cable as installed in Columbus, OH.

Figure 2. HTS TriaxTM Termination

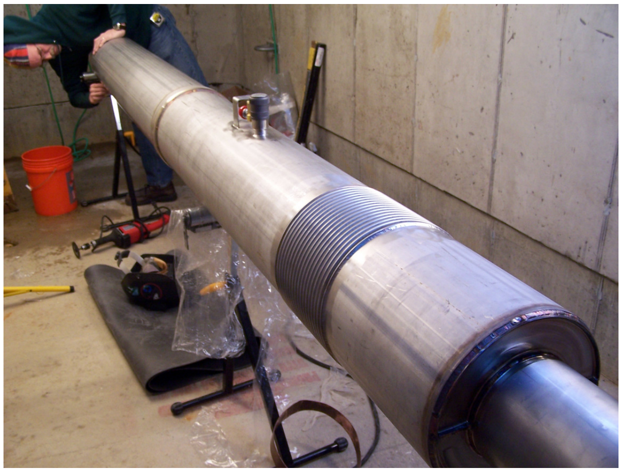


Figure 3. HTS TriaxTM Splice

4 EXISTING COOLING SYSTEM TECHNOLOGY

HTS cables require liquid nitrogen to be circulated through the cable system continuously. The liquid nitrogen is heated by the cable system, and that heat must be removed to re-cool the nitrogen. Therefore, liquid nitrogen refrigeration systems (a.k.a. LN cooling systems) must be installed with each HTS cable system. Liquid nitrogen cooling systems fall into either the open-cycle or closed-cycle design.

Open-Cycle Cooling System

Open cycle LN cooling systems utilize a vacuum-based, cryogenic refrigeration process to continuously circulate and refrigerate liquid nitrogen at around 70 Kelvin (K). The vacuum-based system lowers the nitrogen vapor pressure in a heat exchanger vessel to attain operating temperature, i.e. 70K. The vacuum pumps remove the nitrogen vapor to atmosphere and it is lost, hence the “open-cycle”. A separate closed-loop of liquid nitrogen flows through the cable and terminations where it picks up heat. The heat is then rejected in the heat exchanger vessel via heat exchange with the “open-cycle” side of the system. The open-cycle system is relatively simple design; however, the cooling power is stored via a large tank of liquid nitrogen on site that must be replenished on a regular basis, for example weekly.

The open-cycle design was utilized at the HTS cable systems in Carrollton, GA and in Columbus, OH.

Figure 4. Open cycle cooling system utilized at the HTS TriaxTM cable in Columbus, OH.

Closed-Cycle Cooling System

Closed-cycle cooling systems provide the same function as open-cycle systems, however, both sides of the heat exchanger operate in closed loops, so no vacuum system is used and no nitrogen is lost in the process. Closed-cycle systems utilize refrigerators that re-cool the nitrogen in a heat exchanger vessel. Similar to the open-cycle, a separate closed-loop of liquid nitrogen flows through the cable and terminations where it picks up heat. The heat is then rejected in the heat exchanger vessel. The closed-cycle system is relatively complex, capital intensive, and requires periodic maintenance; however such systems do not require the periodic replenishment of liquid nitrogen inventory.

It is the opinion of Southwire that efficient, low maintenance closed-cycle cooling systems are required for the long term viability of HTS cable systems.

5 PATH TO COMMERCIALIZATION

Various HTS cable projects have proven the technical capability of HTS able systems, including terminations, splices and the cables themselves. There are, however, a number of technical, reliability and financial barriers preventing the commercial acceptance of the technology.

Commercial Barriers

- Cooling systems are large, complex, and need improved reliability
- Factory test capability of HTS cables does not exist
- Long-length (greater than 1 mile) cable systems need to be analyzed and designed
- Limited operating experience with HTS cable systems exists
- HTS cable systems remain expensive compared to conventional technology
- Long term, life cycle characteristics of HTS cable systems needs to be understood.

Following the cancellation of the cable installation in New Orleans, Southwire and DOE developed a set of objectives that would address the commercial barriers. To manage costs, the existing cable in Columbus, OH was to be used to implement the optimized liquid nitrogen cooling system and to study life cycle characteristics of the cable system. Long-length "dummy" cables were scheduled to be produced and deployed in scaled test systems to analyze long-length characteristics and to develop factory high voltage test capability. The following sections describe the architecture of the project to address the commercial barriers.

Long-length Cable System Design

The work plan involved development of designs that would enable long-length HTS cable systems. HTS cable design and HTS wire evaluations would be performed to optimize cable architecture with the goal of lowering AC losses to an acceptable level. A detailed FEA analysis tool would be developed that will model long-length (1 to 5 km) cable systems. The FEA model should incorporate liquid nitrogen flow characteristics as well as thermal properties of the cable system. Proper cryogenic system specifications would be generated that would adequately cool long-length HTS cables. The greatest technical challenges are thermal management and maintaining fluid flow properties over the long cable lengths, especially for counter-flow cooling arrangements as in the HTS Triax$^{\text{TM}}$ cables. Detailed thermal analysis would verify that the inner and outer streams of LN are maintained within proper operating limits.

A 50 meter test bed was to be built to perform thermal and hydraulic tests on simulated cables. Tests would be conducted to empirically verify hydraulic friction factors in corrugated pipes, verify heat transfer mechanisms, and analyze long-length cooling scenarios. These data would be used to ensure the cable and far-end termination are properly cooled and maintained within acceptable operating parameters. This included thermal contraction behavior of the cable. Data from 50 meter system testing would be incorporated into the FEA model for optimization.

Optimized Liquid Nitrogen Cooling System

An optimized HTS cable liquid nitrogen refrigeration system was to be developed and installed at the Columbus, OH HTS cable site. Instrumentation such as temperature sensors and pressure sensors historically used in HTS cable systems would be evaluated for past performance and optimized for the new system. The refrigeration system would undergo a packaging design process to package the equipment in an industrially efficient and economical way. The liquid nitrogen refrigeration system and HTS cable system would be re-commissioned, energized and run for a period of not less than 2 years to qualify the cooling technology for use in utility systems.

Factory Test Development

Capability for HTS cable qualification and routine (or factory) testing would be established. HTS cable system test requirements would be developed by analyzing practices for conventional cables and interviewing industry stakeholders, such as utilities, national laboratories, test consultants, and standards bodies. The test requirements should include qualification, routine, and system commissioning tests. A high voltage, cryogenic test facility would be established that supports test development and factory testing of medium voltage HTS cables. It was anticipated that the test facility for the long-length cable testing would also be utilized as the cryogenic high voltage test facility. A 150 meter dummy cable would be fabricated, delivered to the test site, and tested to validate test protocols.

Life Cycle Analysis

HTS cable system life cycle optimization would include cost analyses, maintenance schemes, repair techniques and reliability analysis. Cost studies would be performed that include detailed analyses of today's HTS cable systems capital, operational, maintenance, and repair costs. HTS cable system components, including HTS wire, refrigeration system, and cryostat, would then be evaluated to determine how costs can be removed within each system component to realize acceptable cost levels. Southwire's HTS Triax™ termination would be modified to support faster and lower-cost installation and repair. Operating and repair scenarios would be evaluated to develop optimized connection and operating schemes that are desirable for utilities. HTS cable system connection and operating designs would be performed based on operating analyses and interviews with potential users. HTS cable fault location techniques would be developed. Maintenance and repair procedures would be developed. Testing would be performed on HTS cables to analyze life-time reliability characteristics.

Outreach Meeting

Near the end of the effort, an outreach meeting was to be held to present the work and results to educate stakeholders on the commercial status of HTS cable systems.

6 PROJECT RESULTS

6.1 Long-Length Cable Analysis

2G Tape Evaluations and HTS Triax™ Cable Design

The initial project scope of installing a 1,700 meter required the analysis of available HTS wires, including performance when stranded into an HTS cable. Two types of HTS wire are available:

BiSrCaCuO	1st Generation (1G)
YBaCuO	2nd Generation (2G)

Although similar in geometry and function, 1G and 2G wires differ significantly in architecture, materials, performance, and cost. Both types of HTS wire were suitable for the proposed 1,700m cable and both would be considered for the purpose of commercializing the technology in the long run. Due to the development efforts underway with 2G wires, the use of 2G was encouraged. There are three HTS wire suppliers capable of producing long-lengths of suitable 1G or 2G HTS wire. HTS wire was purchased from the three suppliers, evaluated for performance as a single wire and evaluated for performance as cabled. Performance metrics included mechanical stability, current carrying capability and AC losses. The most important metric is AC loss, since it contributes significantly to the heat load of the system. The heat load will in turn affect the operational stability of the cable system and the size of the liquid nitrogen refrigeration system.

The suppliers are not identified here due to the sensitivity of the information presented.

Mechanical tests were only performed on certain HTS wires that Southwire did not have previous experience with. Figure 5 shows a typical mechanical performance test arrangement and results. HTS wire samples were wound onto a length of cable representing the inner phase of a HTS Triax™ cable and bent around a radius to simulate manufacturing stresses. It can be seen that certain wires buckled under the stresses. This information was provided to the associated wire supplier(s) as constructive feedback. Visual inspection was adequate criteria for this test.

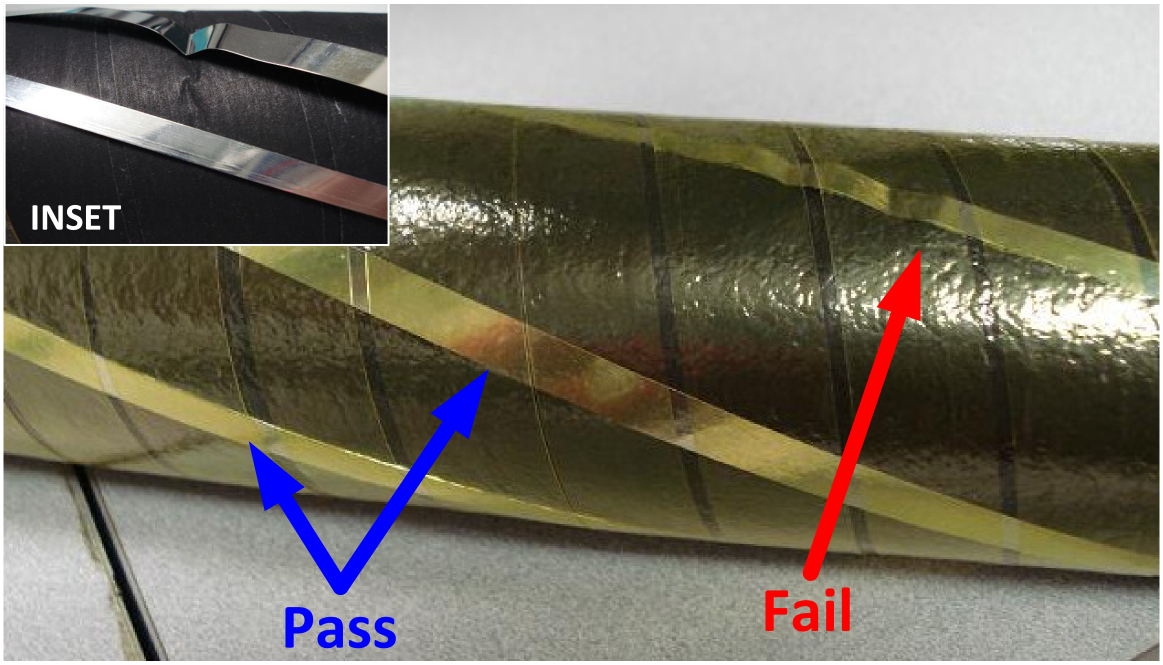


Figure 5. Bending test on HTS wire samples simulating phase 1 of HTS Triax^{TM} cable.

AC loss testing was performed on 3 meter-long cables fabricated from HTS wire from the 3 primary wire suppliers. Cables were fabricated from both 1G and 2G HTS wires. The suppliers and wire types are omitted from the presented AC loss results due to the sensitivity of the information. To date, single phase AC loss measurement is the most reliable method of predicting AC loss. This method gives an adequate comparison of HTS wire performance so that the most effective HTS wire can be selected. Single phase AC loss results can be extrapolated to 3 phase estimations.

AC loss test cables were fabricated by hand. Cable ratings were 2000A_{rms} and 15kV. For each cable, only phase 2 of the HTS Triax^{TM} design was populated, which allowed for the single phase AC loss measurement. The other HTS phases were omitted from the test cables; however, the full cable dielectric system was built inside and outside of the phase 2 HTS conductor to adequately simulate the overall cable geometry. Voltage taps were soldered to both the inside and outside of the HTS joint at each end of the cable sample. Temperature sensors (RTD's) were embedded within the cable construction at various locations. Figure 6 shows a simplified cross-section of the 3 meter AC loss cables. Table 1 shows the specifications for each 3 meter AC loss cable.

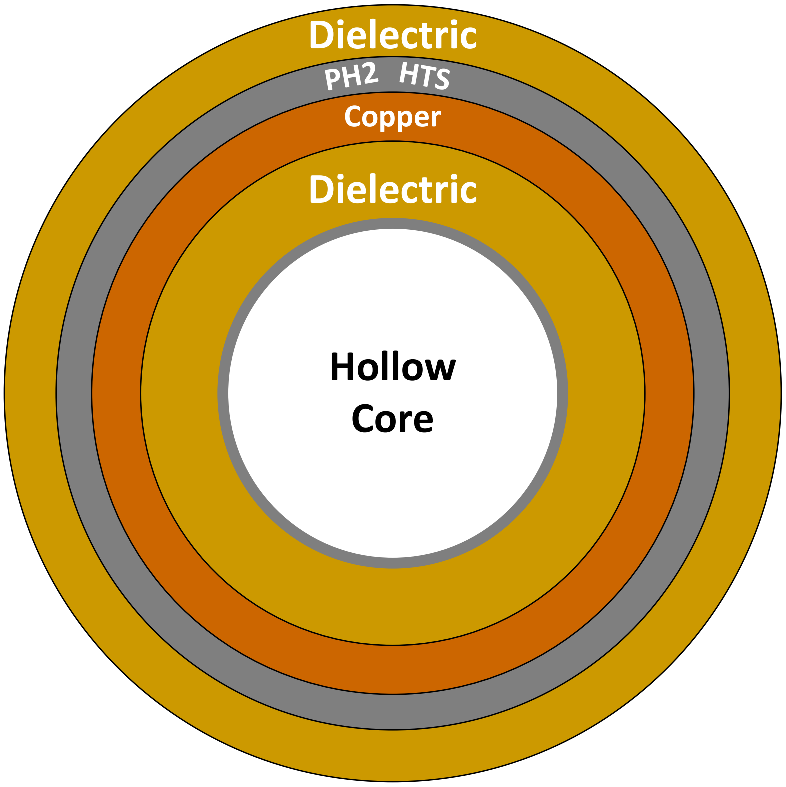


Figure 6. Cross section of HTS cable for AC loss testing.

Table 1. Specifications for the 3-meter AC loss cables.

Cable No.	**1**	**2**	**3**	**4**
Cable Inner Diameter	49.4 mm	49.4 mm	49.4 mm	49.4 mm
HTS Inner Diameter	60.1 mm	61.0 mm	59.7 mm	59.0 mm
HTS Outer Diameter	60.8 mm	63.0 mm	61.2 mm	61.4 mm
Cable Outer Diameter	69.0 mm	72.3 mm	69.6 mm	68.8 mm
*HTS Wire Thickness**	0.36 mm	0.44 mm	0.35 mm	0.35 mm
*HTS Wire Width**	4.5 mm	4.4 mm	4.5 mm	6 mm
HTS Wire I_c *(per wire)**	170 A	95 A	100 A	150 A
No. of HTS Wires	34	68	68	54

*Wire properties are nominal values.

AC loss was calculated by measuring the voltage drop across the length of the cable using lock-in amplifiers. Detailed description of the AC loss measurement is omitted in this report. AC loss results for the four test cables are shown in figure 7. The optimized AC loss for the cable was 0.55 W/m/phase, which corresponds to a total cable loss of 1.65 W/m. For conservative cable design, AC loss of 1 W/m/phase was utilized for long-length thermal analysis as well as for cooling system design and specification.

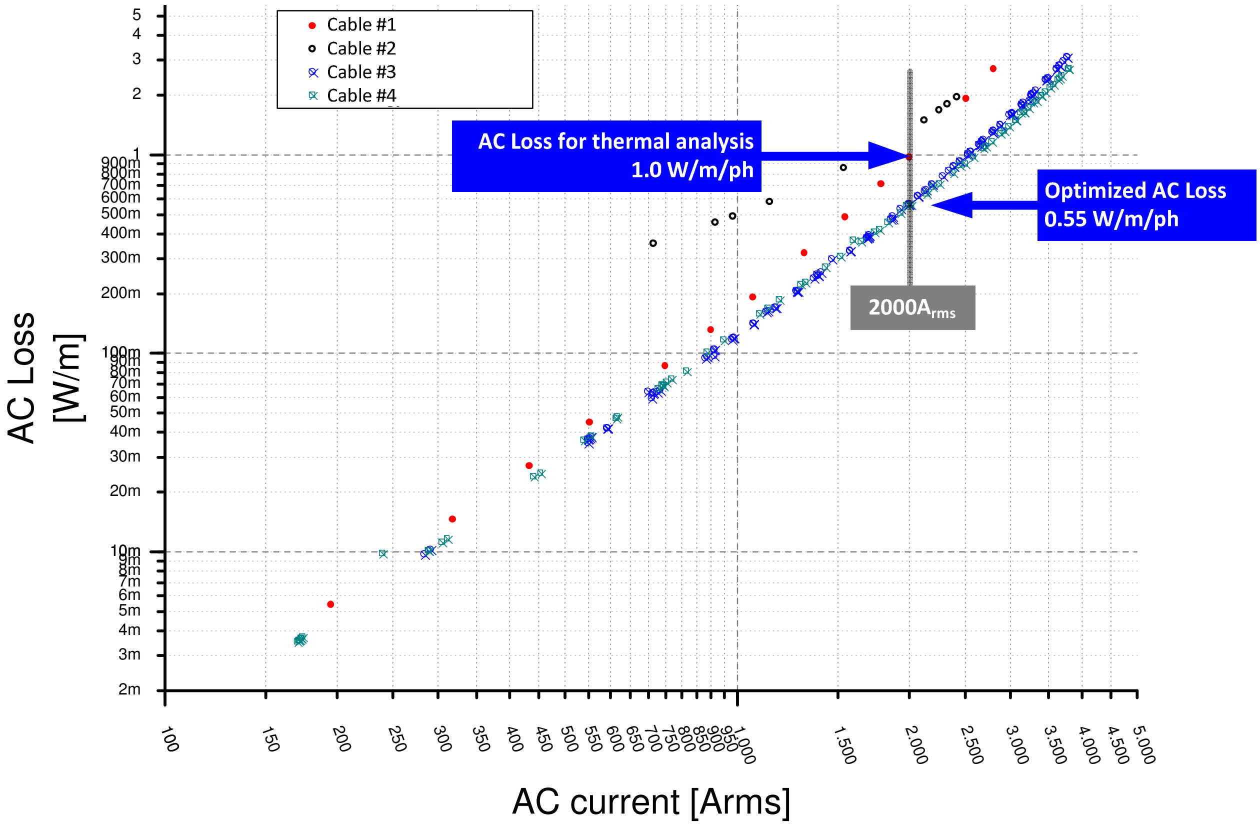


Figure 7. AC loss results for 3 meter long, single phase test cables. Rated current for each cable was $2000A_{rms}$.

HTS wire and Triax^{TM} cable testing has provided the necessary data to design an optimized cable architecture with low AC losses. The final cable design was not completed due to changes in scope and early termination of the project.

Thermal Analysis and Fluid Flow Analysis

It was the goal of the project to develop a HTS cable system that could accommodate “counter-flow” cooling. A counter-flow cooling arrangement utilizes the hollow-core of the cable as the “out” liquid nitrogen flow path. Similarly, the annular space between the outer diameter of the HTS cable and the inner diameter of the cryostat is used as the “return” coolant path. The counter-flow arrangement creates two liquid nitrogen flow paths within a single cryostat which avoids the need for a second cryostat, lowers the associated heat load on the system, and allows the liquid nitrogen refrigeration system to be installed only at one end of the HTS cable.

Early in the project, detailed thermal models for the 1,700 meter HTS Triax^{TM} cable were developed and run to understand the cooling characteristics of the cable. Development of the thermal-hydraulic models required a significant amount of effort and time and the work was performed by a dedicated engineer who concentrated on the long-length cable analysis. Data on the cable materials is critical to the accuracy of the calculations. Several different materials exist in the cable, including insulating polymers, various metals, semiconducting tapes, and nitrogen (both gaseous and liquid). The analysis engineer must make conservative assumptions and ensure that those do not compromise the accuracy of the results. The parameters must be integrated into the calculations within the models to accurately predict the system response. The modeling routine itself is an iterative operation, since certain analyses are predicting dynamic situations where conditions are changing. The programming for such complicated analyses is intricate and takes a lot of time to develop and de-bug. Processing times for each analysis is extensive, requiring up to 24 hours for a single situation (such as cool-down from 300K to 100K).

For steady-state operation, a counter-flow arrangement is preferred and was the focus of the analysis. A typical thermal profile result for the 1,700 meter cable is shown in figure 8. The data shows that an overall temperature rise of 9 K is realized and thermal run-away of the system does not occur. The thermal profile in figure 8 includes both terminations. The left end of the thermal profile is the start of the cable system closest to the liquid nitrogen refrigerator. The liquid nitrogen flows through the near termination and gradually picks up heat as it flows through the hollow core of the cable over 1,700 meters to the far termination. It then flows through the far termination and is turned around to flow back through the cable annular space toward the refrigeration system. At the right end of the profile, there is a sharp temperature increase due to the heat load of the far termination where the peak temperature of the liquid nitrogen circuit occurs. As the liquid nitrogen flows back toward the near termination through the annular space, it cools down again due to the heat transfer with the liquid nitrogen in the hollow core. The liquid nitrogen exits the near termination and is re-cooled in the refrigerator before being circulated back through the cable system.

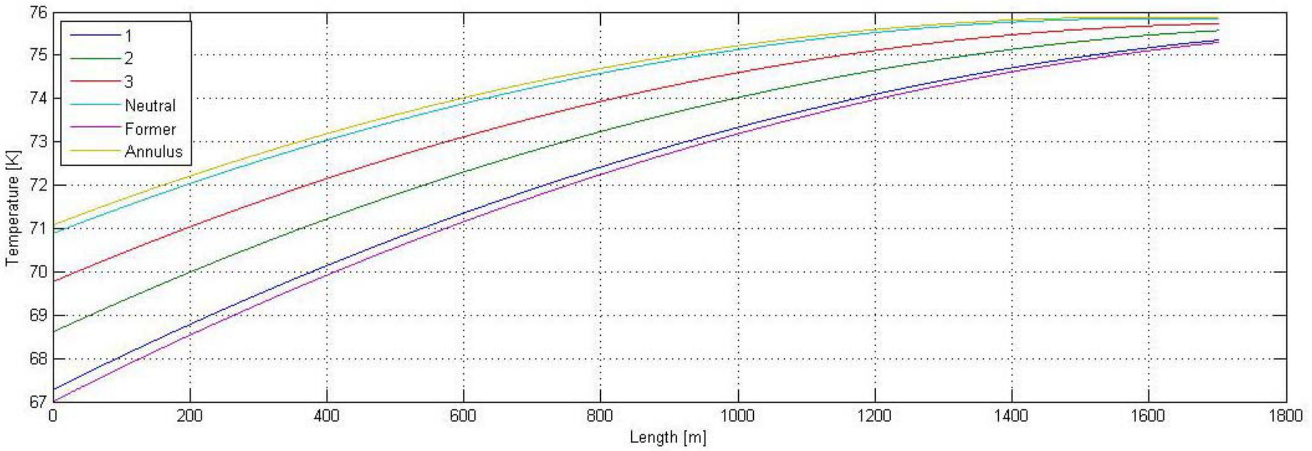


Figure 8. Thermal profile of a 1,700 meter HTS Triax$^{\text{TM}}$ cable at a liquid nitrogen flow rate of 610 g/s.

Analyses were also performed to determine the requirements of cooling the system down from ambient temperatures of around 300K to the operating temperature of around 70K. The 1,700 meter length of cable presents a challenging scenario due to:

1) the heat that must be removed from the massive system,
2) the low thermal capacity of the nitrogen gas at the start of the cool-down process, and
3) the pumping work required to move the nitrogen gas and liquid through the cable system.

The cool-down analysis includes radial heat transfer, longitudinal heat transfer, density and velocity of cooling gas, pressure drop and dissipated heat from the pressure loss. Heat capacity and thermal conductivity for the nitrogen gas, metals, semiconductors and dielectric materials inside the cable are included in the model as temperature dependent properties. Cryostat heat loss is also included as a temperature-dependent loss. The cooling is simulated as a set-up where the cooling gas is flowing in both former and annulus and in the same direction. To cool a cable within a reasonable amount of time, cold gas under high pressure is required. This gives rise to friction between the gas and the cable and cryostat leading to pump-loss and dissipated heat in the gas. As can be seen from the graphs in figure 9, the cold gas cools the near end of the cable while the pump-loss heats the far end of the cable. Details of the cool-down design are not provided due to the sensitivity of the information. Various cool-down schemes, gas flow rates, and starting/ending temperature were analyzed. It was determined that some cool-down situations could take as long as 72 hours and some were found to be impossible. A sample model is shown in figure 9. This particular model allowed the system to reach 100K over 37 hours. The thermal transition down to 100K proved to be challenging and was extensively studied. The next analysis should be the final transition from 100K to 70K; however, this was not completed due to the scope changes in the project. The project team is confident that a cool-down from 300K to 70K is possible; however cool-down time will on the order of 120 hours.

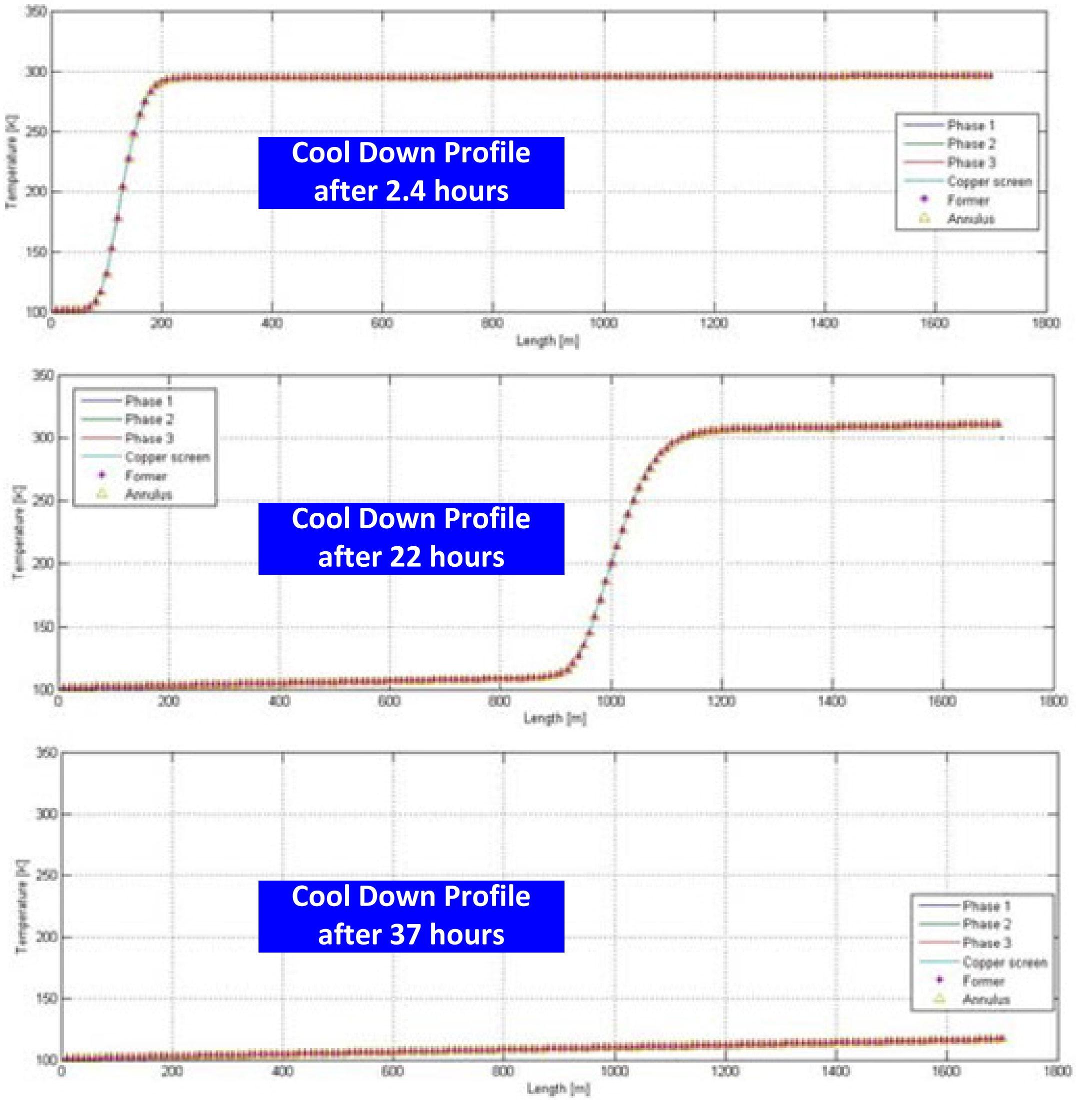


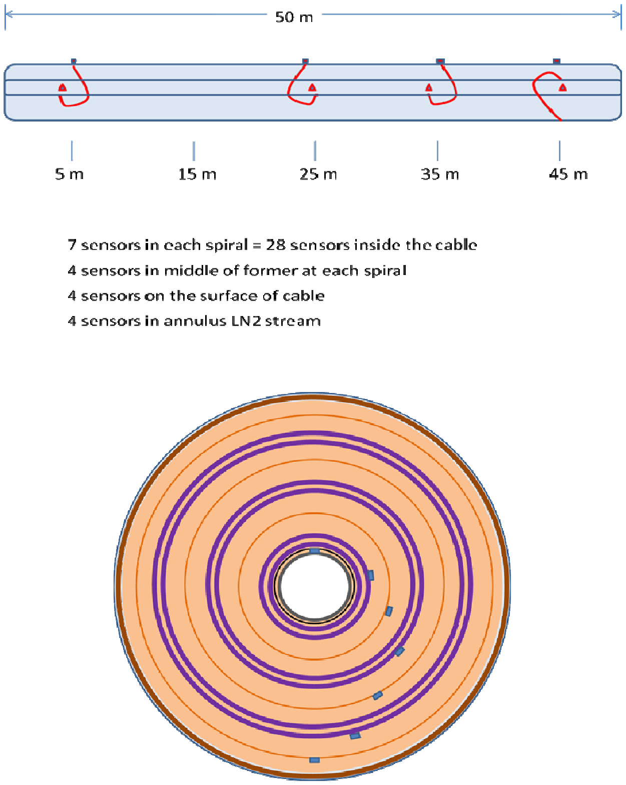
Figure 9. Sample temperature profile during cable cool-down at 2.4, 22, and 37 hours.

Fluid Flow Analysis

To validate the long-length thermal analyses, it was planned to develop and install a 50 meter long cable test facility. The test facility would include a small liquid nitrogen supply system, a 50 meter cryostat, and a heavily instrumented test cable. This integrated test bed would facilitate simulation of cable operating heat loads and a thorough analysis of the thermal-hydraulic characteristics of long-length HTS cables. Experiments would have provided the following information necessary to validate the theoretical models:

- Thermal properties of the cable materials
- Pressure drop in hollow core and annular flow spaces
- Heat transfer characteristics of the system, including convection and conduction
- Cool-down and warm-up temperature profiles

The test cable was to be instrumented with temperature sensors along its length, as indicated in figure 10. Phase conductors were to be simulated using materials with known heat generation rates, so that the heat load could be varied to analyze operating conditions. Pressure, temperature, and flow sensors were designed in to the test system to monitor the flow conditions in the hollow core and annular space of the cable system. In total, 40 sensors are required to carry out such tests. Figure 10 shows the arrangement of temperature sensors around and along the length of the test cable. Figure 11 shows the instrumentation for the hollow-core and annular flow spaces.



7 sensors in each spiral = 28 sensors inside the cable
4 sensors in middle of former at each spiral
4 sensors on the surface of cable
4 sensors in annulus LN2 stream

Figure 10. Arrangement of temperature sensors along the cable length (top) and within the test cable (bottom).

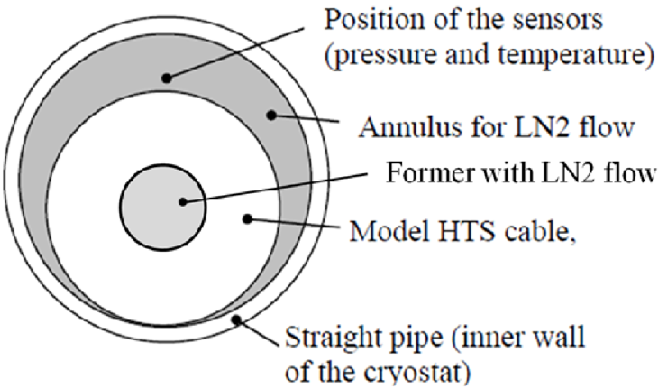


Figure 11. Cross-section of thermal-hydraulic test cable.

Design of the thermal-hydraulic test was finished, however the test hardware was not installed due to changes in scope and early termination of the project. Further, the liquid nitrogen supply system required to perform the testing was also in the original project scope. It was not designed or procured due to changes in scope and early termination of the project.

6.2 Optimized Liquid Nitrogen Cooling System

A primary barrier to commercialization of HTS cable technology is the complexity, size, and cost of the liquid nitrogen cooling system. The cooling system adds an active component to the HTS cable system, whose conventional counterpart (XLPE or EPR) is passive in nature. In order for electric utilities to accept such infrastructure into their systems, the cooling systems must be optimized and simplified to allow for low maintenance, low operating cost, high reliability and small footprint.

To achieve a high reliability combined with energy- and cost-efficiencies, it is necessary to simplify the system design while optimizing functionality. Special attention must be paid to the physical layout of the system components in order to minimize the general footprint and the length of tubing. The system must be attractive system and easy to understand for users and service personnel.

The cooling system was to be designed, fabricated, and integrated into the existing 200 meter HTS Triax^{TM} cable system in Columbus, OH. This would have provided validation of the design under realistic operating conditions. The existing open-cycle cooling system in Columbus, OH was to be removed and replaced with the optimized closed-cycle system.

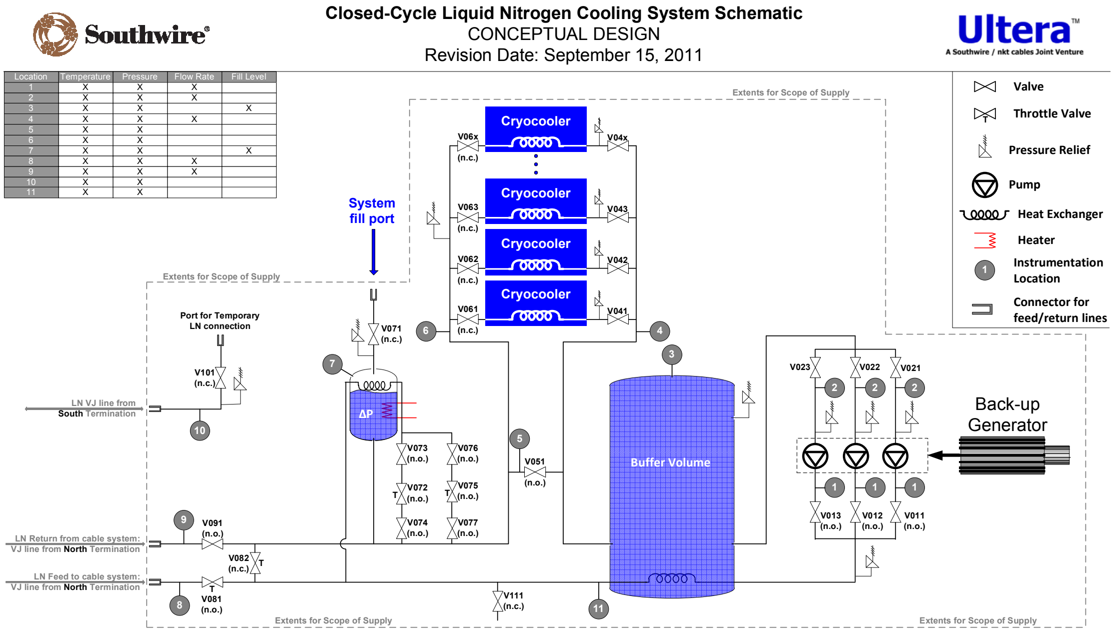
The specification of the proposed cooling system was completed. A closed-cycle system design was selected, which would provide the lowest operating cost and eliminate the need for regular tank filling that is characteristic of open-cycle designs. Table 2 shows the specifications of the proposed cooling system to be installed in Columbus, OH. Data for the existing HTS Triax^{TM} cable system has been accumulated since 2006. This enabled the team to understand all of the operating states, including cool-down, warm-up, transients, loss of cooling system, elevated fault currents on the cable, and normal conditions. Further, before the cable was taken off-line, various system settings were analyzed, such as higher operating temperature, lower liquid nitrogen flow rates, and loss of liquid nitrogen flow. By understanding the various conditions, the new cooling system can be optimized to ensure proper reliability and the highest possible efficiency.

A conceptual design of the optimized liquid nitrogen cooling system was developed by the project team and submitted to potential suppliers for evaluation and quoting. Southwire/Ultera utilized the operating experience of three previous HTS cable installations to design the system. To achieve the goals of low cost, high reliability and ease of operation, the design was simplified as much as possible. Redundancy was to be built into critical components to minimize service disruptions. The conceptual design is shown in figure 12.

It is anticipated that the design would need modifications based on feedback from cryogenic system suppliers; however the requirements to minimize size, cost, and complexity would have remained. Further, a task was included to package the system to achieve a small footprint and good aesthetics but still allow access to the system for maintenance and operation.

The core technology of the closed-cycle liquid nitrogen cooling system is the cryocooler, or refrigeration unit. At the time of the project, only a few cryocooler technologies were commercially available. Commercial technologies do exist today that can accommodate HTS cable systems. The project team also researched new technologies still under development, however, it was decided that a commercially proven system be deployed for the Columbus cable system. More development for the cryocooler technology is necessary to lower component size, improve efficiency, improve maintenance cycles, and improve reliability for a fully optimized system.

A significant amount of work was performed to realize the system specification and conceptual design. The task of optimizing the liquid nitrogen cooling system ended at these steps, however. An optimized system was never constructed due to changes in scope and early termination of the project.



Location	Temperature	Pressure	Flow Rate	Fill Level
1	X	X	X	
2	X	X	X	
3	X	X		X
4	X	X	X	
5	X	X		
6	X	X		
7	X	X		X
8	X	X	X	
9	X	X	X	
10	X	X		
11	X	X		

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Figure 12. Optimized design for closed-cycle cooling system.

Table 2. Specifications for optimized closed-cycle cooling system for Columbus, OH.

Item	Value
Cable System Data	
LN2 Volume in Cable System	1.060 m^3
Thermal Capacity of Cable System	250 MJ
Summer Operating Data - Historical - For information only	
Avg Cable System Inlet Temp	70 K
Avg Cable System Temp	72 K
Cable System Heat Load	2300 - 4000 W
Pressure Drop Across Cable System	0.22 bar
Winter Operating Data - Historical - For information only	
Avg Cable System Inlet Temp	69 K
Avg Cable System Temp	70 K
Maximum Cable System Heat Load	2200 - 2700 W
Pressure Drop Across Cable System	0.26 bar
Closed-Cycle Cooling System Requirements	
Required Cable System Inlet Temperature	69-71 K
Maximum Cable System Exit Temperature	74 K
Required Cooling Capacity	4 kW at 70 K
Cable System Pressure	7.0 ± 0.2 bara
Liquid Nitrogen Flow Rate	400 g/s
Pressurizer minimum volume	0.8 m^3
Cable system circulation pressure drop	0.65-0.73 bar
Estimated return line pressure drop	*est. 0.65-0.73 bar*
Minimum Available Back-up Capacity (Time)	6 hrs
Maximum Back-up Flow Temperature	75 K
Minimum Back-up Flow Pressure	7.0 bara
Estimated Back-up LN2 Volume	2 - 4 m^3
Minimum Available Back-up Flow Rate	400 g/s
Maximum Allowable Noise Level at 3m	50 dB
Maximum System Size (length, width, height)	3 m x 3 m x 4 m
Site Information	
Location	Columbus, OH
Indoor/Outdoor	Outdoor
Site Power to Cooling System	60Hz, 120/240V, 3PH
Existing Foundation	Yes
Site Access	Trucks / Crane
Area Temperature Range (°C)	39/30/-7/-30
Seismic	no activity
Maximum Wind Speed	24 m/s (86 km/h)

6.3 Factory Test Capability

The objectives of the factory test development tasks were to establish industry accepted test protocols for HTS cable systems and establish a test facility that will support such testing. Factory (a.k.a. routine) testing includes high voltage testing of the entire reel of cable after manufacturing. Factory testing is necessary to ensure quality workmanship of the product prior to installation in the utility grid. Conventional insulated power cables undergo 100% factory testing prior to shipment to the customer. HTS power cables incorporate liquid nitrogen as part of the dielectric system, therefore such factory testing with the cable cooled and impregnated with liquid nitrogen is not practical today.

It is generally accepted that test requirements and methods for conventional cable standards would not be possible to implement for HTS cables. New test protocols will need to be developed and could include testing at cryogenic temperatures, scaled room temperature testing, or testing of shorter lengths of cooled HTS cable sections.

New test protocols would include room temperature testing of the cable reel (if possible) and cryogenic testing of short samples cut from the final manufactured length of cable. It is practical and facilities exist today to perform high voltage tests on short lengths (~1 meter long) of HTS cable.

It would be necessary to construct a cryogenic, high voltage facility to validate the new HTS cable test procedures. Southwire currently has extensive high voltage test capability; however an integrated cryogenic system was not in place. The liquid nitrogen supply system that was to be installed for the long-length cable analysis would also be used for the high voltage testing.

A dummy, 150 meter-long HTS Triax™ cable was to be constructed that would serve as the test cable for high voltage factory test development. The goal of the project team would be to develop room temperature testing for each HTS cable reel that would ensure quality workmanship of the cables. This likely would have included testing at room temperature to voltages below what is routinely applied to conventional cables. To achieve this, several short cable samples would need to be tested at cryogenic and at room temperatures to obtain a correlation to test voltages at the two temperatures. Such tests would include high voltage AC and partial discharge testing. The 150 meter-long cable would eventually be tested to validate the new test methods.

Existing industry standards were studied and referenced to compile data on tests for conventional (non-HTS) cables. Table 3 shows samples of relevant data collected from industry standards that are applied to conventional cables today. While these tests and voltage levels would not be achieved on full lengths of HTS cable, they would serve as a model for the factory tests for HTS cables.

A preliminary design for the test procedures was developed, however this was the extent of the work completed. Table 4 shows a preliminary version of the factory test design for HTS cables.

Due to changes in scope and early termination of the project, the high voltage factory test facility was not designed or constructed. The 150 meter dummy HTS cable was not manufactured, thus the development tests were not performed.

Table 3. Example factory (routine) test specifications for conventional XLPE cables.

IEC 60502 Part 2 Ed. 2 (2005-03)								
XLPE cables 6-30 kV (Um=7.2-36 kV)								
Nr.	**Description**	**IEC voltage levels**					**Units**	**Duration**
	U_o	3.6	6	8.7	12	18	kV_{rms}	
	U	6	10	15	20	30	kV_{rms}	
	Um	7.2	12	17.5	24	36	kV_{rms}	
1. Routine tests								
1.1	Electrical resistance of conductor							
1.2	PD test							
	Conditioning at 2 x U_o	0	0	0	0	0	kV_{rms}	10 s
	PD measurement at 1,73 x U_o	0	0	0	0	0	kV_{rms}	
1.3	Voltage test							
	Withstand at 3.5 x U_o	12.5	21	30.5	42	63	kV_{rms}	5 min
2. Sample Tests								
2.1	Conductor examination							
2.2	Check of dimensions							
2.3	Voltage test at 4.0 x U_o	n/a	24	35	48	72	kV_{rms}	4 hours
2.4	Visual inspection of insulation							

IEC 60840 Ed. 3 (2004-01)								
XLPE cables above 30 kV and up to 150 kV (Um=170 kV)								
Cables and accessories, separately or together								
Nr.	**Description**	**IEC voltage levels**					**Units**	**Duration**
	U_o	26	36	64	76	87	kV_{rms}	
	U	45-52	60-69	110-115	132-138	150-161	kV_{rms}	
	Um	52	72.5	123	145	170	kV_{rms}	
1. Routine tests								
1.1	PD test							
	Conditioning at 1.75 x U_o	0	0	0	0	0	kV_{rms}	10 s
	PD measurement at 1,5 x U_o	0	0	0	0	0	kV_{rms}	
1.2	Voltage test							
	Withstand at 2.5 x U_o	65	90	160	190	218	kV_{rms}	30 min
1.3	Voltage test of over sheath							
2. Sample Tests								
2.1	Conductor examination. Measure electrical resistance of conductor & metallic screen.							
2.2	Check of dimensions							
2.3	Visual inspection of insulation							
2.4	Measurement of capacitance							
2.5	Density of insulation material							

Table 4. Preliminary factory HV test requirements.

Preliminary Test Requirements for Factory Testing of HTS Cables						
Nr.	**Description**	**13 kV**	**20 kV**	**30 kV**	**50 kV**	**Unit**
	U_o	7.5	11	17	29	kV_{rms}
	U	13	20	30	50	kV_{rms}
	Um	15	24	36	72	kV_{rms}
1. Routine tests						
1.1	Measure electrical resistance of phase and neutral conductors	Room-temperature measurement				
1.2	Warm PD test in N2 gas	Phase-Phase test to be developed				
1.3	Warm withstand test in N2 gas	Phase-Phase-N test to be developed				
1.4	Cryostat over sheath, DC test	16	16	16	16	kV_{dc}
2. Sample Tests						
2.1	Bending of sample	Bend to specification 3 reverse bends				
2.2	Ic measurement	DC current at 1 μV/cm				kA
2.3	AC loss measurement (optional)	Single-phase or three-phase measurement				W/m
2.4	PD testing	Voltage levels as described under 3.				
2.5	AC Breakdown	Above withstand levels under 3.				5 kV steps
2.6	Impulse breakdown	Above impulse levels under 3.				5 kV steps
2.7	AC withstand of neutral insulation	5	5	5	5	kV
2.8	Check of dimensions	Dissection				
2.9	Visual examination of the insulation	Dissection				
2.10	Examination of the conductor	Dissection				

6.4 Life Cycle Analysis

The goal of the life cycle analysis tasks was to optimize the other technical and non-technical issues that present barriers to commercialization such as:

- HTS cable system cost
- Overall system efficiency
- Long term system reliability
- Termination installation and maintenance complexity
- Termination size
- Electrical fault location

Work to date concentrated on performance testing of the HTS Triax^{TM} cable system in Columbus, OH and development of termination analysis models that would be used to optimize termination design.

HTS Cable Testing

The HTS cable in Columbus, OH had been operating for 6 years and experienced numerous transient events, including thermal cycles (between ~300K and 70K) and fault current events up to 27kA. This HTS cable, therefore, presents a good opportunity to study the life cycle performance of the system. Although the normal operating conditions of the cable showed no performance degradation, it was decided to test certain aspects of the system against baseline conditions where possible.

Test of the existing HTS cable included:

- Vacuum insulation performance testing
- High current testing
- High voltage testing
- Partial discharge testing
- Heat load testing

Vacuum Insulation Performance Testing

Vacuum insulation tests were performed to determine if any degradation had occurred in the thermally insulating vacuum spaces in the system. High quality thermal insulation is required to limit the heat load on the system and enable efficient operation. Total loss of any vacuum insulation components would jeopardize the operability of the system. Basically, every component in the system that carries liquid nitrogen requires vacuum insulation, thus the cable system utilizes of several vacuum insulation spaces including the:

- terminations enclosures,
- termination to cable cryostat joint enclosure,
- cable cryostat,
- splice enclosure,
- flexible vacuum-jacketed liquid nitrogen feed lines, and
- rigid vacuum-jacketed liquid nitrogen return-line.

To test the life of the vacuum quality, several vacuum spaces on the HTS cable system in Columbus, OH were checked for degradation. Figure 13 shows the vacuum space enclosures on the terminations and figure 14 shows the splice vacuum enclosure. Figure 16 shows the rigid vacuum-jacketed liquid nitrogen lines. Vacuum pressure measurements were taken at each of these components by a qualified cryogenic technology company.

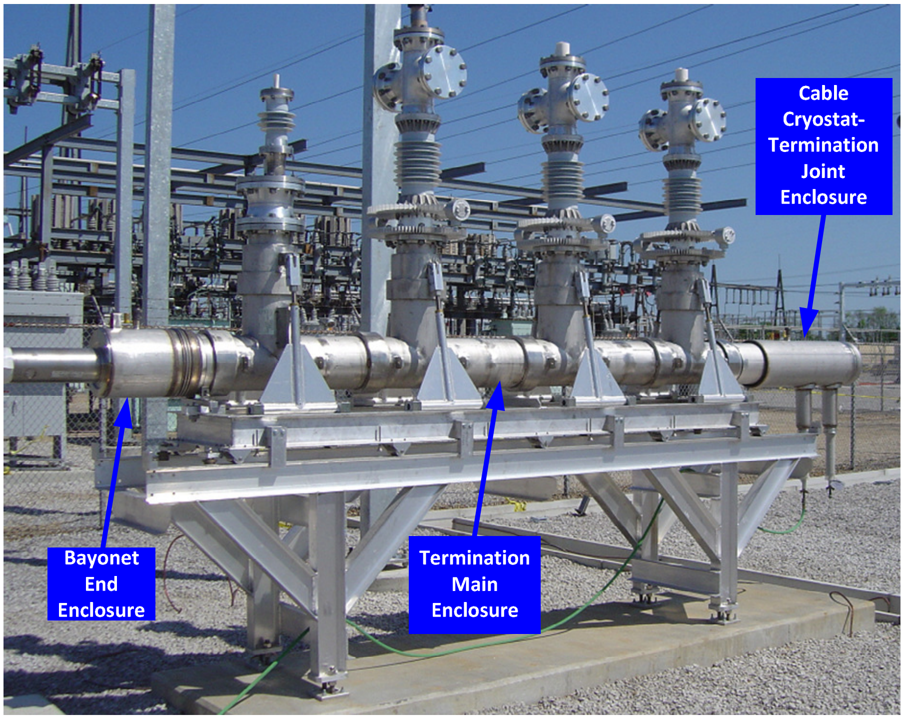

Figure 13. Vacuum space enclosures on HTS Triax^{TM} Termination

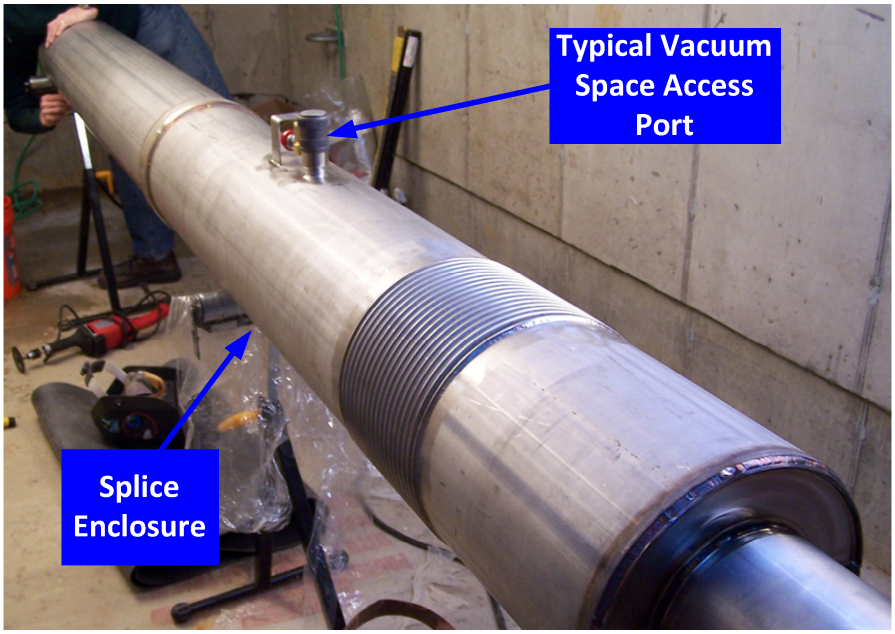

Figure 14. Vacuum space enclosure on HTS Triax^{TM} Splice.

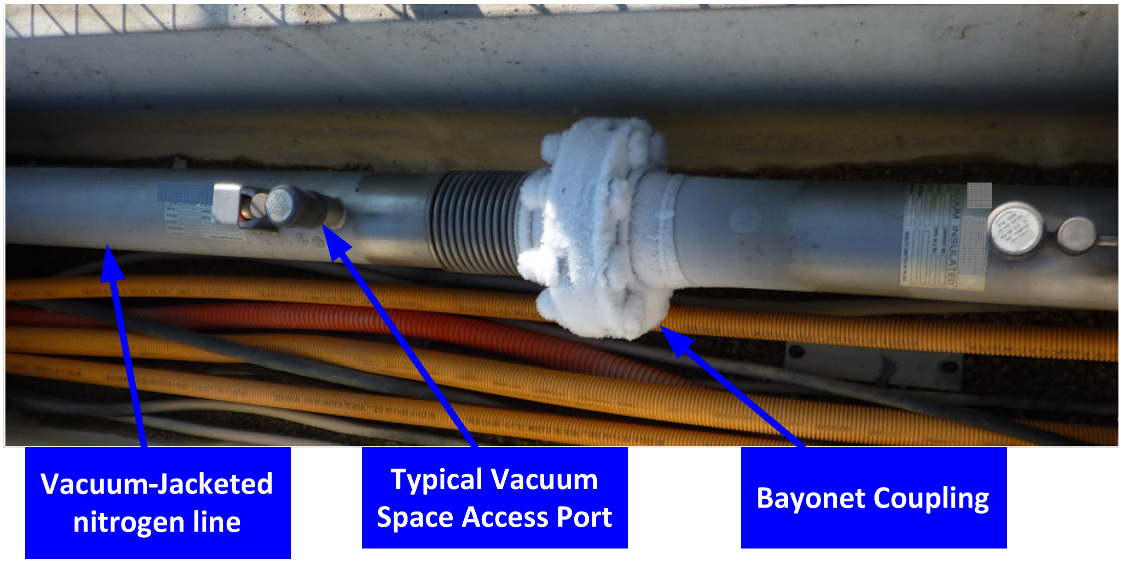

Figure 15. Vacuum-jacketed nitrogen line.

Vacuum tests were performed on the termination bayonet enclosures, cable-cryostat to termination joint enclosure, splice enclosure, and vacuum-jacketed nitrogen lines. The termination main enclosure instrumentation port was not accessible, so vacuum pressure was not measured here. All components were at operating temperature (~70 K) and pressure (~100 psi) at the time of measurement. Vacuum pressure was measured using a hand-held gauge as shown in figure 16.

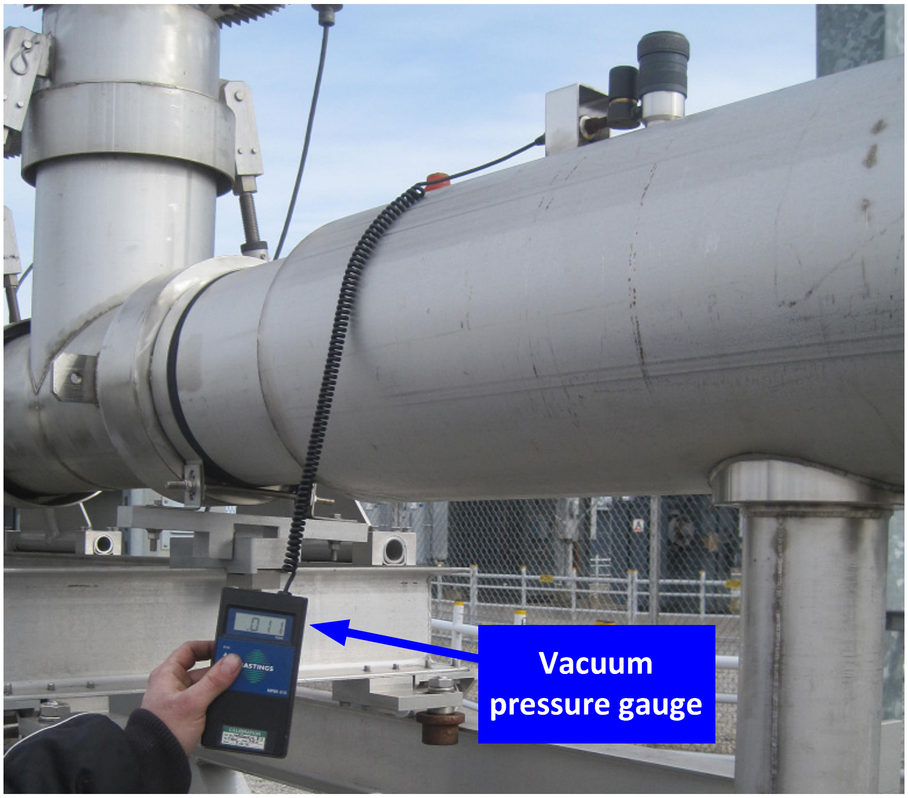

Figure 16. Bayonet enclosure vacuum measurement.

Table 5 shows the vacuum pressure readings on the various vacuum-jacketed spaces. Ideally, all spaces would have a vacuum pressure below 0.010 torr while the system is at 70K. The cryogenic temperatures on the inner walls effectively “cryo-pump” the system which presents an optimal vacuum condition. It was found that all but one of the spaces showed vacuum pressures above 0.010 torr, indicating that some degradation had occurred over the 6 year operation. This level, however, is not detrimental to the operation of the system and has been adequate. Many of these vacuum spaces were established on site during construction, which could be the cause of the slightly degraded levels. On future installations, the procedures should be improved for vacuum spaces established in the field. The data can be used to predict future life-cycle conditions and to establish maintenance intervals.

Table 5. Vacuum pressures on HTS cable system after 6 years of operation.

Vacuum Space	**Termination**	**Vacuum Pressure**
Bayonet Enclosure	South	0.021 torr
Cable/Term Joint Enclosure	South	0.030 torr
Vacuum Jacketed Nitrogen Line	near South	0.000 torr
Main Termination Enclosure	South	Not measured
Bayonet Enclosure	North	0.011 torr
Cable/Term Joint Enclosure	North	0.019 torr
Vacuum Jacketed Nitrogen Line	near North	0.018 torr
Main Termination Enclosure	North	Not measured

High Current (Critical Current, DC-I_c) Testing

High current tests were performed on the HTS Triax^{TM} cable system in Columbus, OH. Critical current is essentially the maximum (peak) current that the cable is capable of carrying while maintaining zero electrical resistance. Above the critical current, the superconducting material quickly becomes resistive and leaves the superconducting state. The critical current for a cable is essentially the sum of the critical currents for each tape that make up the cable, less some expected degradation due to manufacturing and installation stresses. Table 6 shows the calculated critical current of the HTS cable based on the 2006 performance of each HTS wire and the number of wires in each phase.

Table 6. Calculated critical current of HTS cable in Columbus, OH.

HTS Cable Phase	Calculated Critical Current*
Phase 1	7719 A
Phase 2	7885 A
Phase 3	8021 A

*Based on 2006 HTS wire data and number of wires per phase.

Oak Ridge National Laboratory (ORNL) was contracted to perform the high current tests on the cable in Columbus, OH. Southwire transported the test equipment from Oak Ridge, TN to Columbus, OH to facilitate the testing. Personnel from Southwire and ORNL were on site. Praxair, the cooling system operator, was on site to ensure the cable was at proper operating temperature and pressure for each test.

The voltage characteristics for the HTS Triax^{TM} cable were measured for DC currents up to a maximum current of 6,000 A. The limit of the power supplies was 6,000A. The goal for this characterization was to determine whether there was any change in the cable superconductor performance over the six year operational lifetime of the cable and to ensure that the cable remains in the superconducting state up to 6,000 A. Events that occurred during this operational lifetime that could affect the cable current carrying performance consisted of several symmetrical and asymmetrical faults that pushed the current in the cable to 27 kA, as well as loss of circulation while the cable was under load. A similar measurement was performed in July 2006 before the cable was placed in the grid and these results will be used as a baseline. The test configuration for the characterization is shown in figure 17.

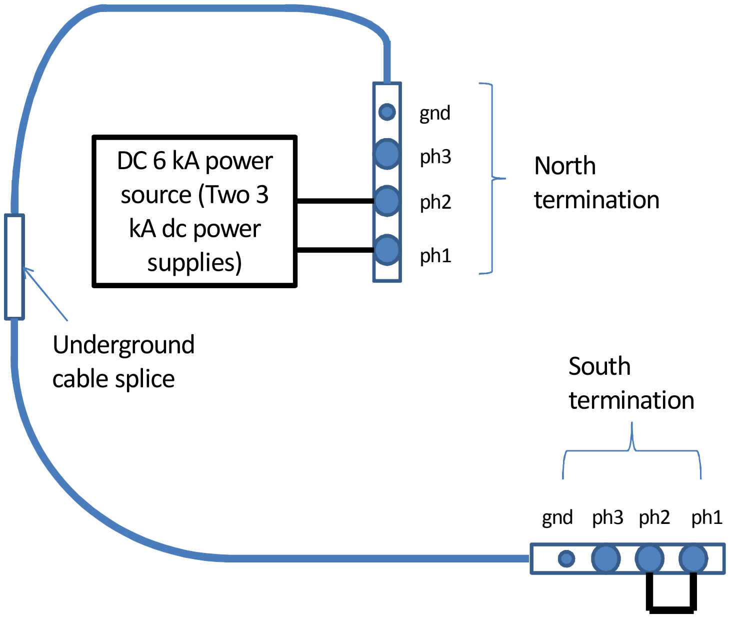

Figure 17. Test configuration for high current testing of the HTS cable in Columbus, OH.

Figure 18 shows a picture of the DC current testing in Columbus, OH. The power supplies were kept in a covered truck to keep them out of the weather. The cable system was disconnected from the utility power system prior to testing. Several test configurations were performed, including various operating temperatures. Care was taken to obtain data to conditions similar to those during the tests in 2006 to ensure data was comparable. Two phases of the cable were measured simultaneously as shown in figure 17 to minimize the inductance of the 200 meter cable and allow for measurement up to 6,000 A. Figure 19 shows the voltage characteristics for all the phases as a function of current.

Figure 18. DC current test set up in Columbus, OH.

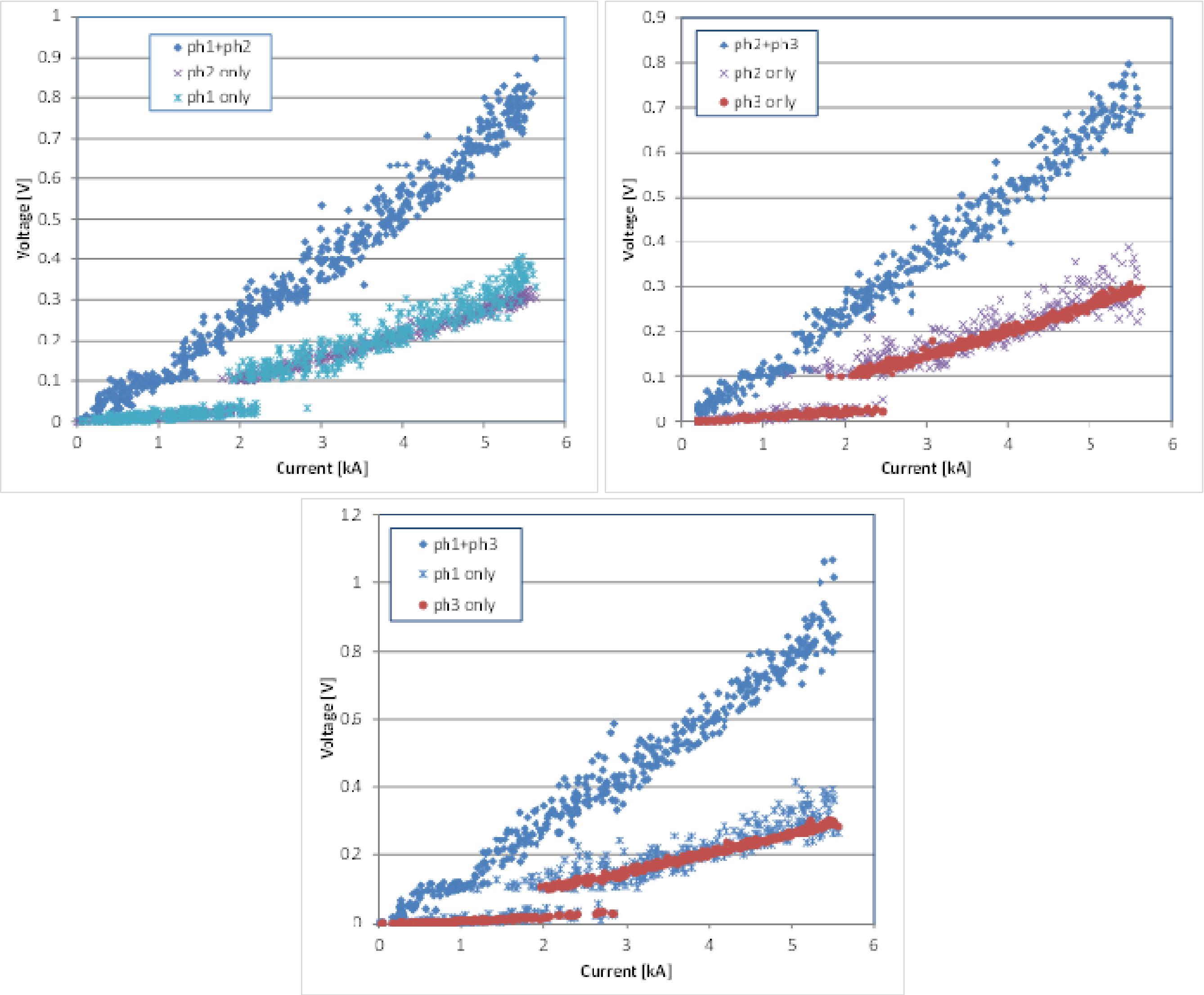

Figure 19. Voltage characteristics for various phase configurations as a function of current.

Figure 20 shows a comparison of the phase 2 and phase 3 data from 2006 and 2012. Some variation in the 2006 and 2012 data is expected due to slight differences in the measurement set up and the use of different power supplies. The comparison shows that no significant degradation in the cable was found after 6 years of operation. This is an important result indicating that the HTS cable can sustain long periods of performance, numerous thermal cycles, and numerous fault currents and still maintain the design performance levels. This information can now be built into the life cycle characteristics of the system.

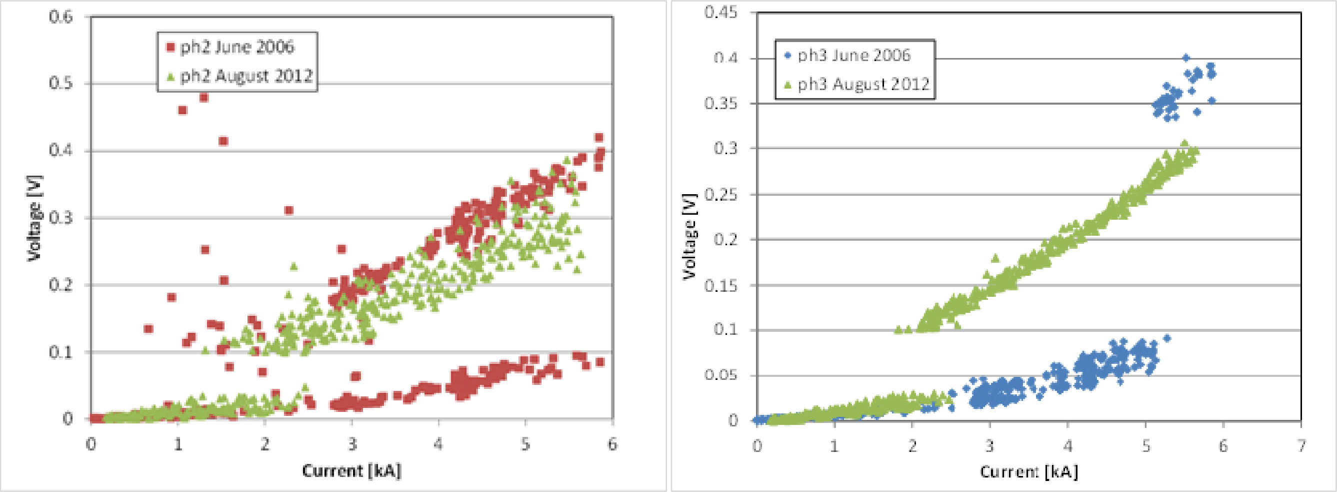

Figure 20. Voltage on phase 2 (left) and phase 3 (right) up to 6kA at 75K as measured in 2006 and 2012.

High Voltage and Partial Discharge Testing

High voltage and partial discharge tests are used to ensure the quality of cable dielectric materials and workmanship. These tests are typically performed on new cable systems and occasionally during the life of the cable to predict the quality after many years of operation. For the high voltage test, an elevated voltage (above the normal operating voltage) is applied to the cable for a short period of time, i.e. 1 to 60 minutes. If the high voltage does not cause a failure in the cable, then the cable has passed the test. A successful test can assure the owner of the cable that it can withstand long term operation at normal operating voltage. Partial discharge (PD) tests are typically performed during the high voltage tests. During PD testing, the voltage is raised to a pre-determined level during which time the cable system is monitored for discharges in the dielectric materials. Specialty hardware and expert test personnel are required to measure PD in cable systems. PD measurement requires the detection of very small signals so sensitive detectors and filtering techniques are also required. If PD is detected in the cable system at relatively low voltages, it could indicate premature deterioration or poor workmanship in the cable system.

It is important to note that PD measurement techniques and prognostics are well understood for conventional, solid dielectric cable systems. To date, only limited PD measurement techniques have been applied to HTS cables which have a vastly different dielectric system than conventional cables. HTS cables employ a liquid nitrogen impregnated tape as the dielectric system. Due to the novelty of HTS cable systems today, the effects of PD are not well understood and PD within the cable is not presumed to indicate limited capability of the system.

In 2012, high voltage and PD measurements were performed on the HTS cable in Columbus, OH. Due to the complexity of the measurements and the required hardware, a company who specializes in the measurements was contracted for the tests. The goal of the high voltage testing was to ensure the cable could withstand elevated voltages after the 6 year period of performance, after numerous thermal cycles, and after numerous fault currents. Partial discharge tests were performed to obtain characteristic data on the cable system. PD data was not obtained during commissioning of the system in 2006, so comparisons are not able to be made to analyze changes in the characteristics. High voltage and PD tests were performed at the normal operating temperature of 70K as well as at an elevated temperature of 75K. A comparison of performance at the two temperatures will indicate if operation at higher temperatures compromises the quality of the dielectric system. It is of interest to operate HTS cables at higher temperatures to improve the overall efficiency of the system. The PD measurements were performed on the entire HTS cable system including cable, terminations, and splice. Each phase of the cable system was tested individually as well as with certain phases tied together.

The normal phase to ground operating voltage for the system is $7.6\text{kV}_{\text{rms}}$, and the normal phase to phase operating voltage for the system is $13.2\ \text{kV}_{\text{rms}}$.

The partial discharge and high voltage tests were performed simultaneously. The maximum voltage applied to the cable system was 20kV_{rms}. High voltage was typically applied to a single phase with the other phases grounded. If PD was detected during a measurement, various phase test configurations were applied isolate the source of the PD to either a certain phase in the cable or to the termination. The test circuit included HTS cable, terminations and a splice. A schematic of the high voltage/PD test setup is shown in figure 21.

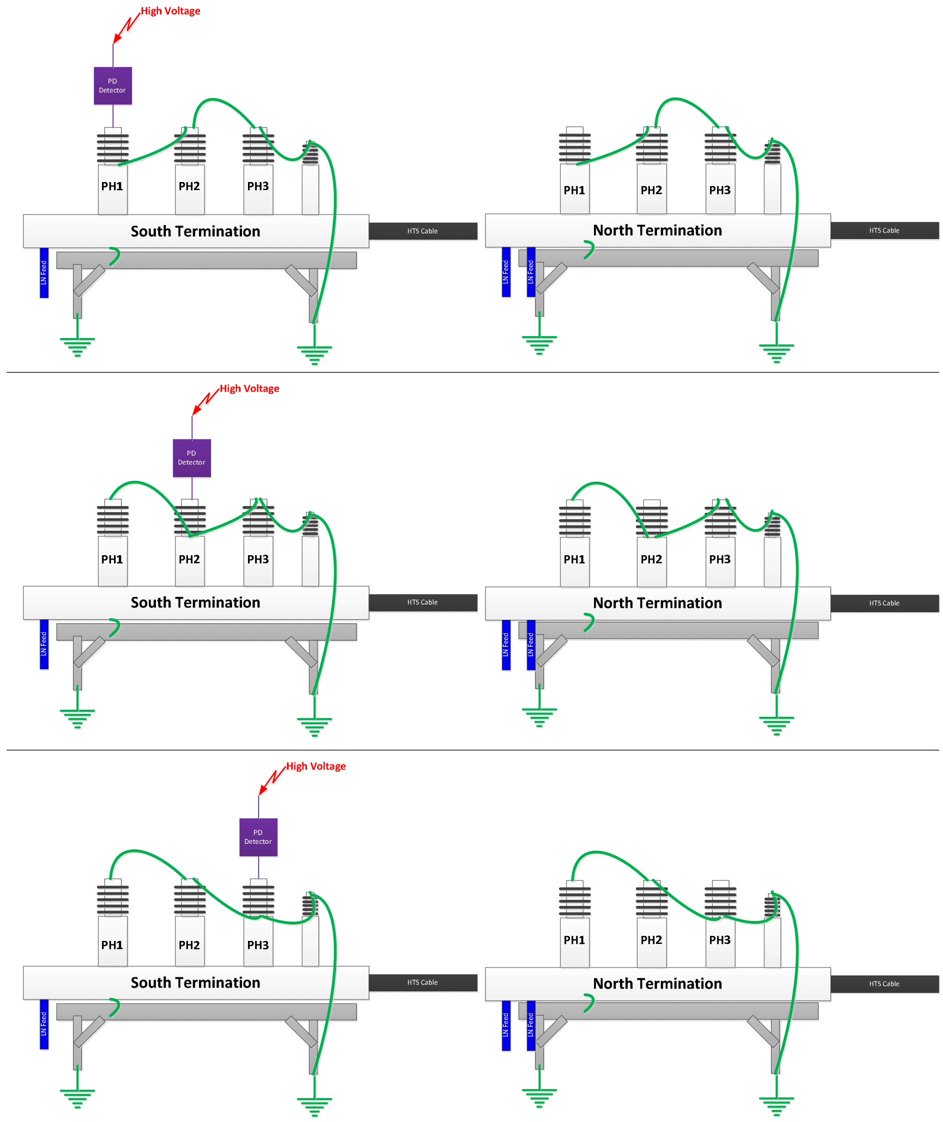

Figure 21. High voltage and PD tests setup for phase 1 (top), phase 2 (middle), and phase 3 (bottom).

Voltage was applied to a single termination phase bushing on the south termination and the respective phase bushing on the north termination was left floating. As shown in figure 21, high voltage was placed on one phase at a time with all other phases and the termination structure grounded.

High voltage and partial discharge test results are summarized in table 7. All phases passed the withstand test up to $20kV_{rms}$. PD was detected in the phase 1 section of the south and north terminations at $4.3kV_{rms}$ and $7.6kV_{rms}$, respectively. PD was detected in the phase 3 section of the south and north terminations at $16kV_{rms}$. No PD was detected in the phase 2 section of either termination up to $20kV_{rms}$. No PD was detected in any phase of the cable or in any phase in the splice. It is not possible to determine the source of the PD for either phase 1 or phase 3. PD measurements were not taken in 2006 during system commissioning, so it is not possible to determine if the PD characteristics have changed over the 6 year life of the cable. The PD in the phase 3 section of the terminations occurred well above the operating voltage in the termination so is at an acceptable level. The PD onset voltage in phase 1, however, is abnormally low and below the operating voltage of that section of the termination. This issue should be investigated further, however, due to the early termination of the project; it was not possible to follow-up. This will be an important issue for the life cycle analysis of the system and should be analyzed moving forward.

Table 7. Summary of high voltage and partial discharge tests.

	PD Onset Voltage				**AC Withstand**
Phase	**South Termination**	**North Termination**	**Cable**	**Splice**	**$20kV_{rms}$**
1	$4.3\ kV_{rms}$	$7.6\ kV_{rms}$	$>20\ kV_{rms}$	$>20\ kV_{rms}$	Pass
2	$>20\ kV_{rms}$	$>20\ kV_{rms}$	$>20\ kV_{rms}$	$>20\ kV_{rms}$	Pass
3	$16\ kV_{rms}$	$16\ kV_{rms}$	$>20\ kV_{rms}$	$>20\ kV_{rms}$	Pass

High voltage and partial discharge measurements were performed at temperatures of 70K and 75K. The test results at each temperature were identical for all phases. Successful high voltage testing at 75K indicates that cable operation at higher temperatures is possible, which will enable better efficiency and lower operating cost for the HTS cable systems.

Heat Load Testing

Part of the life cycle optimization task was to develop a more efficient cable system to lower capital and operating cost. The HTS cable system in Columbus, OH has accumulated 6 years of operating data which was analyzed for heat loads during normal operating conditions. Over this time, system settings were essentially constant, so only seasonal and cable loading variations could be studied. It was also important, however, to study alternate operating conditions, including different liquid nitrogen flow configurations and operating temperatures. The ultimate goal would be to enable higher operating temperatures for HTS cables to improve system efficiency. Two primary tasks were performed to analyze the system heat loads:

1. Analyze operating data over the 6 year operation of the system
2. Alter flow configurations and operating temperatures to determine the effects on system heat loads.

The team reviewed the 6 year operating data and studied the heat loads on the system. Sample heat load data from normal operation are shown in figure 22. Figure 22 represents the system at the normal operating temperature of 70K. Figure 22 (bottom) shows how the system heat loads have varied over the years and (top) shows how the heat loads are spread through the system, i.e. heat loads in the cable vs. terminations vs. cooling system. The oscillations in the heat load vs. time curve are caused by seasonal variations. Summers are the peak periods of electrical demand, which corresponds to the peaks of the oscillations. It is seen that the average heat load of the cable plus terminations is 2.5 to 3kW for the 200 meter cable system. The red points are the parasitic head load of the cooling system. It is important to note that the cooling system accounted for a majority of the heat load that the system became less efficient over time due to problems with the vacuum insulation within the cooling system. Although this did not affect the operation of the cable and terminations, the cooling system is clearly a component that needs optimization.

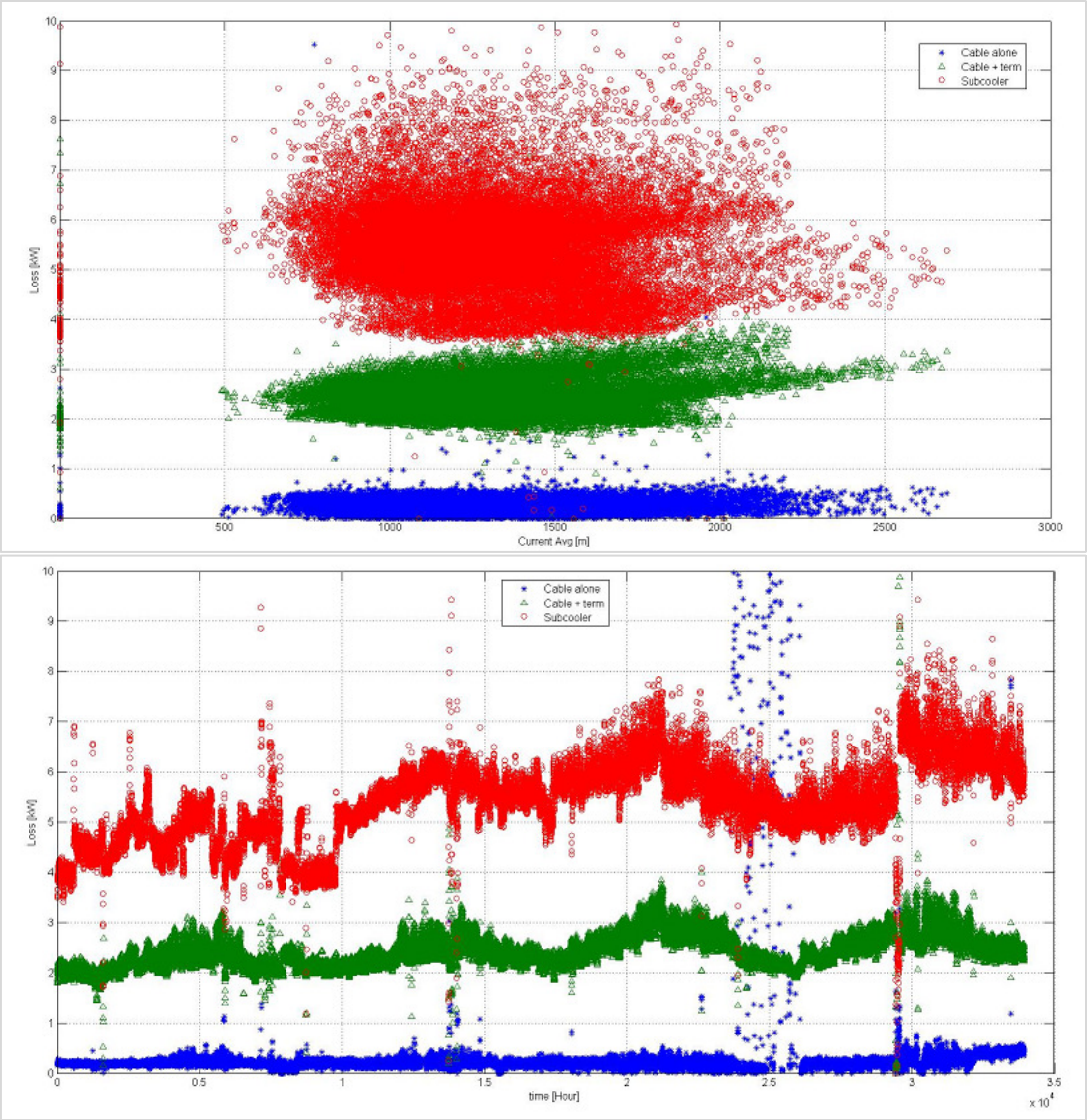

Figure 22. Heat load data for the HTS cable system in Columbus, OH.

The second heat load analysis involved varying the system parameters (liquid nitrogen flow configuration and operating temperature) to understand the effects on the heat load of the cable system. Again, the goal was to enable higher operating temperatures to improve the overall efficiency. It is known that at higher system operating temperatures, the AC losses of the cable itself will rise due to the properties of the superconductor. Higher operating temperatures will, however, allow a minor reduction of the thermal losses in insulating vacuum spaces, and more importantly, will improve the efficiency of the cooling system. The latter was evident when the system nominal temperature was set to 75K (just 5K higher than the normal operating temperature of 70K) and approximately 1/3 of the sub-cooler capacity was required to maintain the higher operating temperature.

For the higher temperature experiment on the 200 meter HTS cable, the target temperature was increased to 75K and the cable was energized (the cable was carrying the substation load). The cable was then allowed to operate for approximately 3 months to acquire operating data at the higher temperature. Heat loads with and without current on the cable were analyzed. Figure 22 summarizes the results from the heat load testing.

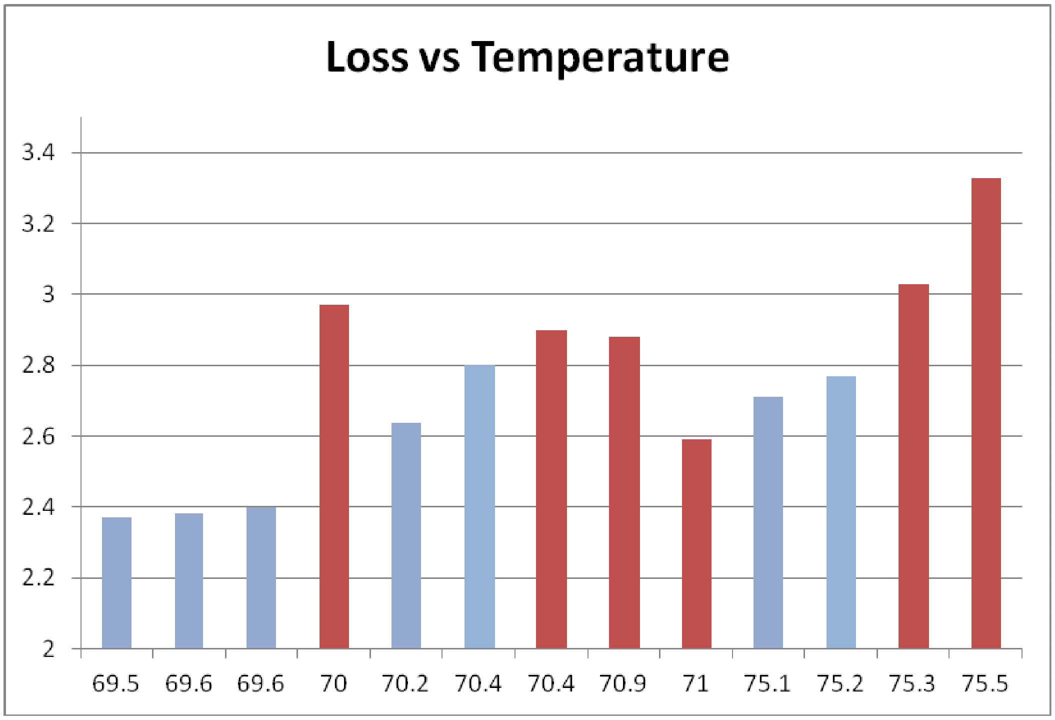

Figure 22. Heat load (kW) vs. operating temperature. Red bars=with current on cable. Blue bars=without current on cable.

Figure 22 indicates the losses increase slightly with the current. At 75 K the 1,300 A seems to add about 250 W and 1,600 A seems to add about 600 W. At 70 K there is no visible correlation between the cable current and the losses as the ambient is fluctuating too much.

The operating temperature of 75 K does not have any visible effect on the losses in the cable system, at least not without current. The temperature difference across the vacuum jackets is changing about 2 % which will cause about the same change in losses. The calculations made on the terminations indicates the heat flux to the liquid nitrogen through the current leads increases about 10 W per termination from 75 K to 70 K operating temperature, which is too low to measure given the resolution of these types of measurements.

The most significant correlation is between the overall losses in the cable and the outside ambient temperature at the site. This is related to the the temperature difference between the liquid nitrogen in the cable system and ambient air. The difference in loss in the cable system between 70 K and 75 K is insignificant when the cable is not energized. It is the same difference as when the ambient temperature increases 5 K. The AC losses should increase slightly with the higher operating temperature though. The dominant contributor to loss is seen in the idle losses which change about 20 % when the difference between ambient and the cable temperature change 20 K (10 %).

Life Cycle Analysis Summary

Experiments were performed to compile data to be used in the life cycle analysis of HTS Triax™ cable systems. One goal of the measurements was to determine if higher operating temperatures are possible, thus allowing design of more efficient cooling systems. High voltage, high (critical) current, and heat load tests were performed at the elevated operating temperature of 75K. All tests showed that it is possible to operate the system at 75K. This will allow more efficient operation of the cooling system; however, due to early termination of the project, the associated efficiency improvements were not analyzed.

The high voltage tests on the 200 meter cable were successful; however, the partial discharge test did show sub-optimal performance in one of the cable phases. This did not prove to be detrimental to the cable operation, but the issue should be addressed in future commercialization efforts. The cable was able to withstand the elevated voltage tests after many years of operation, which proves long-term system reliability.

Critical current testing of the 200 meter long cable showed no degradation to the performance of the HTS cable.

Vacuum pressure readings on the thermally insulating vacuum spaces showed that all spaces were performing adequately after 6 years of operation. Some pressures were above optimal, so procedures should be developed to enable high quality vacuum pressures for long-term cable operation.

The life cycle tasks were left incomplete due to early cancellation of the project. In spite of this, much work, testing and analysis was completed toward the effort. Future commercialization efforts should utilize the data to improve the long-term viability of HTs cable systems.

7 PROJECT MANAGEMENT

Project management tasks were completed throughout the project to:

- Manage project scope changes
- Manage project budget
- Maintain project schedules
- Attend HTS Peer Review meetings
- Submit timely reports according to DOE reporting requirements
- Procure materials required for research
- Manage research activities
- Manage subcontracts with 3rd parties who performed project activities
- Attend industry meetings to current on HTS and cryogenic technologies

8 TECHNOLOGY TRANSFER OUTREACH

A technology meeting was planned for the end of the project to present project results and the state of commercialization of the technology to industry stakeholders, such as utilities, industry organizations, and component suppliers. The technology outreach was cancelled due to early termination of the project.