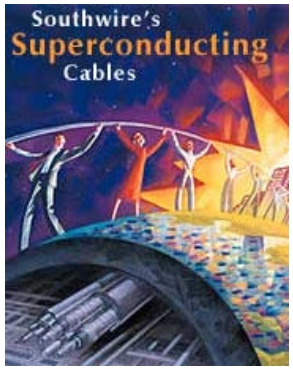
High Temperature Superconducting Cable



2002 Annual Peer Review

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

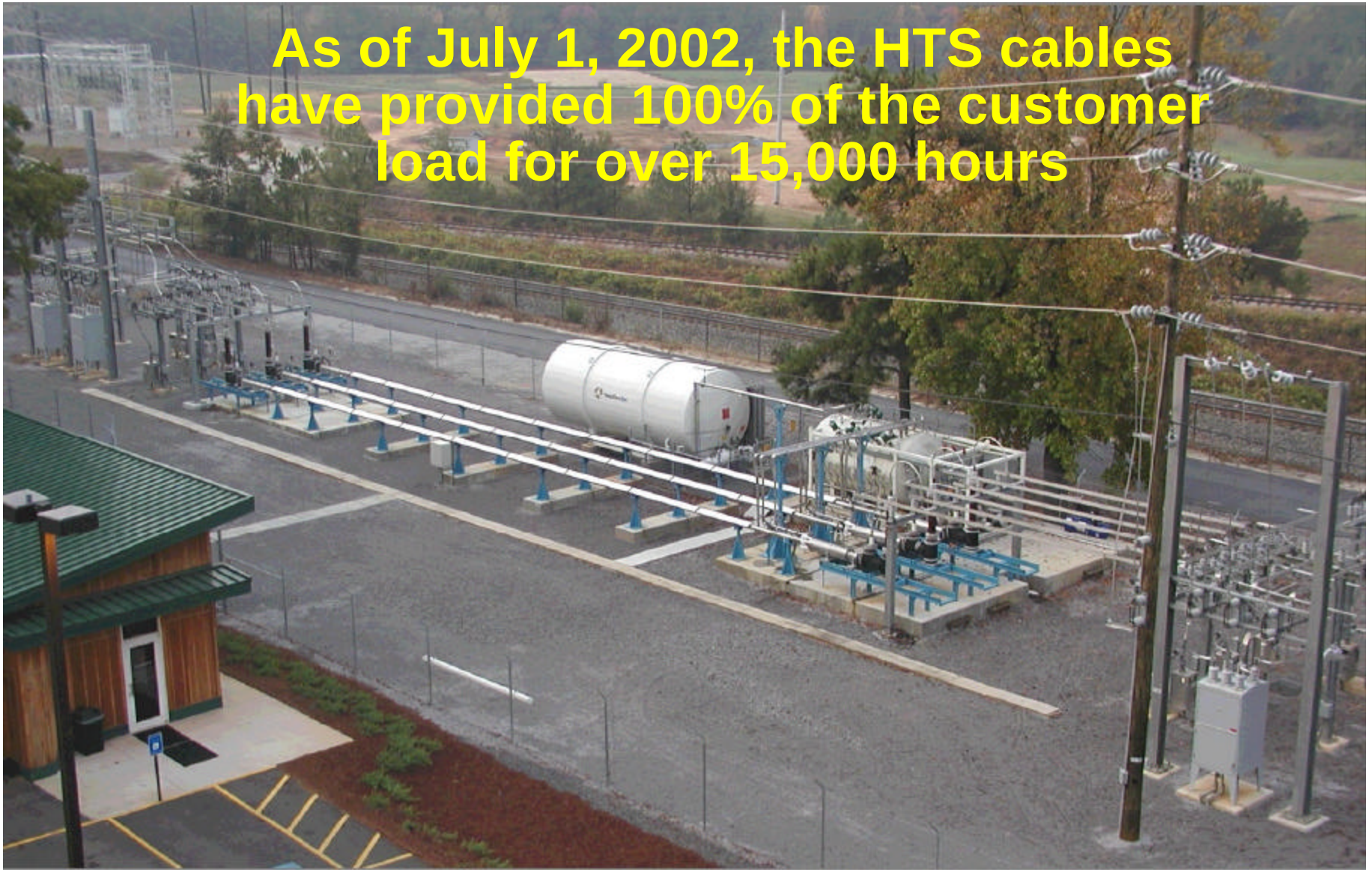
Southwire

ornl

July 17-19, 2002
Washington, DC

OAK RIDGE NATIONAL LABORATORY
U. S. DEPARTMENT OF ENERGY

UT-BATTELLE


As of July 1, 2002, the HTS cables have provided 100% of the customer load for over 15,000 hours

Presentation Outline

- **Southwire Activities** (David Lindsay, Southwire)
  - Introduction
- **FY 2002 Results**
  - 30-m Cable Operation and Testing
  - Cable Research (Mike Gouge, ORNL)
  - Cryogenic Dielectrics Research (Mike Gouge, ORNL)
- **FY 2002 Performance / FY 2003 Plans**
- **Research Integration**
- **Summary**

Project Participants at Southwire and ORNL

- **Southwire**

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

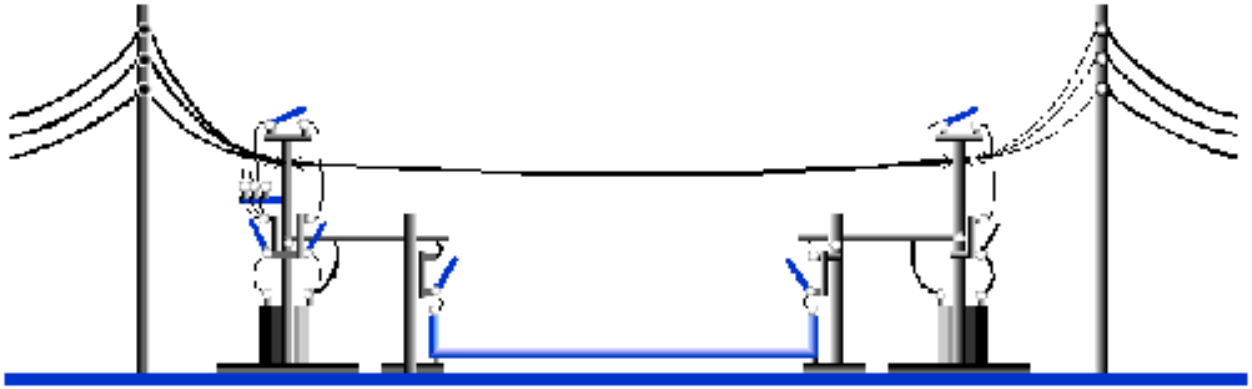
- **Oak Ridge National Laboratory**

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

SPI Project Goal (February 1997)

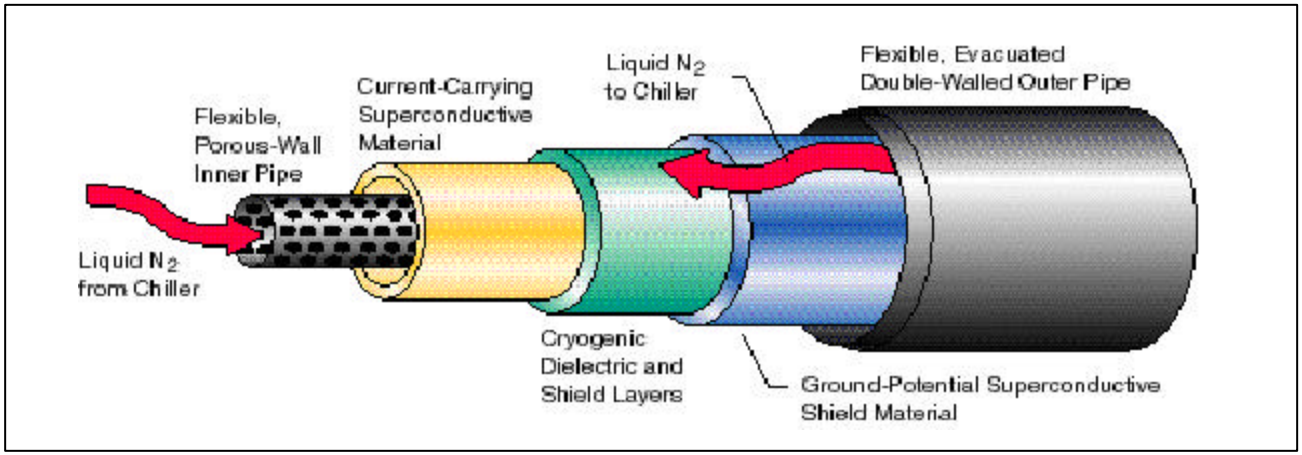
First U.S. Industrial SPI Cable Installation

- **At the end of the five year project, a high temperature superconducting (HTS) cable will be providing electric service to a large industrial customer at 12.4-kV and 1.25-kA.**



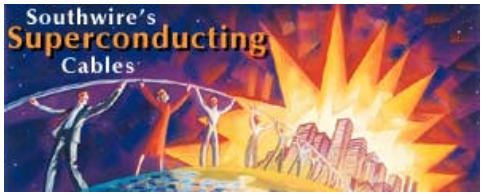
  - Multi-year operation of 30-meter three-phase cable beginning in **FY 2000** at Southwire headquarters in Carrollton, Georgia.

Cable Cross Sectional View



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

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
– Neutral phase connections	Mar. 2001
– Mix HTS and Cu phases	Mar. 2001
– 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

Additional accomplishments

- **Ran with mixed superconducting and copper phases supplying the factory load.**
- **Modified the end configuration of the three neutral bushings to maximize $I_{neutral}/I_{phase}$**
  - **More closely coupled the neutral bushings on each end; the neutral current increased to about 95% of the phase current**
- **Implemented full PLC control of the 30-m cable system for unattended operation.**
- **Web integration for real-time monitoring and data acquisition.**

Southwire High Temperature Superconductor/Cryogenic System (HTS/CS) - Microsoft Internet Explorer

File Edit View Favorites Tools Help

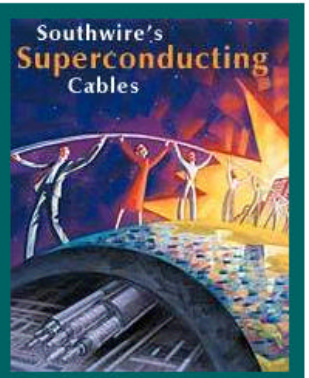
Address Go

Southwire
WE DELIVER POWER

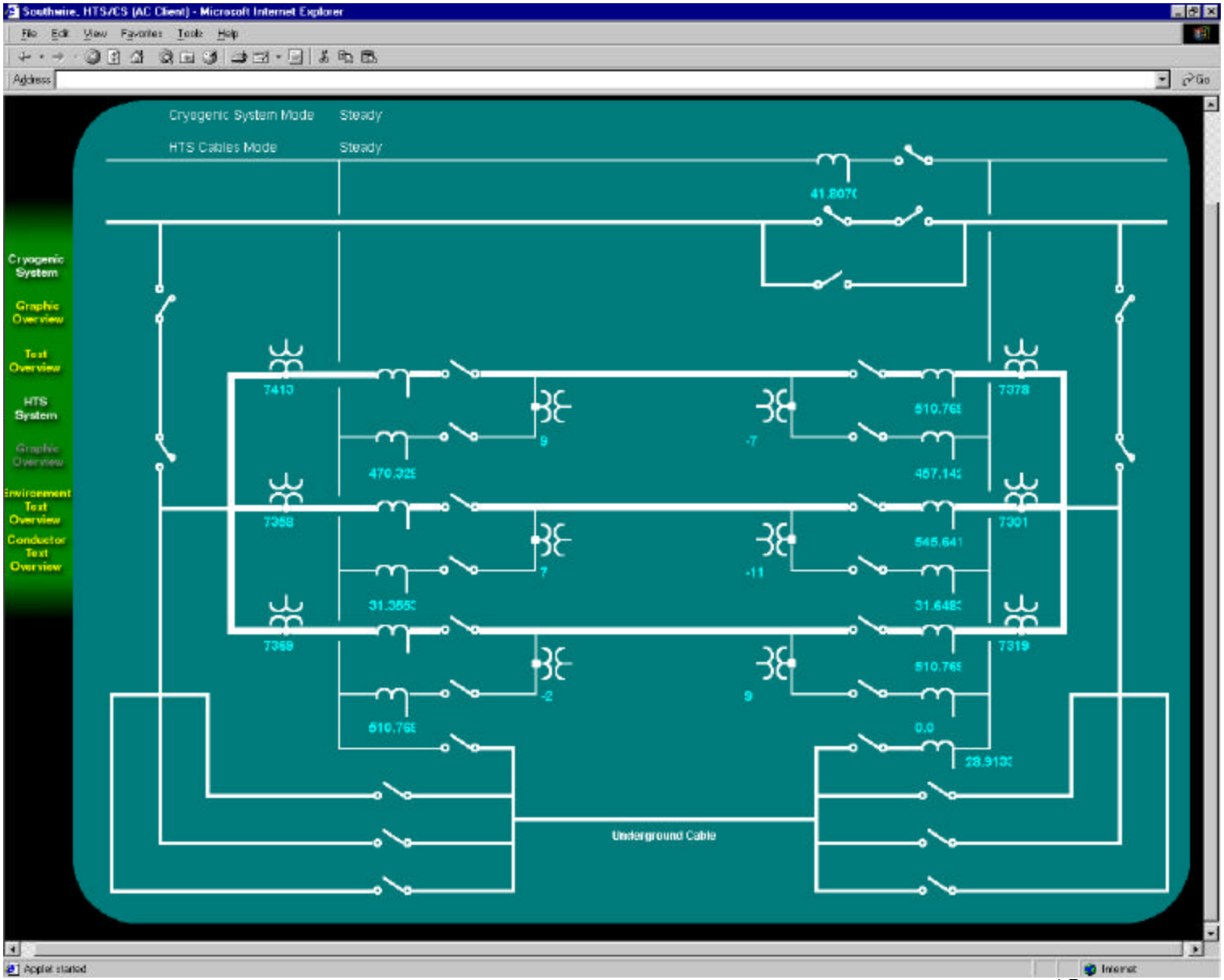
High Temperature Superconductor/ Cryogenic System

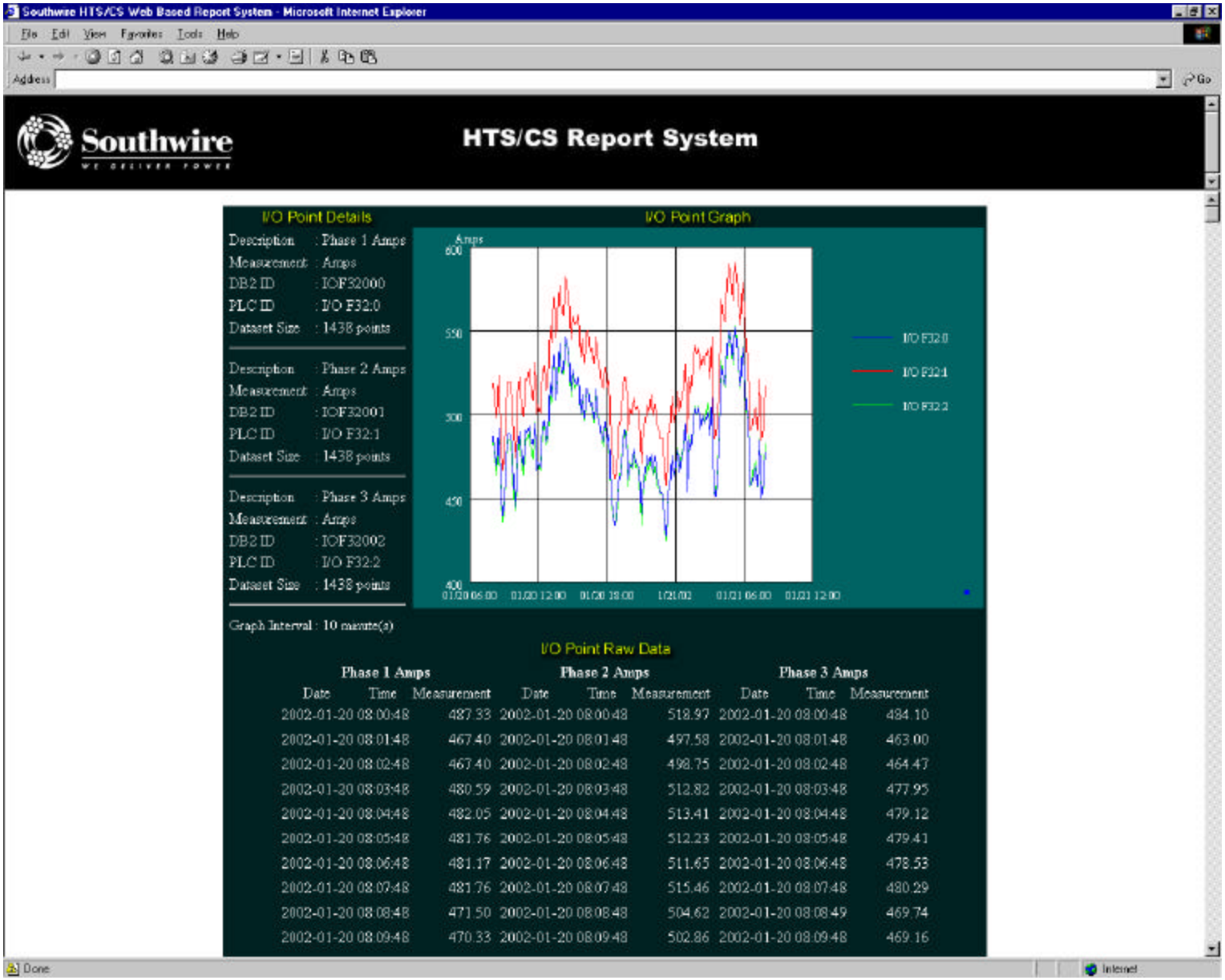
HTS/CS Systems

- Automation Connection Web Client
- Cryogenic System SnapShot
- HTS/CS Report System



Internet

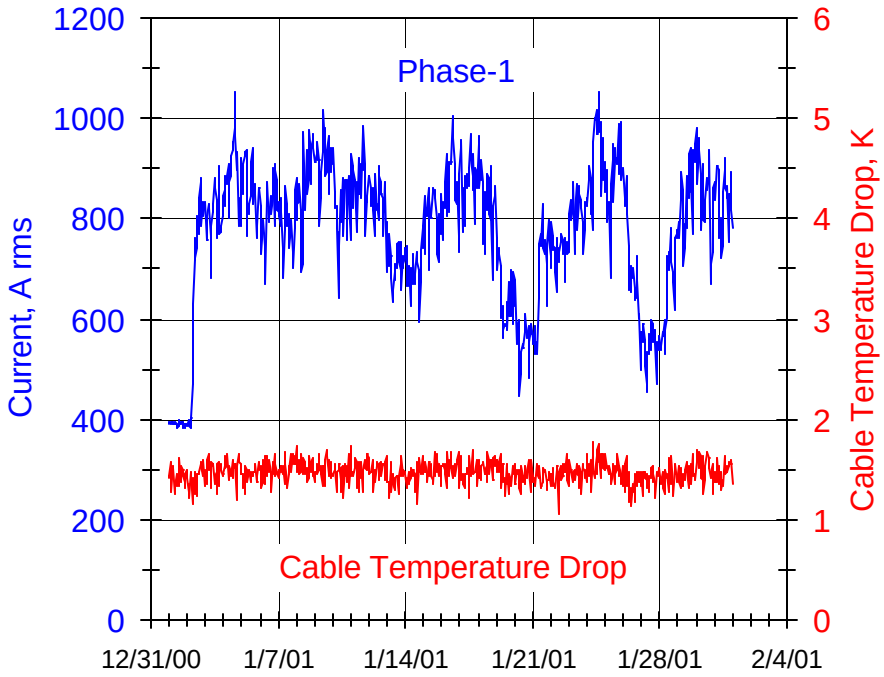

Southwire, HTS/CS (AC Client) - Microsoft Internet Explorer
File Edit View Favorites Tools Help
Address
Cryogenic System Mode Steady
HTS Cables Mode Steady
Cryogenic System
Graphic Overview
Text Overview
HTS System
Graphic Overview
Environment Text Overview
Conductor Text Overview
41.807(
7410
9
470.32
7378
510.76
-7
487.14
7358
7
31.355
7369
-2
510.76
7301
545.641
-11
31.648
7319
9
510.76
0.0
28.913
Underground Cable
Applet started
Internet


Southwire 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
Amps
600
550
500
450
400
01/20 06:00
01/20 12:00
01/20 18:00
1/21/02
01/21 06:00
01/21 12:00
I/O F32:0
I/O F32:1
I/O F32:2
I/O Point Raw Data
Phase 1 Amps
Phase 2 Amps
Phase 3 Amps
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

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



Presentation Outline

- **Southwire Activities** (David Lindsay, Southwire)
  - Introduction
- **FY 2001 Results**
  - 30-m Cable Operation and Testing
  - Cable Research (Mike Gouge, ORNL)
  - Cryogenic Dielectrics Research
  - FY 2001 Performance / FY 2002 Plans
- **Research Integration**
- **Summary**

ORNL FY 2002 Plans
Oct. 1, 2001 to Sept. 30, 2002 (from FY 2001 Peer Review)

- **ORNL will work with Southwire to improve the overall design and capabilities of the HTS cable system. Specific activities include:**
  - **Completion of bend testing of a 5-m HTS cable with a flexible vacuum cryostat,**
  - **Continued development of the pressurized termination concept,**
  - **Design, construction, initial testing and analysis of an innovative, 5-m tri-axial HTS cable including 3-phase terminations,**
  - **Continued development and testing of cryogenic dielectric materials, including cable aging studies,**
  - **Continued research improving cryogenic system performance with industry and NASA.**
- **In addition, ORNL will begin the design and testing of cable subsystems for a long-length cable installation at Columbus, OH in partnership with Southwire and American Electric Power.**

FY 2002 Results

- **30-m Cable Demonstration (Southwire lead)**
  - ***evaluation of 30-m cable operation and performance***
    - **Continued operation of the 30-m cable supplying power to Southwire manufacturing complex**

FY 2002 Results

- **5-m Cable Research (ORNL lead)**
  - ***bent cable testing in flexible cryostat***
    - **completed successful bend tests at 0, 30, 60, 90 degrees**
      - **subsequently bent back to 60 and 30 degrees**
    - **passed ac withstand and BIL test to 110 kV at 90 degree**
  - ***continue development of the pressurized termination***
    - **modified termination for improved dielectric performance: up to 117 kV BIL demonstrated**
    - **heat load reduced**
    - **design improvements**

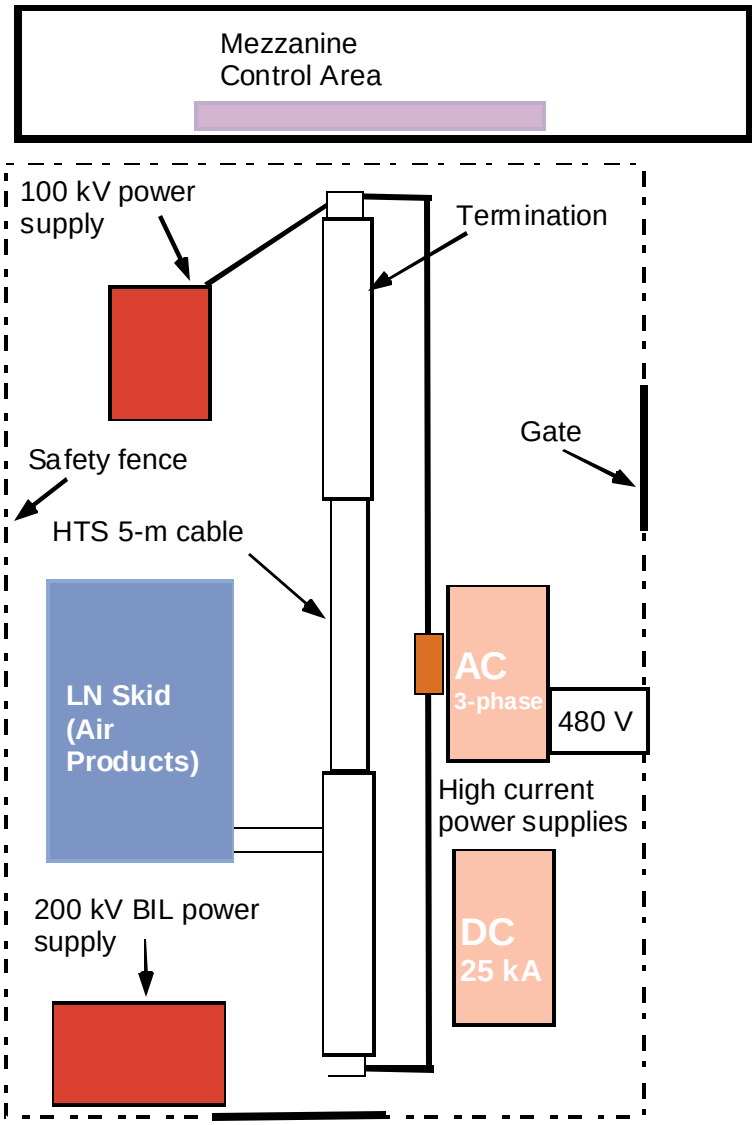
FY 2002 Results

- **5-m Cable Research (ORNL lead) continued**
  - ***Tri-axial cold-dielectric HTS Cable***
    - **potential to reduce required HTS tape and heat losses by ~ ½**
    - **successful 3-phase, tri-axial cable test in open LN bath at ORNL**
      - **low ac losses as reported at 2001 CEC**
    - **designed 3-phase, 5-m cable with 3-phase terminations**
      - **major effort, required R&D on components and materials**
    - **Southwire fabricated 5-m triaxial cable**
    - **outside shops fabricated termination parts: under assembly as of July 2002**
    - **testing expected in 4th quarter, FY 2002**

FY 2002 Results (continued)

- **HTS Cable Component Development**
  - **continued research on cryogenic dielectric materials**
    - **cryogenic dielectric aging tests well underway**
  - **research improving cryogenic system**
    - **have installed and will test flexible cryostat on 5-m cable at ORNL**
    - **ORNL lead role in cryogenics assessment task**
  - **YBCO quench and stability studies**
    - **Working to directly replace BSSCO with YBCO**
    - **Reported at 2001 CEC and in the Wire Session of this meeting. Also invited paper at ASC 2002.**
- **Next SPI Project (AEP)**
  - **Kickoff meeting end of this month at Southwire**

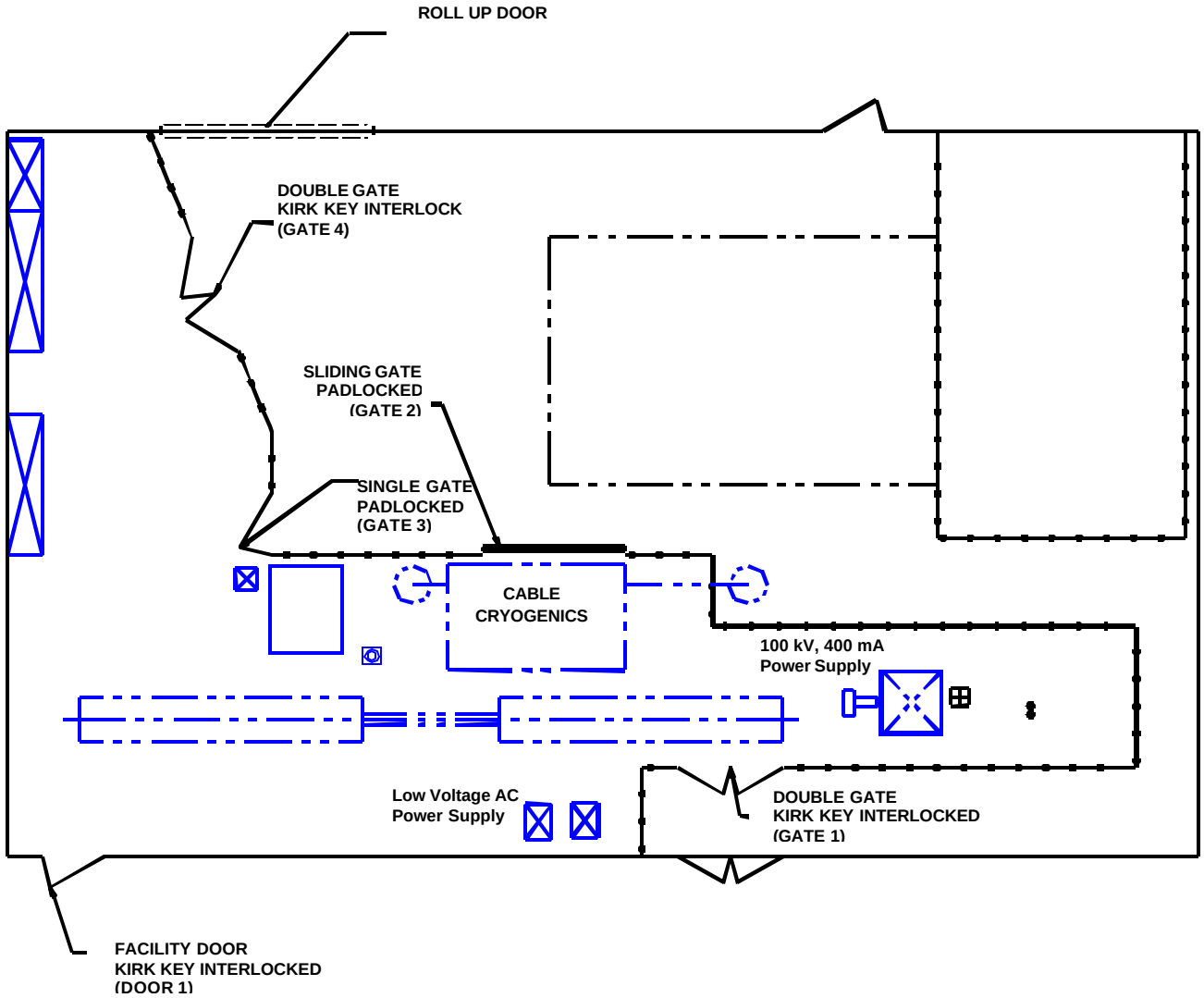
5-m cable research facility at ORNL



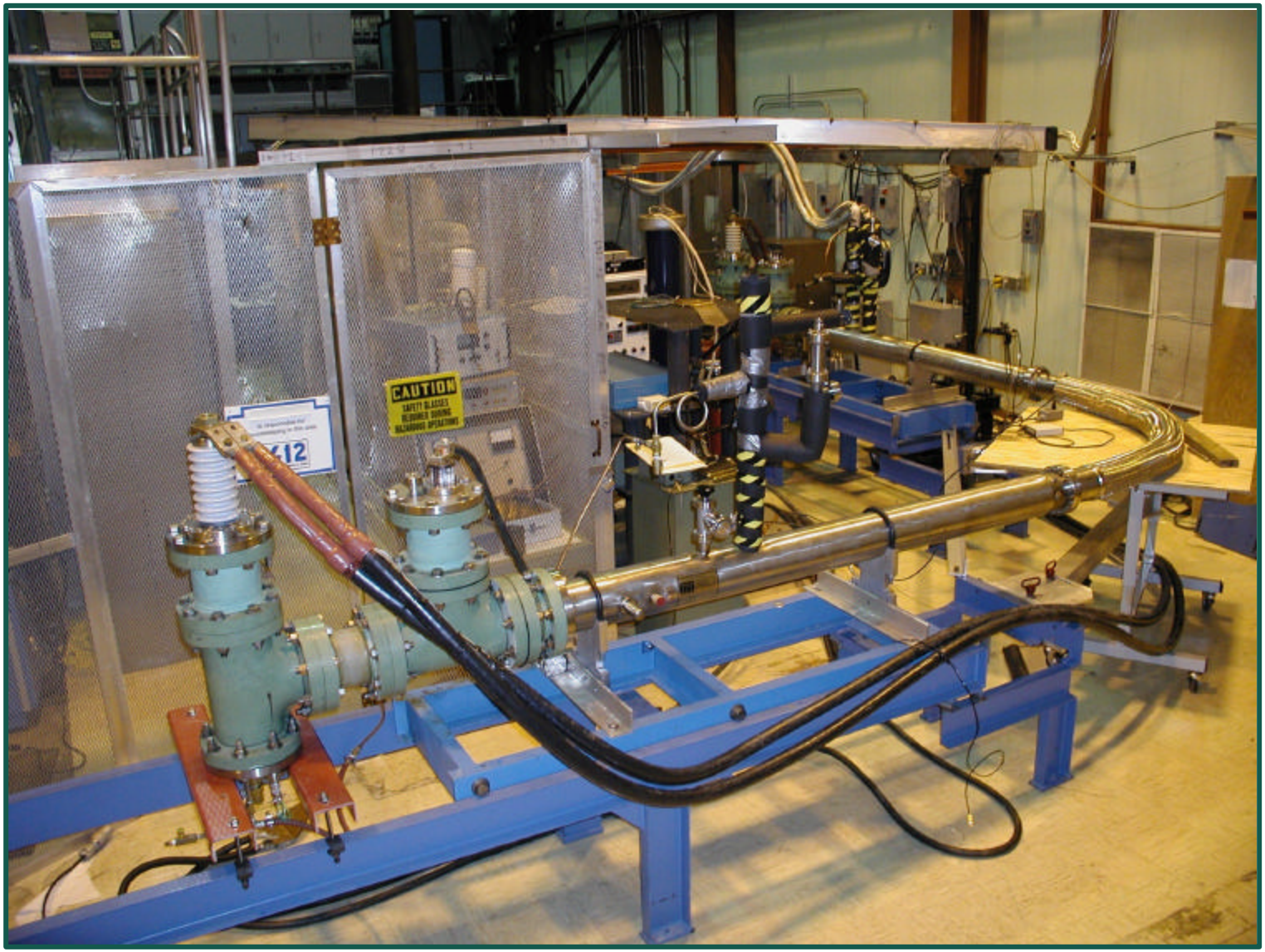
5-m High Temperature Superconducting Cable Research Facility Status: July 2002

- **Facility capability:**
  - impulse power supply to 200 kV (BIL tests)
  - 25,000 A pulsed dc power supply
  - 100 kV ac power supply
  - single-phase, 3000 A ac power supply operational
  - 3-phase, 1500 A ac power supply operational
- **Adjacent test stands used for development of HTS tapes (BSCCO and YBCO)**
  - large capacity cryocooler with power supplies and data acquisition for ac loss, stability and quench testing
  - 20 cm warm bore, 6 T magnet (cooled by pulse-tube cryocooler) for quench and stability studies of HTS conductors

HTS Cable Test Facility Modified for Bend Tests

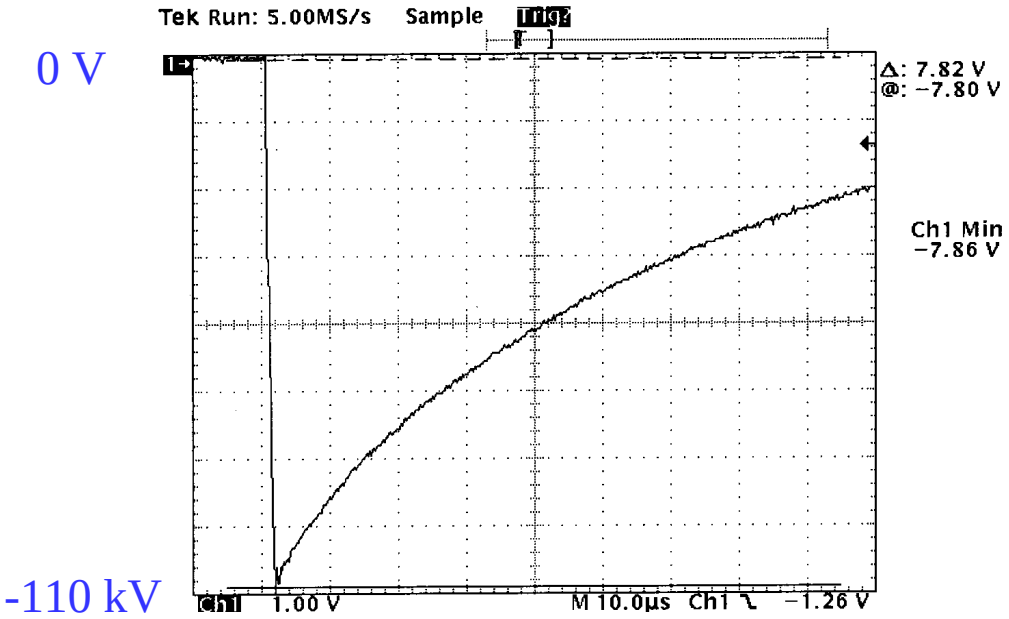


5-m Cable Bend Test – 10/17/2001

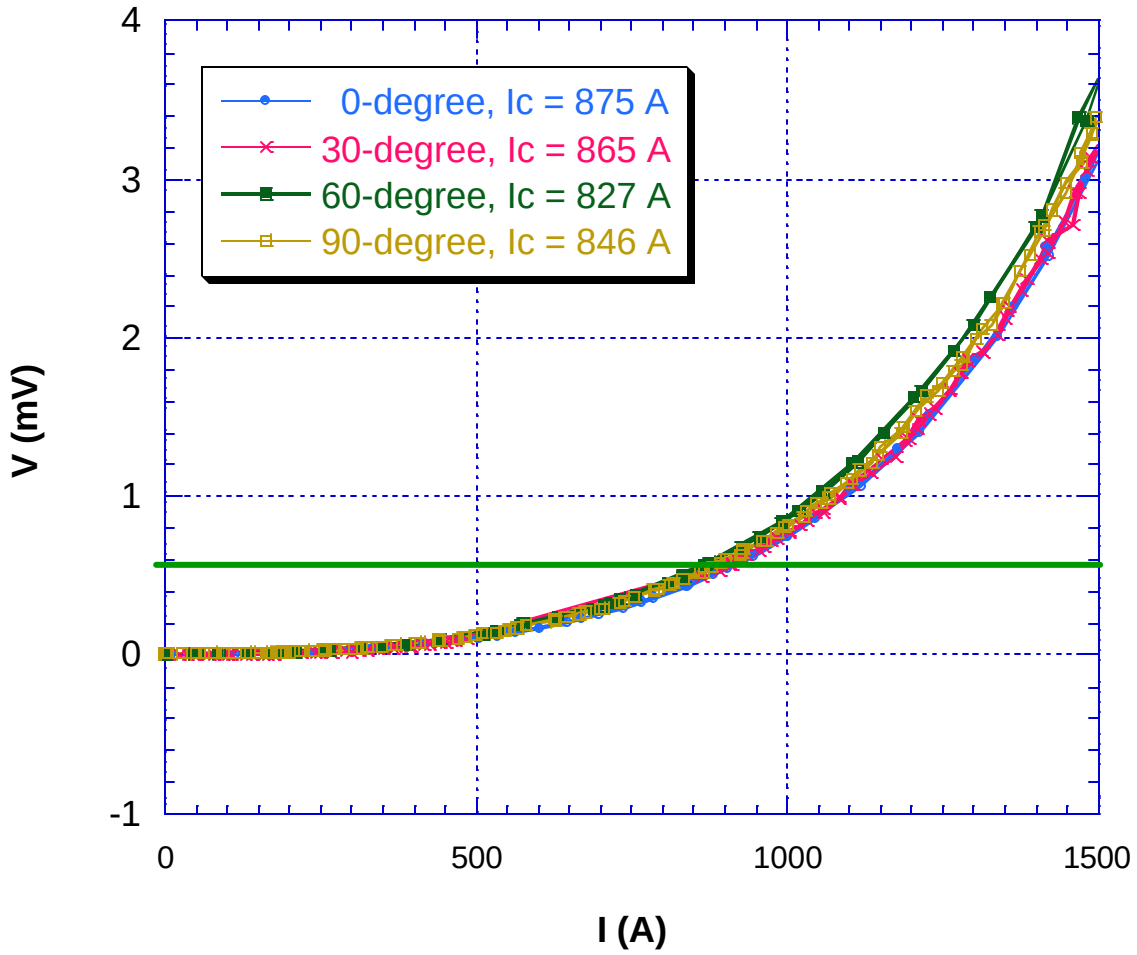


Several tests conducted on the 5-meter HTS cable

- **Tests conducted at bend angles of 0°, 30° (R=145.2 in), 60° (R=72.6 in), and 90° (R=48.4 in).**
  - **DC critical currents and V-I characteristics.**
  - **Rated ac voltage (7.5 kV) and current (1250 A) *(Passed)***
  - **Withstand test at 18 kV ac for 30 minutes. *(Passed)***
  - **Impulse test at 110 kV at 0° and 90°. *(Passed)***



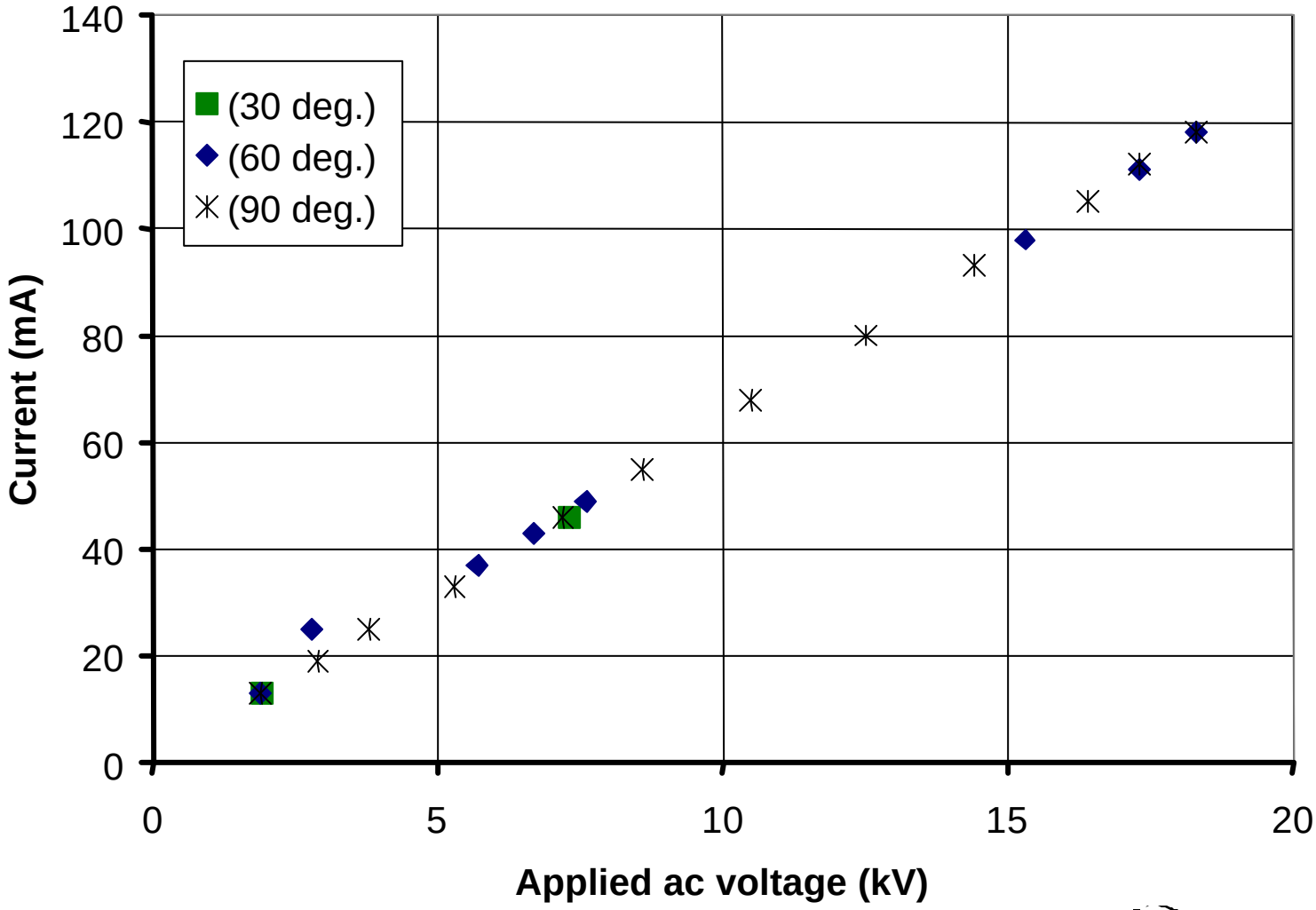
Voltage-current curves for each bend angle.



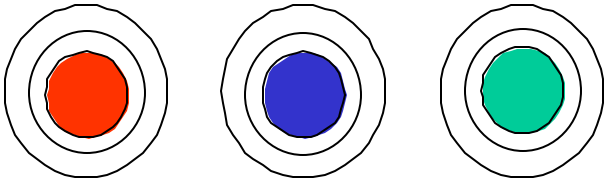
1 μvolt/cm

The critical current decreased less than 5% when bent from 0° to 90°.

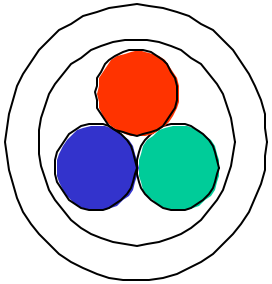
Cable high voltage charging current is unaffected by bending



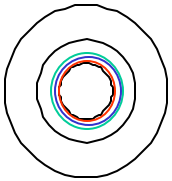
HTS Power Transmission Cable Configurations



3 separate co-axial phases



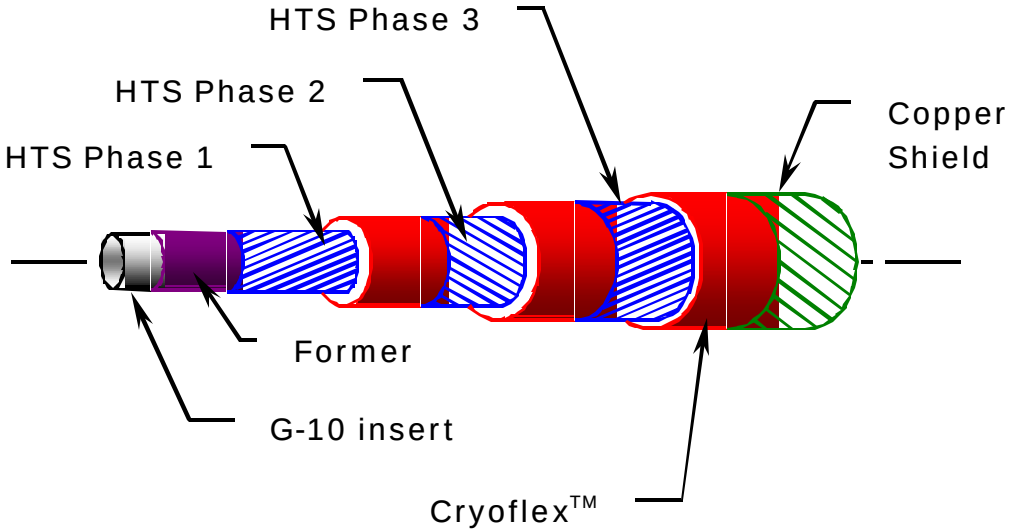
Triad co-axial cable



Tri-axial cable

- Three separate coaxial HTS phases has been demonstrated by Southwire.
- Cold-dielectric with an HTS shield makes it possible to use a triad layout (100-m, Japan).
- A concentric tri-axial cable will require only ~ half the amount of HTS tape and will be more compact.
- The cryogenic surface area and thermal losses will also be reduced.

Tri-axial HTS cable prototype, 1.5-m long, has been designed, built and tested in 2001

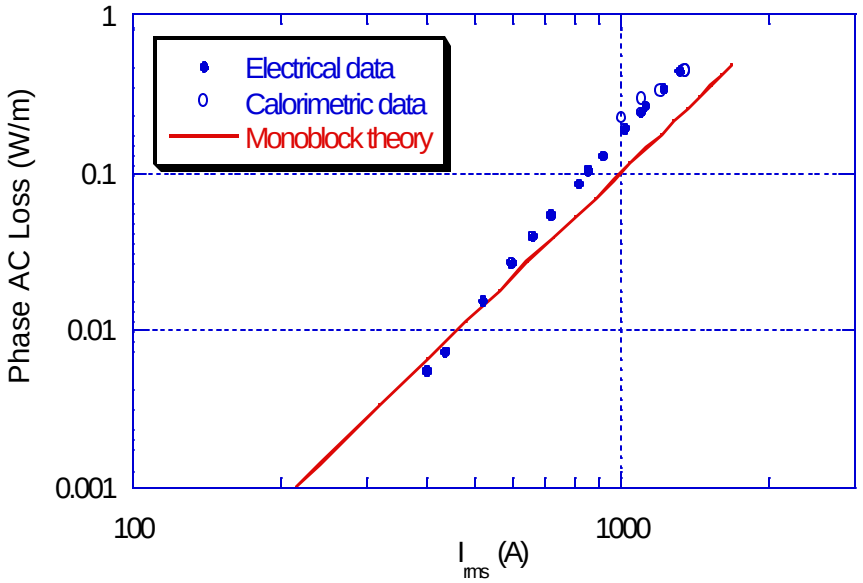


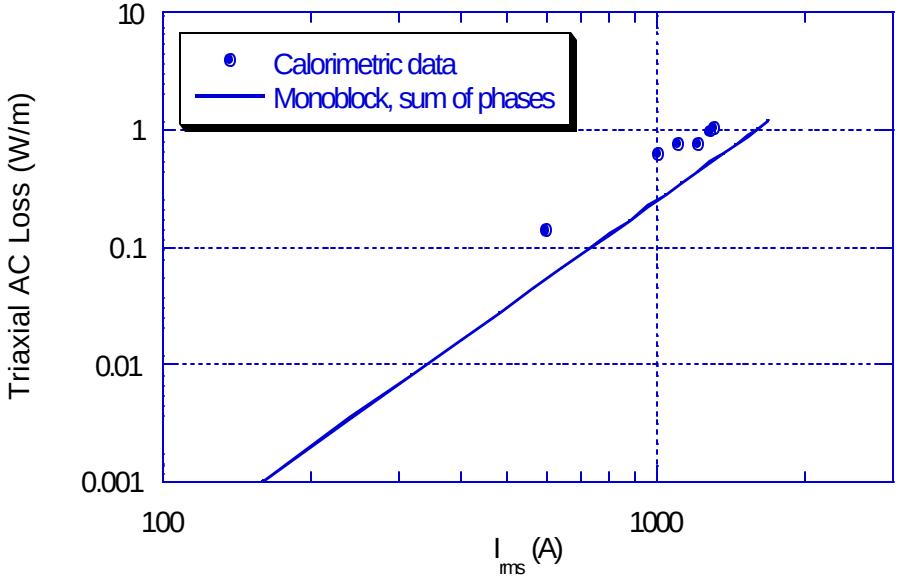
- **A prototype tri-axial cable was fabricated to evaluate its superconducting properties.**
- **Each phase consists of two layers of BSCCO-2223 HTS tapes.**
- **A G-10 insert with thermocouples attached was used for the purpose of a calorimetric measurement of the AC losses in the cable.**

ELECTRICAL TESTS OF A TRIAXIAL HTS CABLE PROTOTYPE
J. W. Lue, J. A. Demko, J. C. Tolbert, U. K. Sinha, R. Grabovickic, G. C. Barber, M. J. Gouge, D. Lindsay, and R. L. Hughey, presented at CEC/ICMC 2001, to be published in Advances in Cryogenic Engineering.

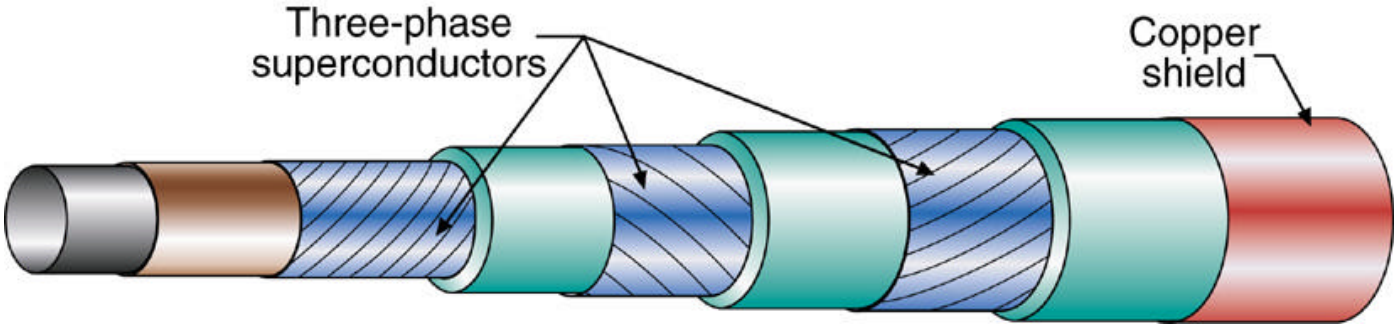
1.5-m tri-axial cable summary and conclusions

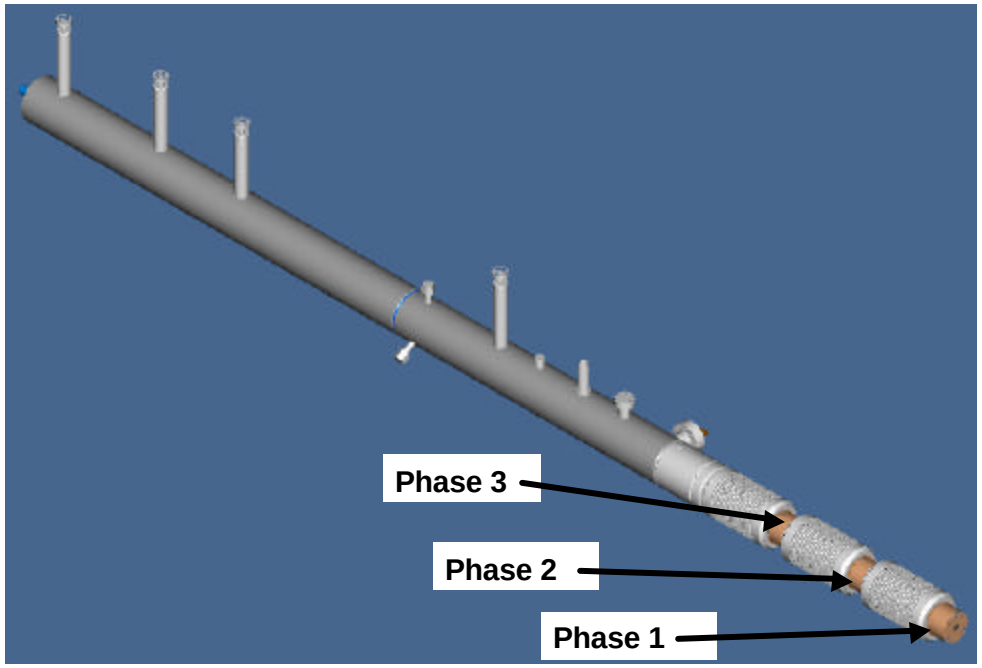
- **AC loss was measured both electrically and calorimetrically.**
- **The 3-phase ac loss data is close to that of the sum of three individual phases.**
- **There is no significant excess ac loss due to the presence of the other concentric phases in tri-axial cable configuration.**
- **Cable system thermal losses will also be lower due to the compact geometry**





Based on encouraging results from 1.5-m prototype, we decided to build a 5-m cable with full-scale terminations





- 15 kV phase-to-phase
- phase current is 1300 A
- BSCCO-2223 silver-alloy tapes
- each phase has 2 layers of these HTS tapes.
- dielectric material is Cryoflex tapes immersed in liquid nitrogen.

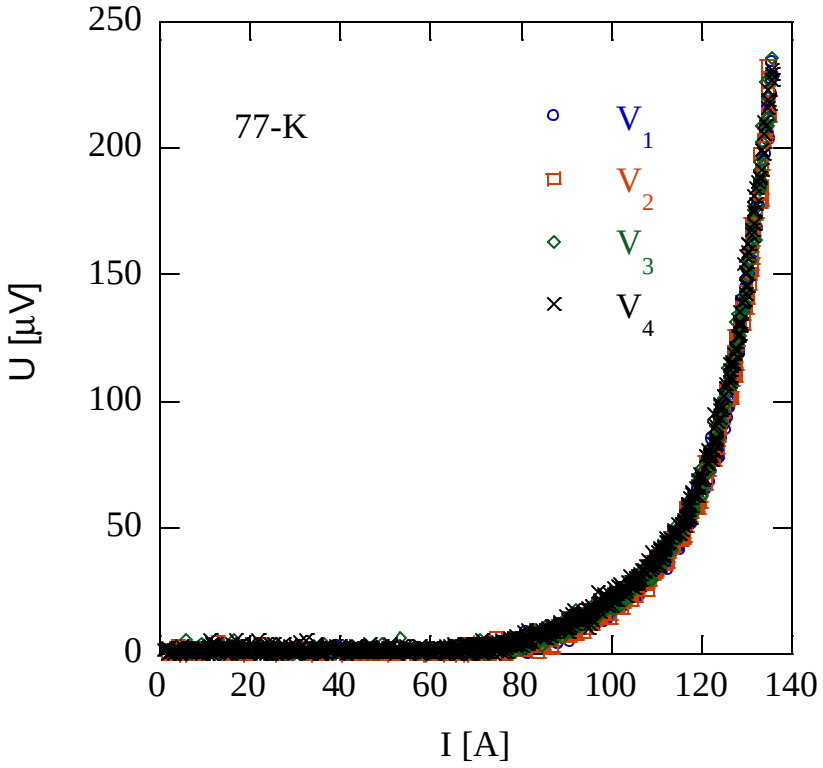
Tri-axial 3-phase termination

- **The 5-m tri-axial cable will be a full-scale demonstration of the technology and will have a full-scale three-phase termination.**
- **The termination provides for ambient temperature connections to the three phases and the shield.**
- **It makes the temperature transition from liquid nitrogen temperature to ambient temperature in the three phase conductors as well as the copper shield conductor.**
  - **The design axial conduction loss at full current is of order 50 watt/phase.**
  - **The induced current in the shield for unbalanced three-phase currents was measured in the 1.5-m prototype cable and found to be small.**

Tri-axial 3-phase termination (continued)

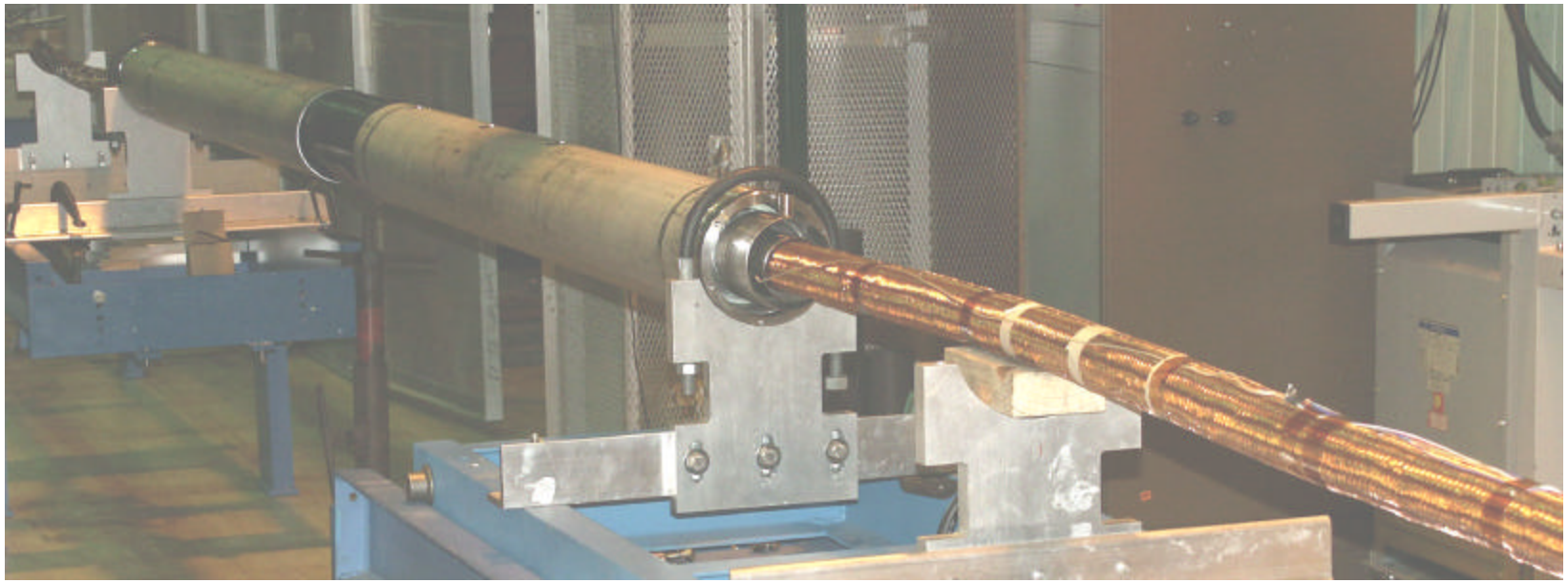
- **A challenging constraint is a design with adequate radial heat conduction from the three electrical phases through the termination cross-section out to the flowing liquid nitrogen coolant.**
  - **the insulation between the phase conductors and between the outer phase and shield conductor:**
    - **has to 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**

I_c of the tape after subjecting to heating simulating termination assembly process

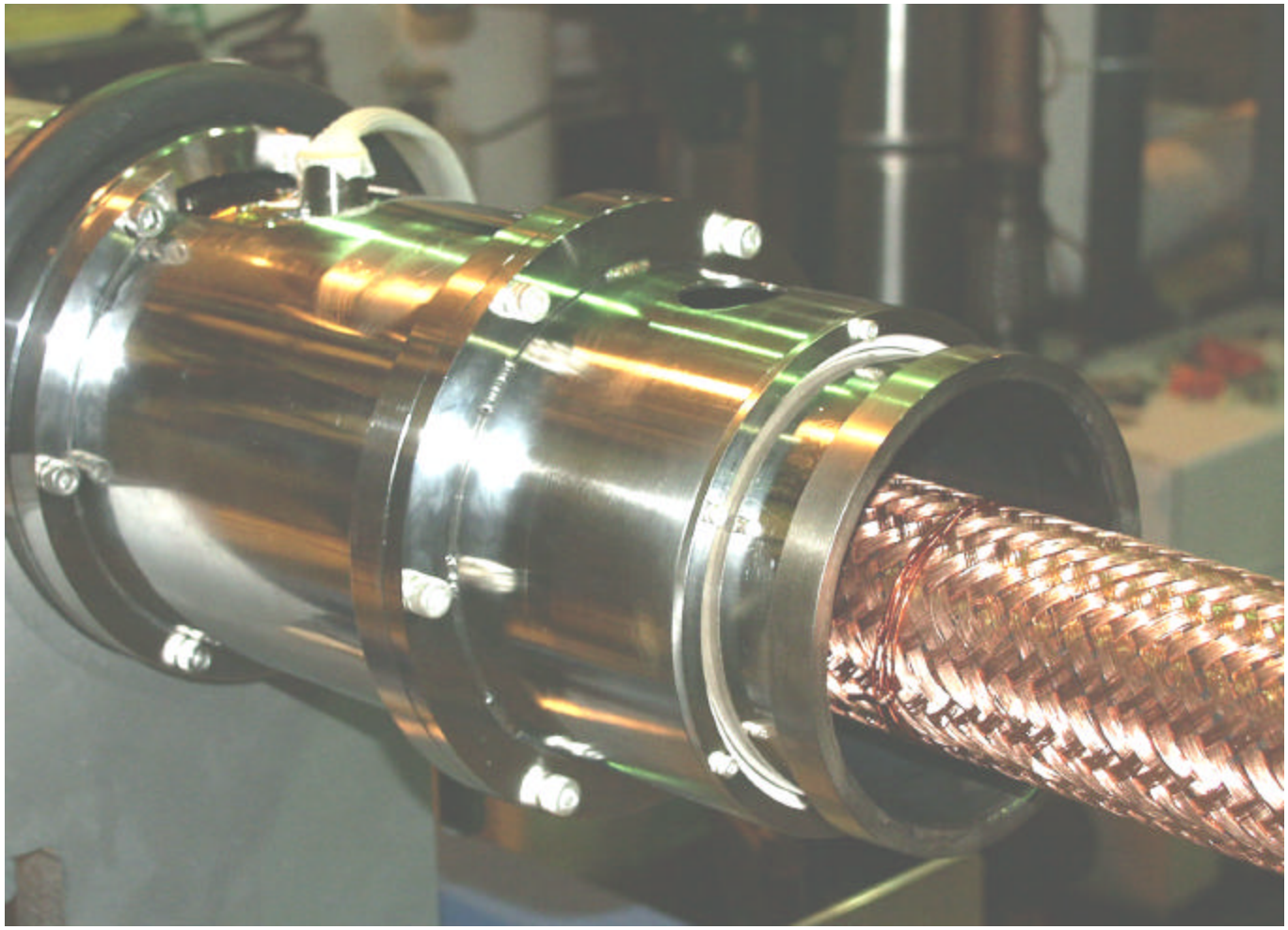


- Heated to >200 °C, constant for several minutes, and then held at ~115 °C for several hours – a (14%) degraded I_c of 100 A was measured.
- Heated to >200°C @ 2°C/min to simulate soldering, followed by a hold at ~75°C for 16 hours - I_c of 99.1 to 95.5 A was measured in 4 LN_2 cycles.

Three-phase cable inserted into cryostat



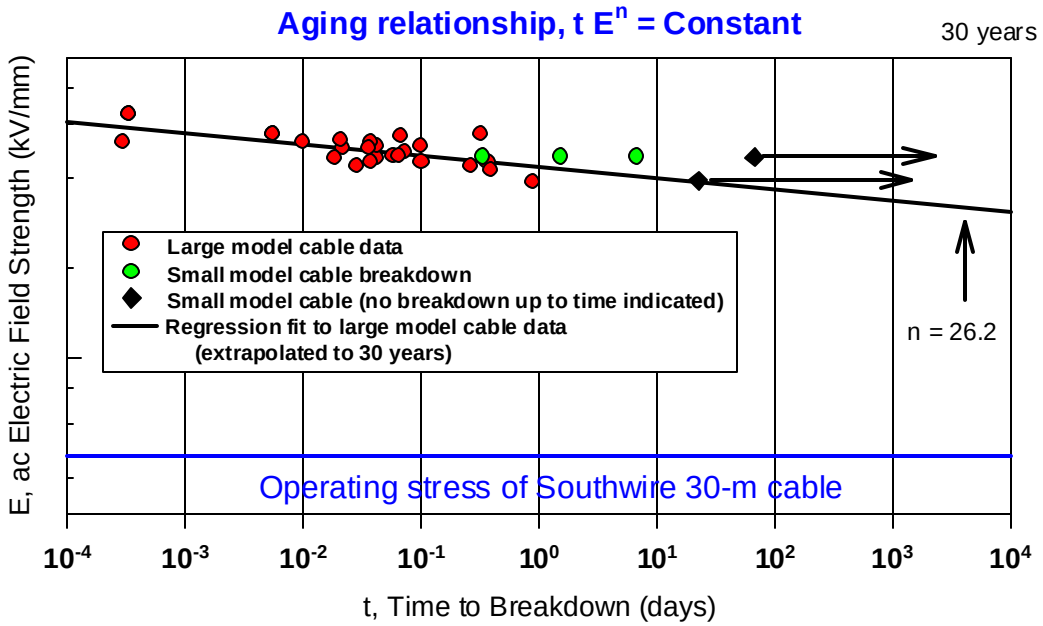
Three-phase cable inserted into cryostat

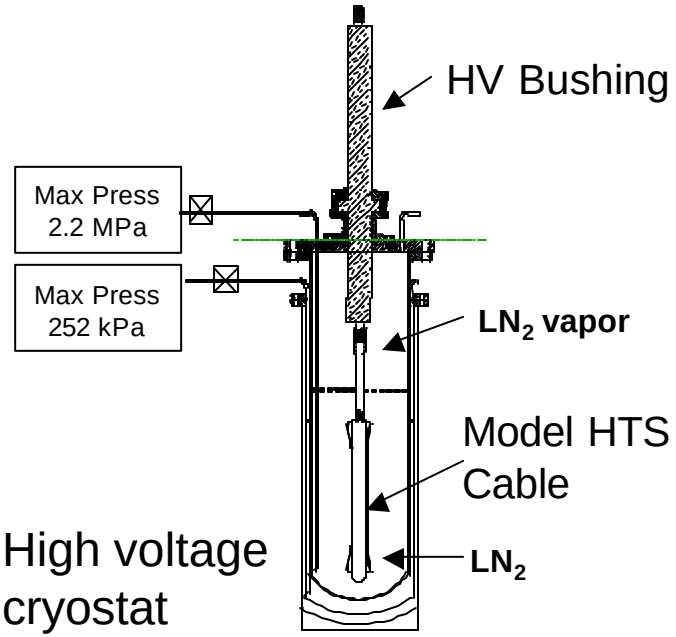


Presentation Outline

- **Southwire Activities** (David Lindsay, Southwire)
  - Introduction
- **FY 2001 Results**
  - 30-m Cable Operation and Testing
  - Cable Research (Mike Gouge, ORNL)
  - Cryogenic Dielectrics Research (Mike Gouge, ORNL)
- **FY 2001 Performance / FY 2002 Plans**
- **Research Integration**
- **Summary**

Cable Aging Studies Yield Important Lifetime Results

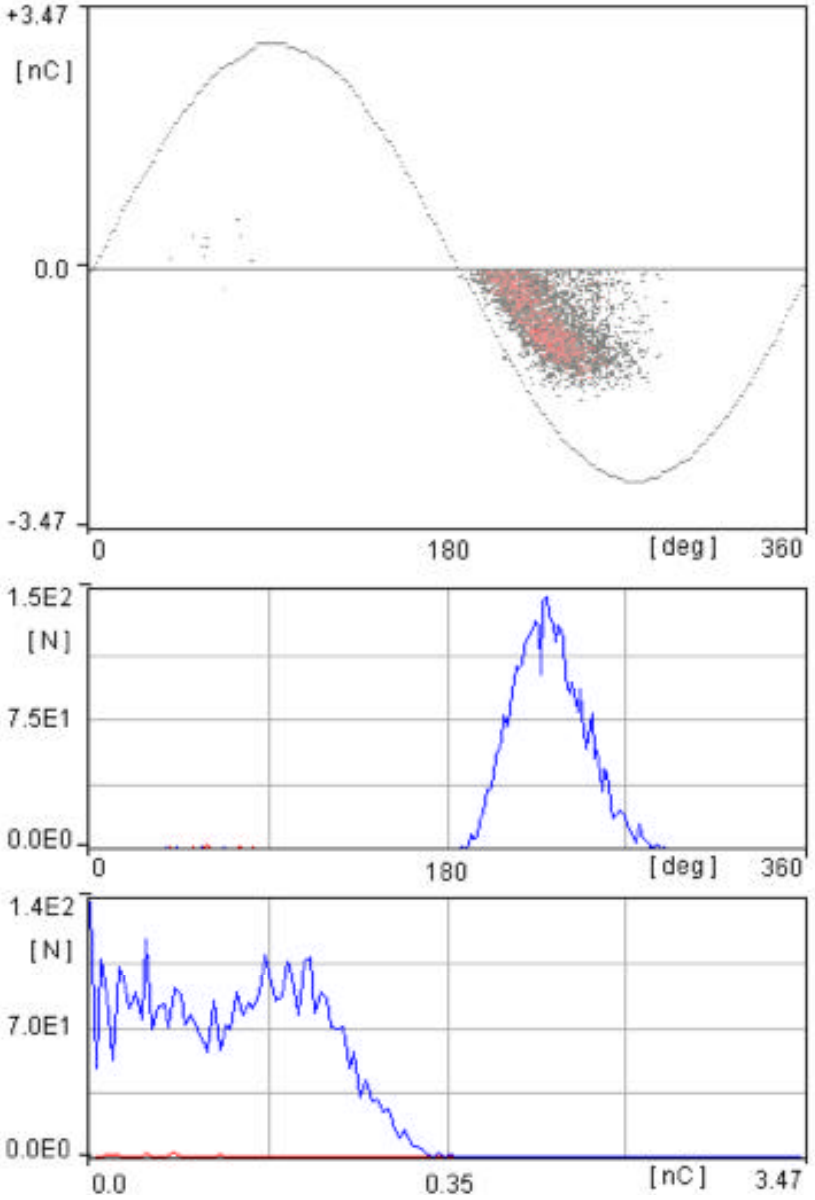




- **long term aging of lapped tape insulated model cable in LN2**
- **extended aging time to 67 days using automated LN2 fill system**
- **monitored partial discharge (PD) during aging**
- **can discriminate between PD coming from within the cable and PD from external sources by “ground side” PD detection**

New partial discharge studies aid in lifetime prediction

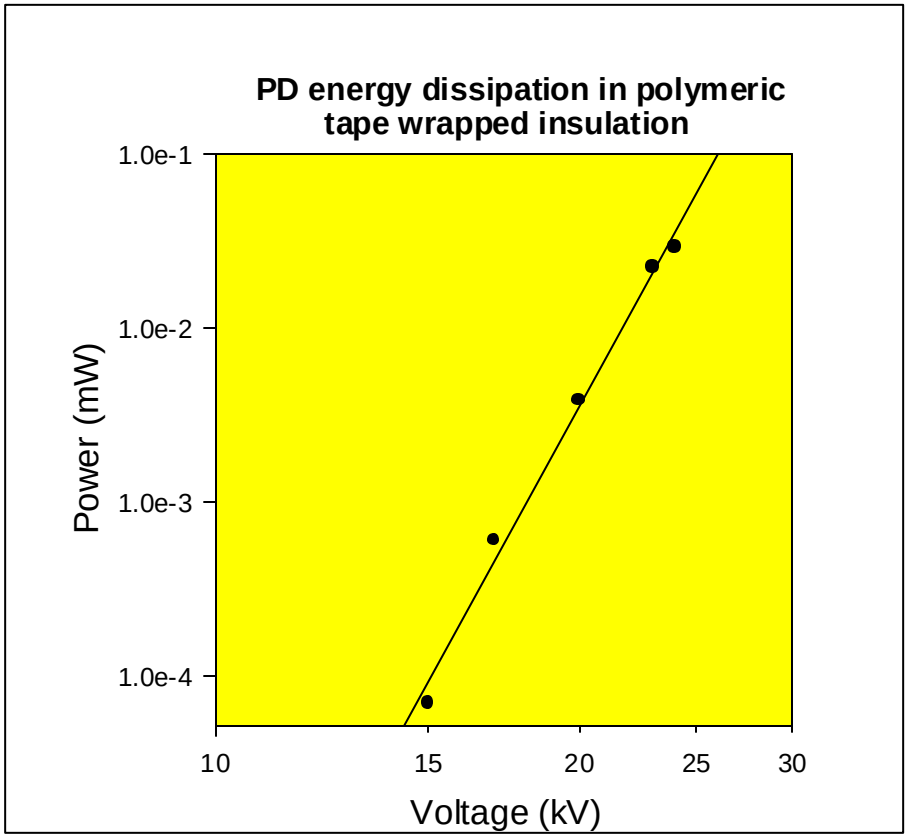
- **PD is believed to be source of damage leading to breakdown and/or puncture of the cold dielectric**
- **Goal is to relate PD energy dissipation in a cryogenic cable to cable life**
- **Plot of PD power versus applied field can lead to a prediction of cable life**



Typical PD data at high stress for accelerated aging on model cables

Determine energy dissipation due to PD in model cables to allow lifetime prediction

- Cable damage occurs through PD which can be measured
- Digitized PD data can be converted to energy dissipated into sample
- Plot of energy dissipation provides measure of “n” value used for determining cable life



Dielectric materials studies for improved high voltage and lifetime

- testing new polymeric tapes for higher voltage cables
  - AC withstand
  - BIL
  - Partial Discharge
  - Aging
- new materials for high voltage terminations

Polymeric tape material wrapped on 4-ft model cable for high voltage testing

HV tests of small scale termination samples for the tri-axial cable

- **sample screening for termination**
- **AC withstand at room and LN2 temperature**
- **PD voltage dependence at room and LN2 temperature**
- **BIL tests**

Samples being aged by high voltage prior to PD testing

ORNL FY 2002 Performance

FY 2002 Plan

- Evaluation of 30-m cable operation and performance (Southwire/DOE decided to extend demonstration at Carrollton, GA)
- Testing of cable bends
- 5-m tri-axial cable with 3-phase terminations

FY 2002 Performance

- Over 15,000 hours of operation
- Critical current measurements show robust superconductor
- Unattended operation (since 6/01)
- Bend testing successful at 0, 30, 60, 90 degrees
- Detailed design completed 2nd quarter, FY 2002
- Cable delivered to ORNL, May 2002
- Termination fabrication and assembly in progress
- Testing in 4th quarter, FY 2002

ORNL FY 2002 Performance

FY 2002 Plan

- **Continue development of the pressurized termination**
- **Continued research on cryogenic dielectric materials**
- **Research improving cryogenic system.**

FY 2002 Performance

- **Improved termination design reduces complexity**
  - **Rated voltage for many hours**
  - **18-kV withstand for 30 minutes**
  - **BIL above 110 kV**
  - **11X fault currents**
- **Aging test further defines lifetime of cryogenic dielectric**
  - **Correlation with PD**
- **Dielectric materials for tri-axial terminations**
- **ASC 2002 paper: cable cryostat vacuum/thermal studies**
- **Cryogenic assessment**

ORNL FY 2002 Performance

FY 2002 Plan

- **ORNL will assist Southwire with the design and analysis of an HTS cable system for siting in Columbus, OH American Electric Power Bixby Rd. substation.**

FY 2002 Performance

- **Partnership with AEP established**
- **Challenging HTS cable application identified and evaluated**
- **SPI awarded to team of Southwire, AEP, ORNL, PHPK, NST, ICE, 3M**
- **Contract negotiations underway with DOE**
- **Kick-off meeting end of this month**

ORNL FY 2003 Plans
Oct. 1, 2002 to Sept. 30, 2003

- **ORNL will work with Southwire to improve the overall design and capabilities of the HTS cable system.**
  - **Continued development of the pressurized termination**
  - **Complete testing and analysis of 5-m tri-axial HTS 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.**
  - **Model cable testing of 34.5 kV class cables, aging studies and continued development of cryogenic dielectric materials, and**
  - **Continued research improving cryogenic system performance with industry and NASA**
- **ORNL will begin the design and testing of cable subsystems for a long-length cable installation in partnership with Southwire and AEP.**
  - **About 50-60 MVA, double the loading of the 30-m cable system at Southwire and of order 10 times the length**

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 and installation of superconducting cables for utility customers.**
- **FY 2002 progress is evidence of well functioning team.**
  - **5-m cable research conducted jointly with Southwire at ORNL.**
  - **30-m cable operation and testing at Southwire**

Research Integration - Partnerships

- **Southwire continues its established technology alliance with NKT Cables to develop superconducting cables**
  - **May 5, 1998 - www.southwire.com/news/050798.htm**
  - **Cold dielectric design developed by Southwire**
  - **Warm dielectric design developed by NKT**
  - **Both designs available to both companies**
  - **Southwire, NKT Cables, and ORNL have exchanged technical information and data during the past 4 years**
    - **videoconferences**
    - **personnel exchanges**
    - **site visits and technical meetings**
- **NKT energized their 3-phase, 30-m superconducting cable demonstration in May 2001 at Copenhagen Energy substation AMK.**
  - **www.supercables.com**

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.**

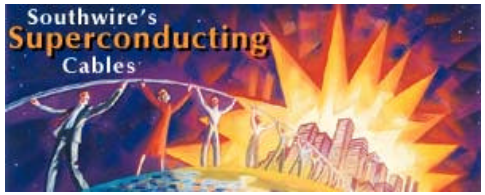
Research Integration - Publications

- **Presentations and publications during the year**
  - **Four technical papers were presented at the Cryogenic Engineering Conference in July 2001 and published in *Advances in Cryogenic Engineering,* 2002.**
  - **IEEE Power Engineering Society Winter Meeting in January 2002.**
    - **Panel presentation and invited paper**
  - **A paper on HTS cables was presented at a DARPA workshop on superconducting devices coupled with cryogenically-cooled power electronics held in January 2002.**
  - **Two papers on HTS cables were presented at the Space Technology Applications International Forum in February 2002.**
  - **An invited review paper on HTS cables was given at the TMS Conference held in Seattle, Washington in February 2002.**
  - **Two technical cable papers planned for the "Applied Superconductivity Conference, ASC 2002," in Houston next month.**
  - **A technical paper on cable aging at cryogenic temperatures is planned for the Conference on Electrical Insulation and Dielectric Phenomena in October 2002.**
- **ORNL supported a technical assessment by Anteon Corporation (for Office of Naval Research) of HTS cables on all-electric ships.**

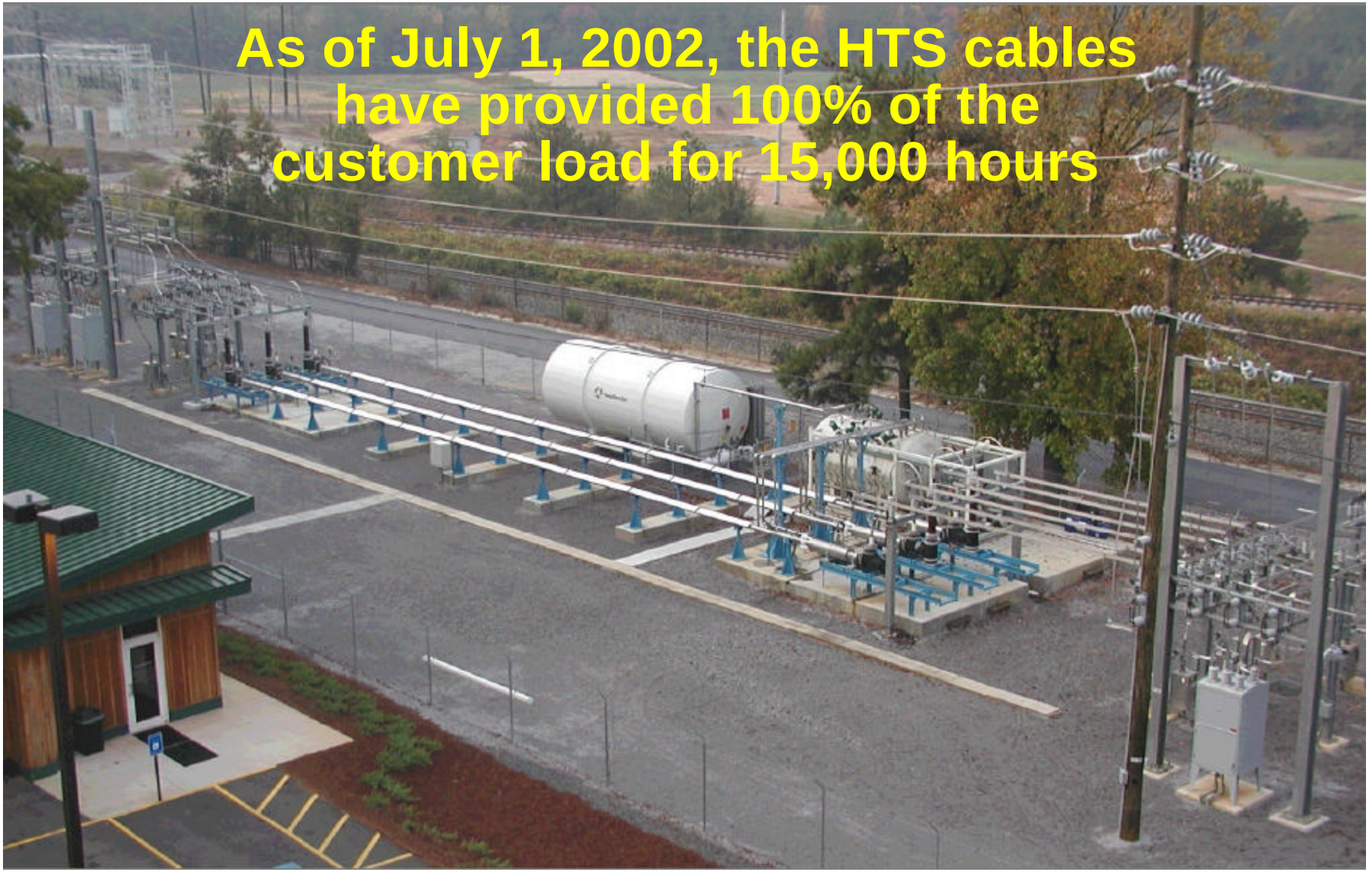
Research Integration - Other

- **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.southwire.com**

Summary



- **FY 2002 goals have been achieved**
  - **30-m HTS cable has over 15,000 hours of flawless operation**
    - **Cable remains robust and is running unattended**
  - **Cable design and testing develops the needed technology base**
    - **5-m cable testing of splices and bends shows ability to make long cable lengths**
    - **1.5-m tri-axial conductor testing shows merits of concept: 5-m tri-axial cables with three-phase terminations nearly ready for testing**
    - **Pressurized cable termination improvement realized**
    - **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, 2002, the HTS cables
have provided 100% of the
customer load for 15,000 hours