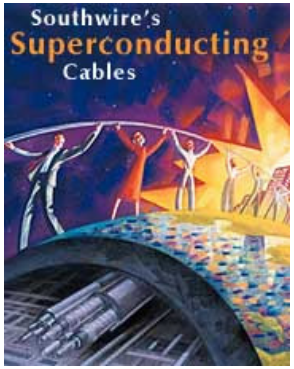
High Temperature Superconducting Cable



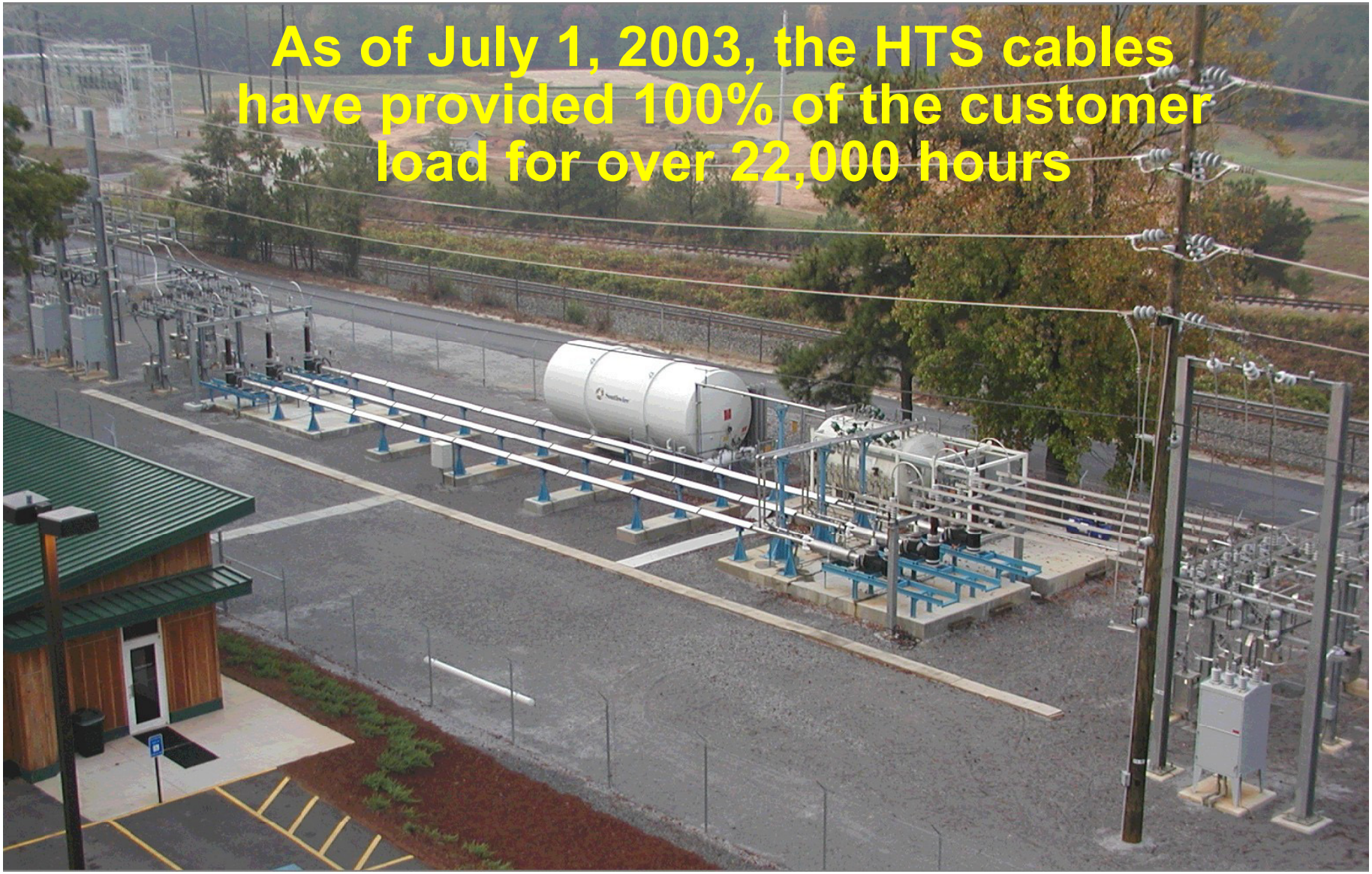
2003 Annual Peer Review

Superconductivity Program
for Electric Systems
U.S. Department of Energy

Southwire
WE DELIVER POWER

July 23-25, 2003
Washington, DC

ornl


As of July 1, 2003, the HTS cables have provided 100% of the customer load for over 22,000 hours

Presentation Outline

- Introduction (David Lindsay, Southwire)
  - Overall SPI Goals & Objectives
  - Design Approach
  - Review FY 2003 Milestones
- FY 2003 Results
  - 30-m Cable Operation and Testing (David Lindsay, Southwire)
  - Cable Research at ORNL (Jonathan Demko, ORNL)
  - Cryogenic Dielectrics Research (Jonathan Demko, ORNL)
- FY 2003 Performance
- Planned FY 2004 & FY 2005 Milestones
- Program risk mitigation strategy
- Research Integration
- Summary

SPI Project Goals & Objectives:

- **SPI-1: 30-m Installation, Carrollton, GA**
  - The cable system will continue to be operated and studied. Optimizations will be made to improve operating efficiencies and reliabilities.

- **SPI-2: Bixby Substation, AEP, Columbus, OH**
  - To complete a long length demonstration with AEP
    - Install 13.2 kV, 3.0 kA (69 MVA) HTS cable system in Bixby substation, about 2 times the power of the Carrollton, GA demonstration
    - Length would be on the order of 10 times the Carrollton, GA demonstration
    - Design and install a simplified and reliable cryogenic system based on prior experiences
    - Demonstrate pre-commercial feasibility of an underground installation.

Basic SPI Project Approach

An integrated team from Southwire, ORNL and other industry partners will design, build and install a reliable cable system.

- **Cables, terminations and other component sub-systems will be proto-typed and fully tested in the lab prior to implementation**
  - **Designs evaluated by use of computer modeling**
  - **Design verification and proto-type testing is facilitated through the use of the 5-m test-bed at ORNL**
- **Where needed, expertise will be brought to the team through the use of outside contractors/consultants**
- **Southwire & ORNL will work with electric utilities to identify market applications and guide technology development to achieve a commercially viable product which meets industry needs.**

Southwire/ORNL FY 2003 Plans (Milestones) Oct. 1, 2002 to Sept. 30, 2003

(From 2002 Peer Review)

- **SPI-1: ORNL will work with Southwire to improve the overall design and capabilities of the HTS cable system.**
  - **Continued development of the pressurized termination** COMPLETED
  - **Complete testing and analysis of 5-m 1.3 kA tri-axial HTS cable including 3-phase terminations,** COMPLETED
  - **Based on results of 5-m 1.3 kA HTS cable system, install and test 30-m tri-axial cable system next to present cable at Southwire complex, Carrollton, GA.**

    CHANGED: A second 5-m 3 kA tri-ax was built to support the AEP project.
  - **Model cable testing of 34.5 kV class cables, aging studies and continued development of cryogenic dielectric materials, and** COMPLETED
  - **Continued research improving cryogenic system performance with industry.** COMPLETED
- **SPI-2: ORNL and Southwire will begin the design and testing of cable subsystems for a long-length cable installation at AEP.**
  - **About 69 MVA, double the loading of the 30-m cable system at Southwire and of order 10 times the length** COMPLETED

Supports SPI-2

Project Participants at Southwire and ORNL

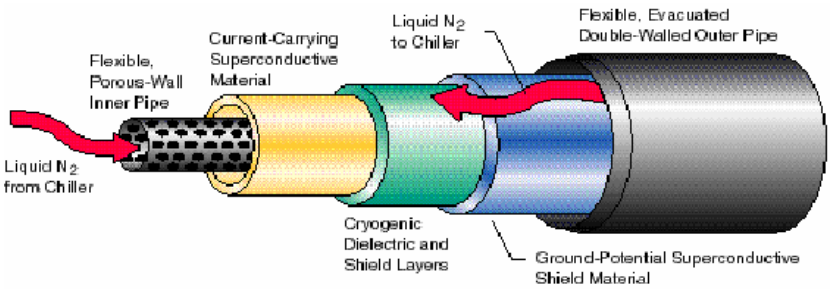
- **Southwire**

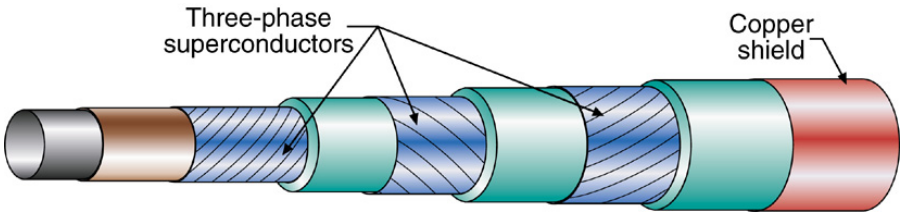
John Armstrong	Steve Owens
Zack Butterworth	Ron Martin
Hugh Butler	Sammy Pollard
Randy Denmon	David Reece
Terry Dyer	Mark Roden
R. L. Hughey	Jerry Tolbert
Gary Hyatt	Lewis Waters
Donnie Kittle	Nick Ware
Kim Knuckles	
David Lindsay	

- **Oak Ridge National Laboratory**

Glenn Barber	Randy James
Bob Benson	Winston Lue
Jonathan Demko	Patrick Martin
Robert Duckworth	Marshall Pace
Alvin Ellis	Isidor Sauers
Paul Fisher	Bill Schwenterly
Chris Foster	Dennis Sparks
Mike Gouge	John Stovall
Robert Hawsey	Marcus Young

Comparison of HTS Cable Designs

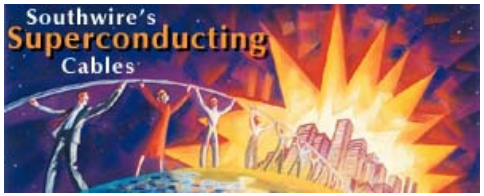




- **Features of the Co-axial HTS cable**
  - **Magnetic field shielded.**
  - **Both conductor and dielectric are wrapped from tapes.**
  - **Cryogenic dielectric reduces size and increases current carrying capacity. The first cold-dielectric cable under development in US.**
  - **Flexible cable to allow reeling**

- **Features of the tri-axial cold dielectric HTS cable**
  - **Potential to reduce the required HTS tape by ~1/2**
  - **Potential to reduce heat loads by ~1/2**
  - **Flexible cable to allow reeling.**
  - **Southwire is fabricating 5-meter, 3,000 A_{rms} cable**
  - **Termination design modified for 3000 A_{rms} to meet AEP project requirement.**

Southwire Project Status



- **Project history**

– Installation & Testing	Aug – Dec 1999
– Cables energized	Jan. 6, 2000
– Dedication ceremony	Feb. 18, 2000
– Continuous operation started	Feb. 21, 2000
– Unmanned operation	June 1, 2001
– Splice design and tests	FY 2000-2001
– 1.5-m tri-axial cable tests	Summer 2001
– Bend testing	FY 2001-2002
– Cable aging/partial discharge	FY 2000-2002
– 5-m tri-axial cable/terminations	FY 2002
– YBCO 1-m cable tests	FY 2003
– 5-m 3kA tri-axial cable	FY2003-2004

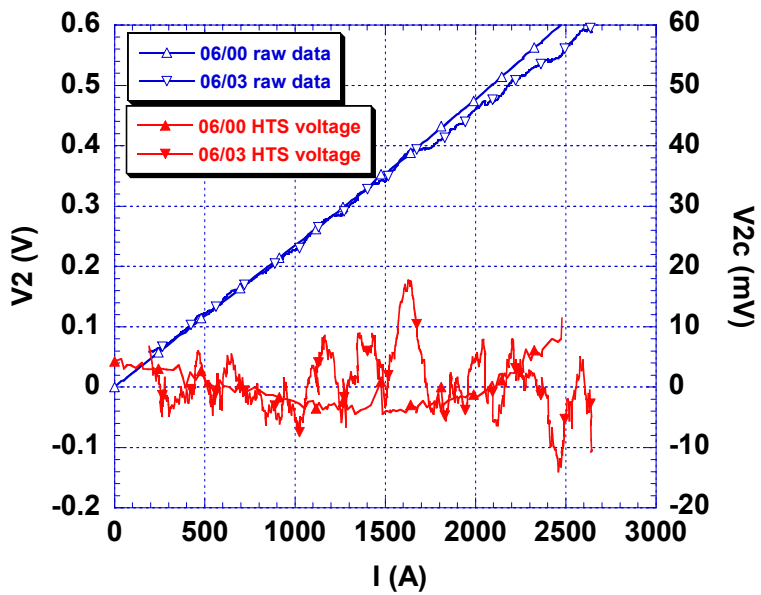
New SPI

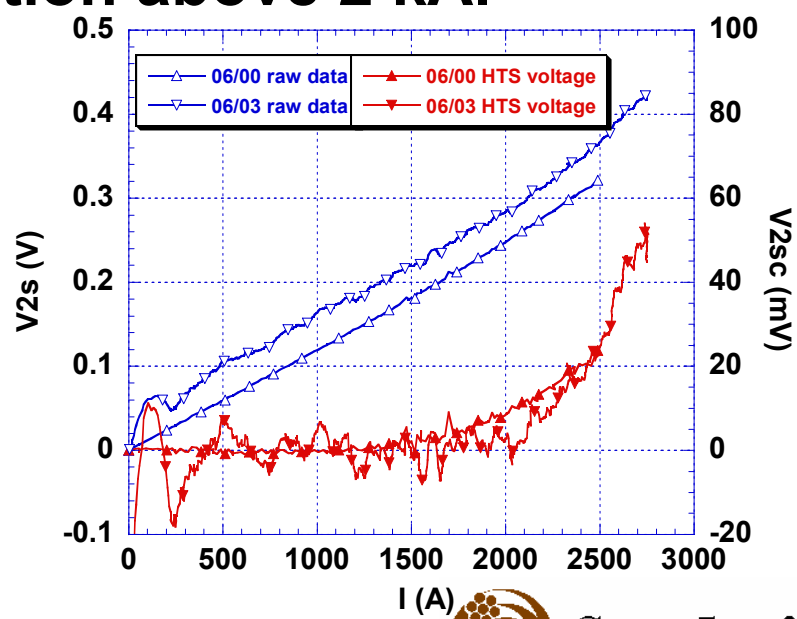
Additional accomplishments

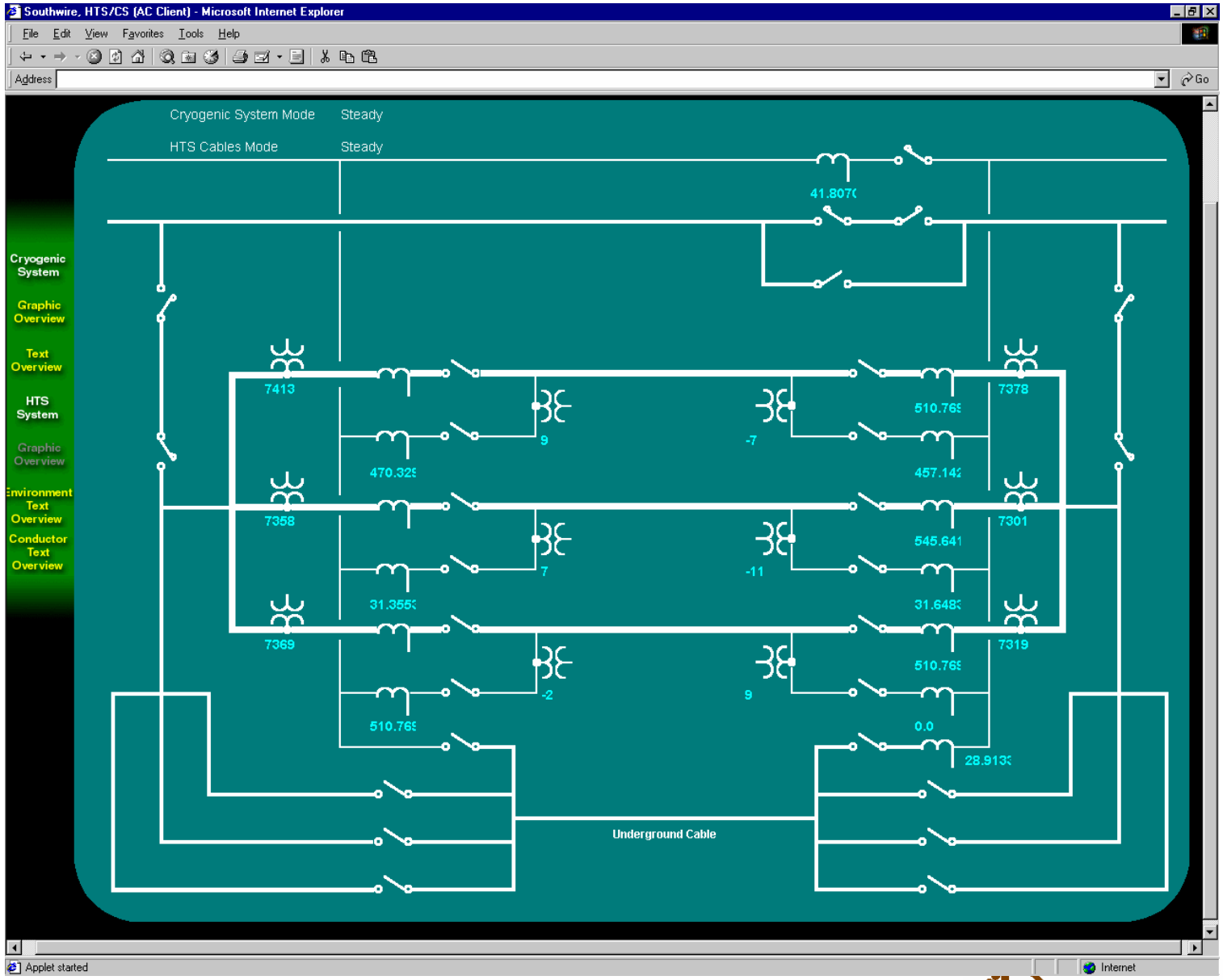
- Setting record for longest running HTS cable installation.
- Completed low voltage testing of 1.3 kA_{rms} tri-axial HTS cable and terminations
- Tested a series 1- to 3-m cables to evaluate AMSC tape for use in AEP project.
- Completed design and fabrication of high current (3 kA_{rms}) tri-axial terminations.
- Fabricated and conducted initial testing of second generation (YBCO) conductor 1.25-m HTS cable.

DC V-I Curves for Main and Shield Conductors Show No Degradation Over Three Years of Operation.

- Voltages are measured from bus, so there is a normal resistive component.
- The main conductor critical current is above the 3 kA limit of the power supply. If the silver were carrying current, the voltage would be significantly higher.
- The shield exhibits a transition above 2 kA.






Southwire, HTS/CS (AC Client) - Microsoft Internet Explorer
File Edit View Favorites Tools Help
Address
Go
Cryogenic System Mode Steady
HTS Cables Mode Steady
Cryogenic System
Graphic Overview
Text Overview
HTS System
Graphic Overview
Environment Text Overview
Conductor Text Overview
7413
7358
7369
7378
7301
7319
9
-7
7
-11
-2
9
0.0
Underground Cable
Applet started
Internet

Southwire HTS/CS Web Based Report System - Microsoft Internet Explorer

File Edit View Favorites Tools Help

Address Go

Southwire
WE DELIVER POWER

HTS/CS Report System

I/O Point Details

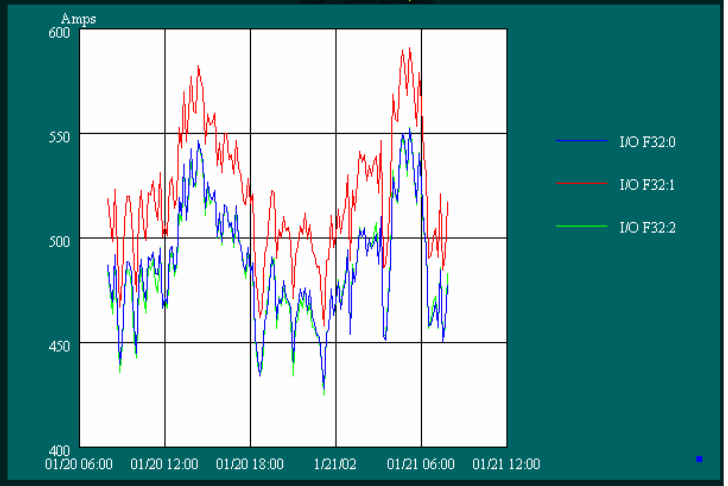
Description : Phase 1 Amps
Measurement : Amps
DB2 ID : IOF32000
PLC ID : I/O F32:0
Dataset Size : 1438 points

Description : Phase 2 Amps
Measurement : Amps
DB2 ID : IOF32001
PLC ID : I/O F32:1
Dataset Size : 1438 points

Description : Phase 3 Amps
Measurement : Amps
DB2 ID : IOF32002
PLC ID : I/O F32:2
Dataset Size : 1438 points

Graph Interval : 10 minute(s)

I/O Point Graph



I/O Point Raw Data

Phase 1 Amps			Phase 2 Amps			Phase 3 Amps		
Date	Time	Measurement	Date	Time	Measurement	Date	Time	Measurement
2002-01-20	08:00:48	487.33	2002-01-20	08:00:48	518.97	2002-01-20	08:00:48	484.10
2002-01-20	08:01:48	467.40	2002-01-20	08:01:48	497.58	2002-01-20	08:01:48	463.00
2002-01-20	08:02:48	467.40	2002-01-20	08:02:48	498.75	2002-01-20	08:02:48	464.47
2002-01-20	08:03:48	480.59	2002-01-20	08:03:48	512.82	2002-01-20	08:03:48	477.95
2002-01-20	08:04:48	482.05	2002-01-20	08:04:48	513.41	2002-01-20	08:04:48	479.12
2002-01-20	08:05:48	481.76	2002-01-20	08:05:48	512.23	2002-01-20	08:05:48	479.41
2002-01-20	08:06:48	481.17	2002-01-20	08:06:48	511.65	2002-01-20	08:06:48	478.53
2002-01-20	08:07:48	481.76	2002-01-20	08:07:48	515.46	2002-01-20	08:07:48	480.29
2002-01-20	08:08:48	471.50	2002-01-20	08:08:48	504.62	2002-01-20	08:08:49	469.74
2002-01-20	08:09:48	470.33	2002-01-20	08:09:48	502.86	2002-01-20	08:09:48	469.16

Done Internet

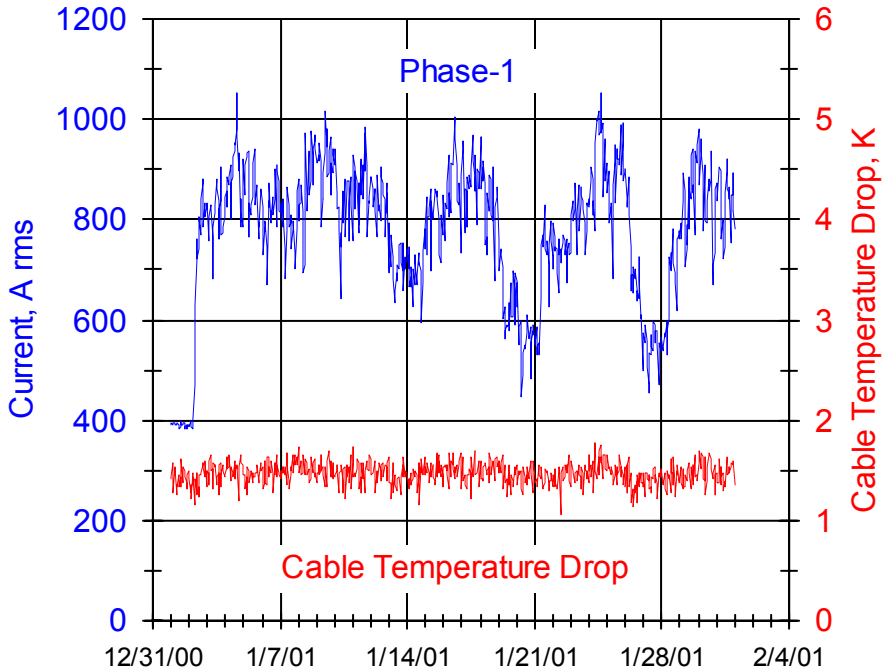
Buswork and ground connections.

- Using the connections shown, over 96% of the phase current was measured to be induced in the shield.
- Magnetic field measured outside the center of the cable was small.

Cryogenic plant has provided reliable cooling since November 1999

- Provided by PHPK, Inc.
- Average total heat load is 2510 w
- Cable and terminations ~ 1500 w
- System running unattended via PLC since June 2001

Typical monthly load data



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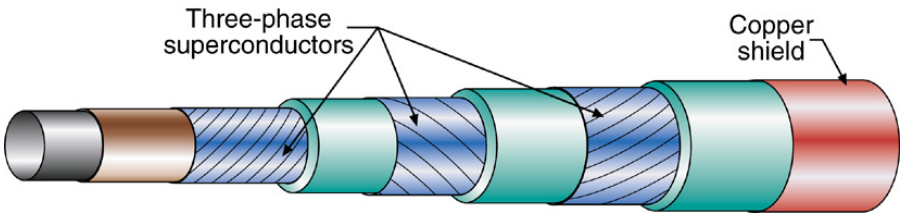
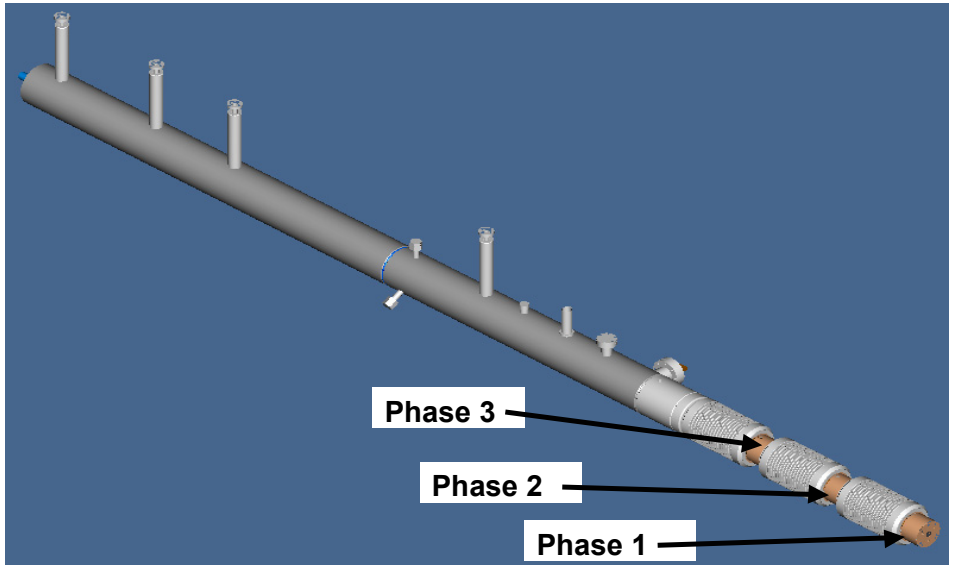
A 5-m 1.3 kA cable with full-scale terminations was built and tested.

- A full-scale demonstration of the technology
- Has a full-scale three-phase terminations.
  - provide for ambient electrical connections.
  - make the transition to liquid nitrogen temperature.
- 15 kV phase-to-phase
- dielectric material is Cryoflex™ tapes immersed in liquid nitrogen.
- 2 layers of BSCCO-2223 silver-alloy tapes per phase

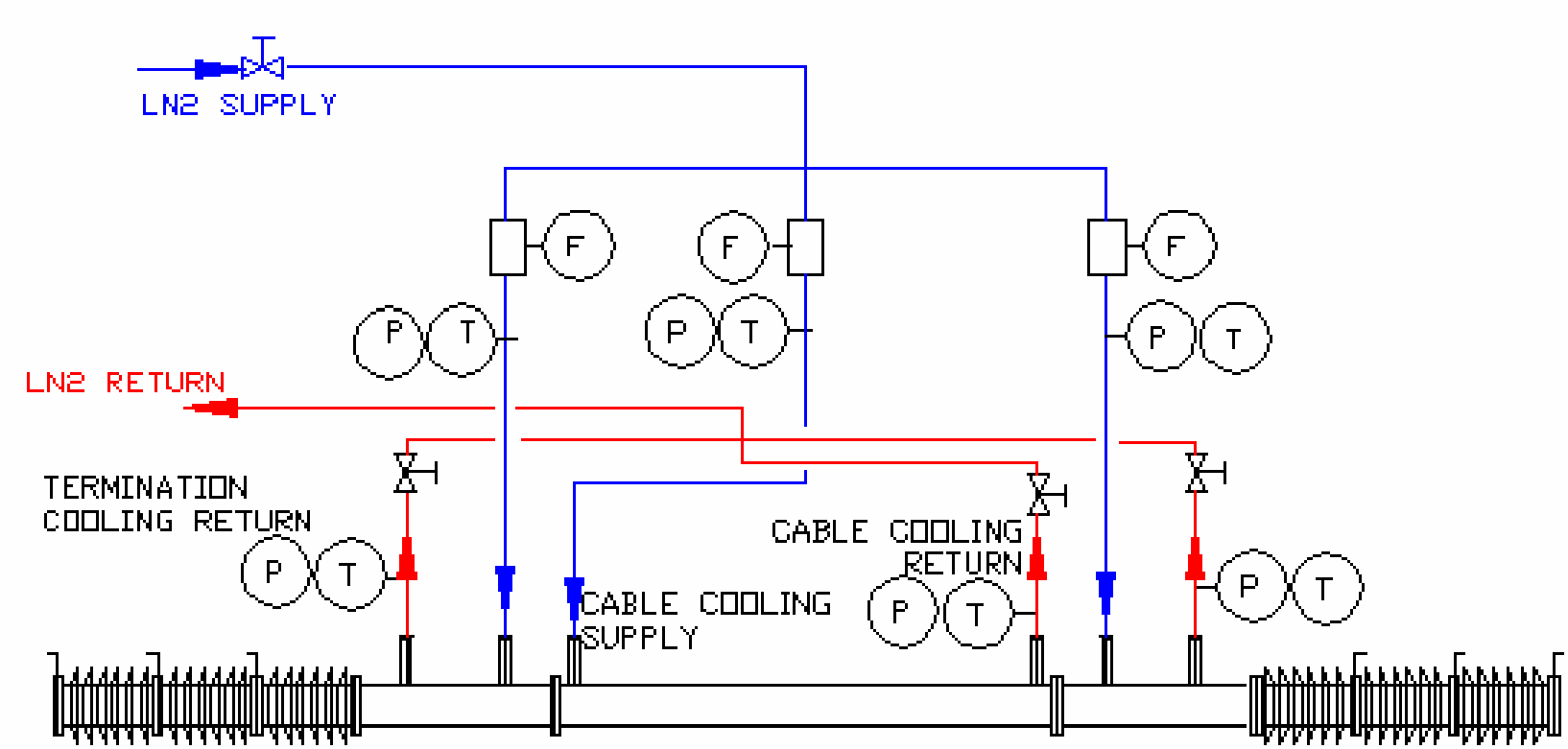




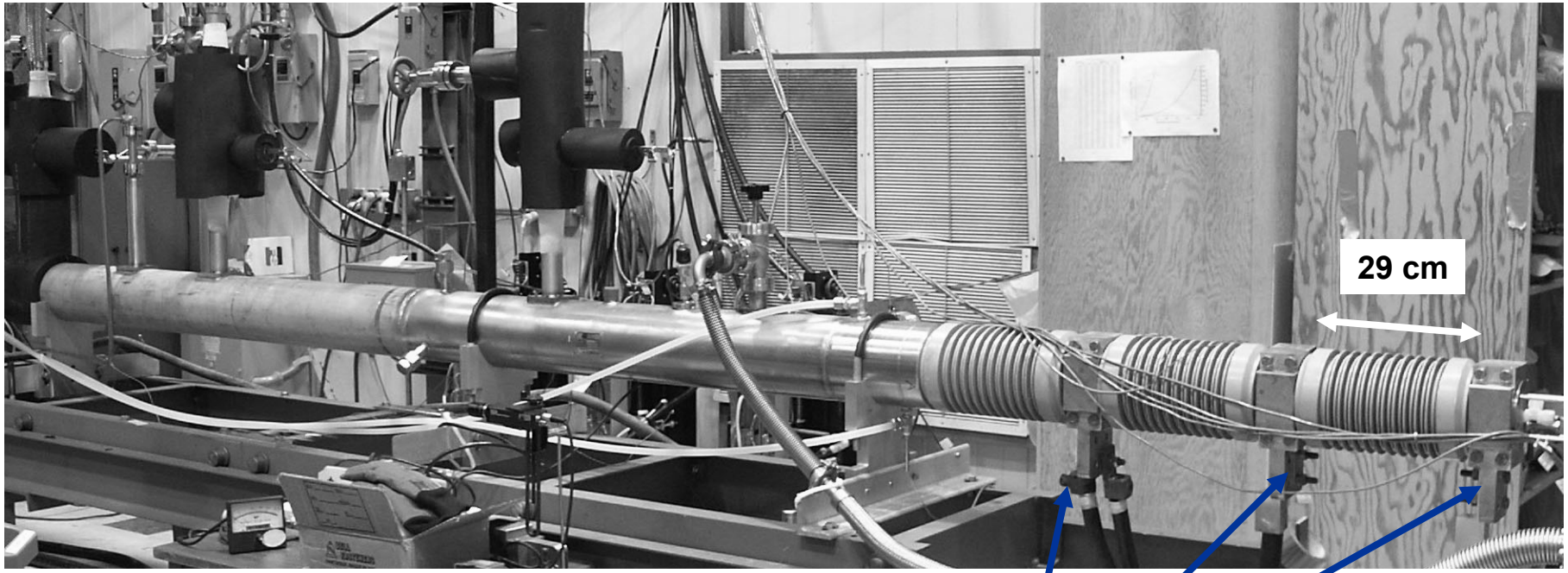
Tri-axial 3-phase termination design challenges.

- **A challenging constraint is a design with adequate radial heat conduction from the three electrical phases through the termination cross-section out to the flowing liquid nitrogen coolant.**
  - **the insulation between the phase conductors and between the outer phase and shield conductor:**
    - **must have adequate thermal conductivity at 77 K and 300 K, and**
    - **acceptable electrical insulation performance over this temperature range.**
  - **termination should be designed for:**
    - **50 kV withstand (1 minute, dry)**
    - **110 kV BIL voltage**
- **During testing of 1.3 kA termination, breakdown occurred at 15 kV after 5 minutes.**
  - **Solid dielectric material and design is being modified to eliminate the problem in 3 kA termination.**
  - **Tests on model terminations indicate low PD and acceptable ac withstand.**

Tri-axial cable and terminations were cooled separately to measure the individual component heat loads.



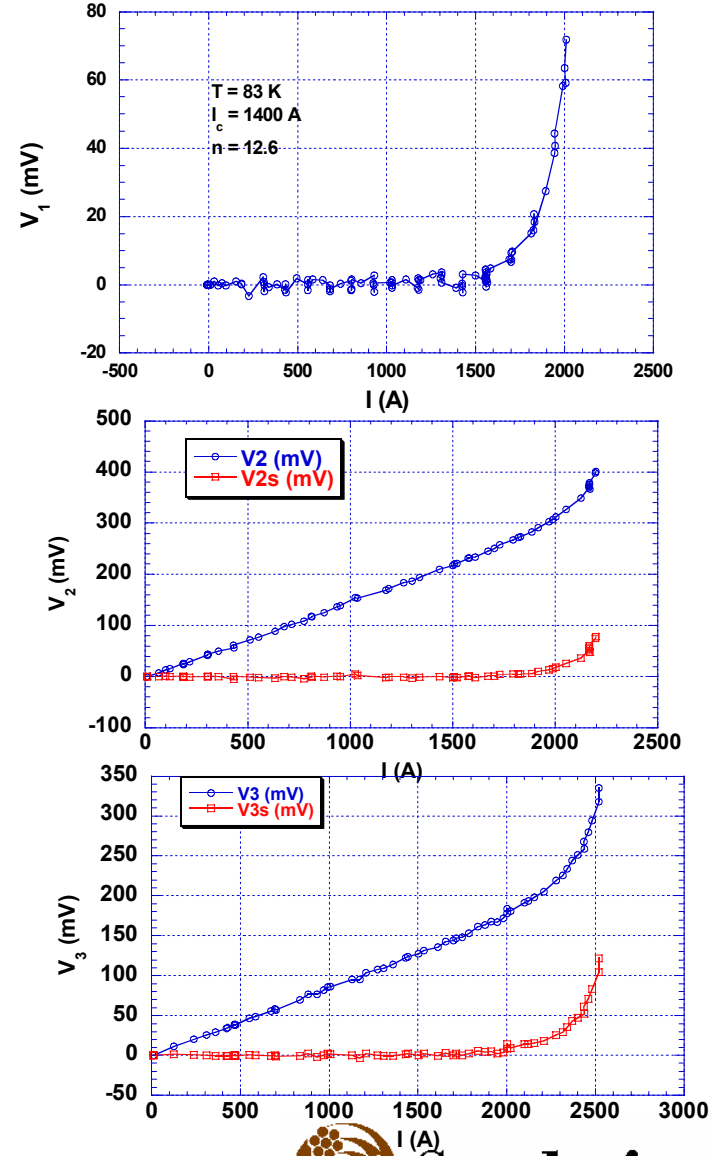
The 5-m Tri-axial Cable Installed at the HTS Cable Test Facility



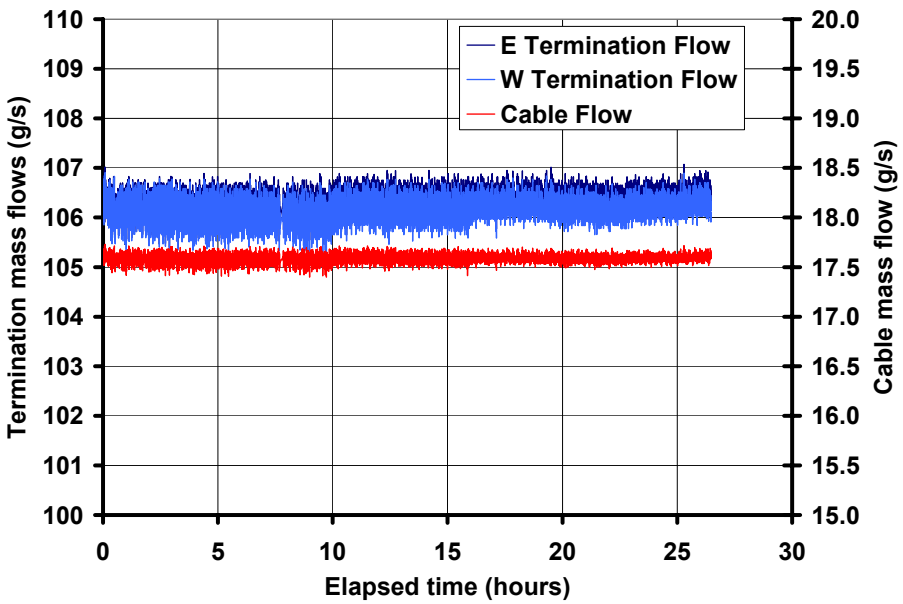
Connections for ac power

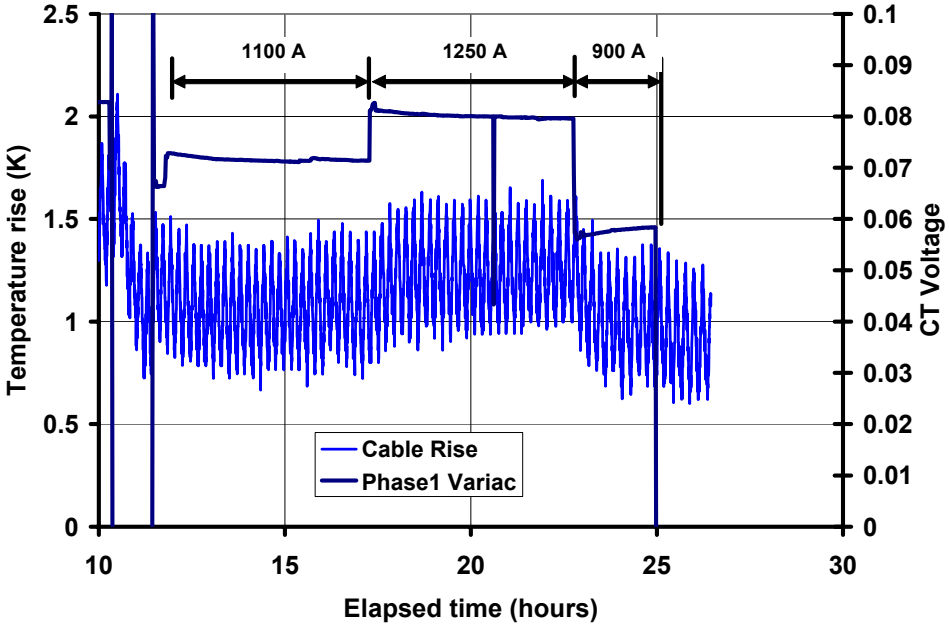
DC VI curves and I_c for the individual phases were measured.

- Phase 1 had voltage taps on the HTS.
- Phases 2 and 3 had voltage taps on the external bus.
  - The voltage drop across the bus was subtracted out to determine the VI characteristics.
- The critical currents measured at 83 K are:
  - Phase 1 = 1400 A
  - Phase 2 = 1570 A
  - Phase 3 = 1610 A
- The critical currents extrapolated to 77 K are:
  - Phase 1 = 1870 A
  - Phase 2 = 2090 A
  - Phase 3 = 2150 A



The tri-axial cable was run at different conditions until temperatures stabilized.

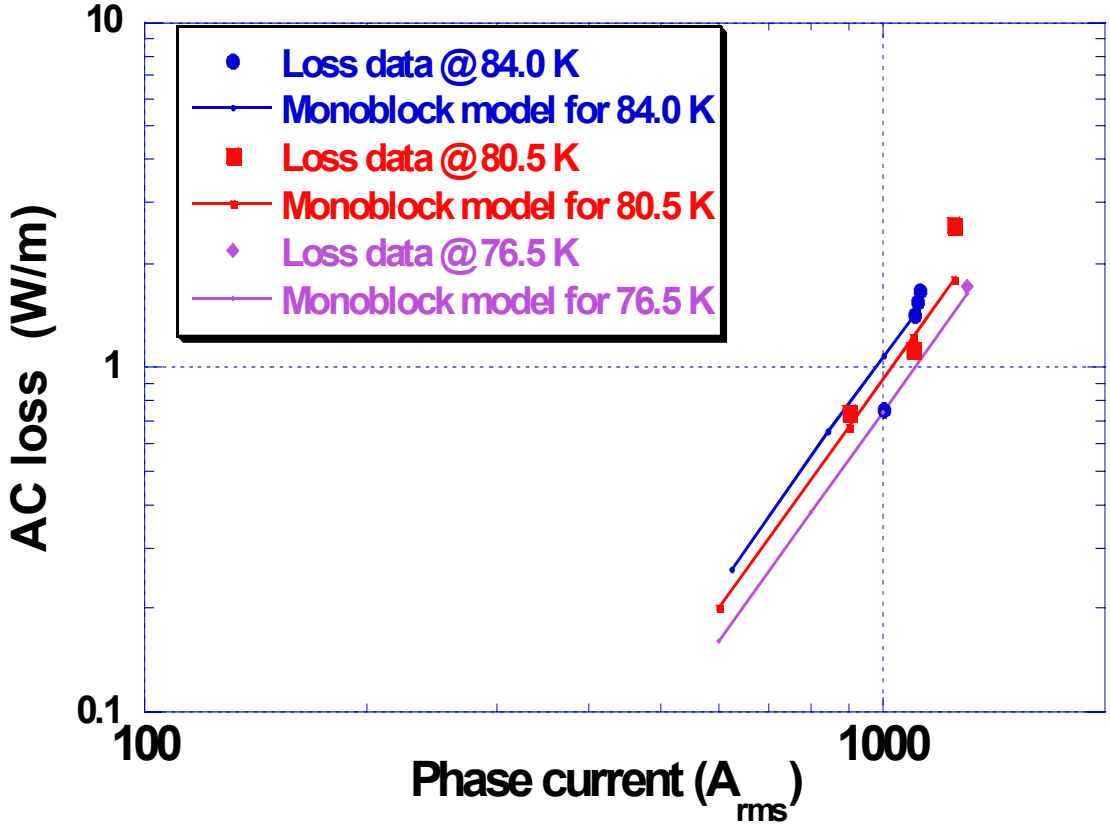




- **Mass flows through the terminations and cable remained steady during the test runs.**
- **Temperatures stabilized at design operating current.**

Data from December 2002

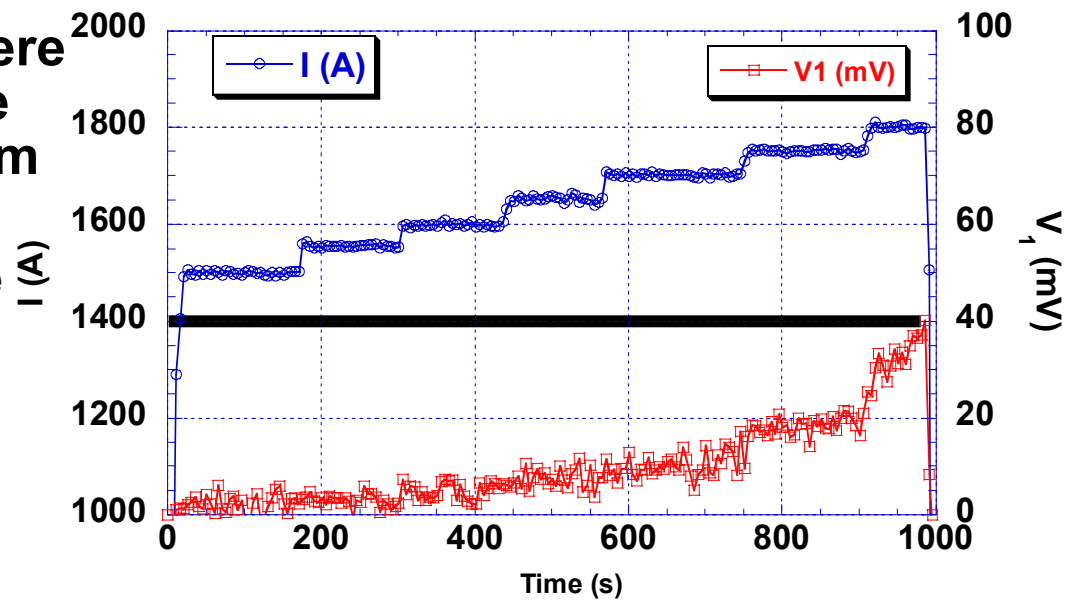
Tri-axial cable ac loss compares well with mono-block model for balanced currents.



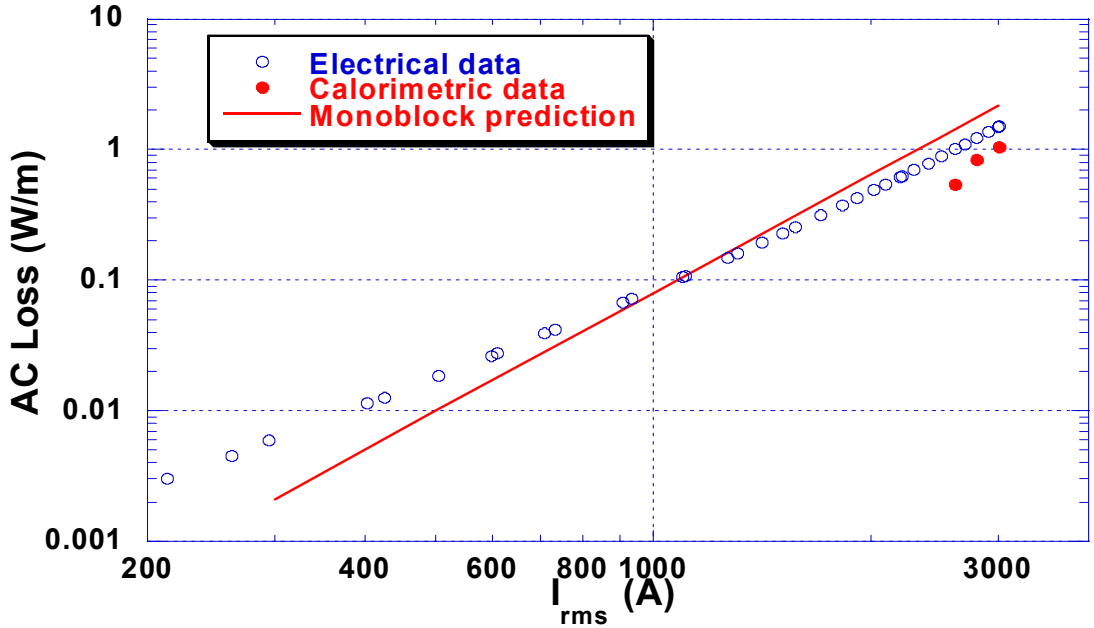
- The induced current in the shield for balanced and unbalanced three-phase currents was measured and found to be small.
- Magnetic field surrounding cable is negligible.

DC over-current tests were conducted on Phase 1 that could be used to determine thermal limit.

- Phase 1 is the innermost phase and farthest away from the cooling stream.
- At the flow conditions that were present for this run, the cable could operate with a maximum of 5.6 W/m on phase 1.
  - Test conducted at 83 K. Cable operation would be at lower temperature.
  - Coolant flow rate was low to allow for calorimetric measurements of heat loads.
- Cable I_c = 1400 A



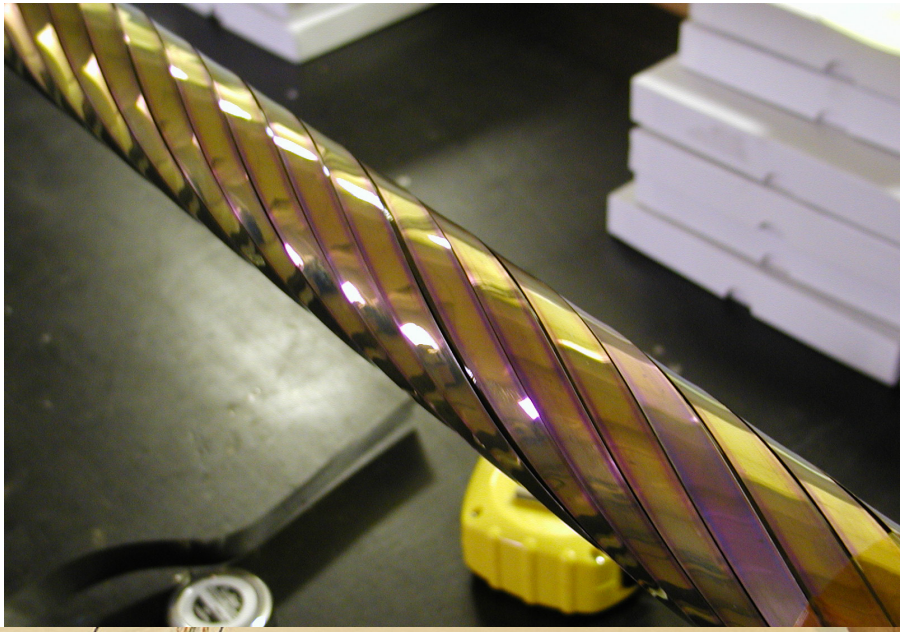
A series of short cables were fabricated and tested to qualify AMSC tape for the AEP project.

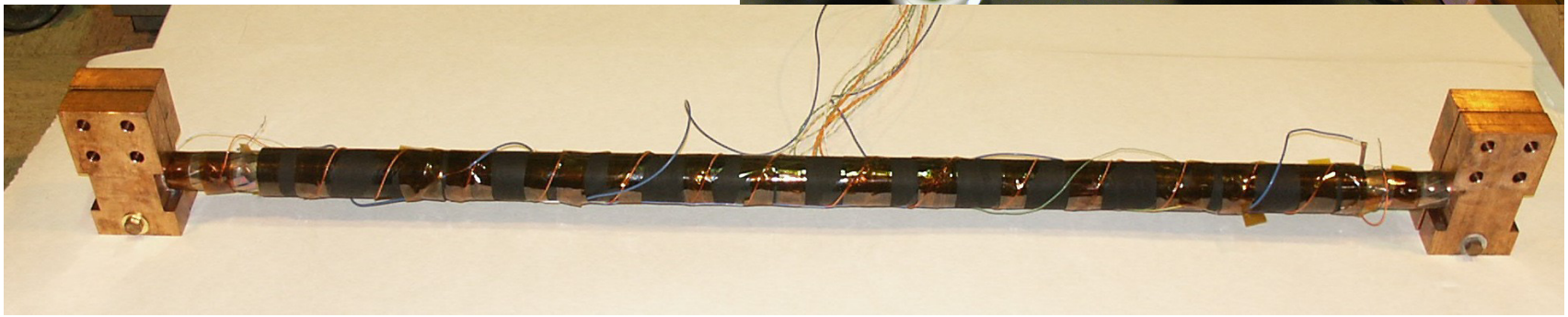


- April 2003: Prototype cable with AMSC BSCCO tape. Tested at ORNL.
- Wound 1.5-m cable with optimum lay angles. Cable had 54 tapes in 2 layers.
  - Tape I_c was 115-126 A. Cable I_c was ~5800+ A
  - AC loss of the 1.5 m cable @ 60 Hz and 77 K, slope of the red curve = 3
- AC loss was 1-2 watt/m at 3 kA; this is acceptable for the 3 kA AEP HTS cable.

The YBCO cable was fabricated by Southwire Co. using AMSC tape and tested at ORNL

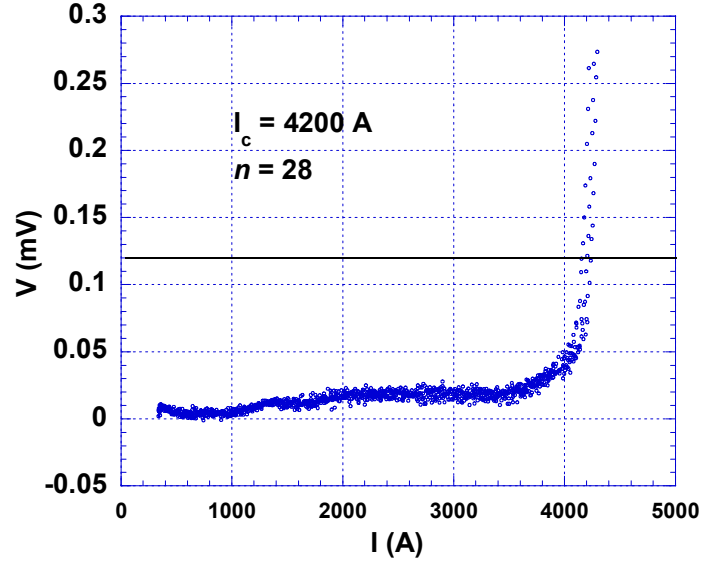
- AMSC delivered 30-ea., 1.5-m 2G YBSO tapes.
- All tapes exceeded ORNL specifications

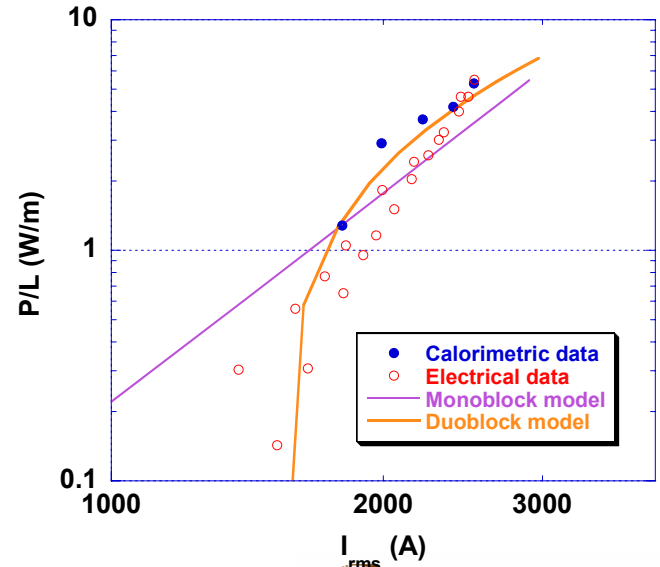




A Second Generation YBCO Conductor Cable was Fabricated and Tested

- Commercial Grade demonstration YBCO cable (I_{ac} > 2 kA)
- No degradation of I_c from winding.
- 50 μm of copper laminated to silver coated YBCO conductor from American Superconductor
- Cable Specifications
  - 1.25 m long
  - 24 tapes
  - Measured I_c of 4200 A with an avg. n of 28
- At I_{op}=2 kA, AC loss ~ 2 W/m.
  - Large gap between tapes causes increased losses.
  - 4 mm wide tapes will reduce losses.





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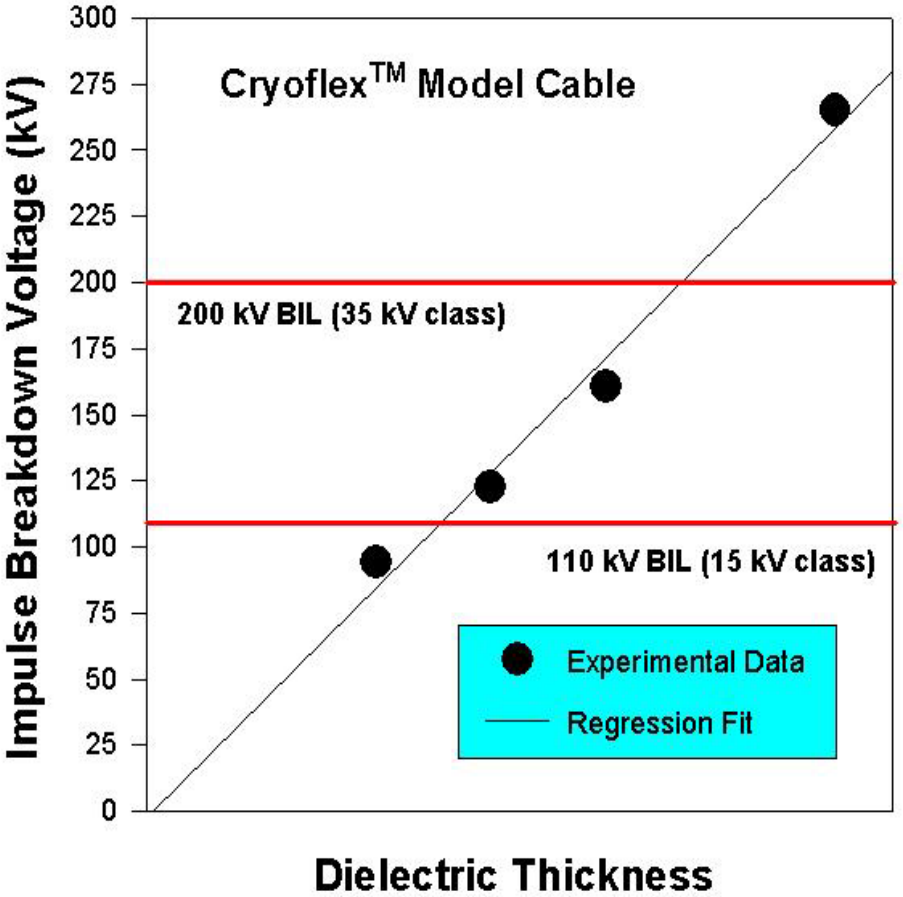
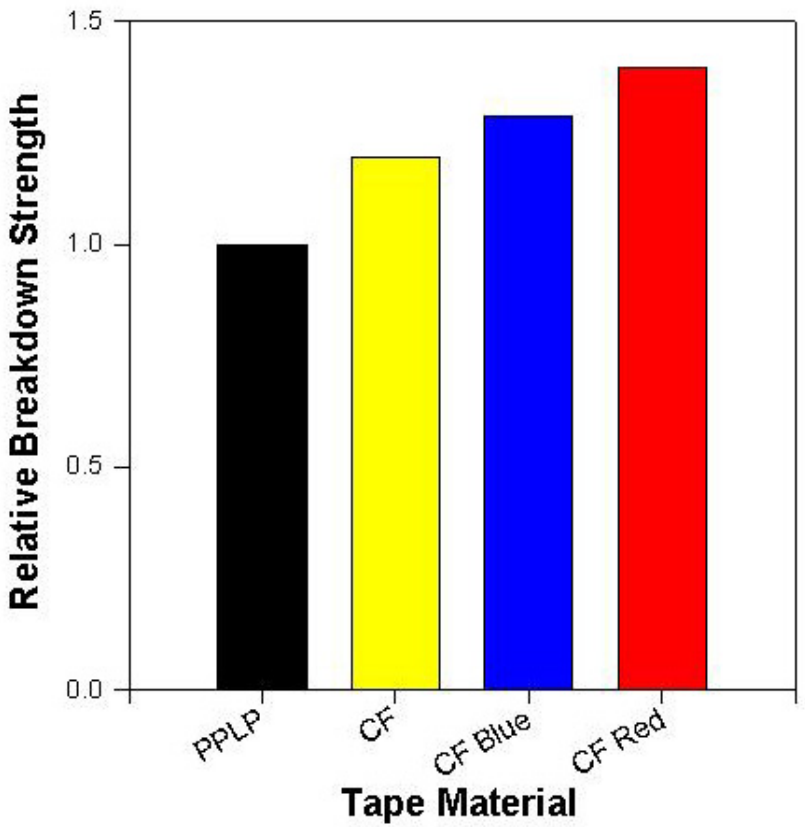
Cryoflex™ Dielectric Meets 35kV Class BIL

- Insulation requirement for 35 kV class cable
  - 200 kV BIL
- Determine dielectric thickness needed to meet BIL
- Impulse strength found to be linear with dielectric thickness
- Stress cone development important for higher voltage designs



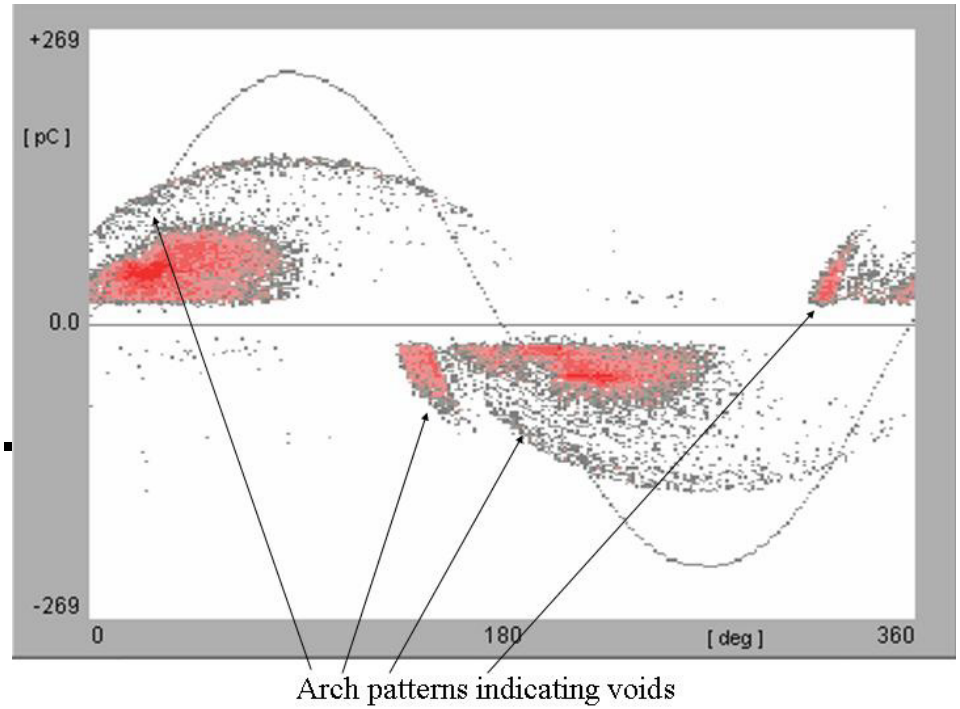
Improved Dielectric Tapes for Higher Voltage Class Cables

- Two new tapes have been developed for future HTS cable insulation
- Both have higher strengths than original Cryoflex™
- Cryoflex™ has higher strength than PPLP which is used in Japan for HTS cable

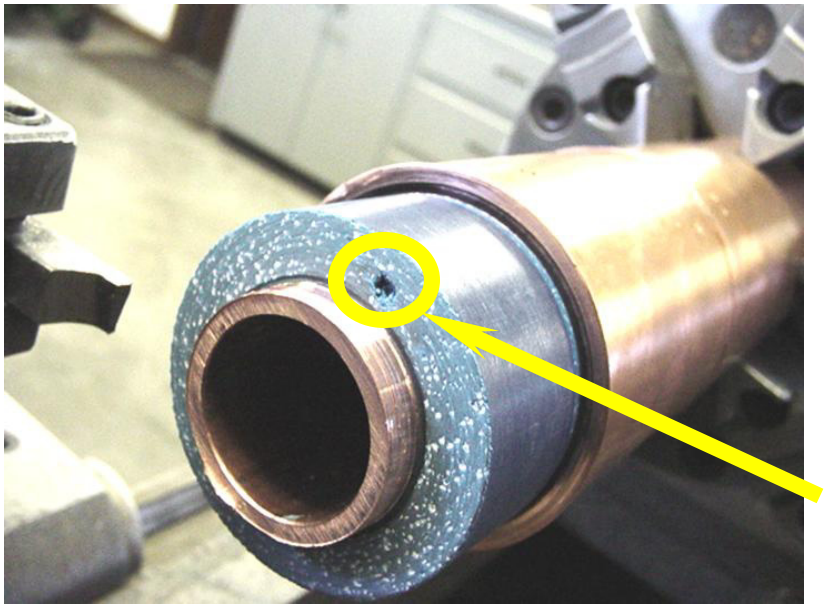


Partial Discharge (PD) Patterns in Model Termination Enabled Void Detection

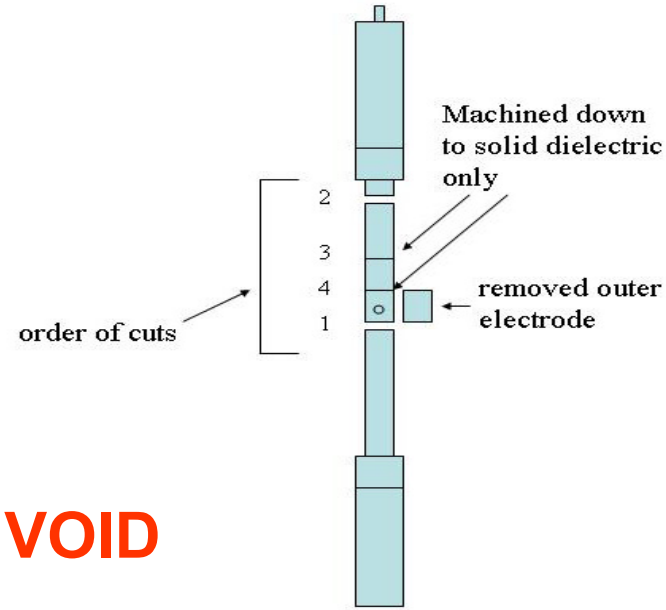
- **Phase and amplitude resolved PD patterns were measured in model terminations.**
- **Arch patterns observed similar to patterns in samples with known or deliberately placed voids.**
- **Subsequent dissection indicated presence of voids.**



Examined breakdown due to voids in solid dielectric

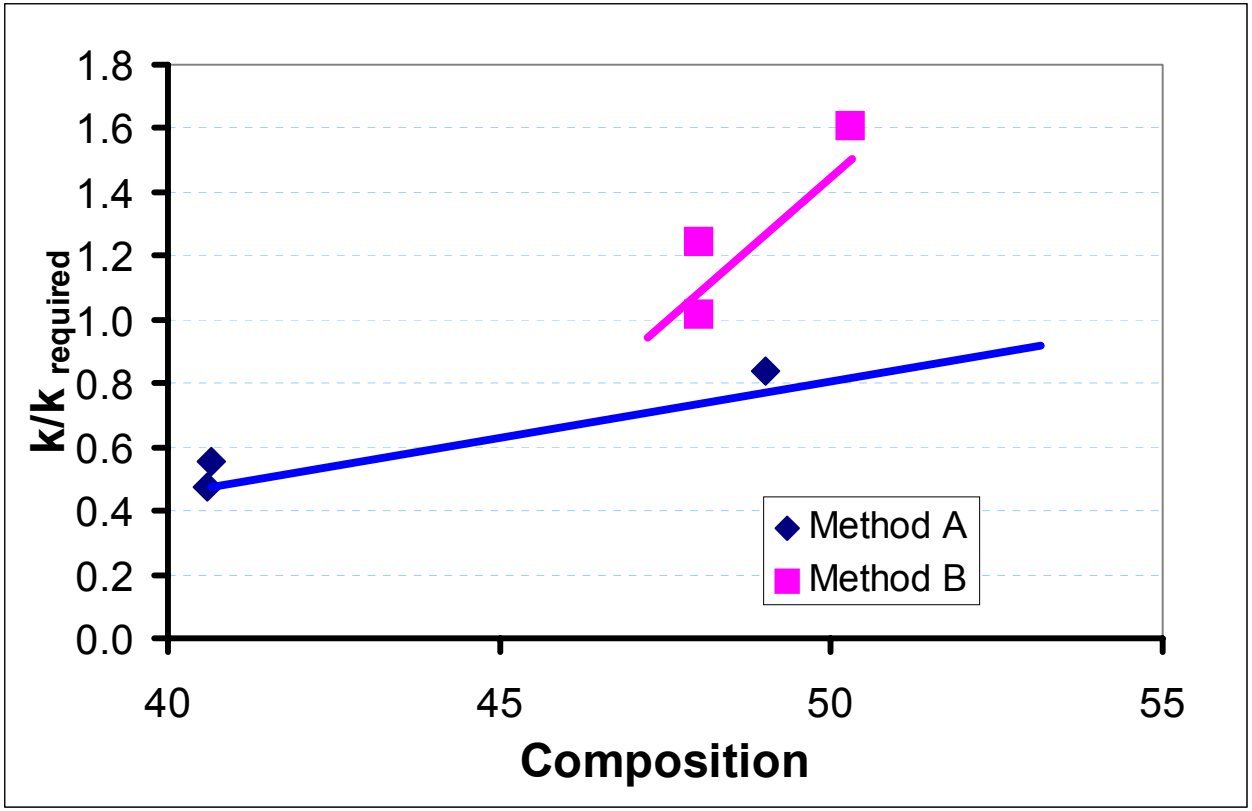


VOID



- Model terminations were made and tested for PD and BD strength
- PD patterns found to be similar to voids
- Dissected insulation using a megger to determine location of a void
- Solid insulation needs to be void free

Solid dielectrics were tested to find some with suitable thermal and electrical properties.



- **Partial discharge and breakdown was measured on all compositions.**
- **Thermal conductivity of selected samples that met electrical requirements were measured to select candidate dielectrics.**

ORNL FY 2003 Performance

FY 2003 Plan

- Evaluation of 30-m cable operation and performance (Southwire/DOE decided to extend demonstration at Carrollton, GA)
- Continued development of the pressurized termination.

FY 2003 Performance

- Over 22,000 hours of operation
- Critical current measurements show robust superconductor
- Unattended operation (since 6/01)
- Shield currents were measured with different grounding arrangements.
- A 3 kA tri-axial termination development was started. This is the required operating current for the AEP project.
- Developing dielectric materials to eliminate PD and 15 kV breakdown.

ORNL FY 2003 Performance

FY 2003 Plan

- Complete testing and analysis of 5-m tri-axial cable including 3-phase terminations
- Based on results of 5-m system, install and test 30-m tri-axial cable system next to present cable at Southwire complex , Carrollton, GA.

FY 2003 Performance

- Measured DC V-I characteristics
- 3-phase ac loss
- Individual phase ac loss
- Over-current tests
- A 3000 A 5-m tri-axial cable and terminations is being fabricated to meet the requirements of the AEP project.
- Addressing the high voltage solid dielectric issue.

ORNL FY 2003 Performance

FY 2003 Plan

- Continued research on cryogenic dielectric materials
- Research improving cryogenic system.

FY 2003 Performance

- Dielectric materials for tri-axial terminations were developed that meet thermal and electrical requirements.
- Tested flexible cryostat on 5-m cable at ORNL
- ORNL lead role in Cryogenics Initiative along with ANL and LANL
  - Prepared and issued RFP to cryogenic industry
  - Reviewed proposals that were submitted.

ORNL FY 2003 Performance

FY 2003 Plan

- ORNL will work with Southwire to begin the design and testing of cable subsystems for a long-length cable installation in partnership with Southwire Co. and AEP.
  - Terminations
  - Refrigeration system
  - Cryostat

FY 2003 Performance

- ORNL personnel participated in site visits to AEP.
- Qualification of AMSC tape for use in AEP HTS cable.
- Specifications for the refrigeration system are being developed.
  - Discussions with PHPK on improvements to the next system based on operating experience in Carrollton, GA.

ORNL FY 2003 Additional Tasks

FY 2003 Plan

- Tested 1- to 3-m cables to evaluate conductor architecture and minimize ac loss
- First 1-m YBCO cable initial testing completed.

FY 2003 Performance

- Tape architecture modified to improve characteristics for cables.
- Measured DC V-I and ac loss

Southwire/ORNL FY 2004 Milestones
Oct. 1, 2003 to Sept. 30, 2004

- **SPI-1: 30-m Installation, Carrollton, GA**
  - **1-3Q, FY2004 (Oct03-Jun04)**
    - Continue operation of system with required PM and system management.
    - SPI contract expires 6/30/2004
  - **3Q, FY2004 (Apr-Jun)**
    - Re-test dc-Ic of cables
- **SPI-2: Bixby Substation, AEP, Columbus, OH**
  - **1Q, FY2004 (Oct-Dec03)**
    - Complete electrical testing of the 5-m tri-axial, 3-phase, 3,000 Arms cable at ORNL,
    - Complete testing of the YBCO cable (Additional ac loss and over-current tests)
  - **Jan2004**; Go/No-Go Decision for Triax at AEP based on 5-m results
  - **2Q, FY2004 (Jan-Mar04)**
    - Completed design for cable demo at AEP Columbus and begin long lead procurements.
    - Begin civil/electrical design & construction work at Bixby station
  - **3Q, FY2004 (Apr-Jun04)**
    - Begin construction of HTS cable for AEP
    - Test model cables and terminations to higher ac voltages (up to 69 kV),
      - Requires upgraded dewar for the higher voltage levels.
  - **FY2004 (Oct03-Sept04)**
    - Continued research improving cryogenic system performance with industry and NASA

Southwire/ORNL FY 2005 Milestones
Oct. 1, 2004 to Sept. 30, 2005

- **SPI-1: 30-m Installation, Carrollton, GA**
  - SPI contract expires 6/30/2004. Final technical report due to DOE.
  - Disposition of system undecided – Southwire may decide to continue operation.
- **SPI-2: Bixby Substation, AEP, Columbus, OH**
  - 1Q,FY2005 (Oct-Dec04)
    - Complete cable construction and off-site verification testing
  - 2Q,FY2005 (Jan-Mar05)
    - Begin delivery of cable system components to Bixby station
  - 3Q,FY2005 (Apr-Jun05)
    - All civil/electrical construction work by AEP completed
    - HTS cable, cryogenic, and control systems installed
  - 4Q,FY2005 (Jul-Sept05)
    - On-site commission testing of all cable system components
  - 1Q, FY2006 (Oct 2005)
    - Energize cable system

Risk mitigation measures: HTS Cable

- **Risk mitigation strategy**
  - **Address risks by incremental R&D steps on models and test cables:**
    - **material tests on small scale samples (solid and tape dielectrics, HTS tapes, etc.)**
    - **material and component tests on scaled model components (model cables and terminations for HV testing)**
    - **System tests on full radial scale, short-length components (1-5 m HTS cables, full-scale terminations at ORNL). Demonstrate reliable performance for moderate periods (days) and test to IEEE requirements (ac withstand, BIL, PD, fault currents)**
    - **System tests on full radial scale, moderate-length components (30-m HTS cables at Southwire). Demonstrate reliable performance for long periods (years). Periodically measure the change if any in HTS tape critical currents**
    - **Multi-year utility demonstrations with cables of length 100's of meters**
  - **Design:**
    - **Tough, comprehensive design reviews at the conceptual and final design points with participation from experts not working directly on the HTS cable project**
    - **SPI readiness review scheduled to coincide with the AEP project FDR in January 2004**
    - **Perform Failure Mode and Effects Analysis (FMEA) on key sub-systems such as terminations, cryogenics and controls**
  - **Assembly:**
    - **Do stringent 300 K leak testing on individual components to minimize global leak rate while cold**
    - **Extreme care in assembly so as not to introduce shorts or continuous current loops**
    - **Cleanliness, material control to reduce out-gassing**
  - **Testing:**
    - **Develop test plans up-front to ensure sufficient data for successful demonstration and for relevant standards development.**
    - **Proceed from lower risk to higher risk testing.**
    - **Key sensors are interlocked for operator warning and then automatic actions for component protection and continuity of power.**

Research Integration - Partnerships

- **Partners with expertise and funding.**
  - **Project is being conducted as a DOE SPI with equal cost sharing by Southwire and DOE. Southwire expertise includes:**
    - **Wire and cable manufacturing,**
    - **Established utility customer base,**
    - **Design and installation of turn-key systems for utilities,**
    - **Design and construction of copper rod mills world-wide,**
    - **Design and construction of manufacturing plants,**

    and now:
    - **Design, installation & operation of superconducting cables for utility customers.**
- **FY 2003 progress is evidence of well functioning team.**
  - **5-m triax cable research conducted jointly with Southwire/NKT at ORNL.**
  - **Multiple short, 1- to 3-m cables fabricated by Southwire tested at ORNL and NKT.**
  - **30-m cable operation and testing at Southwire**

Research Integration - Partnerships

- **Ultera™ created Dec. 2002 – Joint Venture between Southwire and *nkt cables* dedicated to the continued development and commercialization of HTS cable technology**
  - **Dec. 9, 2002 - http://www.mysouthwire.com/Southwire/cda/content/article/0,1443,6_426,00.html**
  - **Evolution of previous "technical-exchange" agreement**
  - **Cold dielectric design developed by Southwire (successful 30-m demo)**
  - **Warm dielectric design developed by NKTC (successful 30-m demo)**
  - **Both designs available to Ultera**
  - **Ultera and ORNL exchange technical information and data regularly**
    - **Teleconferences & Videoconferences**
    - **Interactive web conferencing**
    - **personnel exchanges**
    - **site visits and technical meetings**

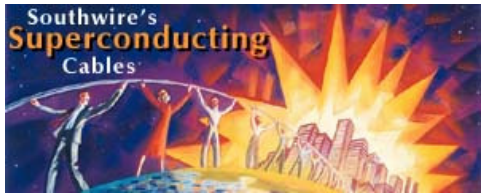
Research Integration - Expertise and Facilities

- **Efficient use of equipment and personnel between ORNL/Southwire.**
  - **Assembly of 30-m cables has involved a team of ORNL, Southwire and subcontracted technicians.**
  - **Shared use of SW ac power supply, ORNL dc power supply, SW PD detector.**
- **Technical capability is being established in industry by subcontracting for subsystems and components.**
  - **Cryogenic system was competitively bid and awarded to U.S. industry (PHPK).**
  - **Components for terminations are being manufactured by U.S. industry resulting from competitive request for quotations.**
  - **Several key consultants have provided technical expertise and analysis.**

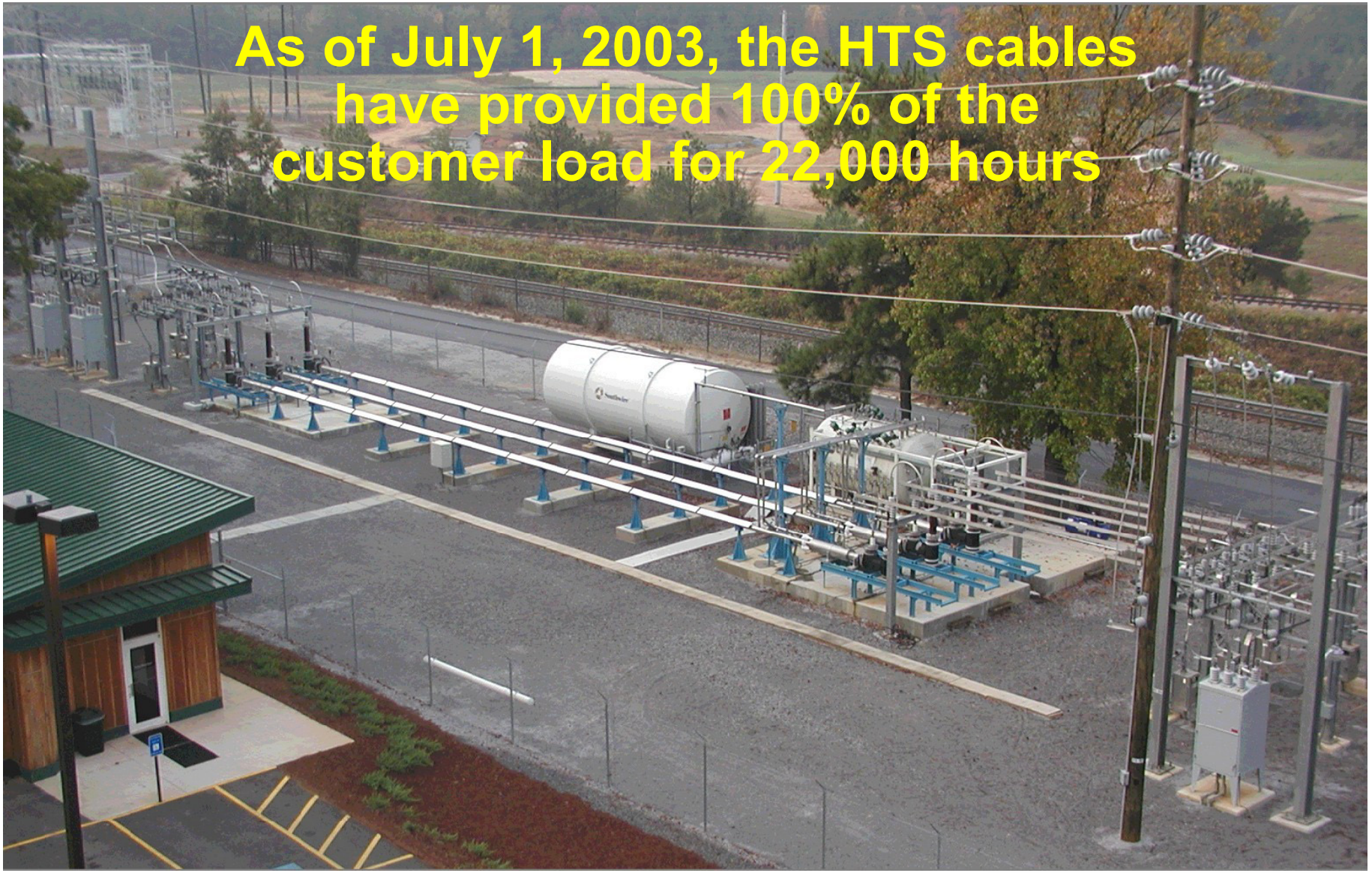
Research Integration - Publications

- **Presentations and publications during the year**
  - **Four papers were accepted for publication in the proceedings of the 2002 ASC and will appear in the *IEEE Transactions on Applied Superconductivity*, 2003.**
  - **One paper was presented at the ISS in Japan and was accepted for publication in *Physica C*, 2003.**
  - **Four technical papers will be presented at the Cryogenic Engineering Conference in September 2003 and submitted to *Advances in Cryogenic Engineering,* 2004.**
- **Web Sites**
  - **ORNL Superconductivity Web Site includes Annual Reports, Peer Review presentations and other project information**
    - **www.ornl.gov/HTSC/htsc.html**
  - **Southwire Web Site includes press releases and project information**
    - **www.mysouthwire.com**

Summary



- **FY 2003 goals have been achieved**
  - **30-m HTS cable has over 22,000 hours of flawless operation**
    - **Cable remains robust and is running unattended**
  - **Cable design and testing develops the needed technology base**
    - **1300 A, 5-m tri-axial cable with three-phase terminations has been tested.**
    - **A breakdown at 15 kV in the termination was caused by voids in the dielectric.**
    - **3,000 A 5-m tri-axial cable and termination assembly in progress.**
    - **Cryogenic dielectric aging tests proves longevity of Cryoflex™**
- **ORNL has provided a breadth of expertise to Southwire**
- **Numerous technical papers have been published in the public domain providing project technical information**
- **Leveraging of technology in partnership with *nkt cables***


As of July 1, 2003, the HTS cables have provided 100% of the customer load for 22,000 hours