High Temperature Superconducting Underground Power Cable

[The "Albany Cable Project"]

Final Report

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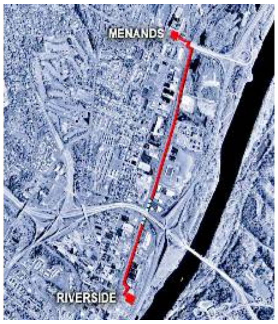
Executive Summary

The purpose of this Project was to design, build, install and demonstrate the technical feasibility of an underground high temperature superconducting (HTS) power cable installed between two utility substations, **Figure 1**. In the first phase two HTS cables, 320 m and 30 m in length, were constructed using 1st generation BSCCO wire. The two 34.5 kV, 800 A_{rms}, 48 MVA sections were connected together using a superconducting joint or splice in an underground vault. In the second phase the 30 m BSCCO cable was replaced by one constructed with 2nd generation YBCO wire. 2nd generation wire is needed for commercialization because of inherent cost and performance benefits.



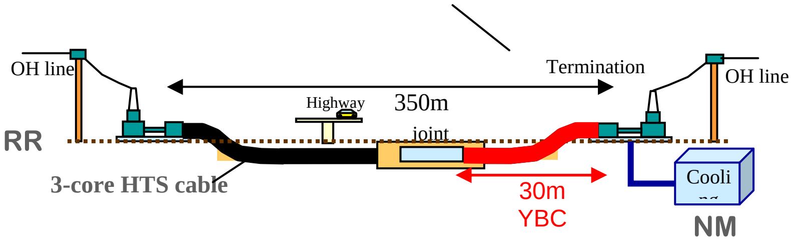


Figure 1 Underground HTS Cable Schematic and Location in Albany NY.

Primary objectives of the Project were to build and operate an HTS cable system which demonstrates significant progress towards commercial progress and addresses real world utility concerns such as installation, maintenance, reliability and compatibility with the existing grid. Four key technical areas addressed were the HTS cable and terminations (where the cable connects to the grid), cryogenic refrigeration system, underground cable-to-cable joint (needed for replacement of cable sections) and cost-effective 2nd generation HTS wire.

This was the world's first installation, **Figure 2**, and operation of an HTS cable, **Figure 3**, underground, between two utility substations as well as the first to demonstrate a cable-to-cable joint, remote monitoring system and 2nd generation HTS.

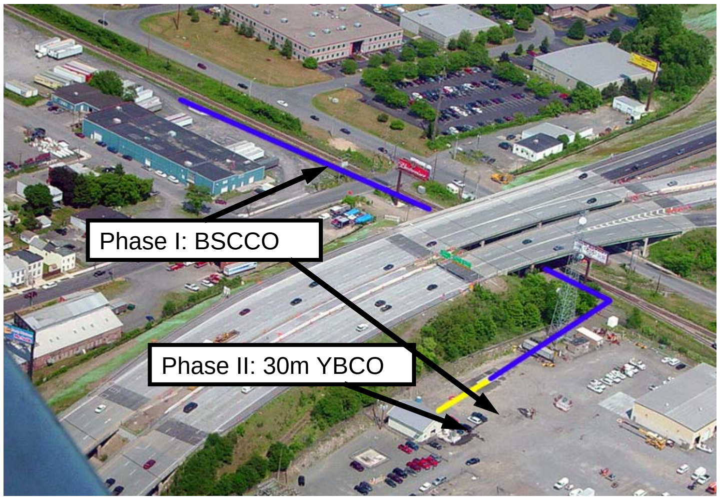


Figure 2 National Grid Installation in Albany NY.

Figure 3 3-in-1 HTS Cable.

The Project team[1] and respective responsibilities were:

SuperPower, Inc. – HTS technology company and manufacturer of 2nd generation wire.

- Project Manager.
- Design, develop and manufacture 2nd generation HTS wire.
- Prepare cable site infrastructure and restore the site upon Project completion.

Sumitomo Electric Industries, Ltd. (SEI) – manufacturer of conventional and HTS cables.

- Design, develop, manufacture, install and test the HTS cables, cryogen return line, superconducting joint and cable terminations.
- Manufacture 1st generation HTS wire.

The Linde Group[2] – manufacturer of cryogenic refrigeration equipment and industrial gas supplier.

- Design, manufacture, install and operate the cryogenic refrigeration system.
- Provide 24/7 remote monitoring and utility interface with the HTS cable.

National Grid[3] – a major utility in the Northeastern United States and Europe

- Provide the site between the Menands and Riverside substations for the HTS cable demonstration in Albany, NY.
- Determine system impact and protection requirements.

The Project, which began on November 1, 2002 was effectively completed on December 31, 2009 was an unqualified success. Major accomplishments were:

- Demonstration of a reliable, high-performing cryogenic refrigeration system.
- Installation of the complete 1st generation BSCCO cable system and operation on the grid..
- The BSCCO cable system became operational on July 20, 2006, and successfully operates for more than 6,720 hours (280 days) before being shut down for installation of the 30 m 2nd generation YBCO cable section on May 1, 2007.
- Manufacture of 9.7 km of 2nd generation YBCO wire completed in December 2006
- Hybrid BSCCO (320 m)/YBCO (30 m) HTS cable becomes operational on January 8, 2008 and successfully operates for approximately 2,250 hours before being shut down upon completion of the operational phase of the Project on April 12, 2008.

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[1] Financial contributions were provided by the team, the US Department of Energy (DOE) and the New York State Energy Research & Development Authority (NYSERDA).
[2] The BOC Group at Project inception, acquired by Linde during the Project
[3] Niagara Mohawk Power Corporation at Project inception, acquired by National Grid during the Project.

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Project Tasks, Responsibilities & Milestones

A Work Breakdown Structure, **Table 1**, was used to define the Project tasks and responsibilities.

Table 1 Project Task Definitions & Responsibilities.

Task	Subtask	Definition	Responsibility*			
			SP	SEI	Linde	Grid
1.0		Specifications & Conceptual Design				
	1.1	Specifications	A	**P**	A	A
	1.2	System Impact Analysis	A			**P**
	1.3	Conceptual Design	A	**P**	A	A
2.0		BSCCO Cable Detail Design & Analysis	A	**P**	A	
3.0		BSCCO Cable Fabrication, Assembly & Test				
	3.1	BSCCO Procurement	**P**	A		
	3.2	BSCCO Cable Suitability	A	**P**		
	3.3	Cable	A	**P**		
	3.4	Cryogenics	A	A	**P**	
	3.5	Terminations/Joint	A	**P**		
	3.6	BSCCO Cable Sample Test	A	**P**		
4.0		HTS Cable Installation/Pretest				
	4.1	BSCCO/YBCO Cable Installation	A	**P**	A	A
	4.2	Site Infrastructure	**P**	A	A	A
	4.3	Site Restoration	**P**	A	A	A
	4.4	System Protection	A	A		**P**
5.0		BSCCO/YBCO Cable Test/Evaluation				
	5.1	Performance/Proof of Concept	A	**P**	A	A
	5.2	Durability/Reliability	A	**P**	A	A
6.0		2nd Generation YBCO Cable				
	6.1	Cable Design/Analysis	A	**P**	A	
	6.2	YBCO Fabrication	**P**	A		
	6.3	Cable Fabrication	A	**P**		
7.0		Project Management	**P**	A	A	A
8.0		Market Research, FMA & Grid Stability				
	8.1	Economic Application Niche Analysis	**P**	A	A	
	8.2	Failure Mode Analysis	A	**P**	A	A
	8.3	Grid Stability Study	**P**	A		A

* Bold indicates **P**rime responsibility with others Assisting as indicated: SP = SuperPower, SEI = Sumitomo Electric Industries, Ltd., Linde = The Linde Group, Grid = National Grid.

Associated with this structure were a number of milestones, **Table 2**. The table lists whether the milestones were achieved or partially achieved and references the **Accomplishments** section that applies. Milestones are also discussed in the **Goals and Objectives** section.

Table 2 Albany Cable Project Milestones.

Type		Milestone Description	Status[1]	Reference[2]
Critical	1.	Finalize cable specifications (length, diameter, voltage, ampacity, inductance, capacitance, fault requirements, etc.).	√	**Ia, IIIc, IVa, IVe**
	2.	Complete BSCCO cable detailed design and hold design review.	√	**IIIa, IVa**
	3.	Verify assembled BSCCO cable meets specifications or obtain a waiver from Niagara Mohawk that exceptions are allowable.	√	**IVd**
	4.	Demonstrate BSCCO cable reliability, durability and maintainability under "real world" utility operating conditions.	√	**IVf**
	5.	Demonstrate hybrid BSCCO/YBCO cable reliability, durability and maintainability under "real world" utility operating conditions.	√	**IVf, Ve**
	6.	Complete fabrication of 9.7 km of 40 A, 4 mm wide YBCO for the YBCO cable.	√	**Va**
	7.	Go/no go decision to proceed with YBCO cable fabrication.	√	**Vb**
	8.	Complete YBCO cable fabrication and pre-grid installation tests.	√	**Vd**
	9.	Complete cost vs. benefit analysis of HTS cable.	**P**	**VIIa**
Key	a.	Complete system impact report (Niagara Mohawk).	√	**Ib**
	b.	Complete preliminary design review.	√	**Ic**
	c.	Complete conceptual design review.	√	**Ic**
	d.	Procure BSCCO for 350 m cable, 80.3 km from SEI I_c = 60 A.	√	**IVb**
	e.	Verify performance of BSCCO cable.	√	
	f.	Complete fabrication of refrigeration system.	√	**IIIb**
	g.	Complete BSCCO cable installation and pre-grid testing.	√	**IIIc, IVe**
	m.	Complete installation of 30 m YBCO cable and splice to BSCCO cable.	√	**Vd**
	n.	Complete BSCCO cable performance tests and confirm suitability for durability/reliability testing on the grid.	√	**IVe**
	o.	Complete YBCO cable detailed design and hold design review.	√	**Vc**
	p.	Complete failure mode analysis and incorporate into conceptual design.	√	**VIIb**
	q.	Complete study of the impact of the HTS cable on grid stability.	√	**VIIc**
	r.	Review Niagara Mohawk protection design for adequacy.	√	**IIc**
	t.	Confirm cable manufacturing process based on results of 30 m model cable testing.	√	**IVc**
	u.	Complete preparation of site for HTS cable installation.	√	**IIa**
	v.	Deliver 62 m of 40 A YBCO to SEI.	√	**Va, Vb**
	w.	Deliver 100 m and 200 m of 40 A YBCO to SEI.	√	**Va, Vb**
Program	h.	Prepare and submit monthly reports to NYSERDA.	**P**	**VIII**
	i.	Conduct project kick-off meeting – SuperPower, SEI, BOC, Niagara Mohawk, DOE and NYSERDA.	√	**VIII**
	j.	Conduct annual project review meetings.	√	**VIII**
	k.	Conduct quarterly project review meetings.	**P**	**VIII**
	l.	Submit final report.	√	**VIII**

1. √ - milestone accomplished, **P** – milestone partially accomplished.
2. Accomplishments section number.

Goals and Objectives

Goals and objectives in the form of a Work Breakdown Structure are listed here. Bold numbers in parentheses refer to the milestones listed in **Table 2**.

Task 1.0 HTS Cable Specification and Conceptual Design

The specifications of the HTS devices are confirmed and a conceptual design completed. The impact of the installation of the HTS cable on National Grid's system is studied.

1.1 Specifications

The specifications for the HTS cable and its cooling requirements (**1**) are confirmed by the team. National Grid will confirm the utility system requirements and SEI assisted by SuperPower and Linde will perform the studies to determine the feasibility of meeting these requirements.

1.2 System Impact Analysis

National Grid assisted by SuperPower will conduct system impact studies to evaluate how the installation of HTS cables will influence their grid. A report defining the potential generic benefits of HTS cables will be written (**a**).

1.3 Conceptual Design

SEI, assisted by SuperPower and BOC, will complete a conceptual design of the HTS cable considering the specifications previously developed and the state of the technology that will exist at the time the cable must be fabricated. The BSCCO cable will be flexible and capable of underground installation. A preliminary design review will be held with National Grid (**b**) before proceeding to the detailed design. The suitability of the 3-in-1 cryostat configuration will be verified (**c**). Linde, assisted by SEI and SuperPower, will complete the conceptual design of the Cryogenic Refrigeration System CRS) considering the specifications previously developed. The conceptual design will include a test and instrumentation plan for the Project.

Task 2.0 BSCCO Cable Detail Design/Analysis

The cable, including joint and terminations is designed by SEI with assistance from SuperPower and Linde to meet the specifications (**1**). Linde with assistance from SEI and SuperPower will design the CRS consisting of the mechanical refrigeration unit, pumped liquid nitrogen loop and heat exchangers, and back-up cooling capability. SEI will be responsible for integrating the CRS into the overall HTS cable system design and designing the cable vacuum system and underground piping components. The design will be based on the cold dielectric concept with three phases in one cryostat utilizing BSCCO manufactured by SEI. This activity will culminate in a design review (**2**).

Task 3.0 BSCCO Cable Fabrication/Assembly/Test

The BSCCO cable and associated refrigeration system is manufactured, integrated and tested to ensure that National Grid specifications are met (**3**) prior to installation on the grid.

3.1 BSCCO Procurement

SEI will establish the tape specifications and fabricate approximately 80.3 km of I_c = 60 A tape (**d**). The quantity assumes two conductor and one shield layer.

3.2 BSCCO Cable Suitability

During the first year of the Project, samples of BSCCO supplied by a vendor were extensively evaluated for mechanical strength, I_c degradation after bending, suitability of splices and AC losses. Due to the technical, schedule and cost risk to the Project, the decision was made to utilize 100% SEI BSCCO. A 30 m long test cable will be constructed and tested by SEI to confirm the manufacturing process before committing to the fabrication of the complete cable in Task 3.3 (**t**). The test cable will be fabricated with a bend and evaluated by SEI, utilizing one BSCCO core and two dummy cores. The cable will be tested for I_c, AC loss, voltage, mechanical properties and joint assembly.

3.3 Cable

The complete 350 m cable consisting of former, HTS phase wraps, shields, cold dielectric, standoffs, vacuum jacket and cryostat and including one splice, 30 m from one end, will be fabricated and tested in-house by SEI (**e**) utilizing SEI BSCCO (**d**). The cable will be tested at various stages of assembly to verify performance.

3.4 Cryogenics

The CRS will be manufactured by Linde (**f**) to meet the specifications (**1**). Linde will consult with SEI to ensure that the CRS is compatible with the HTS cable system. At a minimum the refrigeration system is expected to meet reliability criteria that will result in no more than nine (9) hours of unplanned down time annually.

3.5 Terminations/Joint

SEI will fabricate termination components for integration with the cable at the site. Termination and joint components will be tested to verify they meet specifications (**3**).

3.6 BSCCO Cable Sample Test

A short piece of the end of the cable will be removed and tested to verify that the cable meets specifications (**3**) including bending radius, AC voltage, impulse testing, AC loss and critical current. An installation test will also be conducted.

Task 4.0 Cable Installation/Pretest @ Albany

The BSCCO, and later a short 30 m YBCO, cable is installed at the Albany site. A parallel conventional cable is also installed to provide redundancy should any operational problems arise. The site is prepared for the installation of the HTS cable and, following the completion of testing, returned to conditions defined by National Grid.

4.1 BSCCO/YBCO Cable System Installation

SEI assisted by the other team members will install and pretest the 350 m long BSCCO cable with splice, terminations and CRS at the selected site (**g**) for performance and reliability/durability/ maintainability testing and evaluation. Linde will provide/install/commission the CRS and external liquid nitrogen tank with the assistance of SEI. SEI will be responsible for integration of the CRS into the cable system. Installation will be predicated on the successful demonstration (**3**) that the cable meets the specifications (**1**) or a waiver from National Grid that exceptions are possible. Later a 30 m YBCO cable section will replace the 30 m section of BSCCO cable (**m**).

4.2 HTS Cable Site Infrastructure

SuperPower will have overall responsibility for preparing the Niagara Mohawk site for the installation of the HTS cable with assistance from other team members (**u**). This will include:

- A chiller and associated components;
- Back-up emergency generator and instrument air compressor;
- Installation of cable conduit;
- construction of the vault for the BSCCO to BSCCO/YBCO cable joint;
- a building to house the control and refrigeration systems and instrumentation;
- satisfying siting requirements for an external liquid nitrogen storage tank;
- supplying all necessary utilities for operation (electrical, water, compressed air, communications, HVAC, exhaust, alarms, etc.);
- concrete slabs and fencing for the terminations at each end; and
- roofs for the connections to terminations.

Linde is responsible for the cable monitoring and control system involving around-the-clock support through Linde's Remote Operations Center. This will include making operational data available through BOCNET to the other team members. Linde will provide the communication interface with National Grid that will be used to energize or de-energize the cable. The specifications for these items will be developed by SEI and Linde. The actual construction will be subcontracted by SuperPower.

A 6" diameter duct for the HTS cable and an 8" diameter duct for the LN_2 return will be installed. National Grid will be responsible for the integration of the HTS cable within its system, including the associated System Protection Scheme, which will be designed to protect the system from the consequences of an HTS cable failure, as more fully described under task 4.4 below.

4.3 HTS Cable Site Restoration

SuperPower will have overall responsibility for restoring the HTS cable associated portion of the site to conditions specified by National Grid. The actual restoration will be subcontracted by SuperPower to National Grid or another provider. SuperPower will consult with the other team members and DOE on the equipment to be removed and its disposition.

4.4 Conventional Cable Installation/System Protection Scheme

National Grid will install a conventional back-up cable in parallel with the HTS cable. This installation, designed by National Grid, will employ an appropriate System Protection Scheme so that the integrity and operation of the grid will be preserved if the HTS cable fails. In that event, the HTS cable will be isolated from the grid and operation switched to the conventional back-up cable. SuperPower and SEI will have joint responsibility for thoroughly reviewing the System Protection Scheme and deciding whether it provides adequate protection (**r**). The System Protection Scheme will be designed and procured by National Grid to isolate the HTS cable from the grid should an HTS failure occur and switch operation to the parallel conventional cable. The installation of risers, and switches at each end of the HTS cable and circuit breakers at the Riverside and Menands substations are contemplated.

<u>Task 5.0 BSCCO/YBCO Cable Test/Evaluation @ Albany</u>

SEI will oversee the testing of the HTS cable with assistance from the other team members.

5.1 Performance/Proof of Concept

SEI, with assistance from the other team members, will prepare a test plan factoring in National Grid's requirements for safe and reliable grid operation. After the cable and terminations are installed, the cable will be cooled down and tests conducted to verify conformance to specifications and suitability to operate on the grid (**n**). Linde, with assistance from the other team members, will prepare a test plan for evaluating the response of the CRS to extreme operating conditions, including back-up capability.

5.2 Durability/Reliability

Sustained operation on the grid will begin to address HTS cable reliability, durability and maintainability under real-world utility grid operating conditions (**4**, **5**). Initially, this will be for the 350 m BSCCO cable (**4**). These tests will continue after the 30 m YBCO section is spliced onto the BSCCO cable (**5**). During the testing and operation of the HTS cable National Grid will have the option at any time to switch from the HTS to conventional cable should, in its opinion, the integrity of the grid be in question. Linde will monitor and maintain the CRS, continue testing necessary to establish its reliability and robustness, and provide the ongoing monitoring and communication for the cable system.

Task 6.0 2nd Generation YBCO Cable Integration

Limited quantities of YBCO material with suitable performance and long piece lengths (greater than 100 m) will not be available until later in the Project. Since economies of large-scale manufacturing have not occurred the material is relatively expensive. Thus, both the available quantity and cost dictate that only a small section of cable can be manufactured using YBCO. Nevertheless, it is important to determine as early as possible the suitability of 2nd generation material for HTS cables. This task addresses HTS cable commercialization and includes the manufacture of a 30 m long cable that is joined onto the existing 320 m long BSCCO cable at a predetermined location (Task 4.1). The test evaluation of the hybrid, 320 m BSCCO + 30 m YBCO cable is conducted as the final part of Task 5.2.

6.1 Cable Design/Analysis

The cable is designed by SEI with assistance from SuperPower to meet the specifications (**1**). The design will be based to the extent possible on the existing BSCCO cable recognizing that differences in dimensions and performance of YBCO relative to BSCCO will require some design changes. This activity will culminate in a design review (**o**). It is not expected that this change will require modifications to the CRS. However, Linde will be consulted to verify this assumption.

6.2 YBCO Fabrication

SuperPower will fabricate short samples of 4 mm wide, I_c = 40 A YBCO practice tape for SEI evaluation. One 62 m delivery (**v**) and separate 100 m and 200 m deliveries will be made (**w**). SEI will ensure that the YBCO performance characteristics are incorporated into the overall cable design. 9.7 km of 4 mm wide, 40 A YBCO tape for the cable will be fabricated by SuperPower using its most advanced fabrication process at the time (**6**). Samples of YBCO practice and cable tape will be tested by SuperPower for performance, AC losses and windability.

6.3 Cable Fabrication

An approximately 30 m long section of YBCO cable will replace the 30 m long BSCCO cable between the joint and the South termination (**m**). The YBCO cable will be constructed by SEI utilizing YBCO tape supplied by SuperPower (**6**). Samples of YBCO tape provided by SuperPower (**v**, **w**) will be evaluated by SEI who will determine its suitability for use in the cable (**7**). The cable will be tested at various stages of assembly to verify performance and suitability for installation on the grid (**8**).

Task 7.0 HTS Cable Project Management

SuperPower is the Project manager. Each team member will internally manage its part of the program and will prepare monthly reports that will be combined by SuperPower into a single report for submittal to DOE and NYSERDA (**h**). A program kick-off meeting will be held within the first month (**i**). All Team members will support annual (**j**) and quarterly (**k**) program review and design review (**2**, **o**) meetings. The program review meetings will be scheduled by SuperPower on a quarterly basis. The program review meetings will address technical progress and expenditures compared to plan, evaluate program direction and the need, if any, for changes, assimilate new information and review commercial feasibility. A final Project review meeting will be held and a final report written (**l**).

Task 8.0 Market Research, Failure Mode Analysis (FMA) and Grid Stability

SuperPower, Linde and SEI will address the impact of HTS cables on the market, potential cable failure modes and the impact of the HTS cable on National Grid's 34.5 kV network in Albany.

8.1 Economic Application Niche (cost vs. benefit) Analysis

The SuperPower projected costs for HTS cables will be updated and a cost vs. benefit analysis performed to determine what changes, if any, there will be with respect to the cable market originally estimated by SuperPower (**9**). SEI and Linde will assist SuperPower by providing estimated production costs for HTS cables and the CRS, respectively.

8.2 Failure Mode Analysis

SEI assisted by SuperPower and Linde will conduct a study to evaluate the failure modes of all major components of the HTS cable and its auxiliary equipment (**p**). Examples include the CRS (Linde), loss of vacuum, short circuit and HTS cable defects. The impact of a failure on the traditional components of the circuit will also be assessed with assistance from National Grid. The results of this analysis will be incorporated into the HTS cable conceptual design.

8.3 Grid Stability Study

SuperPower will conduct a before and after HTS cable installation grid stability study on the 34.5 kV Niagara Mohawk network in Albany. A report outlining the impact of installing the HTS cable on the stability of the existing 34.5 kV National Grid network will be completed (**q**) with National Grid and SEI assistance.

Accomplishments

In the interest of improving readability and comprehension, accomplishments are reported in a more logical sequence than that contained in the Work Breakdown Structure (WBS). All WBS elements are addressed but in revised order. As was the case in **Goals and Objectives** bold numbers in parentheses refer to the milestones listed in **Table 2**.

I. HTS Cable Specification and System Conceptual Design (Task 1.0)

a. Specifications (Task 1.1)

The specifications for the cable (350 m long, 34.5 kV, 800 Arms, 23 kA for 38 cycles fault) were confirmed (**1**) based on National Grid requirements and are well within the capabilities of existing BSCCO and estimated YBCO wire performance.

b. System Impact Analysis (Task 1.2)

The system impact analysis (see IIc) was completed (**a**) with the conclusion that with appropriate system protection safeguards there would be no impact on the National Grid network from the HTS cable. Any potential problems were mitigated by the existence of a parallel conventional cable which can, should an anomaly be detected in the HTS cable or CRS, be instantly switched into the circuit without impact on the grid.

c. Conceptual Design (Task 1.3)

The conceptual design was completed, **Figure 4**, and reviewed by the team members,

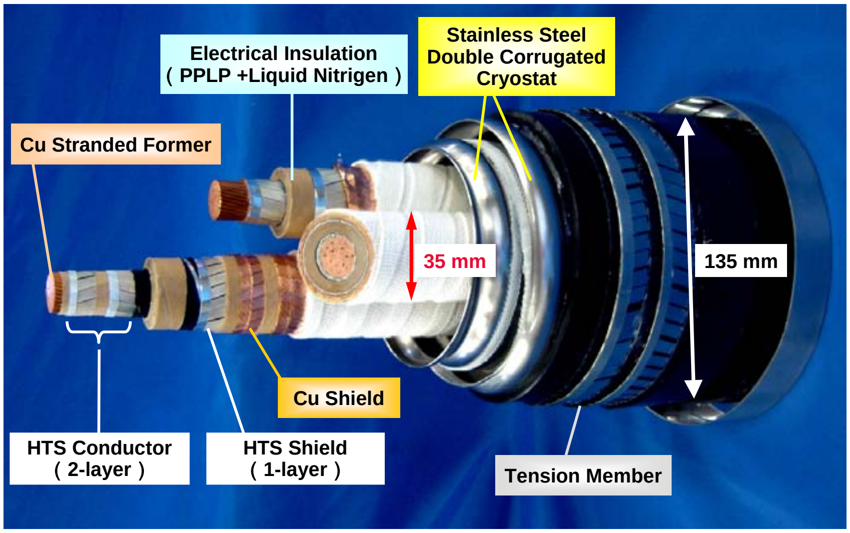


Figure 4 3-in-1 Cold Dielectric HTS Cable Design.

DOE and NYSERDA at the Conceptual Design Readiness Review (**b,c)** building upon SEI's earlier experience on the Tokyo Electric Power Company (TEPCO) project in Japan. A three cable cores (one for each electrical phase) in one cryostat cold dielectric, stranded copper core design was utilized. The HTS wire in each core (2 conductor and 1 shield layer for BSCCO) is wound around a copper former with cryogenic LN_2 cooling flowing around the three cores. The conductor shield layer and copper core provide capability to handle excess currents. Return LN_2 is provided by a separate cryogen return line similar in design to **Figure 4** but without the cable core.

Advantages of this design are:

- Compact size (5.3" outer diameter)
- Near perfect magnetic shielding (95% cancellation of field)
- Significant reduction in contraction (0.3%) forces due to slack winding
- Stainless steel tension members on outer wall for pulling
- AC loss minimized with equal current distribution among phases
- PPLP insulation with high dielectric strength and small tangential loss
- Excellent fault current protection
  - cable remains superconducting at worst fault condition with copper former and shield layer
  - survives extended duration fault (2nd contingency) without damage
- Low heat influx with stainless steel cryostat
- Stainless steel cryostat to minimize heat inflow

The conceptual design of the CRS was completed by Linde, **Figure 5**, and extensively reviewed the Conceptual Design Readiness Review (**b**, **c**).

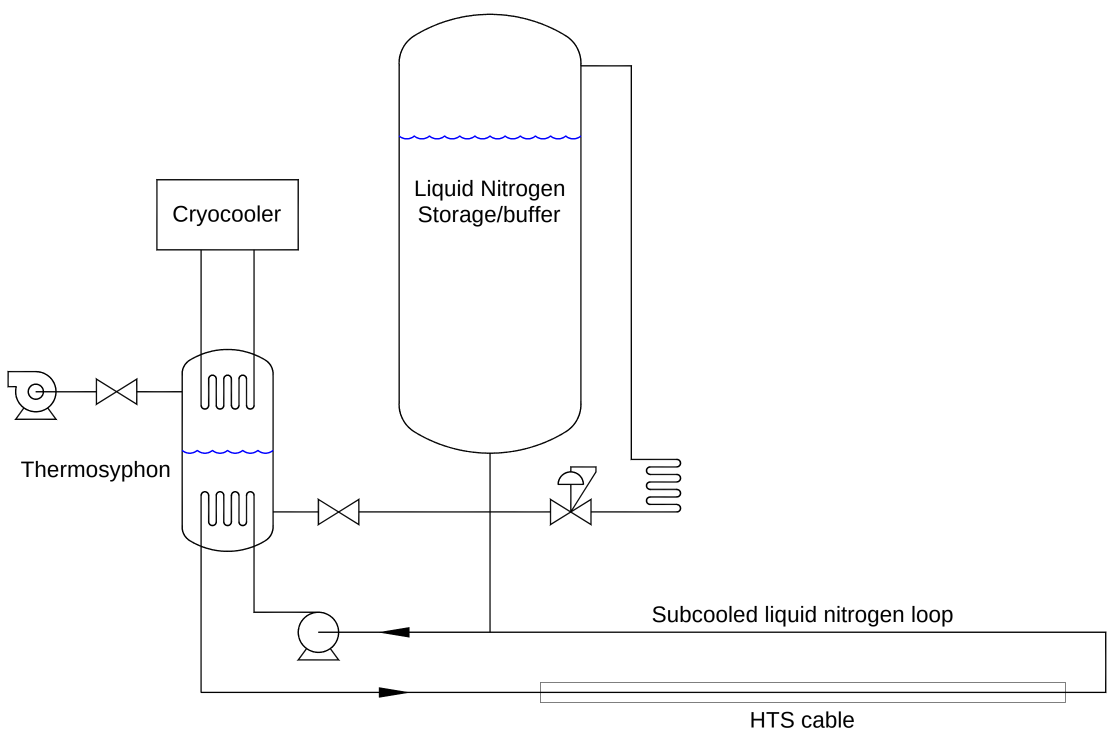


Figure 5 Cryogenic Refrigeration System (CRS) Design Approach.

The design consists of a revolutionary combination of open and closed cycle, or hybrid, cooling.which allows the transparent use of bulk liquid nitrogen as a backup. The thermosyphon provides a common heat exchanger interface between the HTS cable and open or closed refrigeration sources. This approach has excellent reliability/cost ratio, compact footprint, a flexible plug and play capability and good efficiency.

The primary cooling is closed loop mechanical (cryocooler) refrigeration providing a minimum of 5 kW @ 77º K and 3.7 kW @ 70º K. Normal operating temperature is 67 – 77º K ± 0.1º K, subcooled LN_2 operating pressures between 1 – 5 b_{gauge} ± 0.2 bar and cooling loop flow rates between 30 – 50 lpm ± 1 lpm. The backup cooling is provided by vaporizing bulk liquid nitrogen operating as a low pressure subcooler. In the backup mode the same conditions are maintained but with a ± 1º K loop temperature sensitivity.

II. HTS Cable Site Infrastructure and Remote Monitoring and Control

Prior to the installation of the cable and its associated equipment, it was necessary to prepare the site, develop a system to automatically control and monitor the HTS cable system, including the CRS, and to ensure there was adequate protection for the National Grid network should any problems be encountered.

a. Site Infrastructure and Restoration (Tasks 4.2 & 4.3)

Most of the cable and cryogenic equipment was located on National Grid property. However, a portion of the cable, as well as the North termination, was located on Delaware and Hudson (D&H) Railway property. The necessary permits and permissions for construction were obtained from the City of Albany, the NYS Department of Environmental Conservation, National Grid and D&H.. Since this was an underground HTS cable, it was necessary to install conduits, **Figure 1**. Three 6" diameter conduits were installed using horizontal directional drilling and open trench (for the 90º bend), **Figure 6**, for the HTS cable, the LN2 return line and instrumentation leads, respectively.

Figure 6 Conduit Installation.

A vault was fabricated and placed underground for the cable-to-cable joint, **Figure 7**, and concrete pads and footings were poured for the two terminations and an LN_2 storage tank. A prefabricated building was erected to house the CRS, **Figure 8** (**u**).

Figure 7 Underground Vault Installation for Cable-to-Cable Joint.

Figure 8 Cryogenic Refrigeration System Building, LN_2 Storage Tank and South Termination.

Upon Project completion, major equipment was removed from the site under SuperPower and National Grid supervision: the CRS by Linde and the conduit contents (HTS cables, cryogen return line, and instrumentation), terminations and joint by SEI.

Per agreement with National Grid and D&H Railway the underground vault and conduits were left in place with the latter cut off below ground level and capped.

Title to the CRS building was turned over to National Grid in exchange for them restoring the site to the desired condition. This entailed filling in the vault and leaving the concrete pads for the South termination and liquid N_2 tank intact. A similar agreement with Canadian Pacific transferred title to the fenced in concrete pad that contained the North termination.

b. Remote Monitoring and Control (Task 4.2)

Remote monitoring of the HTS cable system, as well as communications among the partners in the Project, **Figure 9**, was provided via hook-up to the BOC (now Linde) Remote Operations Center (ROC) in Bethlehem, PA, **Figure 10**. This existing facility was used to provide round-the-clock monitoring and control with a formal interface to National Grid's Eastern Regional Control Center. In the event of a problem the system would either intervene remotely or dispatch a trained crew from Linde's service center in Selkirk, NY, just South of the Albany cable site.

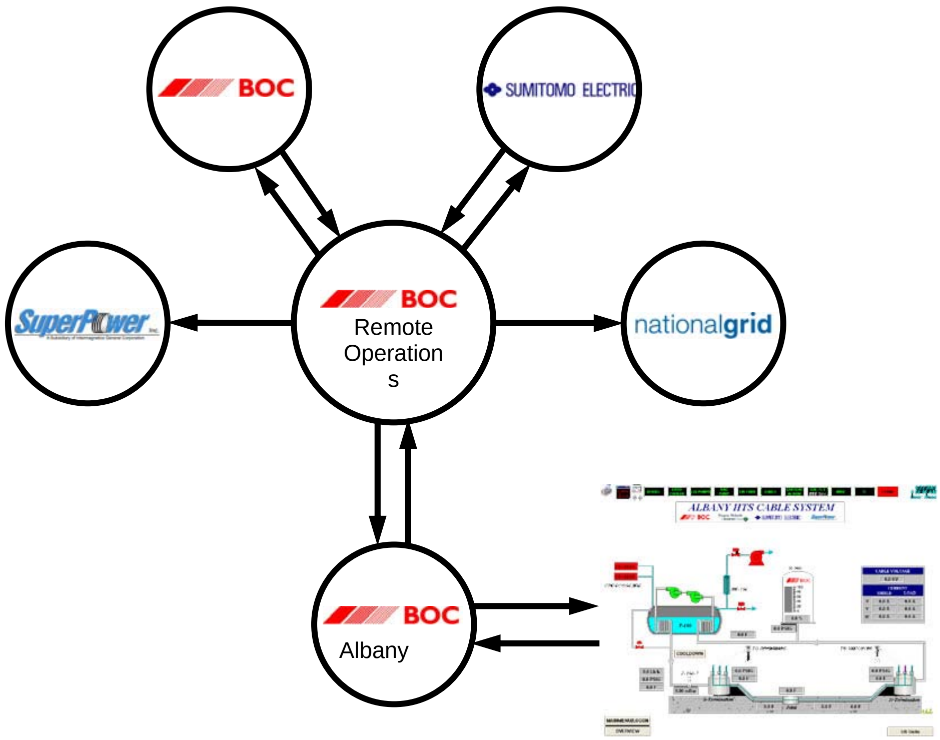


Figure 9 Albany Cable Project Communications Protocol via the Remote Operations Center.

Figure 10 Linde Remote Operations Center in Bethlehem, Pennsylvania.

The protocol for de-energizing the HTS cable entailed a direct telephone link between the ROC and Eastern Regional Control Center. This was used for scheduled (non-urgent) de-energization. If there was an urgent (system impacting) event the HTS cable would be de-energized and the load switched to the parallel conventional cable. For a critical event the HTS cable would be de-energized immediately and automatically by the protective circuit breakers.

In addition to the normal alarms, critical alarm logic was incorporated into the Linde Programmable Logic Controller installed at the site focusing on conditions that required immediate HTS cable de-energization. The system data structure was set-up so that there were groupings of similar measurements or calculations, e.g., HTS cable/coolant temperature, HTS cable pressure, LN_2 flow rate, etc. Typically, two independent measures within a data set and a time delay were required for a critical alarm to be initiated. Critical alarms were transmitted to National Grid via two independent signal paths.

c. Conventional Cable/System Protection (Task 4.4)

In order to preserve the integrity of National Grid's system, a parallel conventional cable was installed by National Grid in case the HTS cable encountered problems and had to be de-energized and a protection system designed and reviewed (**r**).

The system protection philosophy applied between the Riverside and Menands substations is indicated in **Figure 11**. The worst case fault determined by National Grid would be 23 kA_{rms} (33 kA_{peak}). The HTS cable was designed to withstand a 2^{nd} contingency of 23 kA_{rms} for 38 cycles, **Figure 12**.

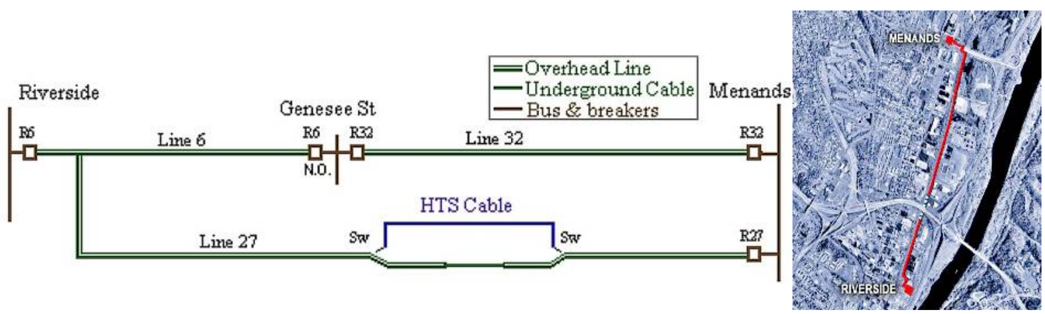


Figure 11 National Grid System Protection Scheme.

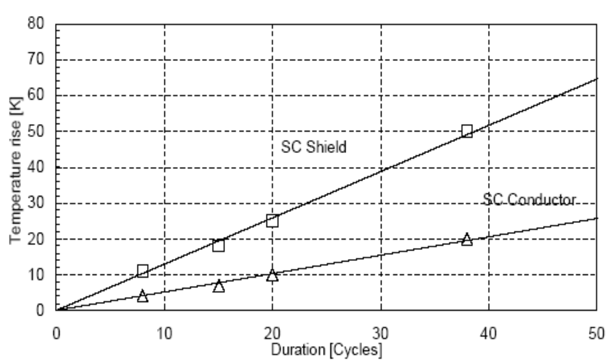


Figure 12 HTS Cable Temperature During 23 kA_{rms} Fault.

Multiple levels of relays and breakers were utilized for protection. The primary protection was the RFL-9300 charge comparison relays (87L) with 8 cycle clearing time located at Menands and Riverside. The secondary level consisted of the SEL-311B relay packages with 8 (zone 1) to 38 (zone 2) cycle clearing times. This secondary level consisted of three zones (80% of the line, 20% of the line and the 3rd outside of Riverside and Menands). Breaker failure protection was provided by initiating fault clearing by tripping breakers on the associated Riverside and Menands 34.5 kV buss, cleared in 20 – 50 cycles (0.33 – 0.83 seconds).

Overall system monitoring is provided by the ROC and National Grid Eastern Regional Control Center as previously described.

There was only one event where the system protection system came into play. On November 12, 2006 a breaker in another substation had an external flash over, subjecting the HTS cable to 7.3 kA peak current. Power was switched to the conventional parallel cable. There was no damage and the HTS cable was back on line four days later.

III. Cryogenic Refrigeration System (CRS)

a. CRS Design and Analysis (Task 2.0)

The detail design of the CRS was completed by Linde, **Figure 13** and reviewed at the Detail Design Readiness Review (**2**). Key features are the hybrid refrigeration scheme, with cryocoolers for normal operation and bulk nitrogen with a vacuum pump for backup, and an efficient thermosyphon heat exchanger. The CRS minimum design parameters are listed in **Table 3**.

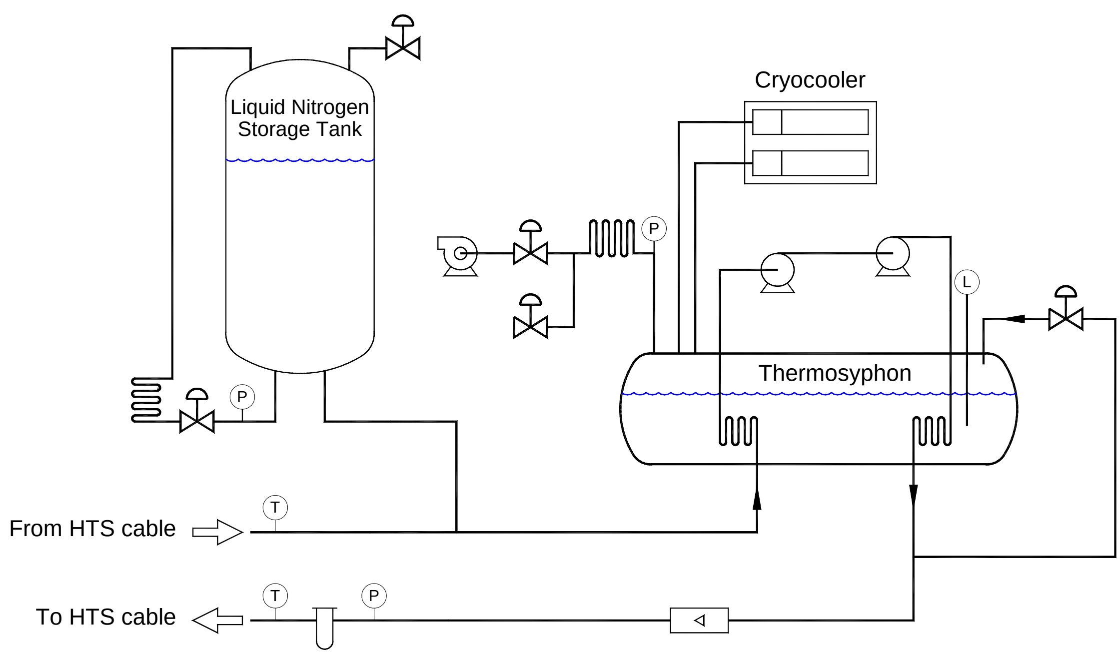


Figure 13 CRS Final Design.

Table 3 Cryogenic Refrigeration System Minimum Design Parameters.

Item	Specification
Coolant supply temperature	67 to 77 K
Temperature stability	+-0.1 K - normal operation
	+-1.0 K - backup operation
Refrigeration capacity	5 kW at 77 K
	3.7 kW at 70 K
Minimum coolant pressure	1 to 5 barg +-0.2
Maximum coolant flow rate	50 liter/min +-1

b. CRS Manufacture and Component Testing (Task 3.4)

The various components of the CRS, **Figure 14**, were manufactured (**f**) and tested by Linde prior to shipment to the site, **Figure 15**. The testing evaluated the performance and stability of the core CRS components: thermosyphon, cryocooler and liquid and vacuum pumps. The figure indicates the response to a step heat input of 2 kW (from 3 to 5 kW) at 30 liters/minute LN_2 flow rate. Performance was well within specifications.

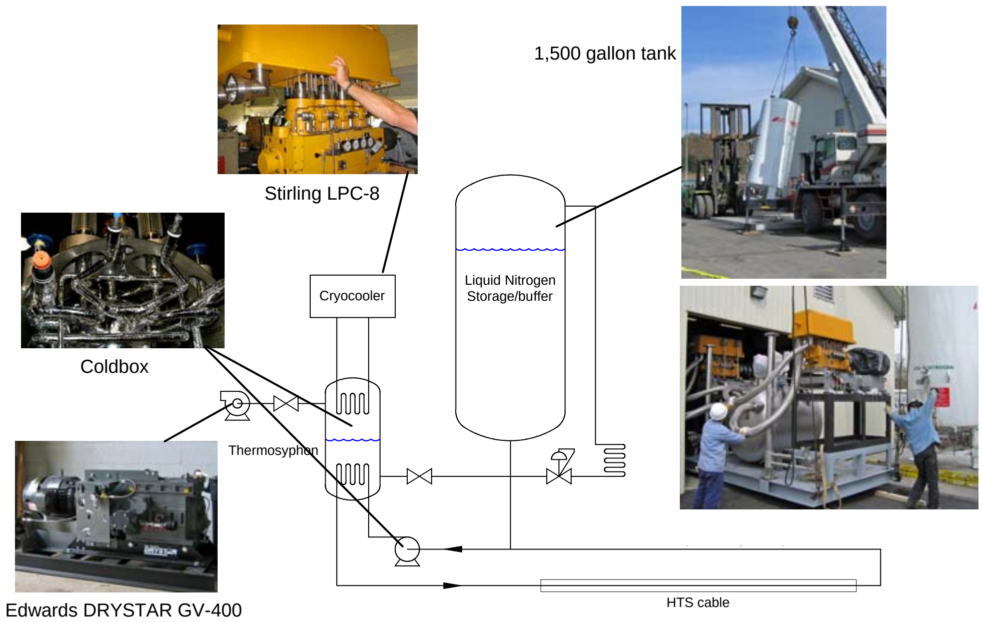


Figure 14 Cryogenic Refrigeration System Components.

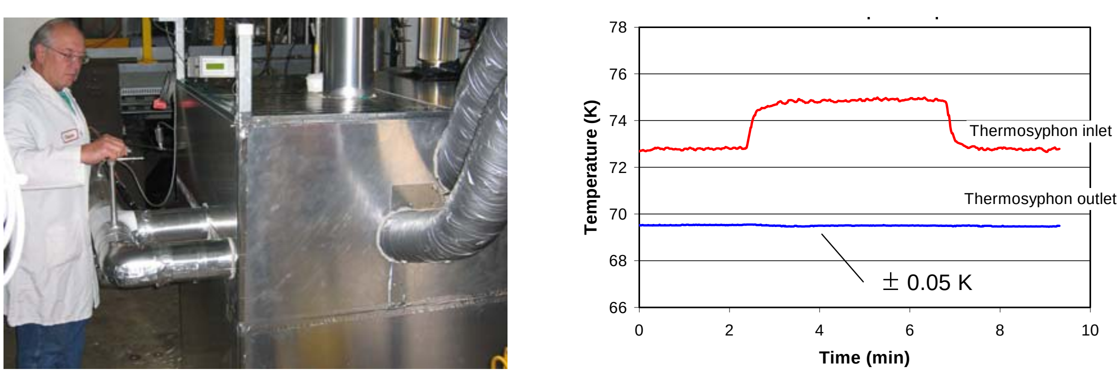


Figure 15 CRS Laboratory Testing.

c. CRS Installation and Pretesting (Task 4.1)

The CRS, **Figure 16**, was installed (**g**) by Linde (note: BOC at the time of installation). The cold box, containing the thermosyphon, and associated Stirling cryocoolers are indicated in **Figure 17**.

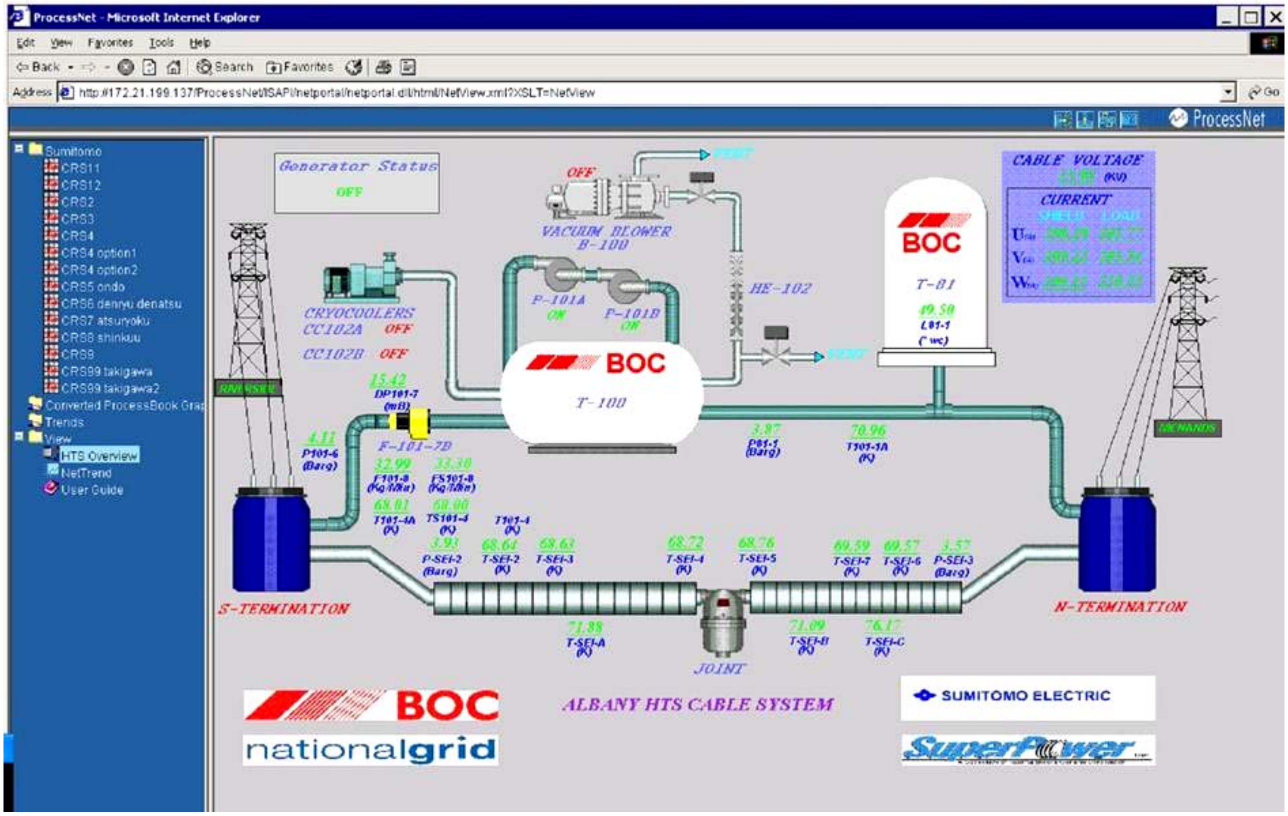


Figure 16 CRS Installed by Linde.

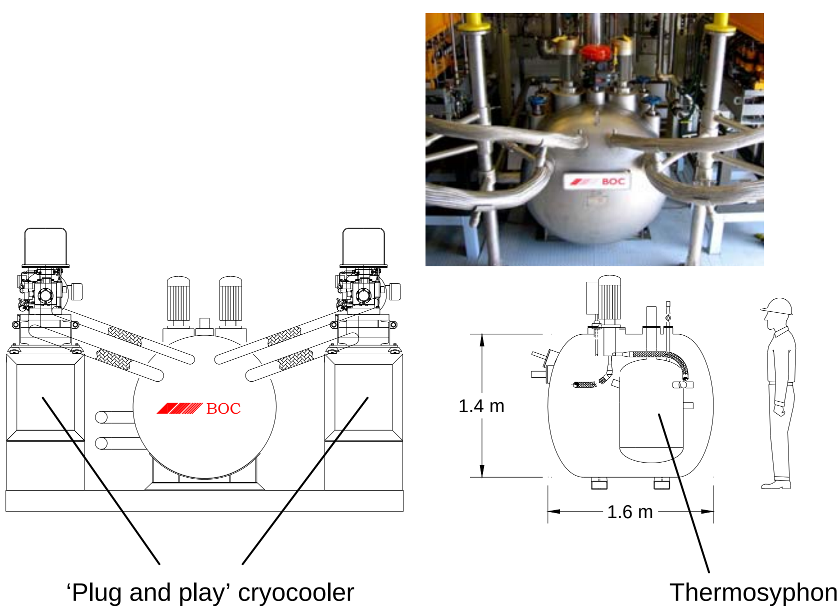


Figure 17 Cold Box With Thermosyphon and Associated Cryocoolers.

Following installation, the CRS was tested (**g**) to determine temperature response to a nominal 1.6 kW heat input, **Figure 18**, the worst case control scenario for normal (with cryocooler) and backup (without cryocooler) conditions. In either case the BSCCO cable outlet temperature was within acceptable limits.

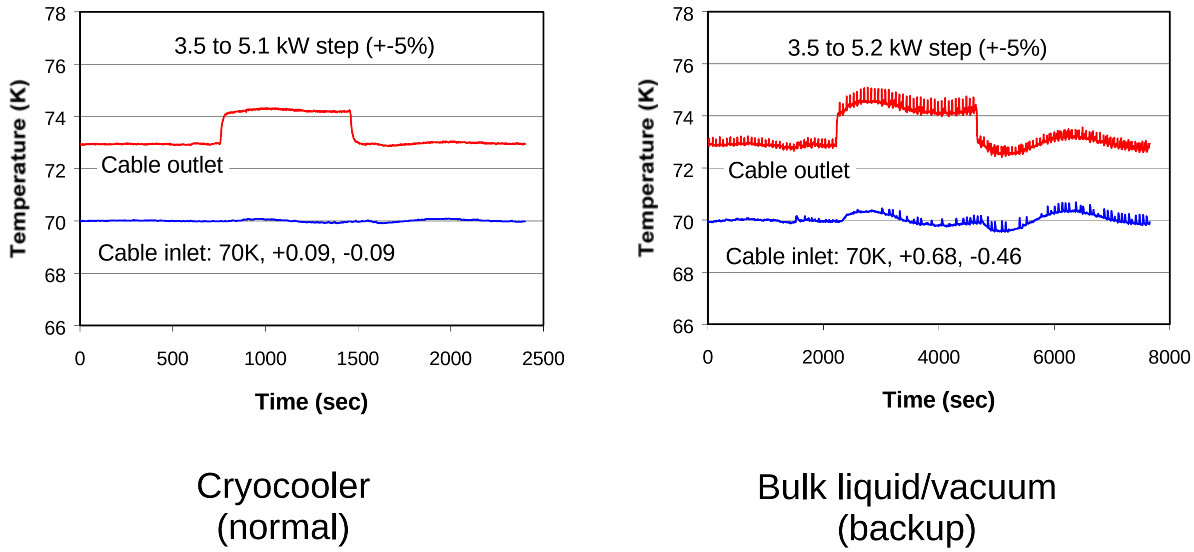


Figure 18 BSCCO Cable Inlet & Outlet Temperatures After 1.6 kW Step Increase in Heat Input.

The response of various CRS temperatures to BSCCO cable energization was evaluated, **Figure 19**.

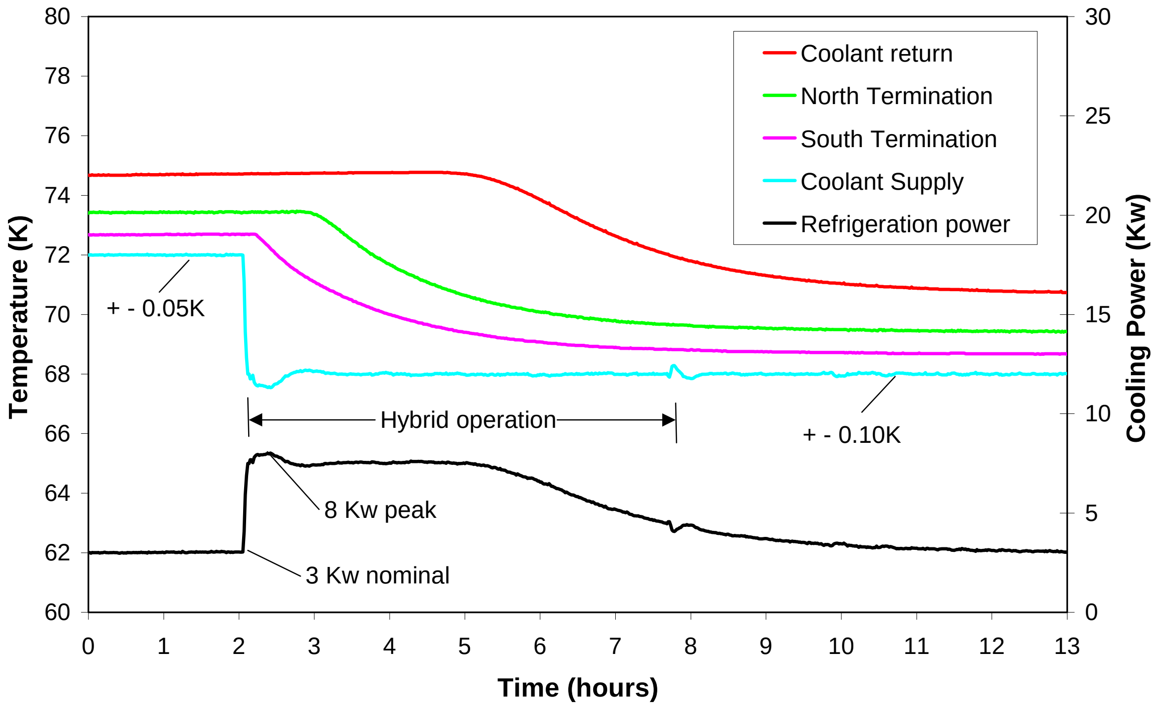


Figure 19 Cryogenic System Response to Energization (3 kW nominal before, 3.1 – 3.3 kW after).

In summary, the CRS system design, installation and test checkout (**g**) highlights were:

- Initial Hazardous Operations Review completed December 2003.
- Laboratory testing of core CRS testing completed September 2004.
- Final Hazardous Operations Review completed February 2005.
- Skid mounted CRS delivered to Albany cable site April 2005.
- All mechanical and control equipment installed and operational June 2005.
- Initial operation and performance testing of all equipment completed on site. July 2005 including controls and communication and primary and backup operation.
- All systems met or exceeded specifications (**1**).

IV. Phase 1 - BSCCO Cable, Terminations and Cable-to-Cable Joint

a. BSCCO Cable Detail Design and Analysis (Task 2.0)

Design of the BSCCO cable, **Figures 4** and **20**, and cable-to-cable joint and termination, **Figure 21**, was completed by SEI (**1**) and reviewed at the Detail Design Readiness Review (**2**).

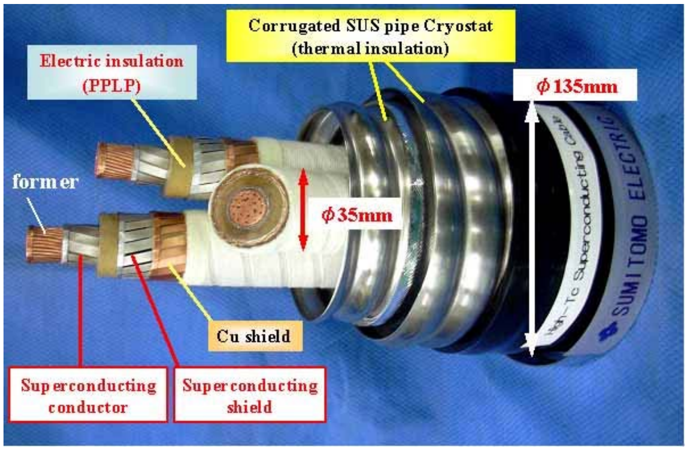


Figure 20 BSCCO Cable Design Details.

The termination design, **Figure 21** uses the thermally efficient three phases in one cryostat approach and is based on the technology used for the TEPCO project, e.g., FRP bushing, epoxy unit and current lead proven to be capable of withstanding electrical stresses. The LN_2 vessel was designed to ASME standards. Prior to finalizing the design a voltage test was successfully performed on a single phase model using a bushing and epoxy unit based on the IEEE standard of no breakdown up to AC 90 kV for 10 minutes and no breakdown up to +/- 200 kV impulse for 10 repetitions.

The cable-to-cable joint features a compact design based on TEPCO experience where the formers are connected manually and the HTS superconductors are connected with a low resistance joint. The vacuum space is independent of that for the cable cryostat. As was the case for the termination, tests were completed to verify the joint design. A 5 ton tension test was completed, **Figure 22**, and fault current capability verified – no damage of the connection after 23 kA for 38 cycles and a < 20º K temperature rise.

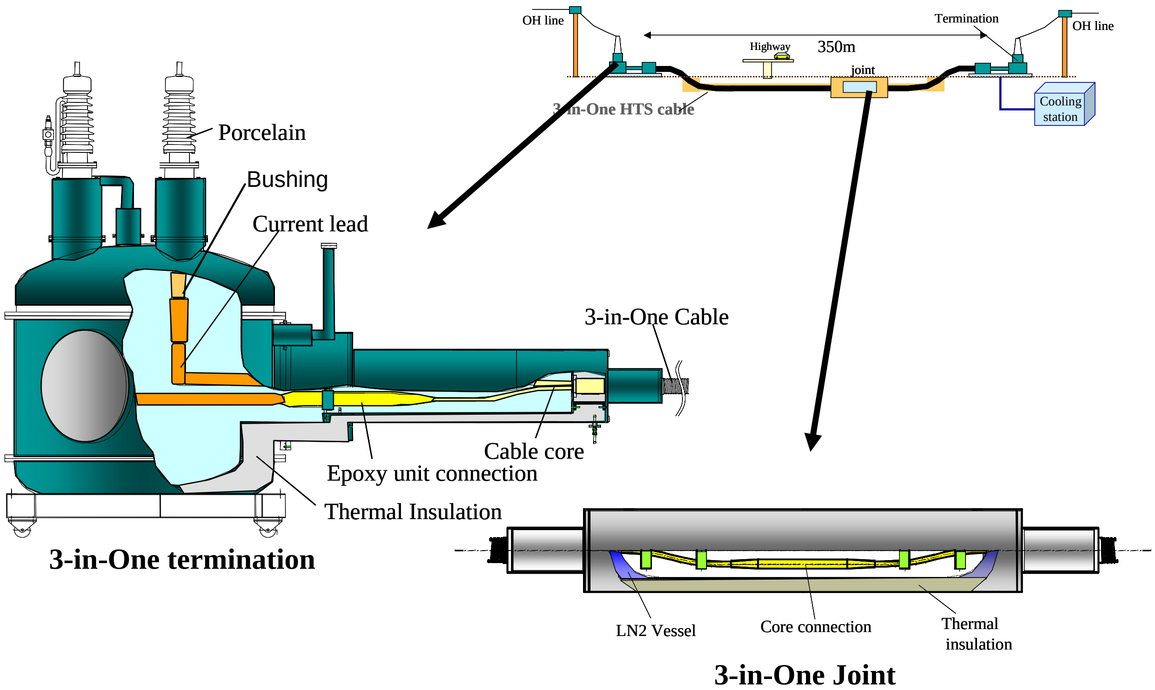


Figure 21 HTS Cable Joint and Termination Design.

Figure 22 Tension Test of Three Phase Cable-to-Cable Joint

b. BSCCO Conductor (Task 3.1)

The BSCCO selected and manufactured (**d**) for Phase 1 of the Project was SEI's drastically improved (DI) BSCCO manufactured by a controlled overpressure process in long lengths, **Figure 23** with the specifications indicated in **Table 4**. It is noted that the critical current (I_c) of this wire is well in excess of the Project requirement of 60 A.

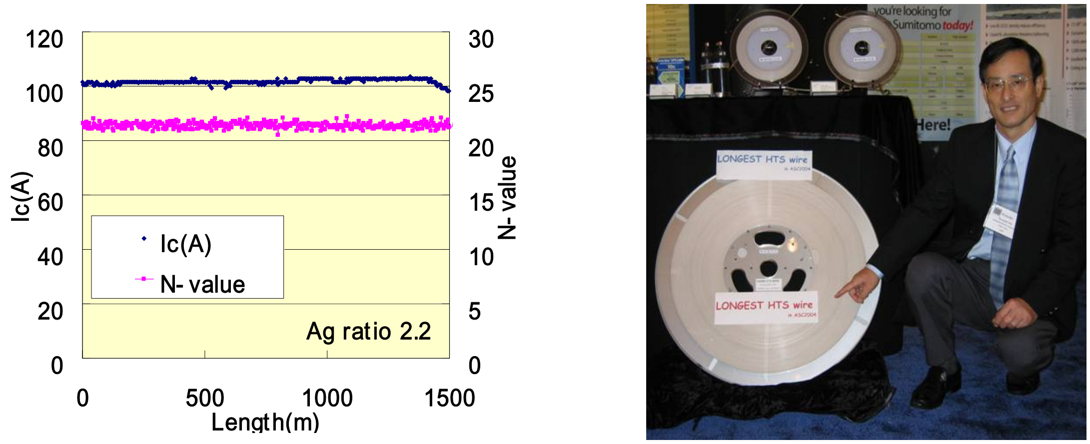


Figure 23 Long Length BSCCO Wire Manufactured by SEI.

Table 4 BSCCO Wire Specifications for Phase 1.

Quantity	70,000 m
Piece length	500 m
Size	Width： 4.1 ± 0.2 mm Thickness： 0.22 ± 0.02 mm
Ic	> 65 A (End-to-end)
N-value	> 15 (End-to-end)
Hermeticity	Liquid nitrogen immersion under 1 MPa for 24 H
Mechanical Properties	Critical tensile stress : >120 MPa Critical bending diameter : <100 mm Critical spiral winding pitch : <150 mm (16 mm former)

c. BSCCO Cable Proof-of-Concept Tests (Task 3.2)

Following the procurement of the BSCCO, a number of cable samples were manufactured and extensively tested to verify the suitability of the design prior to committing to the manufacture of the 320 m and 30 m BSCCO cables (**t**). In actuality, the approach was to manufacture a 350 m long cable and then cut it to form the two lengths once verification tests were completed on the model cables.

A three cable core sample as well as complete cable models were constructed and cut into 30 m and shorter 1 – 5 m long sections for various proof-of-concept tests, including a bending test around a 1.2 m radius, **Figure 24**.

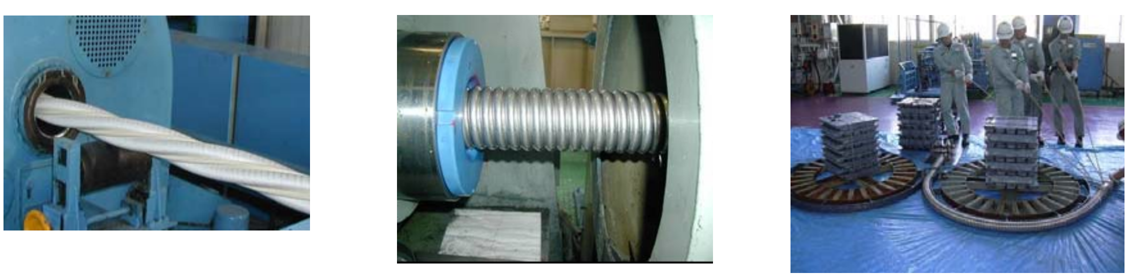


Figure 24 Core Sample (left), Corrugated Pipe (center) and Bend Test (right).

The performance of the BSCCO tape was evaluated after various stages of manufacturing and bending with no degradation observed, **Figure 25**.

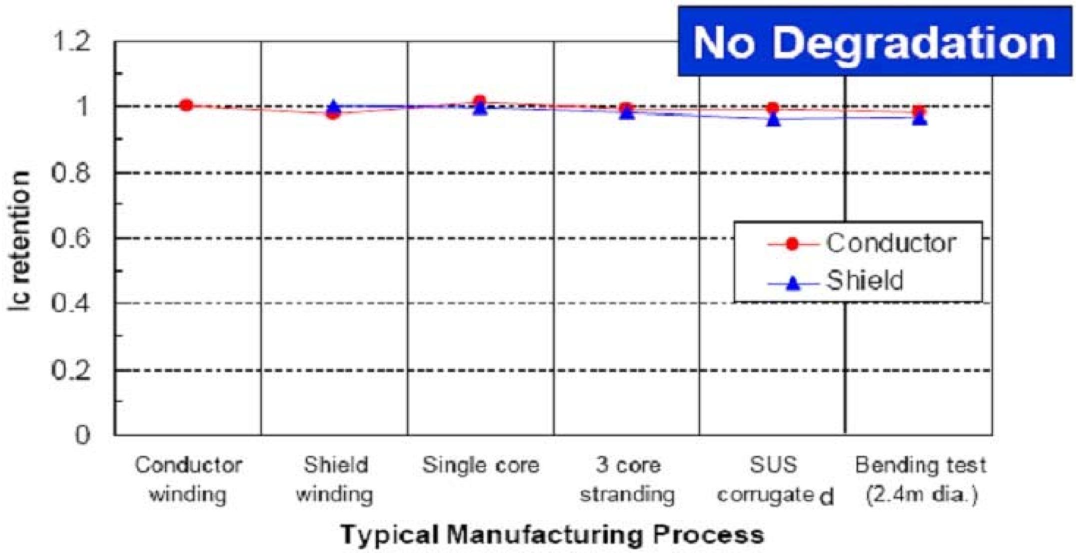


Figure 25 BSCCO Cable Critical Current Retention After Manufacturing and Bending.

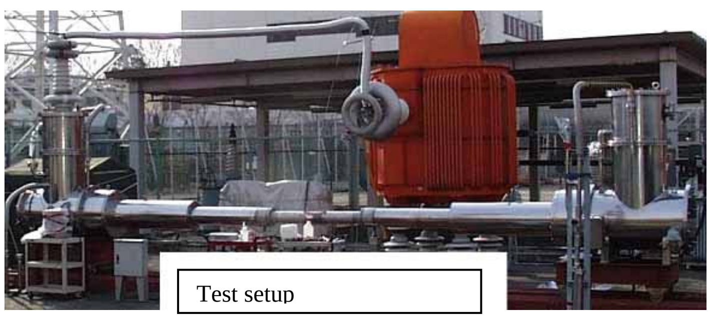
Another test conducted was to pull (3.5 tons of tension) a 30 m long corrugated pipe with tension members (the part of the cable surrounding the cable core) into a conduit with a 90º bend and 6 m radius. No mechanical deformation or elongation was noted.

Voltage tests conducted on a 30 m long cable core indicated no partial discharge or breakdown issues, **Table 5**.

Table 5 Voltage Tests of a 5 m Cable Core.

Test items	Parameter	Result
AC withstanding voltage test	69 kV for 10 min.	No partial discharge (Sensitivity 20 PC)
Lightning Impulse voltage test	±200 kV for 10 repetitions	No breakdown
DC withstanding voltage test	DC 100 kV for 5 min	No breakdown

LN2 condition is 72K at 0.1MPaG



Fault current tests were also conducted on a cable core sample, **Figure 26**, to verify that the required levels are satisfied:

Fault Current Conditions	Through Fault conditions
• 23 kA_{rms} (58 kA_{peak}) maximum • 1st contingency: 8 cycles for 133 ms • 2nd contingency: 38 cycles for 323 ms	• 9 kA for 25 cycles (417 ms) • 2.7 kA for 55 cycles (917 ms)

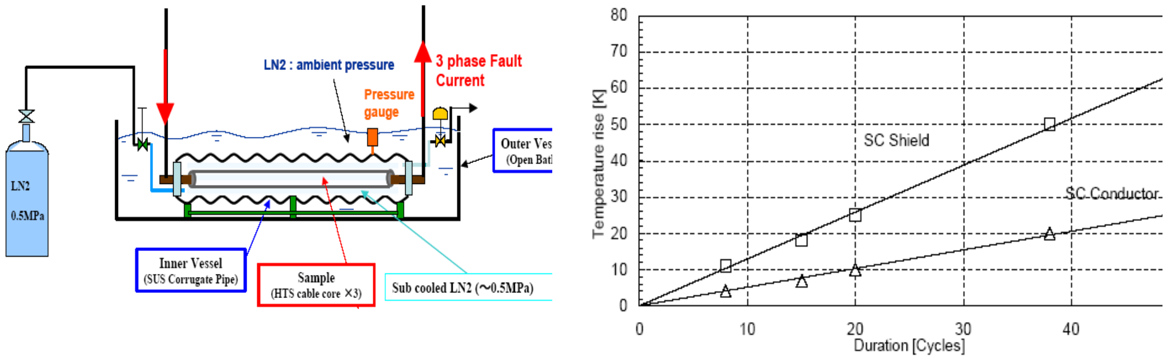


Figure 26 Cable Core Fault Current Test Setup and Results.

Test results indicated no damage to the HTS tapes or insulation and no degradation in critical current. The temperature rise was 4º K in the conductor layer and 11º K in the shield layer after 8 cycles and 20º K in the conductor layer and 50º K in the shield layer after 38 cycles. There was minimal temperature rise during the through faults.

A summary of the various proof-of-concept tests (**t**) performed on the cable, terminations, and joint is contained in **Table 6**.

Table 6 Proof-of-Concept Test Summary.

Mode	Items	Purpose	Status / Results	Remarks
Cable Design Confirmation	30m Cable manufacturing	New wire applicability New structure with Cu shielding	No Ic degradation or damage for the cable through inner SUS pipe process	
	AC loss measurement	Measuring AC loss	1.0 W/m at 800 A	
	Bending tests	Confirmation of minimum bending radius	No damage at 1.2m R (18 D) D: Cable diameter	based on AEIC
	Voltage tests	Confirmation of electric insulation properties	No break down at AC 69 kV* for 10 min at +-200kV* with 10 times at DC 100 kV for 5 min	based on AEIC *Voltage to ground
	Fault current test	Influence of the cable and coolant	No degradation of Ic or no damage on the cable insulation at 23kA for 8 cycles (1st) at 23kA for 38 cycles (2nd) at 9kA 25 cycle (through F) at 2.7 kA 55 cycle(through F)	
		Voltage test in N2 gas	No PD up to 42kV* in N2 gas at 100-170K at 0.2MPaG No PD up to 21kV* in N2 gas at RT at 0.2MPaG	*Voltage to ground
	Installation test	Performance of Tension Member	No damage or No elongations at 3.5 ton	Expected tension is 2.5 ton
	Cryostat cooling tests	Measuring thermal insulation	2.0 W/m with 50 m cryostat	Target <2.5 W/m
	350m Cryostat vacuuming test	Measuring vacuuming performance	on going	
Joint Design Confirmation	Connection of Joint tests	Electrical resistance Tension performance	small No damage up to 5 ton	
	Assembling and Electric voltage tests	Assembling method voltage performance	Planning	
Termination Design Confirmation	Electric voltage tests for single phase model	voltage performance	No breakdown at AC 90 kV, for 10 min. at +-200kV with 10 times at DC 100 kV for 5 min	based on IEEE

d. BSCCO Cable Manufacture and Pre-Shipment Testing (Task 4.1)

The two BSCCO cables, 320 m and 30 m in length as well as the 350 m long cryogen return line were manufactured by SEI and subjected to performance testing to demonstrate conformance to specification (**3**) prior to shipment to the Albany cable site, **Figure 27**. Testing demonstrating the capability to withstand 69 kV for 10 minutes and +/- 200 kV impulse for 10 cycles (AEIC requirements). Measured critical current was 1,800 A (DC), the same as design, and ac losses were 0.7 W/m/phase at 0.8 kA_{rms}, 60 Hz – the same as the design value. No degradation in critical current was observed after bending tests.

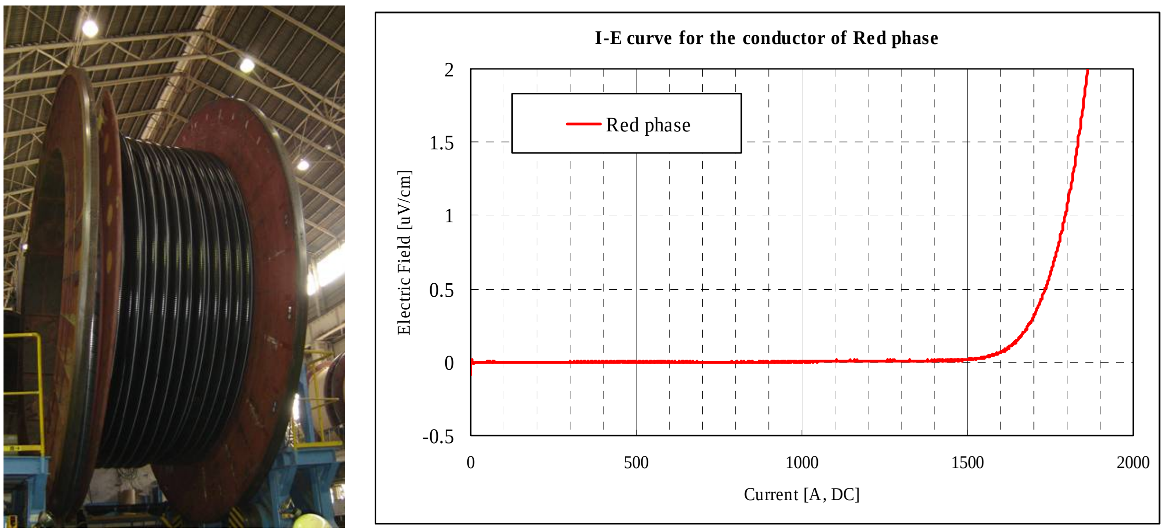


Figure 27 Electric Field Performance of BSCCO Cable.

The 350 m long cryogen return line was tested for vacuum with a leakage rate < 10^{-10} Pam^3/s indicated a vacuum maintenance level > 10 years, **Figure 28**.

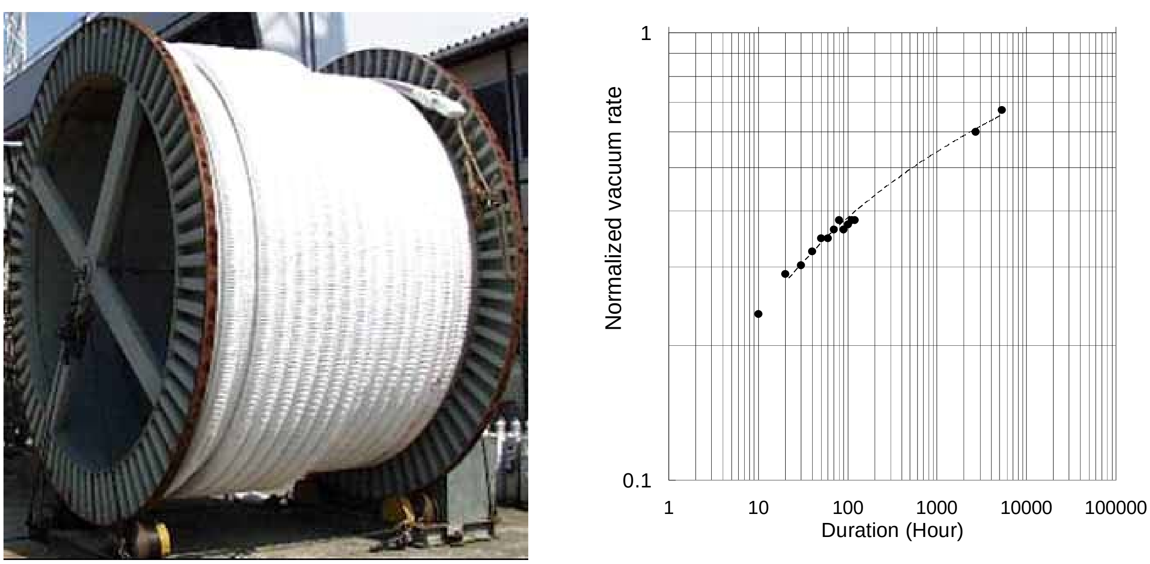


Figure 28 350 m Cryogen Return Line and Vacuum Test Results.

e. BSCCO Cable Installation and Commissioning (Tasks 4.1 and 5.1)

The various parts of the HTS cable (two cable sections, LN_2 return line and instrumentation lines) were installed in three underground conduits (previously discussed under ***Site Infrastructure***), the North and South terminations installed on their concrete pads and the cable connected to the terminations. The two cable sections were connected together in the underground vault. The BSCCO "cable" was wound onto three spools for shipment from Osaka, Japan to Albany, **Figure 29**. The three spools contain the 320 m long cable, the 30 m long cable and the LN_2 cryogen return line. The installation of the cables and return line used a push-pull method for the South and North terminations with the North pushing system illustrated in **Figure 30**. Pulling tension was close to estimated values, **Figure 29**. Installation entailed traversing one 90º bend and a 3m elevation changes, **Figure 31**.

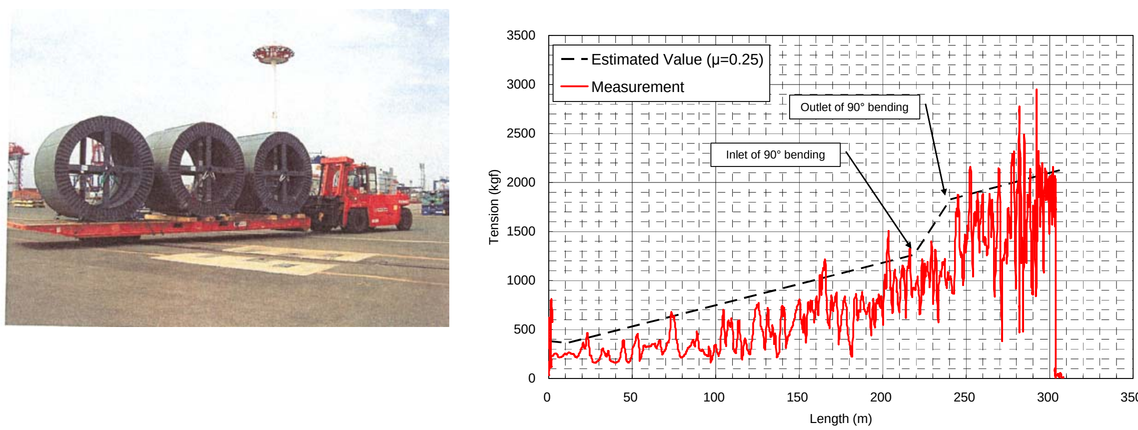


Figure 29 BSCCO Cables and Cryogen Return Line on Spools & Pulling Tension.

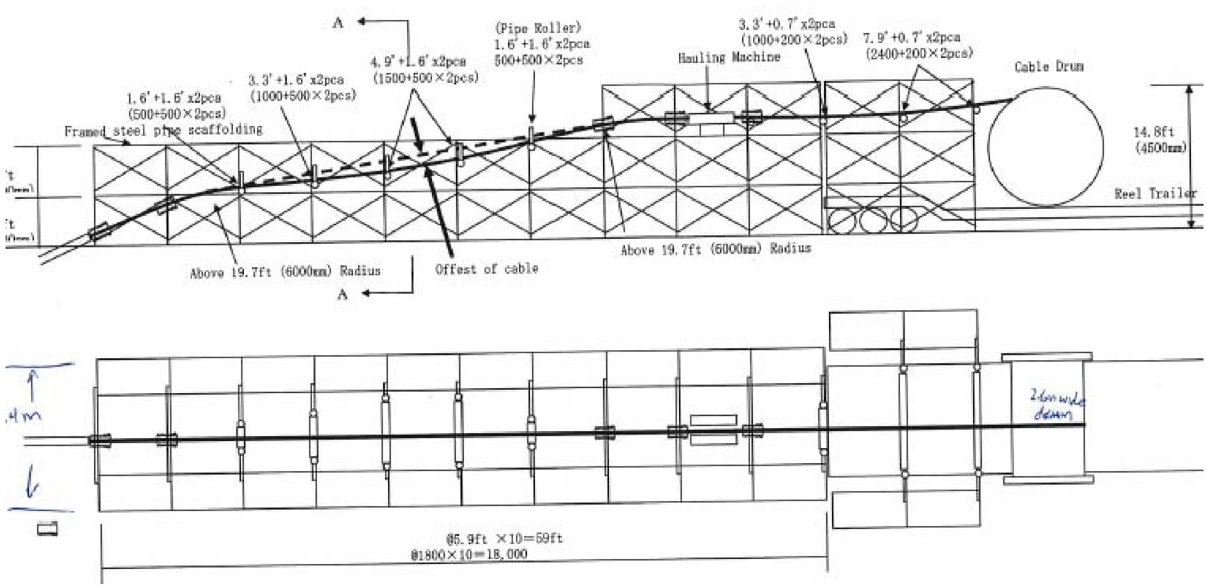


Figure 30 North Termination Installation of 320 m BSCCO Cable & LN_2 Return.

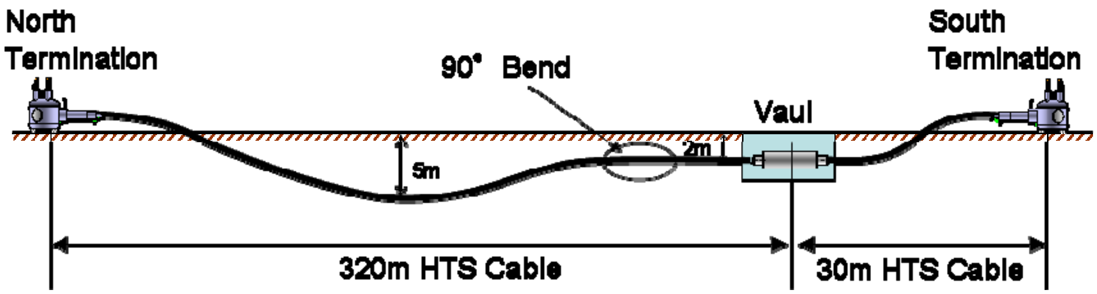


Figure 31 Cable/Return Line Conduit Path.

Various stages of the BSCCO cable, terminations and joint installation are illustrated in **Figure 32**. Clockwise from the top left: the 30 m cable being installed at the South termination end, cable-to-cable joint assembly, South termination, completed joint with cryostat and, cable pulling.

Figure 32 BSCCO Cable, Terminations and Joint Installation.

More details on the assembly of the joint and one termination are provided in **Figures 33** and **34**, respectively. The final stage of installation entailed installation of equipment for connection to the National Grid system, **Figure 35**.

Prior to actual connection the cable was cooled down and system temperatures and performance monitored, **Figures 36 – 38**, and verified (**g**). It is noted that no vacuum leaks developed during cooldown in any of the vacuum spaces. The maximum cable tension was approximately 800 kg – minimized by the slack winding approach used by SEI.

3 Cable cores before connecting

3 Cable cores after connecting

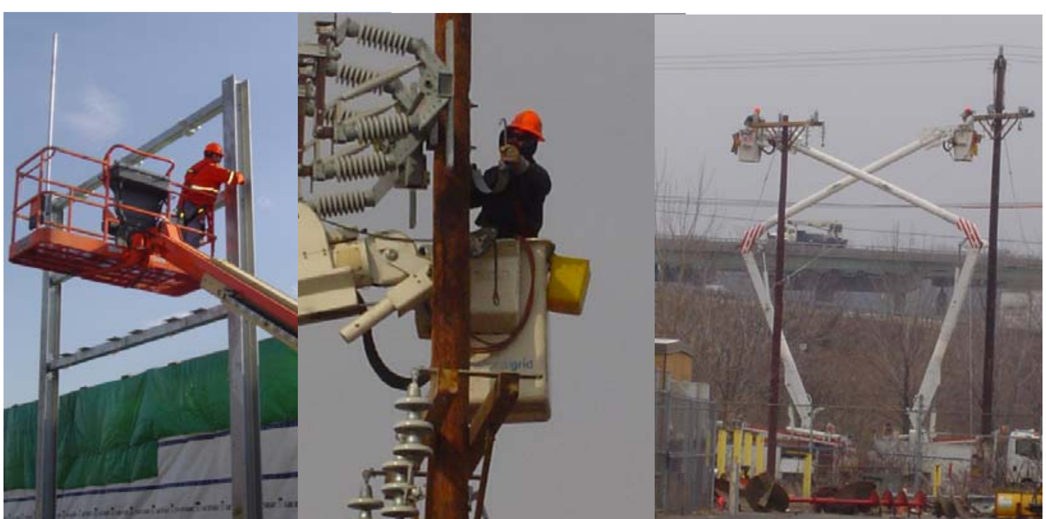
Joint box with vacuum vessel
(before covering with water-tight tapes)

Figure 33 BSCCO Cable-to-Cable Joint Assembly.

Spread three cable cores.

Three-in-one Termination

Figure 34 South Termination Assembly.



Take-Off Structure Installation

Installation of Disconnect Switches

Tie-in to Line 27 and Pulling Overhead Conductor

Figure 35 Connection of BSCCO Cable to National Grid System.

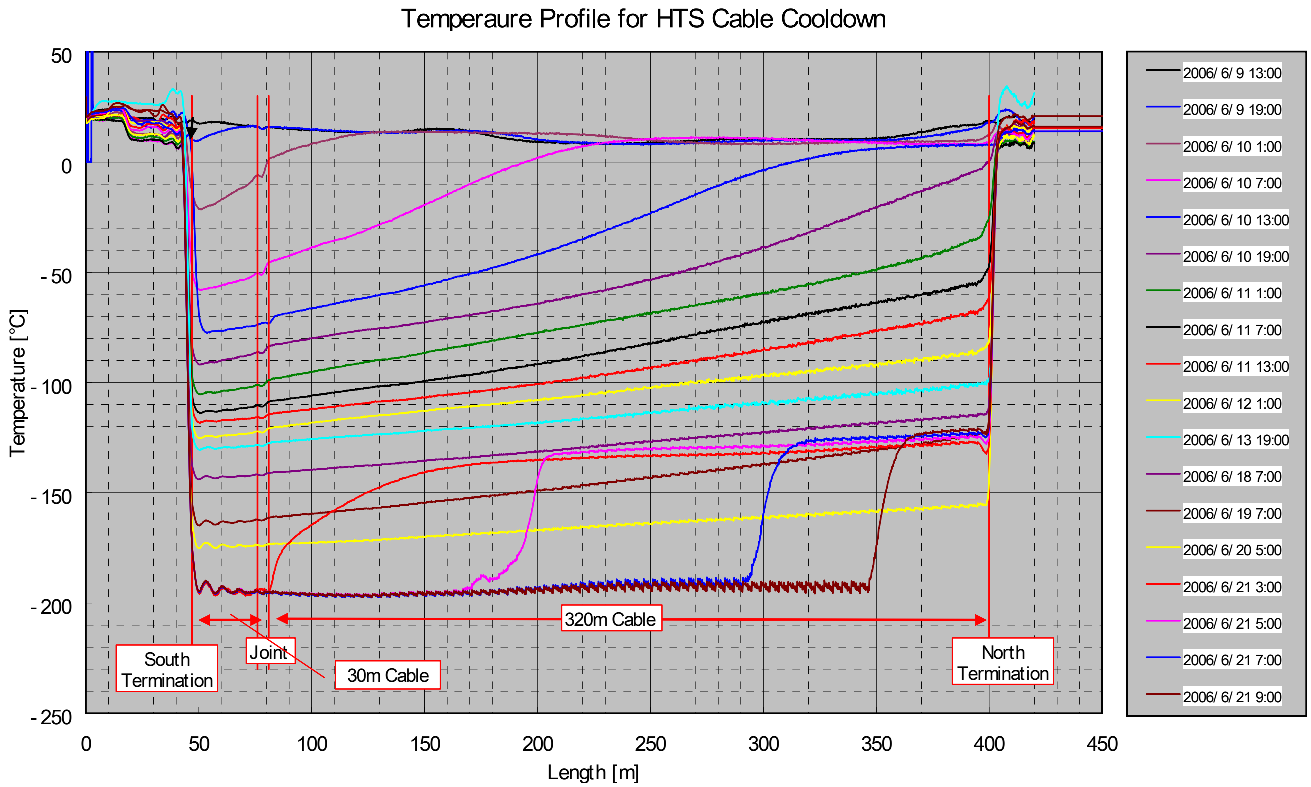


Figure 36 Temperature Profile of 320 m BSCCO Cable During Initial Cooldown.

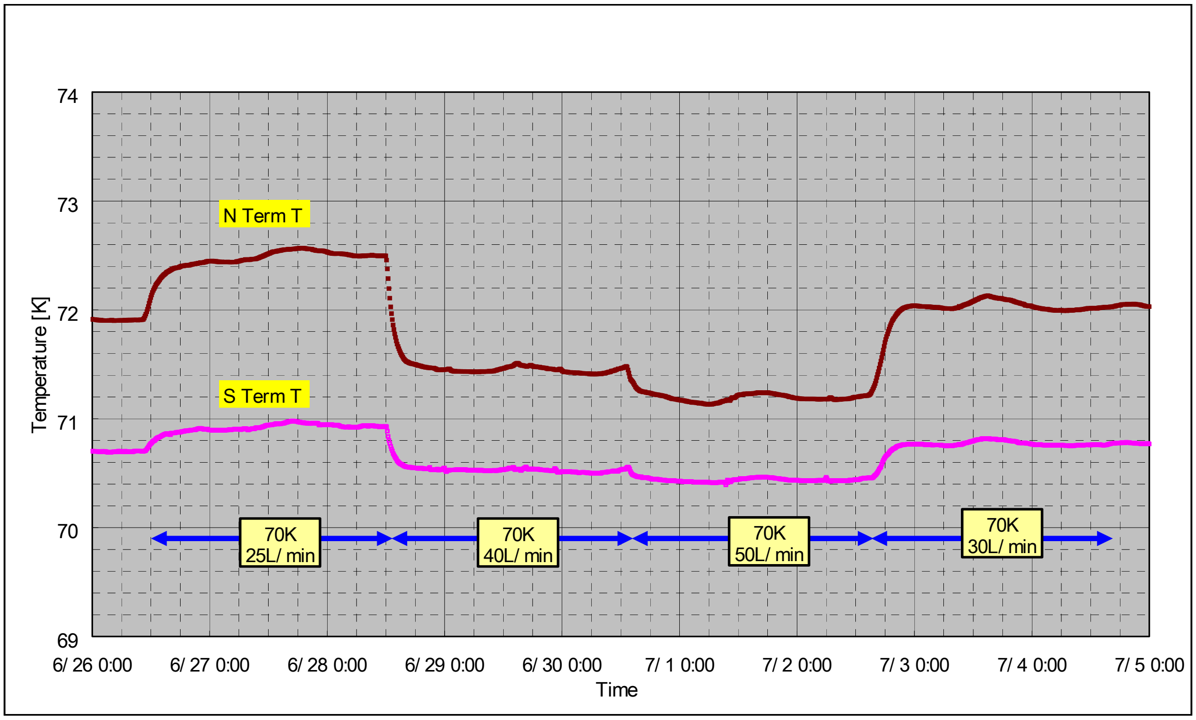


Figure 37 Temperatures at North and South Terminations During Initial Cooldown.

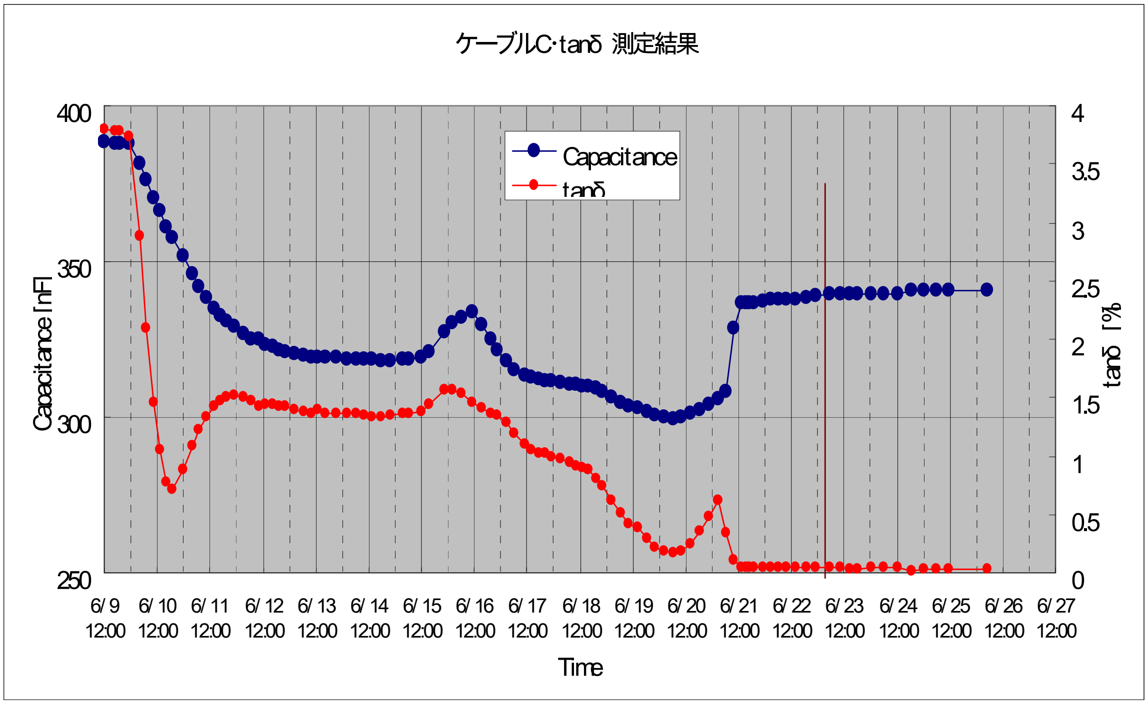


Figure 38 BSCCO Cable Capacitance and Tan-Delta During Initial Cooldown.

Once cooldown was completed the BSCCO cable system performance was verified (**n**). Pressure drop measurements indicate values close to design, **Figure 39**. Pressure stability tests conducted at 25, 30, 40 and 50 liters/minute indicated values within the design specification of ± 20 kPa.

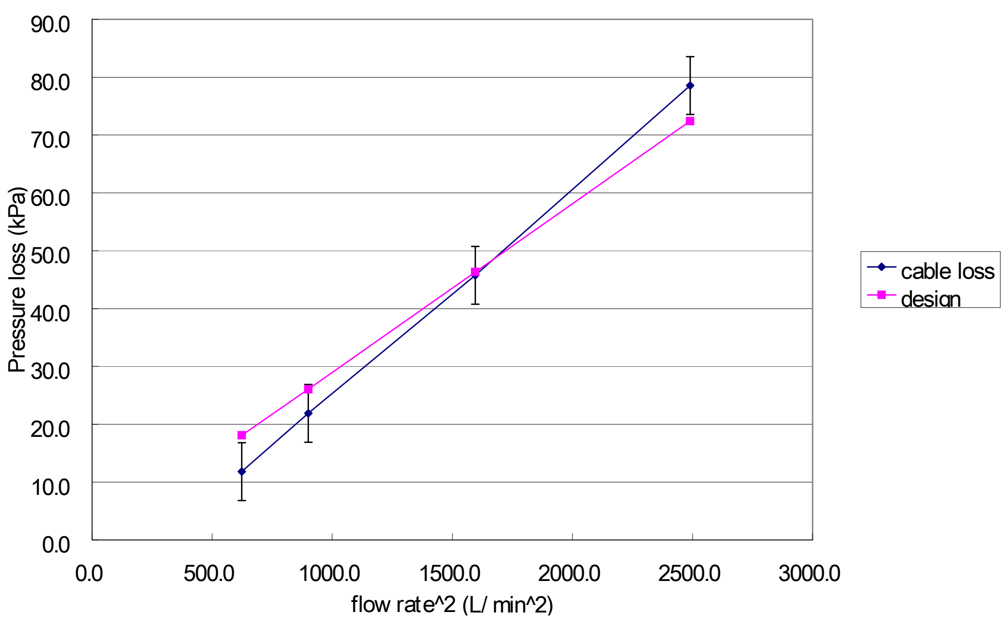


Figure 39 BSCCO Cable Measured Pressure Drop Between Terminations vs. Design.

Heat loss measurements confirmed values nearly identical to the design number of 0.96 kW, **Table 7**.

Table 7 BSCCO Cable Measured Heat Loss Between Terminations Without Power.

Flow Rate	30 l/m	40 l/m	50 l/m	Slope	Heat Loss*
350 m Cable	1.104 K	0.817 K	0.642 K	35 K (l/m)	1.0 kW
Total	3.536 K	2.610 K	2.115 K	108 K (l/m)	3.1 kW

* Heat loss = slope x density (841 kg/m^3 x specific heat (2037 J/kg). Valid for small pressure loss.

A summary of the commissioning tests is provided in **Figure 40** and **Table 8**. All design objectives were met (**1**) and the system readiness for grid connection verified (**n**).

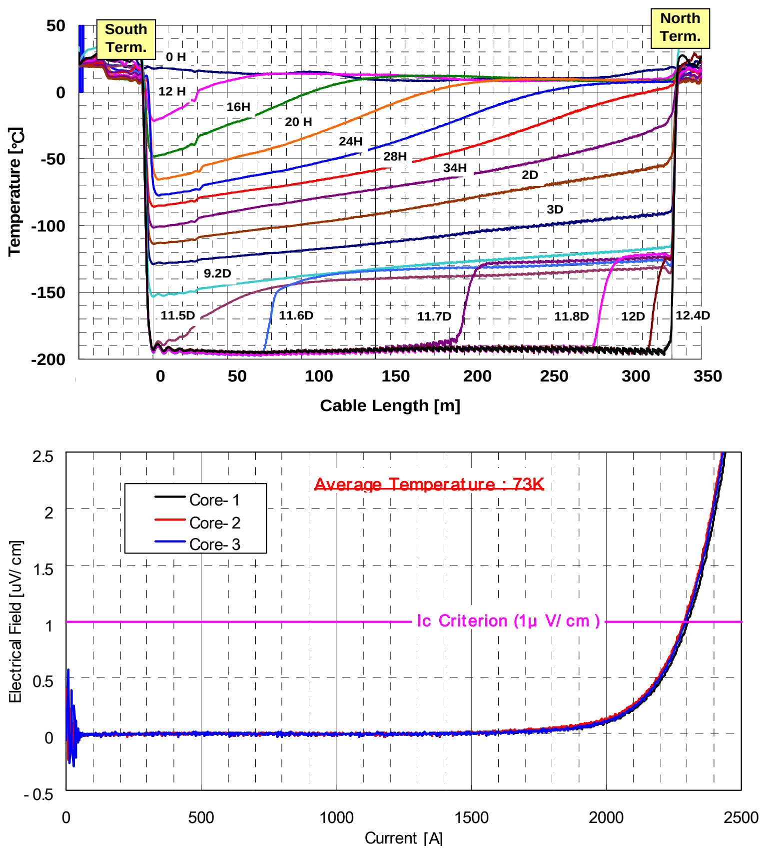


Figure 40 BSCCO Cable Commissioning Test Results.

Table 8 BSCCO Cable Commissioning Test Results Relative to Design.

Test	Result
System withstand pressure	• 0.61 MPAg (based on ASME code): good
Initial cooling test	• Maximum core tension (minimized by loose stranding): ~ 800 kg • Vacuum level at each part: good (no leakage) • Core behavior inside joint: within design scope
Ic (DC, 1 μV/cm)	• 2.3 kA @ 73° K, 2.8 kA @ 69° K – same as the design value
No load heat loss measurement	• 350 m cables (including joint): 1.0 kW • Entire cable system (not including CRS): 3.1 kW
DC withstand voltage	• 100 kV, each phase for 5 minutes (based on AEIC): good

Critical current (1 µV/cm) measurements yielded results well in excess of the design requirement of approximately 1,720 A. Phases 1, 2 and 3 were 2,300, 2,290 and 2,290 A, respectively. These measurements were made at an average LN_2 temperature of 73 K, tank pressure of 35 b_{gauge} and flow rate of 40 lpm. A final test was done to demonstrate the capability of the BSCCO cable to withstand DC voltage. Each phase was successfully subjected to 100 kV_{DC} for 5 minutes per AEIC (Association of Edison Illuminating Companies Code C55-94).

f. BSCCO Cable Durability/Reliability (Task 5.2)

The cable was connected to the National Grid system on July 20, 2006, **Figure 41**.

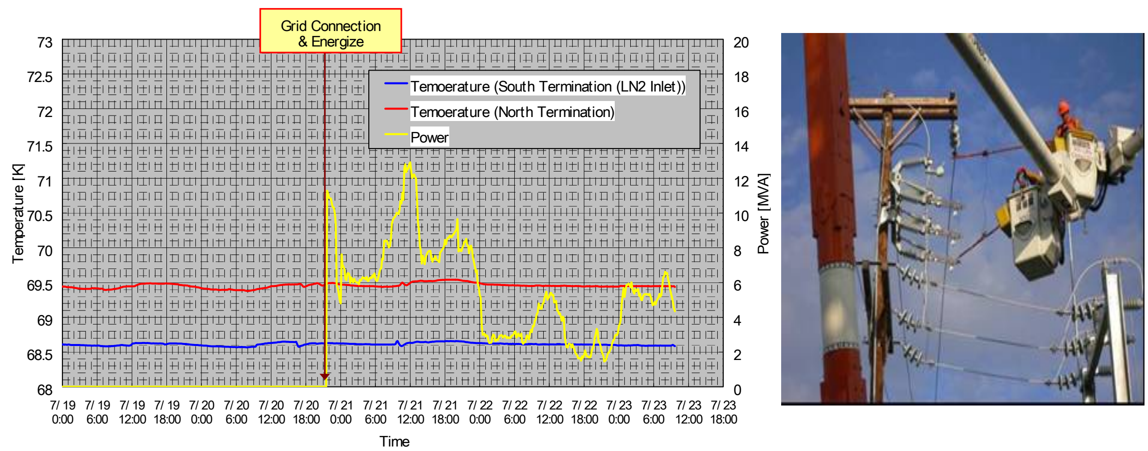


Figure 41 BSCCO Cable Connected To National Grid System on July 20, 2006.

Phase 1 (30 m BSCCO and 320 m BSCCO cables connected by an underground joint) successfully operated for more than 6,720 hours (280 days) until it was shut down for Phase 2 on May 1, 2007, **Figure 42**, demonstrating durability and reliability (**4**, **5**) There was one unscheduled shutdown due to a fault elsewhere in the National Grid system.

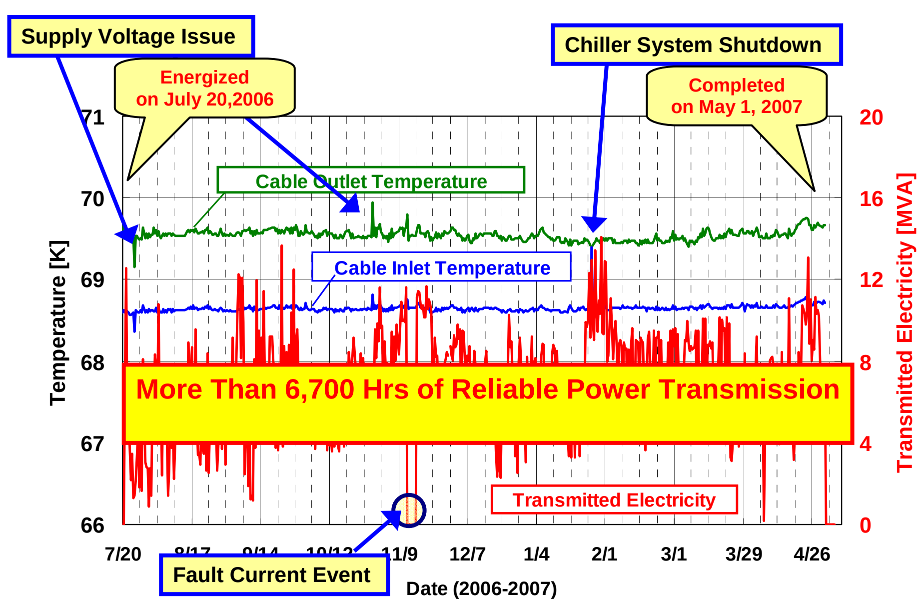


Figure 42 Phase 1 BSCCO Cable Operation.

In preparation for the YBCO cable installation, the system was warmed up and various checks made. There was no vacuum leakage and cable tension returned to its pretest value of approximately 200 kg compressive force.

V. Phase 2 - YBCO Cable and Termination/Joint Reassembly

During Phase 2 of the Project the 30 m long BSCCO cable, located between the South termination and the cable-to-cable joint in the vault, **Figures 1**, **21** and **31**, is replaced by a new cable section utilizing 2^{nd} generation YBCO conductor.

a. YBCO Conductor Development and Manufacture (Task 6.2)

For Phase 2 of the Project it was necessary to fabricate 9.7 km of 2^{nd} generation YBCO conductor. This amount of YBCO, in long lengths had never been fabricated before and was SuperPower's primary technical contribution to the Project entailing both development and manufacturing. This milestone (**6**) was successfully achieved. Smaller quantities (**v**, **w**) were also delivered to SEI for cable development. The YBCO conductor consists of multiple layers, **Figure 43**, and processing steps. The tapes are produced in 12 mm widths and then slit into 4 mm widths. Finally, the tape is surrounded by copper stabilizer after slitting.

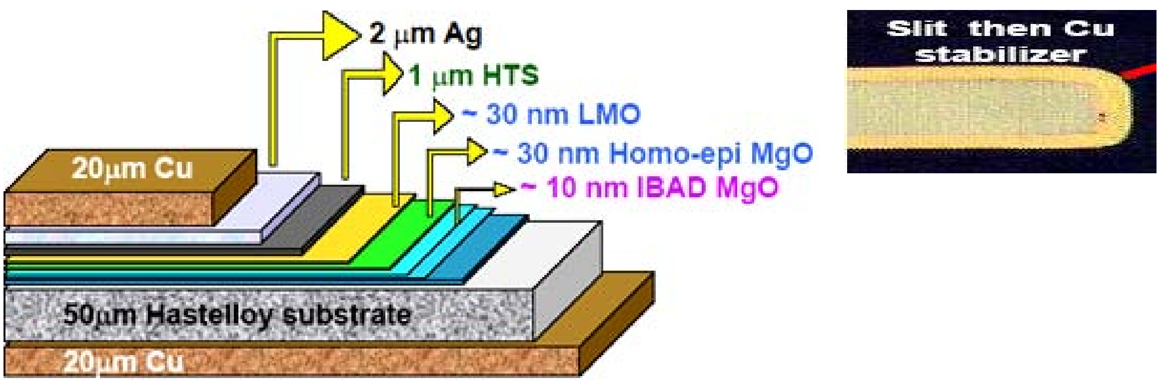


Figure 43 SuperPower YBCO Conductor Layers.

SuperPower, in collaboration with SEI, developed the YBCO specifications, **Table 9**.

Table 9 YBCO Tape Specifications.

Item	Specification
Dimensions	Width: 4.1 ± 0.5 mm, Thickness: 0.1 ± 0.02 mm
Minimum Piece Length	42.6 mm (33 pieces), 44.0 m (192 pieces)
Total Amount	9.6 km
Minimum Local Ic	40 A
Minimum Local N-value	15

The development of the YBCO conductor, produced by the MOCVD process, resulted in extraordinary progress in the production of long lengths and current carrying capability during the four years from approximately July 2002 through July 2006, **Figure 44**.

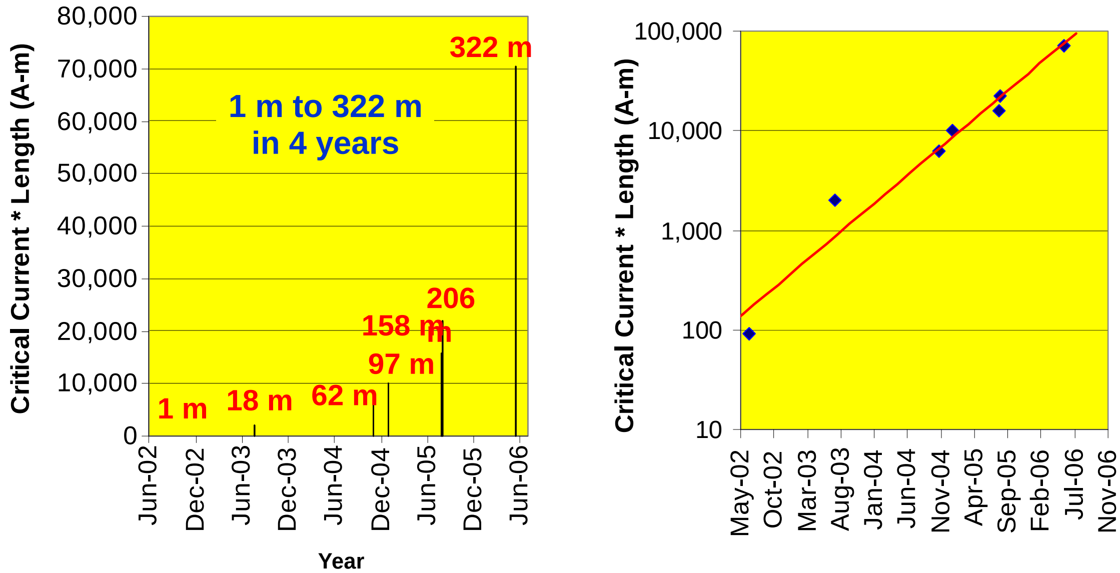


Figure 44 SuperPower Four-Year Progress in Fabricating Long-Length YBCO Conductor.

During 2006, YBCO conductor was produced in sufficient quantities, lengths and performance for use in the 30 m cable, **Figure 45**. The conductor was comparable in critical current (100 A over 270 m in 4 mm width) and had about twice the engineering critical current density, J_e, (26.3 kA/cm^2) as 1st generation BSCCO (13 – 17 kA/cm^2). The YBCO J_e includes 20 microns of surround copper stabilizer (40 microns total).

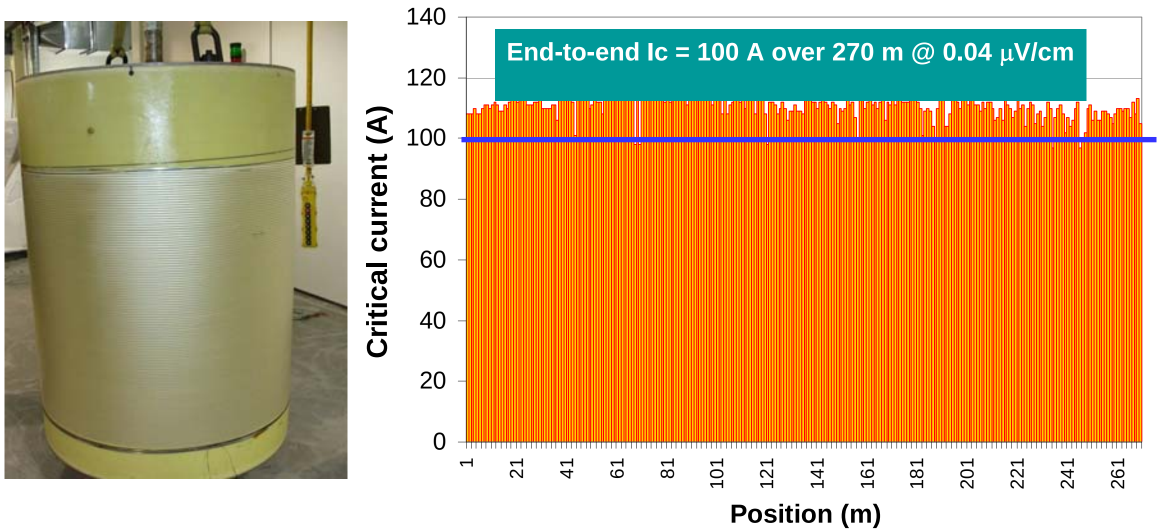


Figure 45 YBCO Conductor Long-Length Performance.

Beginning in May of that year, 300$^+$ m lengths of YBCO were routinely being produced, **Figure 46**. This compares to the specification requirement of 42.4 m. In total, 35% of the MOCVD tapes produced and 71% of those produced beginning in May were in excess of 200 m in length. Of those produced starting in May, 43% were in excess of 300 m in length. A total of 31 production runs produced 5,720 m of 12 mm wide tape – the equivalent of 17,160 m of 4 mm wide tape after slitting.

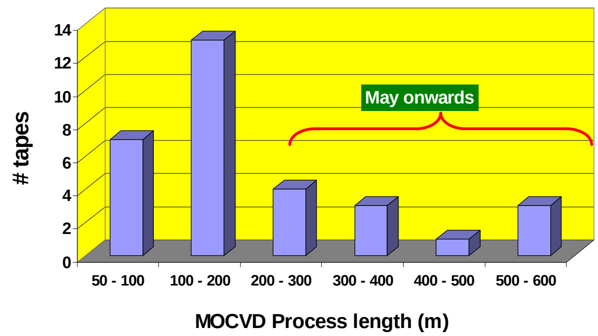


Figure 46 SuperPower Long-Length YBCO Conductor Manufacturing Summary.

The critical currents achieved in these long-length tapes were routinely in the 200 – 240 A/cm range, **Figure 47**.

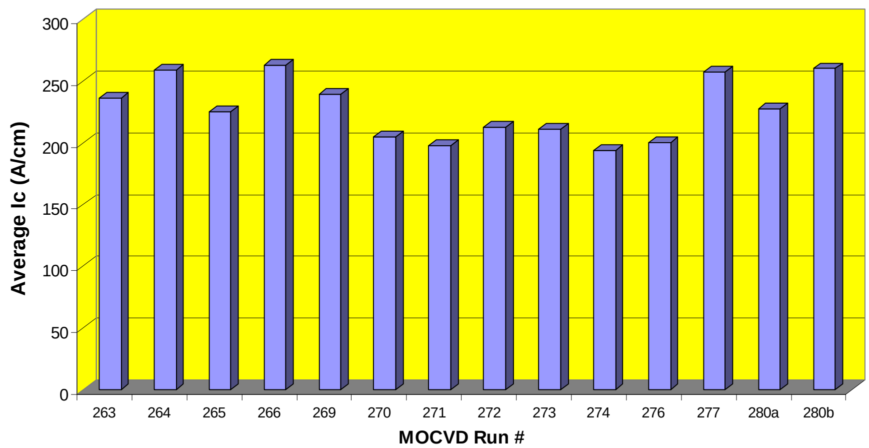


Figure 47 Critical Current of Long-Length YBCO Tapes After May 2006.

More than 12,000 m of qualified tape were produced in 2006 for the Project, **Figure 48**. 55% of these were greater than 100 m and 27% were greater than 200 m in length compared to the specification of 42.4 m.

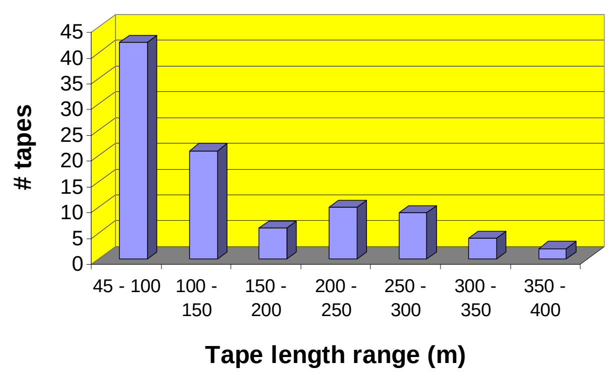


Figure 48 Long-Length Qualified YBCO Tape Produced by SuperPower.

Qualification of the YBCO tapes prior to shipment to SEI consisted of tests/measurements to confirm that all specifications, **Table 9**, were met as well as demonstrating hermeticity. Of the 9.7 km used in the fabrication of the 30 m YBCO cable (225 segments each 42.4 – 44.0 m long after cutting), the average minimum I_c was

70 A, well in excess of the 40 A requirement. 56% of these segments had I_c > 70 A. The average minimum n-value of the 225 segments was 24, again well in excess of the specification. 56% of these had n-values greater than 25, **Figure 49**.

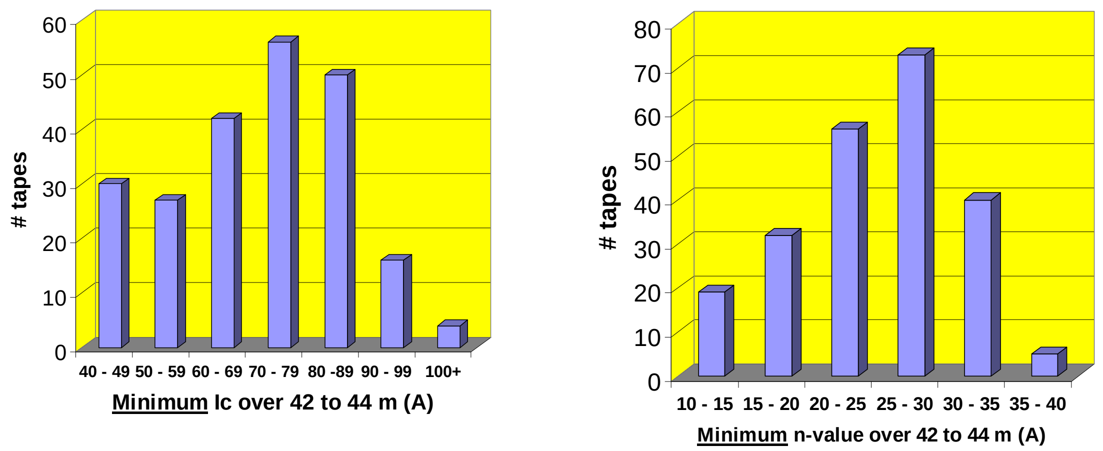


Figure 49 Minimum I_c and n-value of SuperPower Produced YBCO Tapes Used in the Cable.

b. YBCO Model Cable Core Testing (Task 6.3)

A large number of model cable cores (without cryostat) were built and tested throughout the program beginning in 2004 with the production of limited amounts of YBCO. As the conductor performance continued to evolve additional models were built to verify the YBCO cable design based on this conductor.

In 2004, SuperPower delivered sufficient 4 mm wide YBCO for SEI (**v**) to fabricate a 1 m long sample cable and evaluate its performance, **Figure 50**.

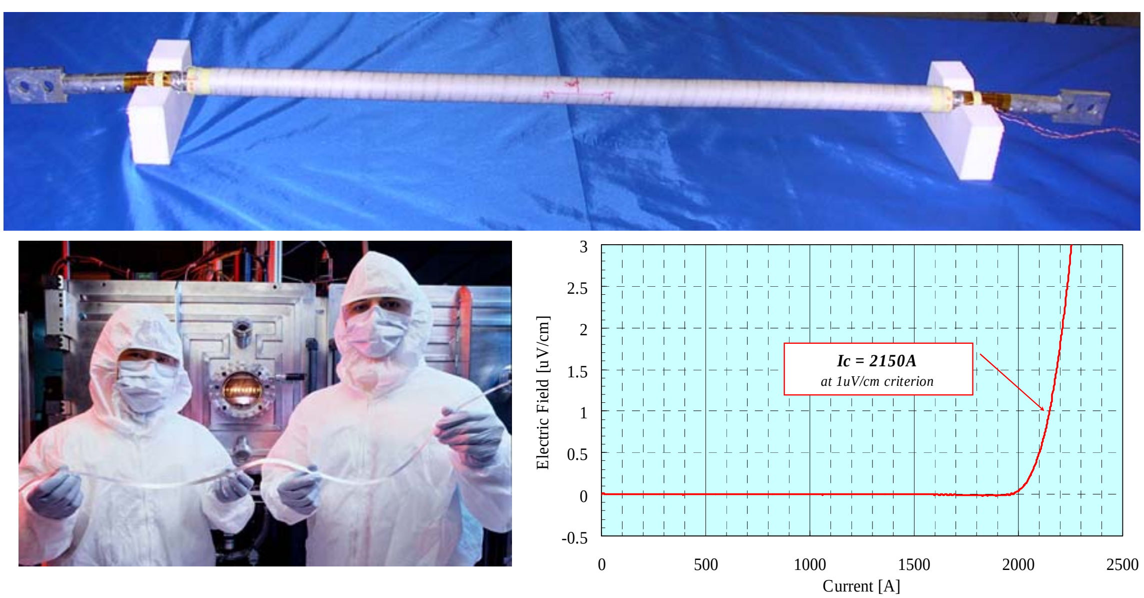


Figure 50 YBCO 1 m Sample Cable and Performance - 2004.

The following year a second delivery (over 100 m) was made to SEI (**w**) and another 1 m sample cable was constructed using four conductor and two shield layers and tested, **Figure 51**.

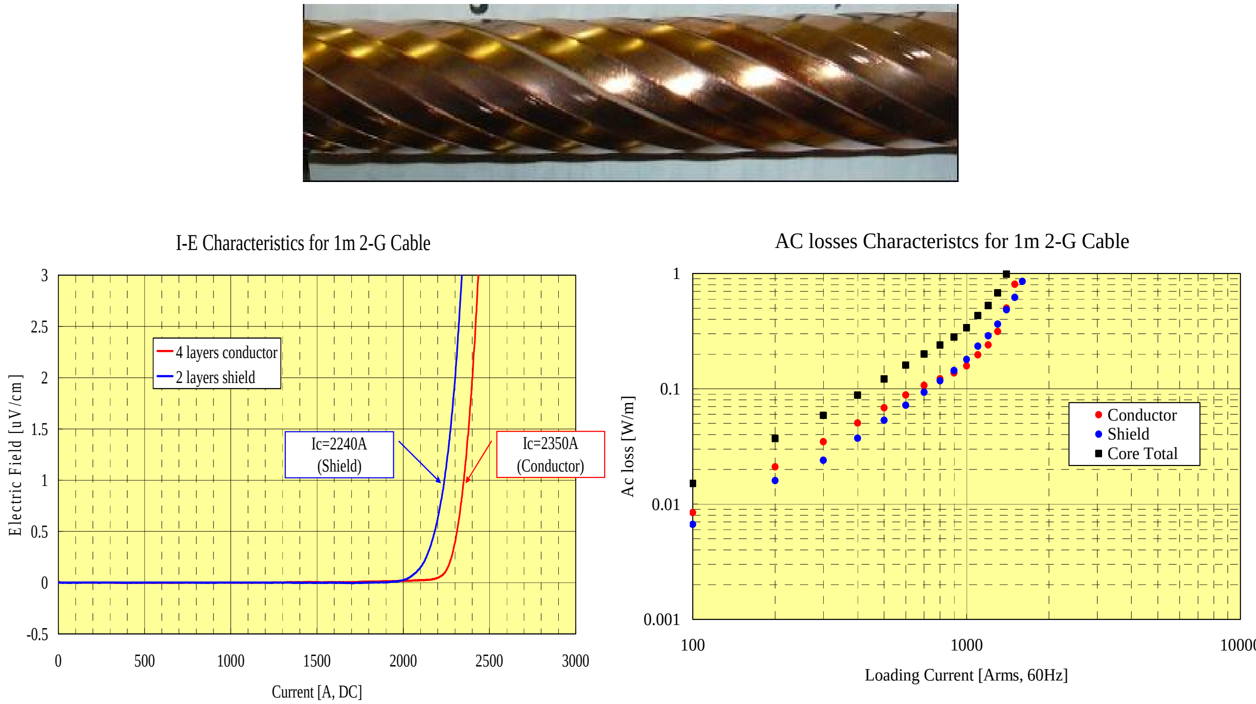


Figure 51 YBCO Sample Cable – 2005 - I_c and AC Loss Characteristics.

A 10 m long YBCO cable core was manufactured using the production conductor (previously shown in **Figure 49**), **Figure 52**, demonstrating good winding performance and no I_c degradation after fabrication.

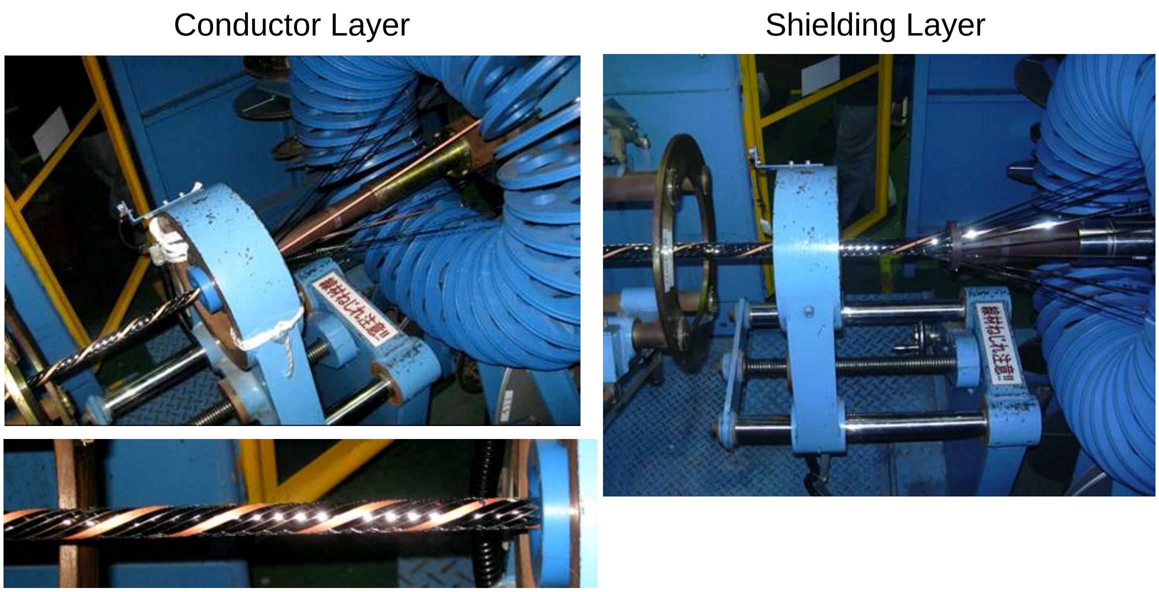


Figure 52 10 m YBCO Cable Manufacture.

Tests on 1 m long 3 core sample, **Table 10**, yielded critical currents, I_{cDC}, (1 µV/cm @ 77 º K) close to design values (1,440 A vs. 1,500 A for the conductor layer and 1,970 vs. 1,900 A for the shield layer) , **Figure 53**, and AC loss (800 A_{rms}, 60 Hz) of 0.4 W/m/core.

Table 10 1 m YBSO Core Specifications.

Item	Specification
Former	Stranded copper wires, 16 mm
HTS wire	3 layers
Dielectric	PPLP – 4.5 mm
HTS shielding	2 layers
Protective layer	Copper tape, Kraft paper
Outer diameter	34.5 mm

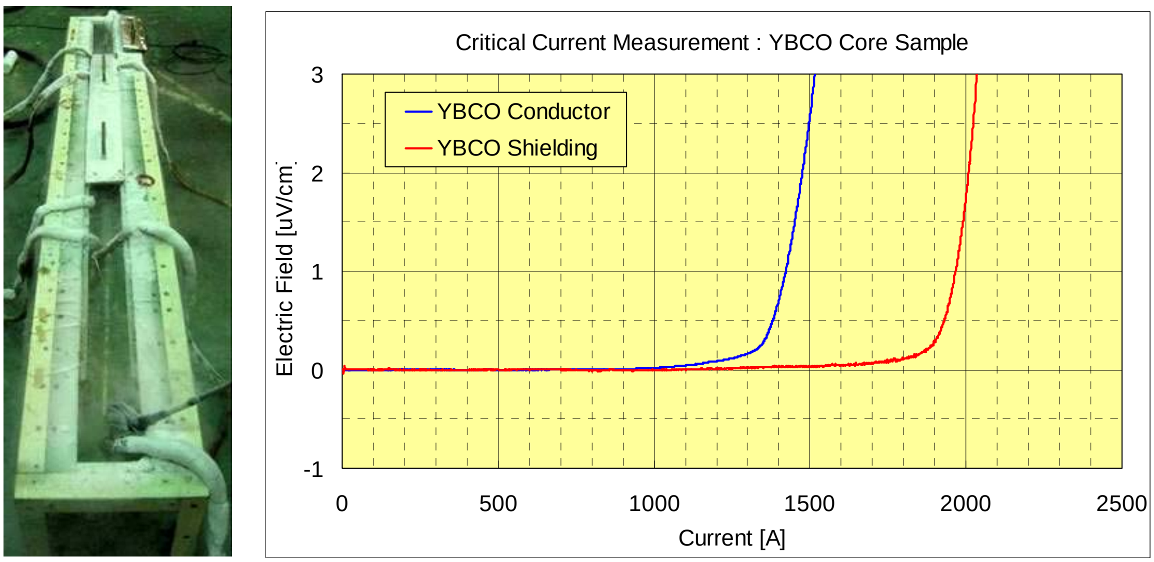
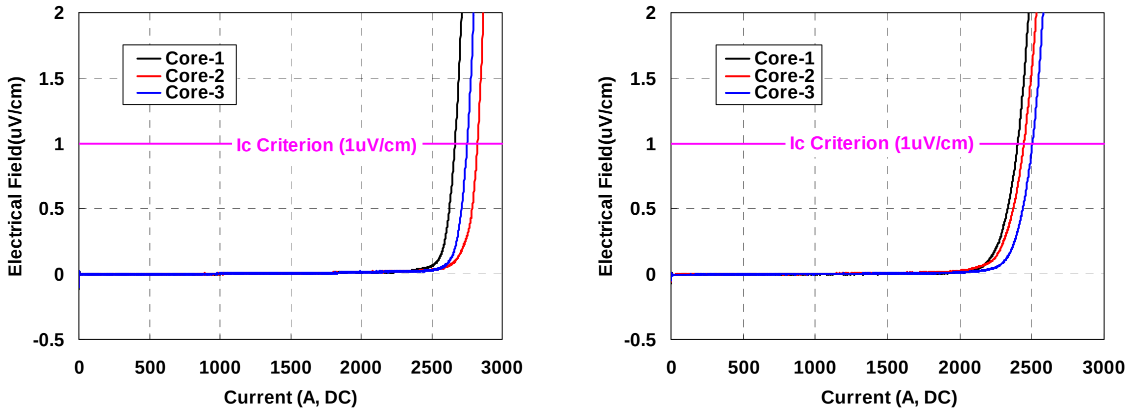


Figure 53 1 m YBCO 3 Core Sample Test Setup and Critical Current Results.

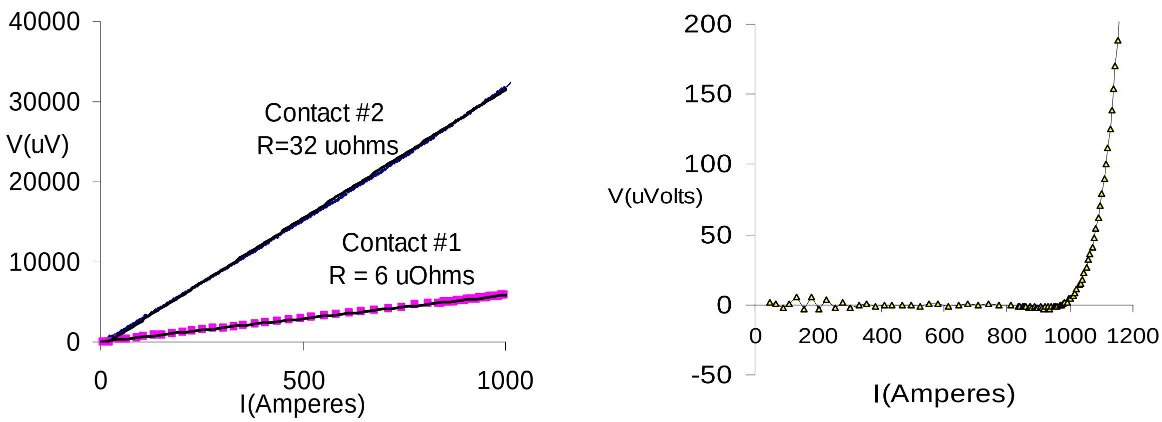
Additional cable core models were made. Critical current results were obtained on a 3 m long cable core indicating close correlation between design and measured values, **Figure 54**. Conductor layer I_c ranged from 2,660 – 2,820 A while the shield layer I_c was 2,400 – 2,500 A (77º K, DC, 1µV/cm). Other results were obtained by Los Alamos National Laboratory (LANL) on a 1 m long model cable, **Figure 55**. These results were obtained at 75.5º K self field. Finally, AC loss measurements on a 2.5 m single phase sample gave results, 3.4 W/m/phase @ 800 A, , **Figure 56**, slightly better than those obtained with a 1 m test sample core. The current loading for these tests were go and return through conductor and shield with measurements made by a four terminal lock-in amplifier.

The net result of all model testing was that performance was more than adequate to allow the fabrication of the 30 m long YBCO cable for installation on the grid (**7**).



Conductor Layer **Shield Layer**

Figure 54 3 m Model YBCO Cable Core Critical Current Test Results.



Contact made with single strand to 12 strands. I_c (self field, 75º K,) = 92 A. Measurements made in superconducting state.

Distance between voltage taps ~ 75 cm. I_c = 965 A (1μV/m) 1,100 A (1μV/cm)

Figure 55 1 m YBCO Cable Conductor Layer Critical Current Test Results – Courtesy of LANL.

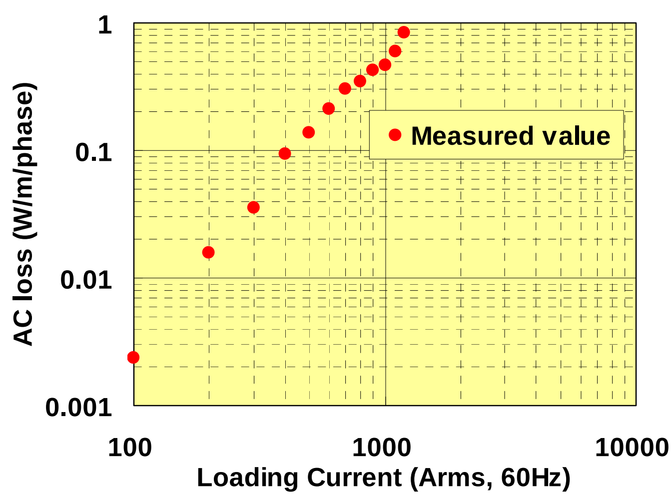
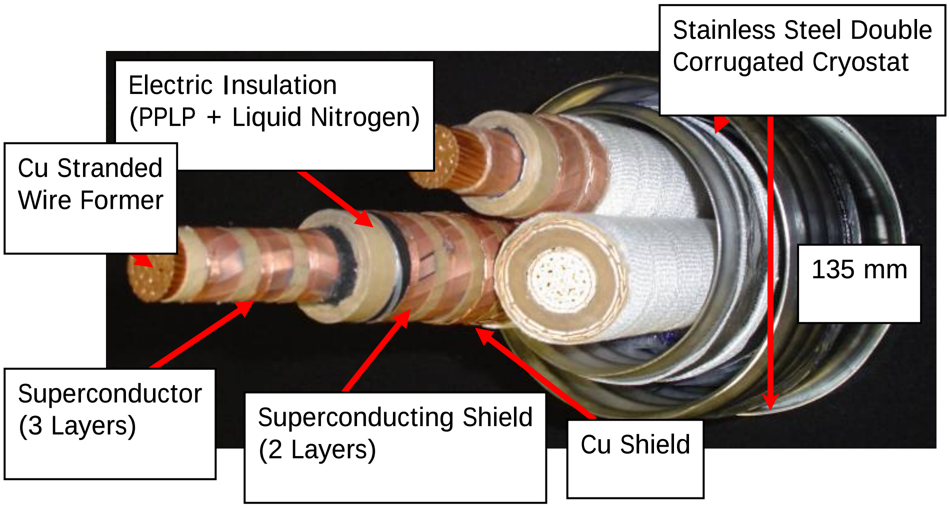


Figure 56 2.5 m Single Core YBCO Cable AC Loss Measurements.

c. YBCO Cable Design, Fabrication and Pre-Ship Testing (Tasks 6.1 & 6.3)

A design comparison of the YBCO and BSCCO cables is summarized in **Figure 57**. Basically the differences are the result of the different conductor characteristics.



	BSCCO cable	YBCO cable
Former	Stranded Cu wires with insulation (φ16 mm / 140 mm^2)	
HTS conductor	2 layers	3 layers
Electric insulation	PPLP (thickness 4.5 mm)	
HTS shield	1 layers	2 layers
Protection layer	Copper tapes	
Core outer diameter	35 mm	35 mm

Figure 57 YBCO and BSCCO Cable Design Comparison.

The design was reviewed at the Final Design Readiness Review (**o**). The fabrication of the 30 m YBCO cable followed the techniques used on the BSCCO cable, **Figure 58**.

Following fabrication in March 2007 and prior to shipment, approximately 3 m long samples from the complete YBCO cable were evaluated for various performance parameters, **Table 11**.

Table 11 YBCO Cable Tests Prior to Shipment Summary.

Parameter	Test Results	
Critical Current @ 77° K	Conductor: 2,660 – 2,820 A_{DC} Shield: 2,400 – 2,500 A_{DC}	
AC Loss	0.34 W/m/Φ @ 800 A_{rms}, 60 Hz	
Bending Test	No Ic loss, defects upon inspection	
Voltage Tests (AEIC)	AC: 69 kV for 10 min, ± 200 kV impulse – 10 shots DC: 100 kV for 5 min	

Figure 58 YBCO Cable Fabrication.

d. YBCO Cable Installation and Commissioning (Tasks 4.1 and 5.1)

The 30 m long YBCO cable, manufactured by SEI, was shipped to the Albany test site in the Spring of 2007, **Figure 59**.

Figure 59 YBCO Cable Shipment to the United States from Kobe, Japan.

Prior to arrival the two sections of cable (30 m BSCCO and 320 m BSCCO) were warmed up and the cable-to-cable joint and South termination connection of the 30 m BSCCO cable disassembled. The 30 m YBCO cable was then pulled into the conduit and reconnected to the South termination and the 320 m BSCCO to 30 m YBCO cable joint reconstructed, **Figure 60**.

Various YBCO cable commissioning tests were successfully conducted (**8**) following installation and reconnection to the 320 m BSCCO cable (**m**), **Table 12** and **Figure 61**.

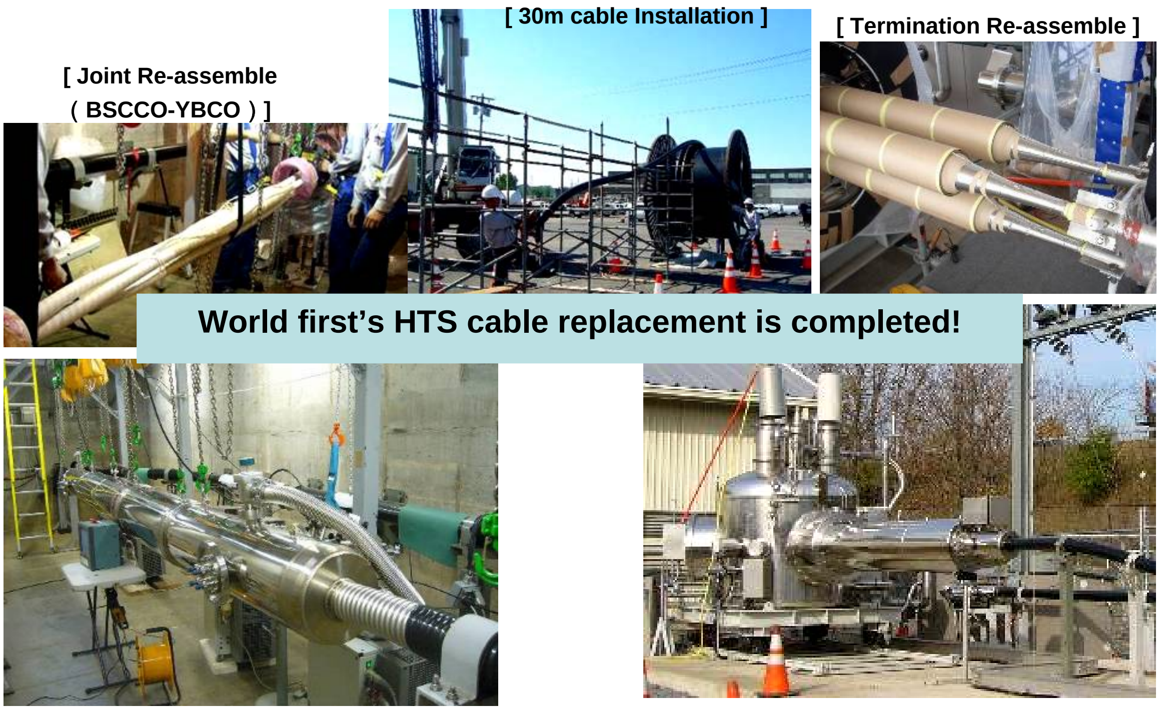


Figure 60 YBCO Cable Installation and South Termination/Joint Reassembly.

Table 12 YBCO Cable Commissioning Tests and Results.

Test	Result
System withstand pressure	• 0.61 MPAg (based on ASME code): **good**
Initial cooling test	• Maximum core tension (minimized by loose stranding): **~ 1,000 kg** • Vacuum level at each part: **good (no leakage)** • Core behavior inside joint: **within design scope**
Ic (DC, 1 μV/cm)	• **2.3 kA @ 73° K, 2.8 kA @ 69° K – same as Phase 1 BSCCO**
No load heat loss measurement	• 350 m cables (including joint): **1.0 kW** • Entire cable system (not including CRS): **3.4 kW**
DC withstand voltage	• 100 kV, each phase for 5 minutes (based on AEIC): **good**

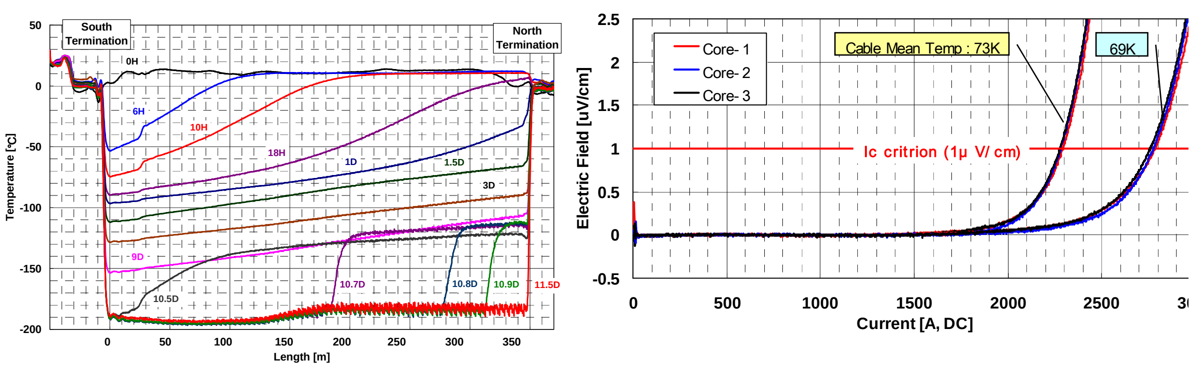


Figure 61 YBCO Cable Cooldown and Critical Current.

e. YBCO Cable Durability/Reliability (Task 5.2)

The hybrid, 320 m BSCCO and 30 m YBCO, cable system was then placed back in service on January 8, 2008, **Figure 62**. The cable operated unattended and flawlessly (**5**) until it was shut down on April 12, 2008 after accumulating another approximately 2,250 hours for a total Phase 1 + Phase 2 operating time of 6,720 + 2,250 = 8,970 hours.

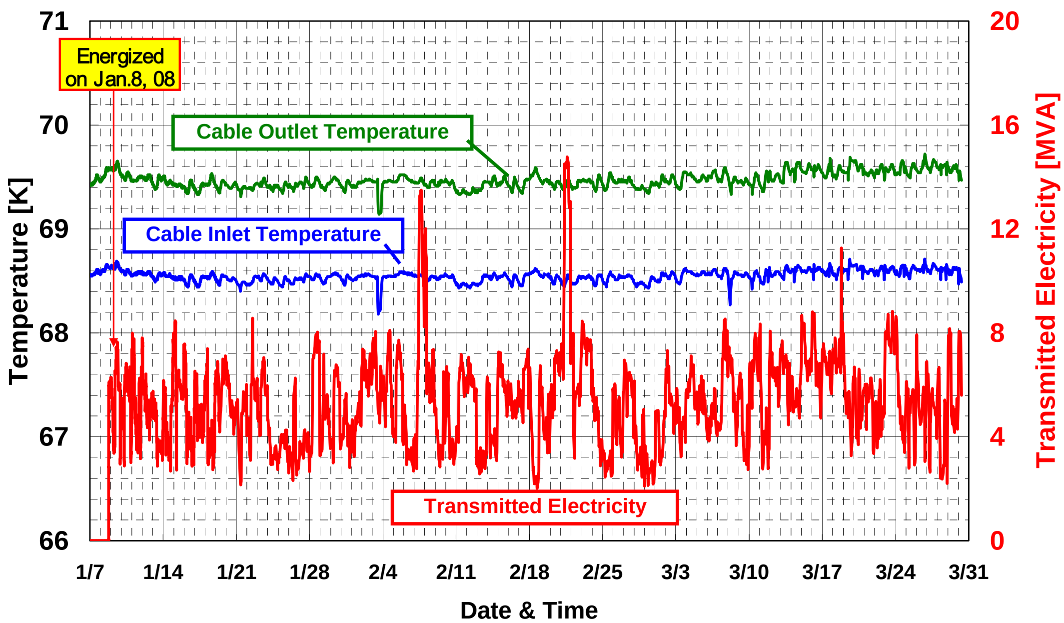


Figure 62 Hybrid BSCCO/YBCO Cable Energized January 2008 - 08.

VI. YBCO/BSCCO Cable Comparison

There was no detectable difference in system temperatures between Phases 1 and 2, **Figure 63**. Overall the variation between cable inlet and outlet temperature was 0.9 +/- 0.1° K. This difference was very stable over the entire in grid operating time with no change in heat loss.

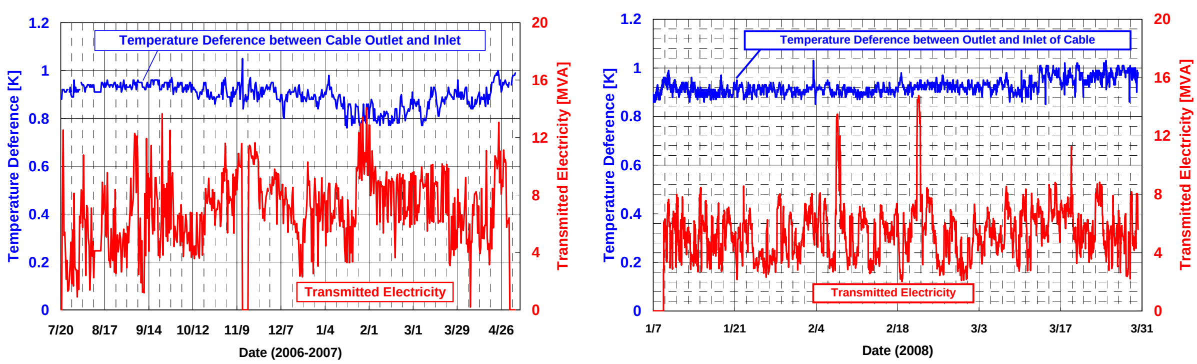


Figure 63 Variation in System Temperature Between Phases 1 (left) and 2 (right).

One of the questions successfully answered by this Project was would cable performance (current carrying capability) deteriorate over time or through thermal cycling, warm-up/cooldown being necessary in the real world for cable splicing and cryogenic system repairs? A related question was could short sample tests accurately reflect the results obtained with a long cable? The Project demonstrated no change in I_c over time and that short sample results do reflect the actual cable, **Figure 64**. A comparison of AC losses, using 1 mm cable core models indicated similar values, **Figure 65**.

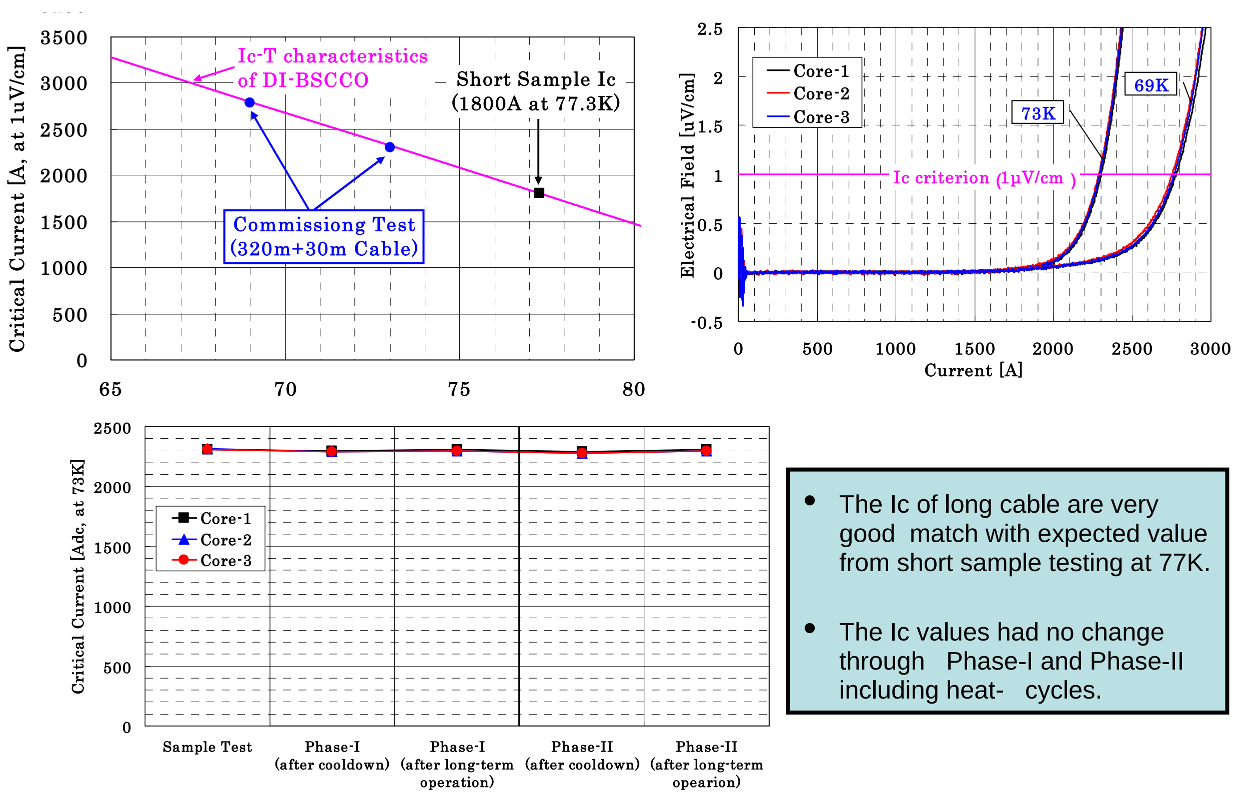


Figure 64 Variation in Critical Current from Phase 1 Through 2.

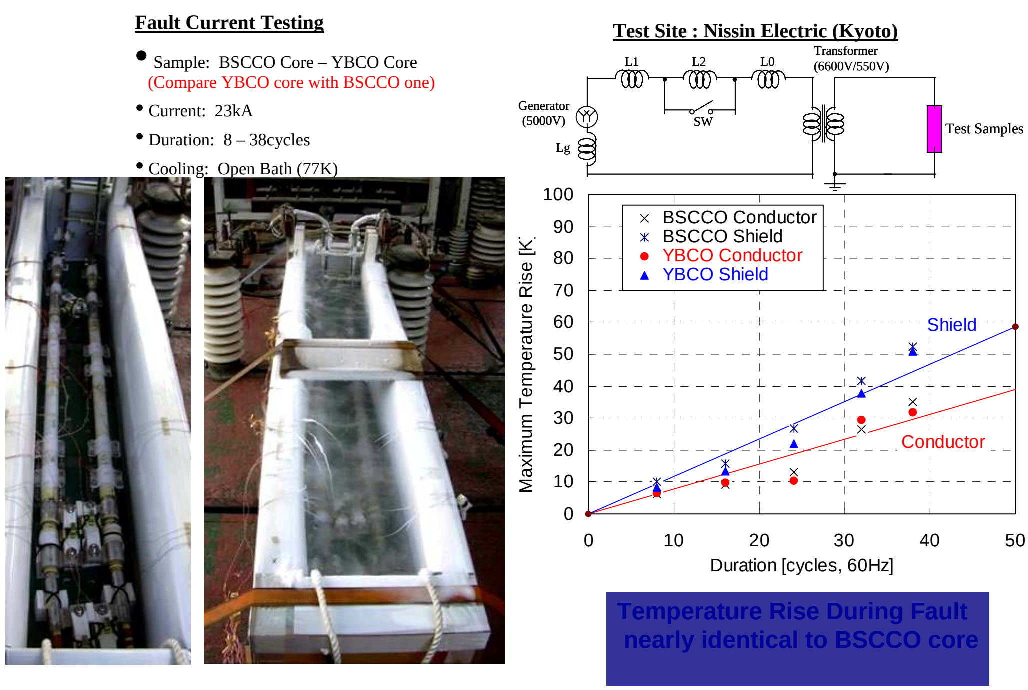


Figure 65 BSCCO/YBCO 1 m Cable Core Fault Current Comparison.

VII. Market Research, Failure Mode Analysis and Grid Stability (Task 8.0)

a. Economic Applications Niche Analysis (Task 8.1)

SuperPower's business plan at the start of this Project (circa 2002) contained an economic analysis of the cost of HTS cables, **Table 13**. Also included in this table are estimates made by Dr. Alan Wolsky of Argonne National Laboratory in work sponsored by the International Energy Agency. Although there are differences in the numbers and Dr. Wolsky's analysis does not include margin (profit) it may be concluded that the major cost drivers were the HTS wire and cryogenic refrigeration system.

Table 13 Relative Cost of High Voltage, 2,000 A, 3 kW Heat Load HTS Cable.

	SuperPower 2000 Estimate	Alan Wolsky 2004 Estimate[1]
HTS Conductor Cost	$20/kA-m	$25/kA-m
HTS Conductor[2]	34%	34%
Cable Cryostat	10%	19%
Refrigeration[2]	23%	47%
Manufacture & Margin	33%	

1. HTS Cable – Status, Challenge and Opportunity Draft Report, September 14, 2004, Appendix VII, Alan Wolsky. Low (production) estimate used for refrigeration cost.
2. Including cost of copper stabilizer.
3. Refrigerators, heat exchangers, cooling loop and cryogen.

Hence, the major emphasis in this Project was directed towards the development of high performance, long length, low cost 2nd generation YBCO conductor and a cost-effective and reliable cryogenic refrigeration system. The performance and reliability of the conductor and CRS are discussed elsewhere in this report and all goals were exceeded.

With respect to cost, SuperPower during the course of this Project has steadily reduced the price it charges to customers for YBCO conductor. The price was essentially infinity in 2002 (lengths were < 1 m at that point) and has steadily decreased as long lengths, increased critical current and improved manufacturing yields were achieved, **Table 14**.

Table 14 SuperPower Progress in YBCO Wire as Reported at the 2008 DOE Peer Review.

Metric	2005 review	2006 review	2007 review	2008 review	Improvement in 2008
Ic (A/cm) over 1 m	236	470	595	813	37%
Ic (A/cm) at 77 K, 1 T			116	229	97%
Ic (A/cm) at 65 K, 3 T			181	340	88%
Ic over 200 m (A/cm)	106	246	227*	314*	38%
Length with Ic > 200 A/cm (m)		322	322	945	193%
Completed 2G wire piece length (m)	207	322	595	1,311	120%
Ic ´ L (A-m)	22,000	70,520	102,935	200,580	95%
2G wire price ($/m)	500	100	65	40	39%
2G wire orders (m)			6,400	33,000	415%

The need to reduce the cost of the cryogenic refrigeration system, particularly cryocoolers, remains to be achieved and was beyond the scope of this Project. The issue was addressed in the sense that every effort was made by Linde to design low cost and redundancy (reliability) into the CRS and cable monitoring system as previously discussed.

The accurate prediction of the cost and sales of HTS cables is elusive (and highly proprietary to the companies involved) and must, in the final analysis, await commercial sales (**9**). Studies continue to be done to address this issue, most notably a study performed by Navigant Consulting, Inc. entitled "High Temperature Superconductivity Market Readiness Review" in August 2006. Using input from SuperPower, SEI, Linde and others in the HTS community the following assumptions were made by Navigant:

- There are two primary markets for HTS cables: underground transmission and conversion of conventional overhead transmission (> 69 kV) to HTS underground.
- The installed base in the U.S. in 2004 was 5,200 miles and 400,000 miles, respectively.
- 1% of the overhead market will go underground due to renewed emphasis on reducing power outages and NIMBY.
- A growth and replacement rate for underground transmission cables will be 1.6% and 1.25%, respectively.
- Only ¼ of this market will require the higher power density offered by HTS cables.
- The first commercial (as opposed to demonstration) HTS cable will be in 2014.
- The rest of the world HTS transmission cable market will be three times the U.S. market with a similar timeline for market entry and adoption.

The Navigant prediction for their medium (they also do a low and high) scenario is provided in **Table 15**.

Table 15 Navigant Prediction for Underground HTS Cable Adoption – 1st Installation in 2014.

Years to 10% of Ultimate HTS Market	Years to 50% of Ultimate HTS Market	Ultimate HTS Market Share - %
3	10	25

While we don't agree with all of the conclusions of this report, particularly with the time to market and size of the market, it certainly was a very thorough study and probably the most comprehensive ever done as multiple inputs were used. We accept this as a conservative estimate (**9**) and consistent with our business plan except for the timing and size.

b. Failure Mode Analysis (Task 8.2)

The potential failure modes and mitigation of all major elements of the HTS cable system: CRS, HTS cable, HTS wire, dielectric, cable cryostat, terminations and joint were evaluated via a number of interactive mechanisms (**p**):

1. Conducting a Hazardous Operations Study (HazOp) which is similar to FMEA.
2. Reviewing the results at critical stages of the Project via DOE Readiness Reviews attended by all team members, DOE and NYSERDA:
    a. Conceptual Design Review – December 2003,
    b. Detail Design Review – November 2004, and
    c. Final Design Review – April & June 2006.
3. Comprehensive testing and validation plan for components, subsystems and systems.
4. Prior team member experience.

HazOp uses a risk ranking matrix consisting of the severity or consequences of failure on one axis and the likelihood (frequency) of occurrence on the other. At the extremes a failure which is of minor consequence and is a remote possibility would have a risk factor of 0 while a failure with major consequences and high probability of occurrence would have a risk factor of 4. An example of this analysis presented for the CRS at the Conceptual Design Readiness Review is provided in **Table 16**.

Table 16 CRS HazOp Study Key Results.

Deviation (risk factor)	Possible Cause	Consequence	Comments/Mitigation
Loss of Containment (2)	Line rupture, safety valve stuck open, vent valve or valve shaft open, earthquake, car accident.	LN_2 release to environment, loss of coolant, personnel exposure.	Loss of LN_2 inventory, Consider actuator on tank isolation valve, rupture will result in vacuum loss, ROC should have this signal.
Utility Failure (2)	Electrical failure, instrument air failure.	System shutdown.	Consider UPS or PLC, hot stand-by for PLC, back-up for instrument air.
Machinery Failure (2)	Pump failure.	Low flow, no flow.	Direct drive, VFD driven pumps, consider IT in VFD.
Control Valve Failure	Bypass valves.	Low flow, no flow.	Consider limit switches, routine testing in addition to limit switches.
Operability (2)			Switchover from cooldown to on line, consider pump cavitation remediation.
Machinery Failure (2)	Cryocooler blower.	System shutdown.	Consider proactive back-up mode running. Cryocooler failure not an issue.
Control Valve Failure (2)	Control valve and automated isolation valve.	See high level/low level, high pressure, high impurity.	Consider routine testing of valves to ensure they are ready when needed.
Low Pressure (2)	Failure of pressure builder, both PSV, top fill from driver.	Tank pressure collapses. Out of spec on cooling.	Operation instructions need to address tank filing.
High Pressure (3)	High tank pressure, nozzle not installed or sized correctly. Two phase and liquid flowing out of vent.	Liquid into cable, shock to cable	Consider temperature cutoff, heating vent liquid/gas to atmosphere.

An analysis for the HTS cable from the same design review is provided in **Table 17**.

Table 17 HTS Cable System Risk Analysis.

Deviation	Possible Cause (risk factor)	Consequence	Comments/Mitigation
Voltage Failure	Breakdown in cable, termination or joint. (3)	Non-operation.	Cable sample and shipping tests.
	Insulation degradation. (2)	Partial discharge.	Electrical design, experience, cable sample and shipping tests.
	Bubbles in LN_2 (2)		CRS control.
Current Failure	Break or heavy degradation of HTS wire. (3)	Non-operation.	Design and testing of HTS wire.
	Degradation of HTS wire, cryostat or CRS failure. (2)	Higher heat losses.	Design and testing of HTS wire, cryostat & CRS.
Lower Pressure	Leak in cable, termination or joint (2)	Partial discharge, breakdown.	Design experience, pressure test at various stages.
	CRS failure. (3)		See **Table 16**.
Higher Temperature	Increased heat invasion. (2)	Decreased electrical conductivity, bubbles in LN_2, breakdown	Design experience, pressure test at various stages.
	Large current. (2)		Fault current test & study.
	Refrigeration failure. (2)		See **Table 16**.
Lower LN_2 Flow Rate	Cooling path obstruction. (3)	LN_2 temperature rising.	Design experience.
	LN_2 pump failure. (3)		See **Table 16**.
Electrical Conductivity Degradation	HTS wire ballooning. (2)	Current failure.	HTS wire experience & testing.
	Excessive electromagnetic force. (2)		Experience in cable pulling.
Cable Cryostat, Joint or Termination Leak	Cryostat deflection. (3 & 2, respectively)	Closed circulation.	Experience and pressure testing.
		Degradation of vacuum.	Experience and pressure testing.

Color key: During operation During fault condition

Particular attention was paid to the response of the HTS cable system to the maximum, second contingency fault of 23 kA for 38 cycles. The analysis indicated that the maximum LN_2 expansion was 90 liters (maximum rate, 21 l/sec.) with a maximum potential pressure rise of 57 bar. To mitigate for this possibility pressure reliefs were installed at the terminations (9 b_{gauge}) and the LN_2 tank (5 b_{gauge}).

The pressure rise in the HTS cable will be greatest at the furthest distance from the terminations bounded by the pressure relief setting at the terminations and the maximum potential pressure rise. The maximum rise is well within the limits of the cryostat which has a burst pressure of 120 bar at room temperature and 260 – 270 bar at cryogenic conditions.

c. Grid Stability Study (Task 8.3)

Every effort was made to ensure that the HTS cable was transparent to National Grid's 34.5 kV network in Albany, e.g., no effect on grid stability:

- Installation of a parallel conventional cable that could be seamlessly switched into the system should there be a problem with the HTS cable. There was only one event in the entire course of the program where this became necessary and the power was switched over without any interruptions.

- Remote 24/7 monitoring of the cable and cryogenic refrigeration system with provisions for stages of intervention as discussed in the ***Remote Monitoring and Control (Task 4.2)*** section
- System protection through the addition of multiple levels of relays and circuit breakers between the Riverside and Menands substations to handle worst case 2nd level contingency faults as discussed in the ***Conventional Cable/System Protection (Task 4.4)*** section.

This effort was completely successful. To quote William Flaherty, Energy Solutions Regional Director for National Grid: "Of importance to National Grid is that this project has demonstrated the reliability of the technology. We encountered no difficulties in integrating the project into our grid and the entire installation was totally transparent to our customers. The system has stood up to very exacting utility standards and we look forward to further developments in HTS technology." (**q**)

VIII. Project Management (Task 7.0)

During the course of this Project a kick-off meeting (**i**) and three Readiness Reviews were held for DOE for the: conceptual design – December 2003, the detail design – November 2004 and final design review – June 2006. Regular Project review meetings were held with the partners at points were travel from Japan could most economically be done (**k**). Annual reviews (the DOE Peer Review) were conducted (**j**). The final reports to DOE and NYSERDA were submitted (**l**). Some of the NYSERDA reports were not done on a monthly basis (**h**).

Collaboration was established with two DOE National Laboratories. Los Alamos and Oak Ridge assisted SuperPower in the development of 2nd generation YBCO conductor. LANL also examined and tested sections of model cable.

Outreach to the public and technical community occurred via more than twenty tours and public events and more than fifty presentations and technical articles. A representative sample from 2007 DOE Peer Review listed the following in a one year period:
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<u>Presentations</u>

- ASC '06 – Seattle, WA – 8/28-9/1/06
- EPRI S/C Workshop – Columbus, OH 9/13-14/06
- Tech Valley Chamber Executive Institute – 10/22/06
- Leadership Tech Valley Group – 10/23/06
- DOE Wire Workshop – Panama City, FL 1/16-17/2007
- IEEE Schenectady Chapter – 1/19/07
- HTS Cable Collaborative Meetings
- IEEE PES General Meeting – Tampa, FL– 6/25-28/07
- ISIS-15 (Erlangen, Germany) – 9/27-29/06
- North. Colonie High School Technology Night – 10/16/06
- Knolls Atomic Power Lab (Schenectady, NY) – 10/31/06

- Defense Manufacturers Conference (Nashville, TN) – 11/27-29/06
- SCCC Technology Club – 1/26/07
- Questar III METS Program – 1/31/07
- National Electricity Delivery Forum (Washington, DC) – 2/22/07
- Hannover Fair (Hannover, Germany) – April 2007
- RPI Alumni Group – 6/19/07
- CEC/ICMC (Chattanooga, TN) – July 2007

Tours & Events

- Phase I Commissioning Ceremony – 8/2/06
- Phase II Kick-Off Event – 5/2/07
- Tours of the ACP site were conducted for 12 different organizations
- (8) different countries represented

News Articles

- T&D World Article – March 2007 "Superconducting Cable Connects the Grid"
- Times Union – 3/4/07 "SuperPower plans for amazing future"
- Times Union – 5/3/07 "Project comes down to the wire"
- Elektronik – 10/2007 "Energie sparen durch Kaelte"
- Christian Science Monitor – 12/12/06 „Electric breakthrough goes commercial"
- Daily Gazette – 12/22/06 "SuperPower ships first of new wire"
- The Business Review – 12/20/06 "SuperPower announces first major superconducting wire shipment"
- Power Magazine – October 2006 "First live superconducting cable"
- T&D World – 8/24/06 "High-Temperature Superconducting Cable Project is On-Line in Albany, New York"
- Wire & Cable International – 8/14/06 "Albany cable project now online" & "Three-to-five times more power"
- Times Union – 8/3/06 "Cool cable line put to test"
- Business Review – 8/2/06 "$27M cable project commissioned"
- Daily Gazette – 8/3/06 "Officials celebrate start of power test"

The Albany Cable Project successfully executed all phases of the program:

- All technical goals and objectives were met or exceeded.
- The HTS cables operated flawlessly for more than one year with no instances of downtime caused by the cable, related components or cryogenic refrigeration system.
- The HTS cable system proved to be reliable and robust, capable of handling the real-world utility operating environment. All systems and equipment responded as designed without any adverse effects.
- The biggest reliability concern – the cryogenic refrigeration system – was addressed and proved to address commercial requirements.
- Successfully demonstrated the world's first
    - HTS cable between two utility substations
    - Underground HTS cable
    - cable-to-cable joint
    - YBCO cable