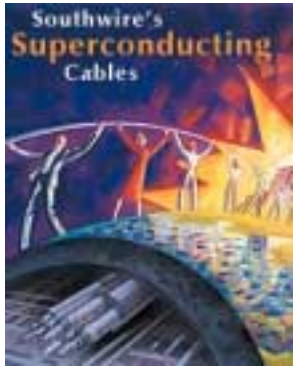
High Temperature Superconducting Cable



2001 Annual Peer Review

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

Southwire

August 1-3, 2001
Washington, DC

ornl

As of August 1, 2001, the HTS cables have provided 100% of the customer load for 8500 hours

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** **(John Stovall, ORNL)**
- **FY 2001 Performance / FY 2002 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

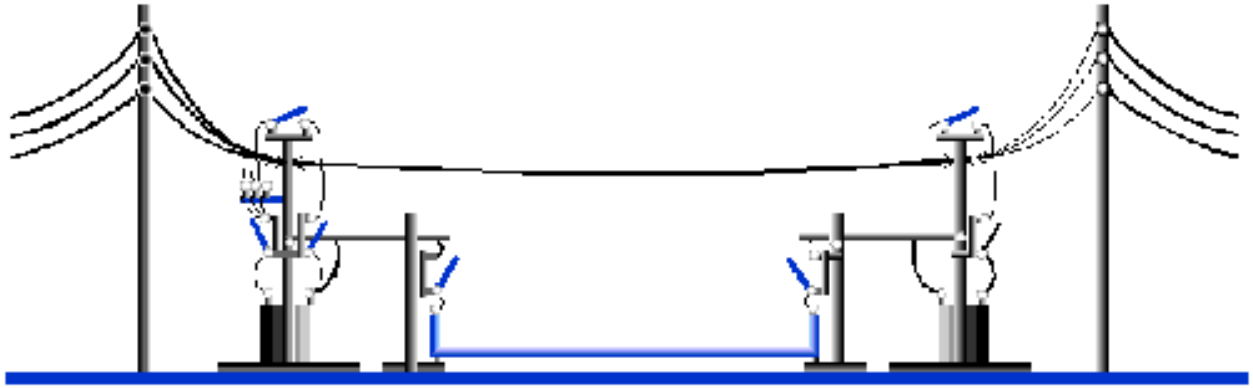
- **Oak Ridge National Laboratory**

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

SPI Project Goal (February 1997)

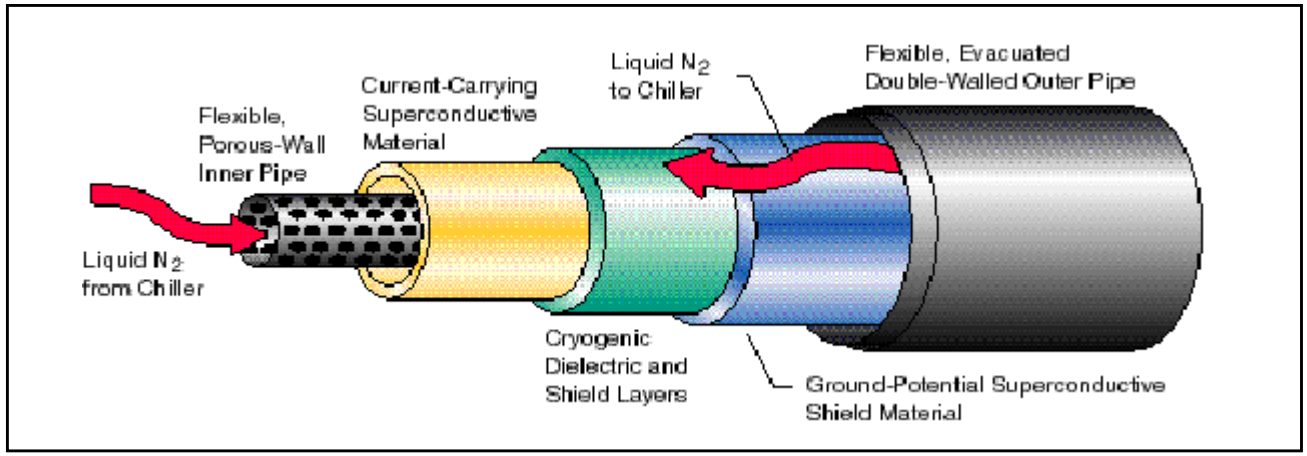
First U.S. Industrial SPI Cable Installation

- **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

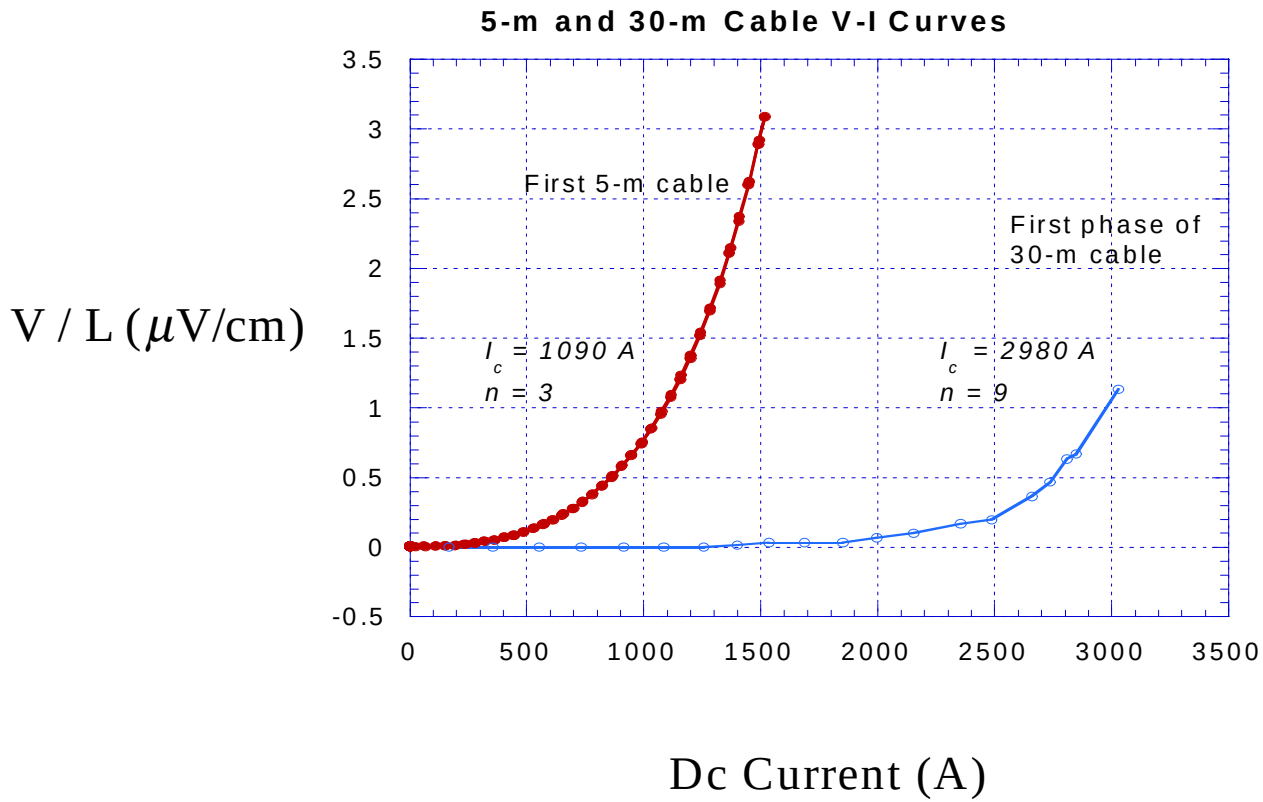
- **FY 2001 goals have been completed.**

– Cables installed	Aug 99
– Cryogenic system delivered	Sept. 99
– Cable terminations assembled	Sept. 99
– Cryogenic system tested	Oct. 99
– Off-line electrical testing	Nov/Dec 99
– Cables energized	Jan. 5, 2000
– Dedication ceremony	Feb. 18, 2000
– Continuous operation started	Feb. 21, 2000
– Off-line research	June 7- 30, 2000
– Off-line research (dc V-I)	Mar. 2001
– Neutral phase connections	Mar. 2001
– Mix HTS and Cu phases	Mar. 2001
– Unmanned operation	June 1, 2001

HTS cable critical current has been measured

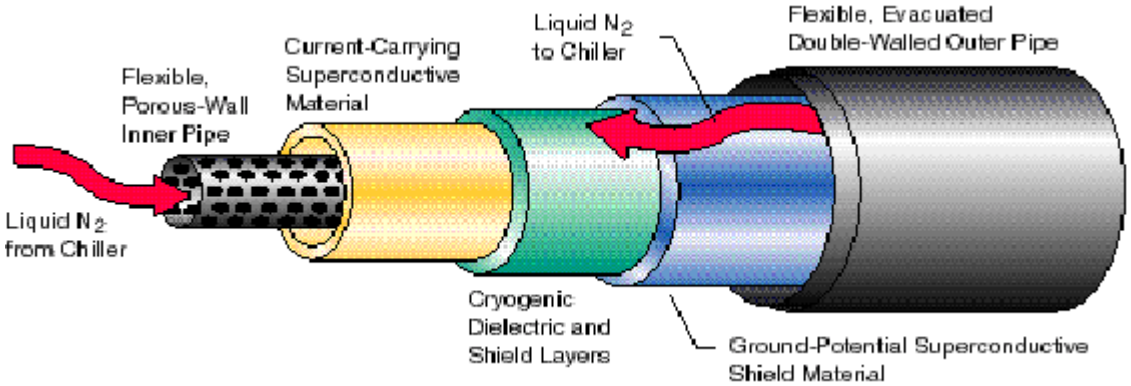
- DC tests to measure cable V-I curve and determine critical current have been conducted
- Factory Floor Test
  - Phase 1 (4/99)
  - Phase 2 (5/99)
- Field Tests on all 3 phases
  - Nov. 1999
  - Jun. 2000
  - Mar. 2001
  - Current transition test (3/01)

DC tests - Phase 1 Factory Floor Test (4/99)



- **Testing was performed on the core and shield conductors in the cable cryostat with liquid nitrogen at a small pressure above atmospheric and a very low liquid nitrogen flow rate.**

Both core and shield conductors are measured



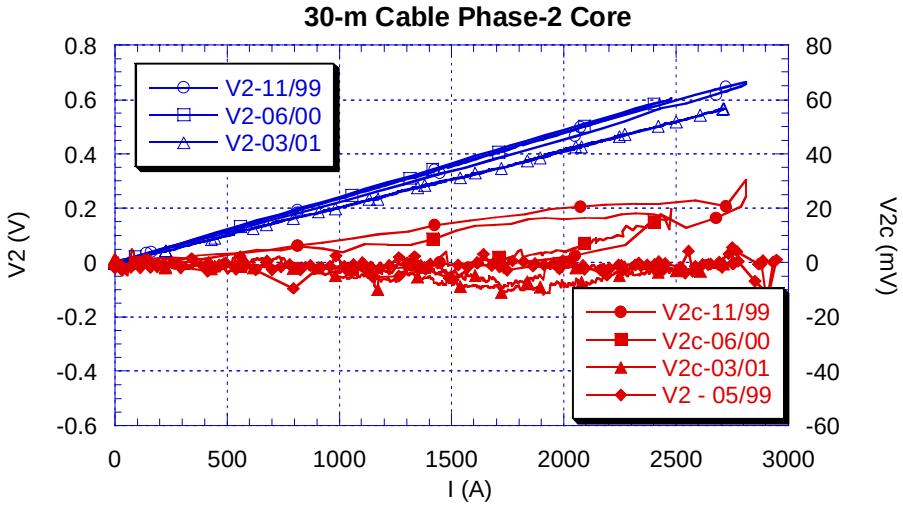
- **In the cold dielectric design, both the core and shield conductors are constructed with HTS tapes.**

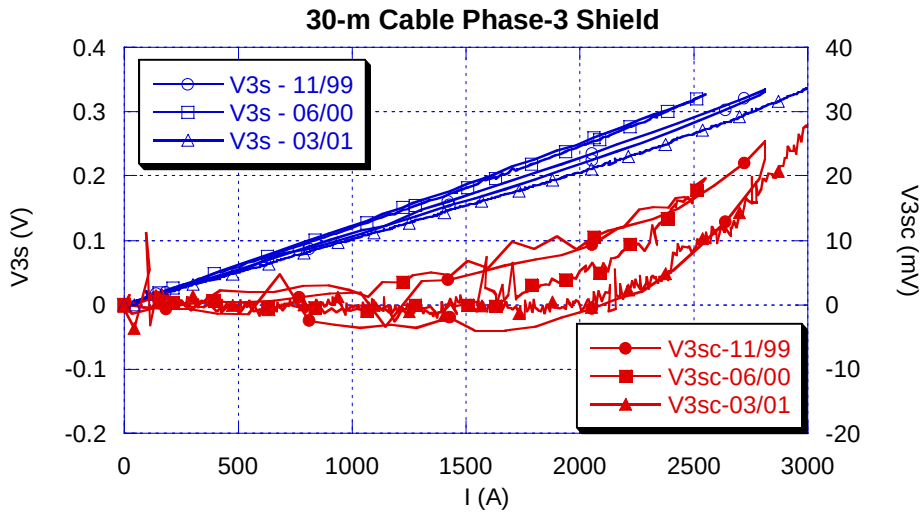
- **Field measurements include cable termination resistance of copper connections**

DC power supply and lead cables

- **3000 amps dc / 2000 lbs.**
- **1000 lbs. of cable leads**

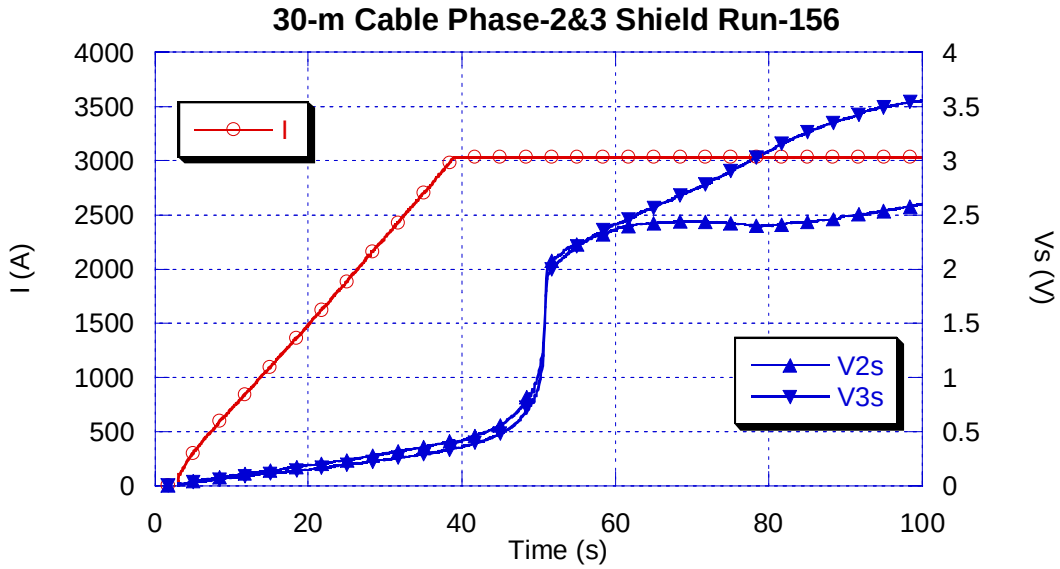
Based on dc tests, cable critical current has not degraded with time and thermal cycles





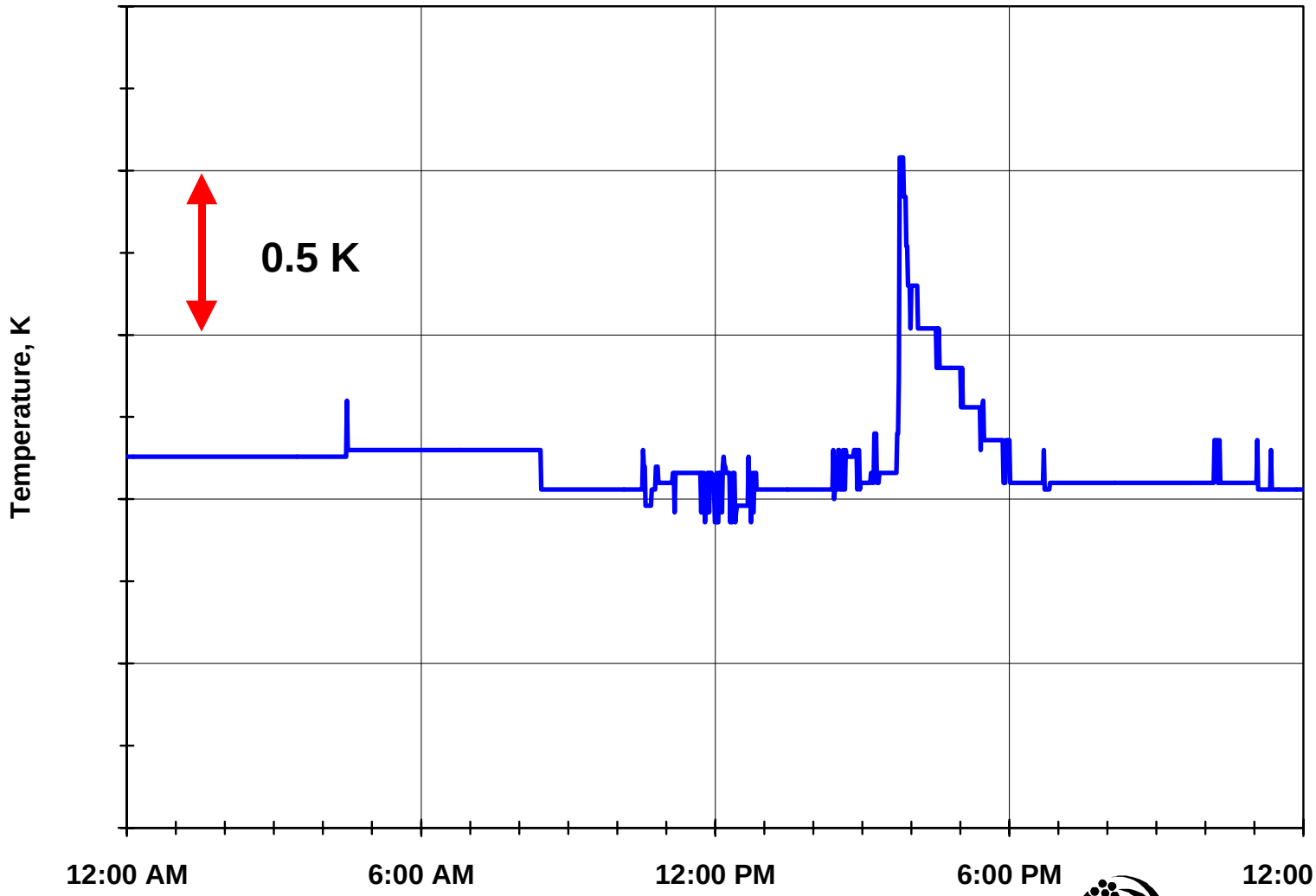
- **Measured dc critical current in May 99 before installation and in November 99, June 2000 and March 2001 during operation at Carrollton, GA.**
- **The three phase conductors showed critical currents above the 3000 A rating of the dc power supply for all four tests.**
- **The three neutral conductors had critical currents in the 2000-2300 A range and showed no degradation with time.**

Tested phases 2 and 3 shield to 3000 A (~1.5 I_C) for 1 minute with no performance degradation



- **Shield conductors were heated above critical temperature at ~t = 50 s.**
- **After this time the shields were completely normal and current is flowing in the silver matrix.**
- **Developed a heat input of 13 kW, more than 3 times the cryogenic system capacity of 4 kW. Corresponds to 0.4 watt/cm^2 surface heat flux.**
- **The cryogenic system temperature increased by ~ 1 K.**
- **The V-I curves did not change after this test.**

Outlet temperature response to current transition test - Mar. 28, 2001 (1 minute data)



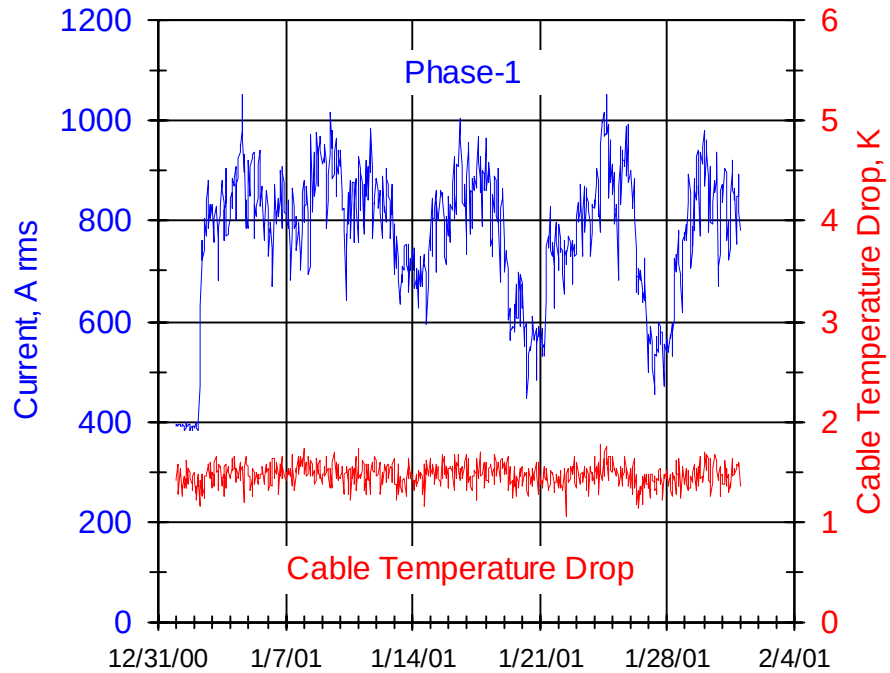
Additional accomplishments

- **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.**

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

System data for January 2001



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** **(John Stovall, ORNL)**
- **FY 2001 Performance / FY 2002 Plans**
- **Research Integration**
- **Summary**

ORNL FY 2001 Plans
Oct. 1, 2000 to Sept. 30, 2001
(from FY 2000 Peer Review)

- **ORNL will work with Southwire to improve the overall design and capabilities of the HTS cable system. Specific activities include:**
  - **evaluation of 30-m cable operation and performance,**
  - **research and development and testing of cable splices,**
  - **continue development of the pressurized termination,**
  - **continued research on cryogenic dielectric materials, and**
  - **research improving cryogenic system.**
- **In addition, ORNL will assist Southwire with the design and analysis of an HTS cable system for siting in a large urban area with a utility partner.**

FY 2001 Results

- **30-m Cable Demonstration (Southwire lead)**
  - **evaluation of 30-m cable operation and performance**
    - **dc V-I curves on phase and neutral conductors (1999-2001)**
    - **modified HTS cable neutral end connections to increase $I_{neutral}$**
    - **evaluated performance of mixed HTS and Cu phases**
    - **unattended operation of 30-m cryogenic and substation systems**

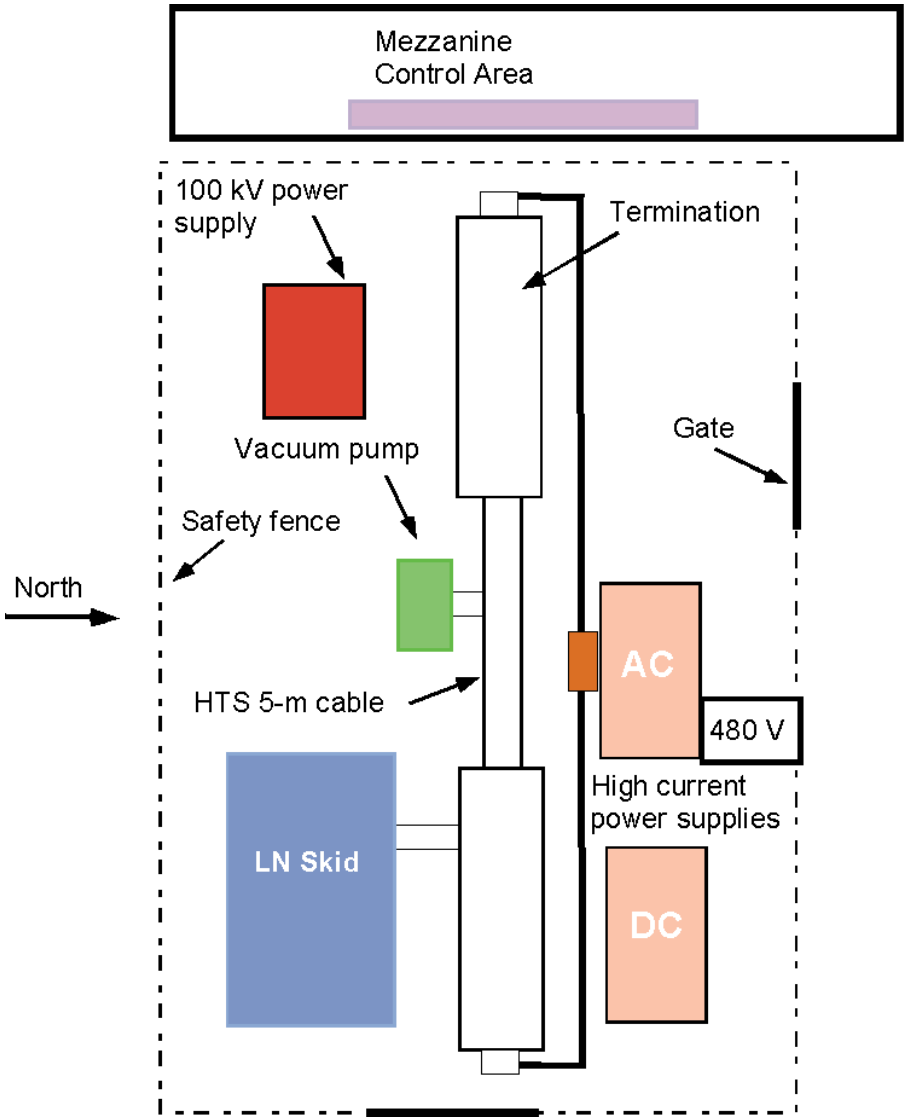
FY 2001 Results

- **5-m Cable Research (ORNL lead)**
  - **research, development and testing of cable splices**
    - **completed a successful test program on a cold-dielectric cable splice**
  - **continue development of the pressurized termination**
    - **modified termination for improved dielectric performance: up to 117 kV BIL demonstrated**
    - **heat loss reduced**
    - **design improvements**
  - **Tri-axial cold-dielectric HTS Cable (New Task for FY 2001)**
    - **successful 3-phase, tri-axial cable test in open LN bath at ORNL**
      - **low ac losses as reported at 2001 CEC**
    - **designing 3-phase, 5-m cable with 3-phase, pressurized terminations**
    - **potential to reduce required HTS tape required by ~ ½**
    - **next generation HTS cable**

FY 2001 Results (continued)

- **HTS Cable Component Development**
  - **continued research on cryogenic dielectric materials**
    - **cryogenic dielectric aging tests well underway**
  - **research improving cryogenic system**
    - **collaboration with NASA Kennedy Space Center Cryogenics Test Bed on low thermal loss, flexible cryostats: positive results reported at 2001 CEC**
    - **Have installed and will test flexible cryostat on 5-m cable at ORNL**
  - **YBCO quench and stability studies**
    - **Working to directly replace BSSCO with YBCO**
    - **Reported at 2001 CEC and in the Wire Session of this meeting**

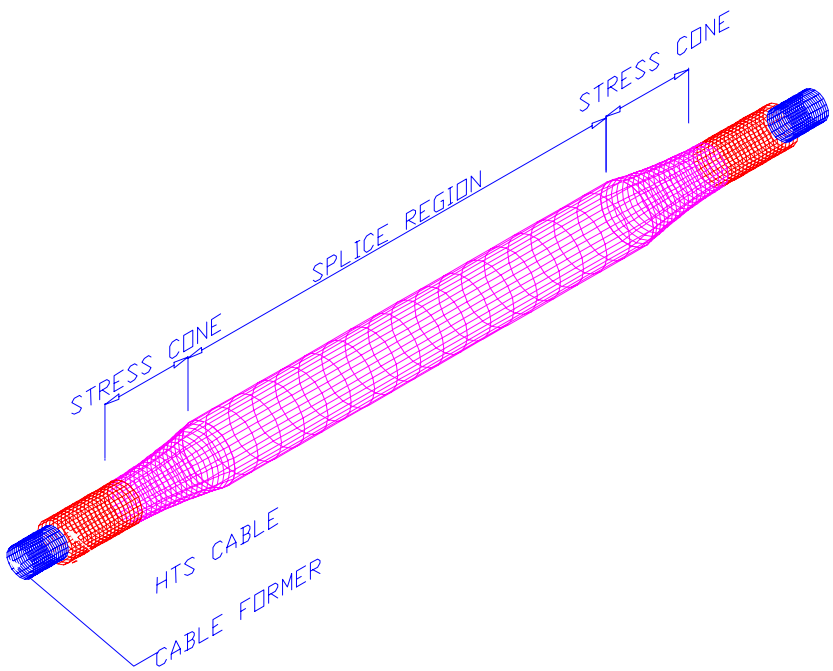
5-m cable research facility at ORNL



5-m High Temperature Superconducting Cable Research Facility Status: August 2001

- **Facility upgrades complete**
  - **impulse power supply upgraded from 100 to 200 kV (BIL tests)**
  - **25,000 A pulsed dc power supply fully operational**
  - **100 kV ac power supply on order for higher voltage cables**
  - **single-phase, 3000 A power supply operational**
  - **3-phase, 1500 A power supply operational, will upgrade to 3-phase 3000 A ac**
- **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**

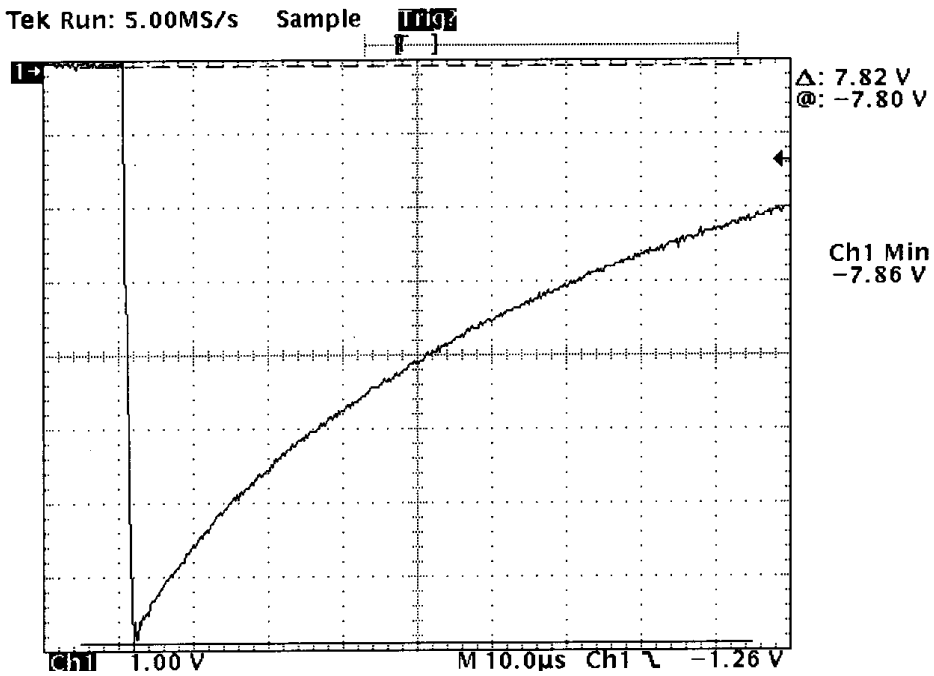
A cold-dielectric HTS cable splice has been made and tested



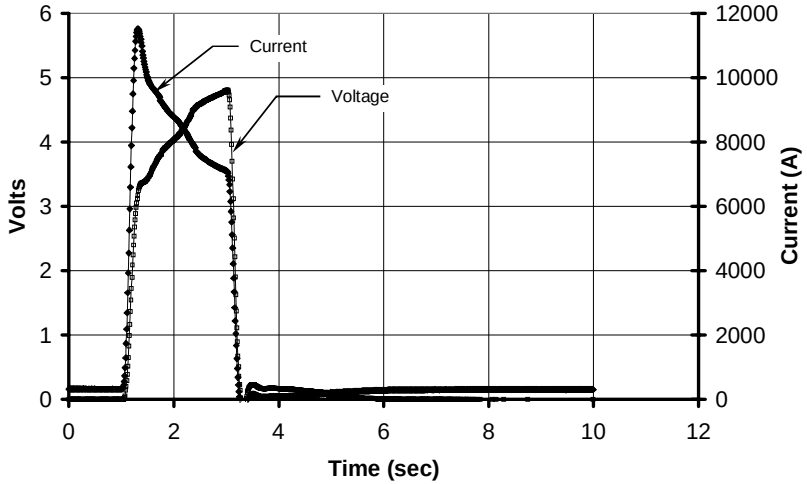
- **Splice connects two sections of cable and joins:**
  - **Liquid nitrogen flow path**
  - **Main HTS conductor**
  - **Dielectric**
  - **Shield HTS conductor**
- **Overall length ~1.2 meters**
- **Diameter about 10% larger than cable OD**
- **BSCCO-2223 silver alloy tapes**
- **Less than 1 watt of heat generated by splice**

5-m HTS splice cable and terminations were impulse tested to ~110-120 kV

- **Requirement is 110 kV for distribution-class cables.**
- **No breakdowns up to 117 kV with + and – polarity pulses**
- **Passed ac withstand to 18 kV after BIL testing**
- **Smaller model cable tested to breakdown at 156 kV in LN.**

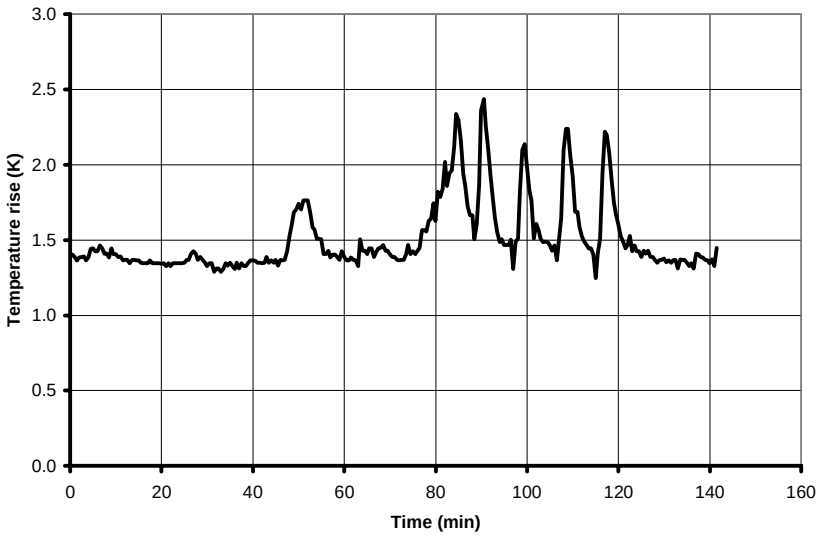


The splice showed no degradation with ~ 12 kA, 2-s over-current pulses to simulate downstream fault



The temperature increased in the silver alloy sheath, increasing the resistance; the power supply reduced the current to maintain output voltage.

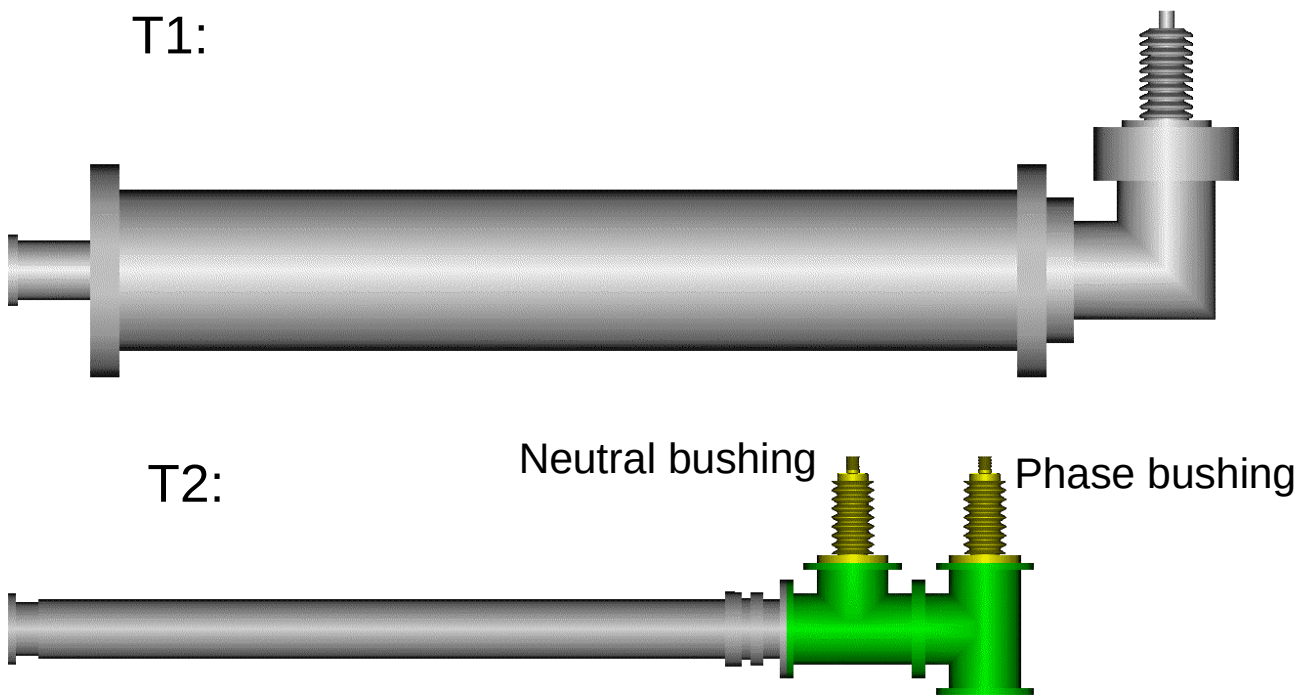
The transient current pulses produced measurable temperature excursions in the LN flow.



Second generation pressurized termination (T2) developed

- **An innovative new termination has been developed and refined**
  - **the design uses liquid / gaseous nitrogen at a few to 10 bar pressure**
  - **the inner and shield conductor cold bushings are eliminated**
  - **the vacuum pumping system, system pump-down and leak checking from the previous vacuum design T1 are eliminated**
  - **simple flange and bus arrangement**
  - **the concept is reliable and uses pressure rated components familiar to the utility industry**
  - **heat losses have been reduced about a factor of 2 from the 1999 T2 prototype**

T2 (pressure termination) is more compact than T1 (vacuum termination)



Testing of T2 (pressure termination)

- **T2 terminations have been through many cooldown cycles both at ORNL and Southwire. Cooldown is efficient with no component being stressed by the rate of cooldown.**
- **High current runs:**
  - **dc current scans to about 2500 amp on the center conductor.**
  - **10 x over-current to 13 kA for 2 s**
- **Performed an ac withstand test at 18 kV ac for 30 minutes.**
- **Impulse tested to ~117 kV (exceeds requirement).**
- **Measured heat loads and LN pressure drops.**

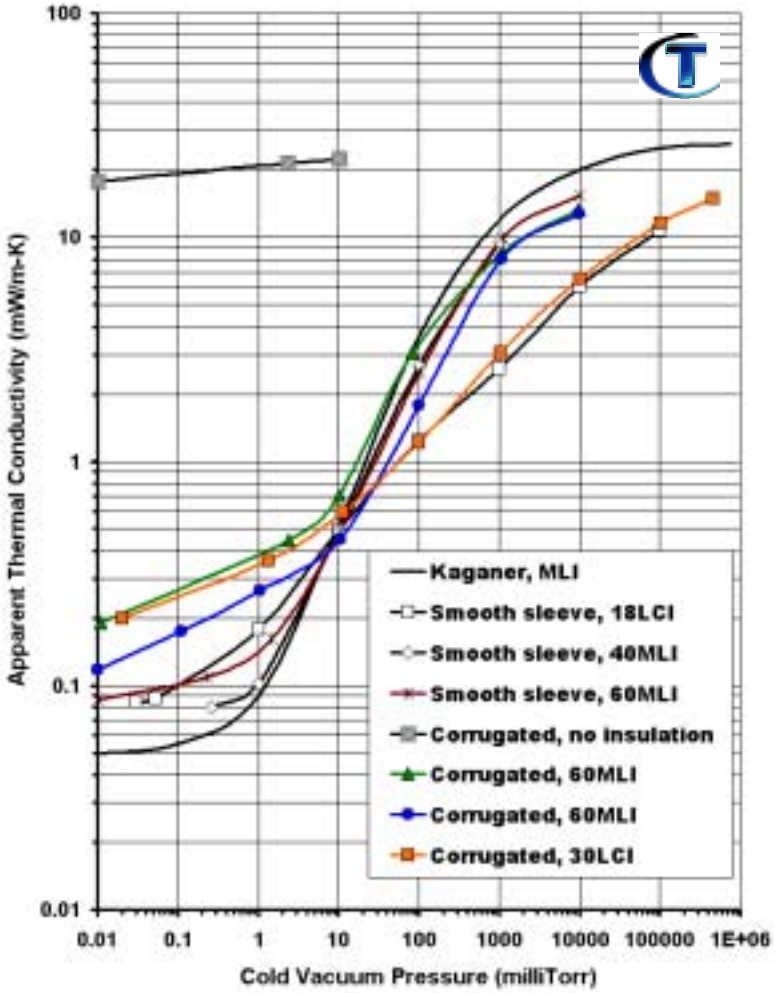
Simulated flexible cryostat testing was conducted with NASA Kennedy Space Center

- **Testing completed on simulated flexible cryostat geometry.**
- **Goal is to design flexible thermal insulation with heat loads approaching rigid cryostat values.**
- **Plan to test practical length vacuum jacketed flexible line performance.**

CryogenicsTestbed
John F. Kennedy Space Center

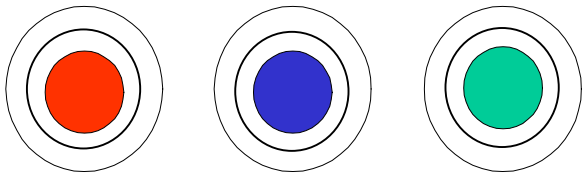
Southwire

The heat load of corrugated, flexible, vacuum jacketed, cryogenic lines can be reduced.

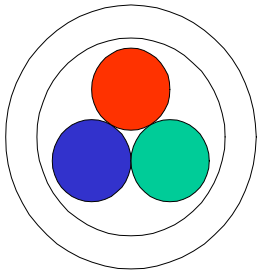


- **Conducted over 90 tests of 12 different thermal insulation systems at the NASA KSC Cryogenics Test Laboratory.**
  - **Investigated rigid (smooth wall) versus flexible (corrugated).**
  - **Effects of spacers.**
  - **Simulated bending of flexible lines.**
- **A NASA KSC developed layered composite insulation (LCI) performs better than standard multi-layer insulation systems *especially* if vacuum degrades.**

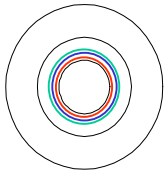
HTS Power Transmission Cable Configurations



3 separate co-axial phases



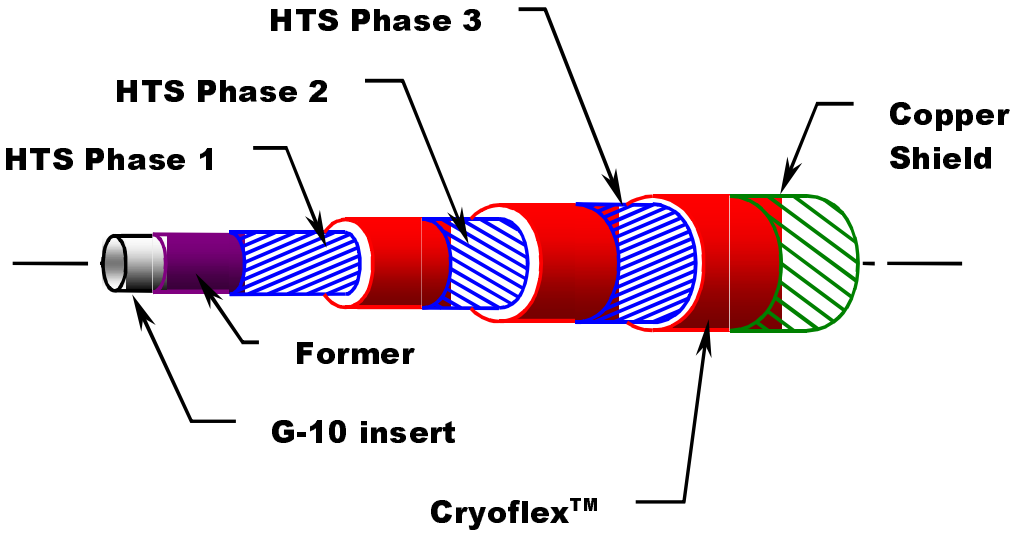
Triad co-axial cable



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.

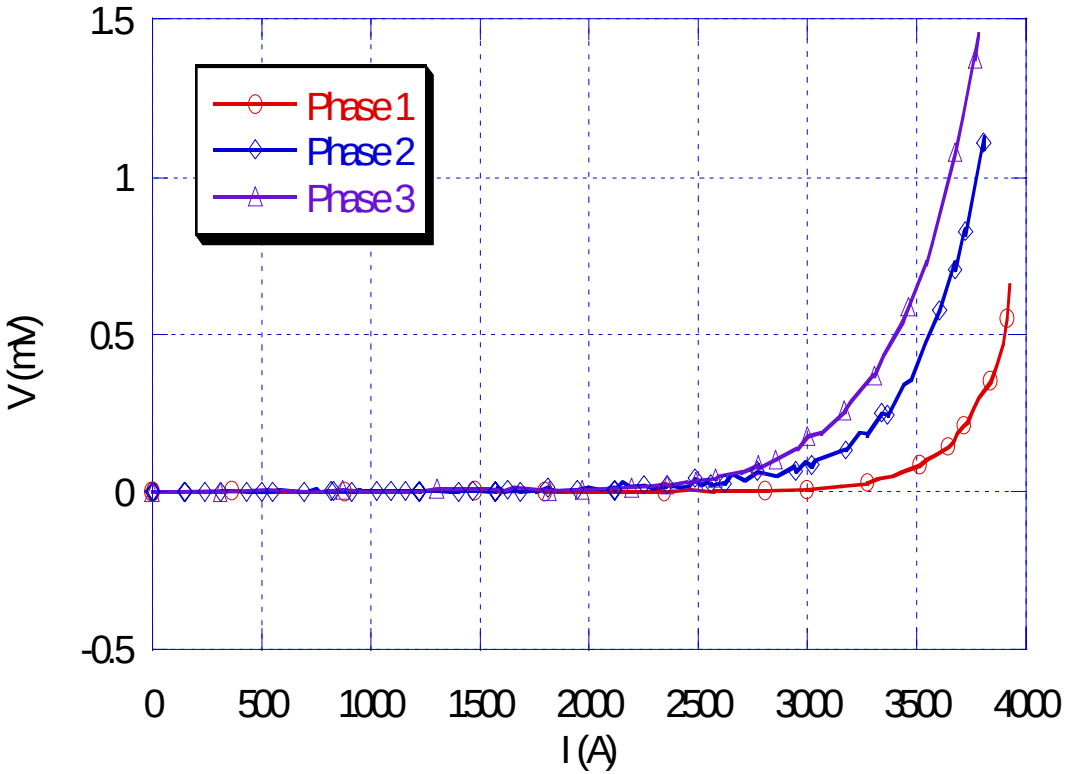
Tri-axial HTS cable prototype, 1.5-m long, has been designed, built and tested in 2001



- 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.

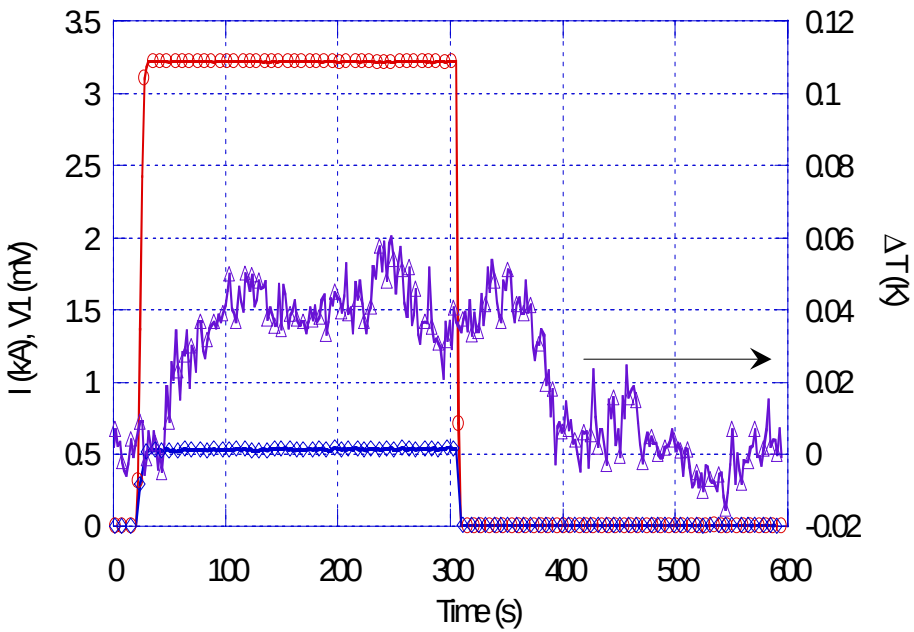
ELECTRICAL TESTS OF A TRIAXIAL HTS CABLE PROTOTYPE
J. W. Lue, J. A. Demko, J. C. Tolbert, U. K. Sinha, R. Grabovickic, G. C. Barber, M. J. Gouge, D. Lindsay, and R. L. Hughey, presented at CEC/ICMC 2001, to be published in Advances in Cryogenic Engineering.

Tri-axial cable dc V-I measurements



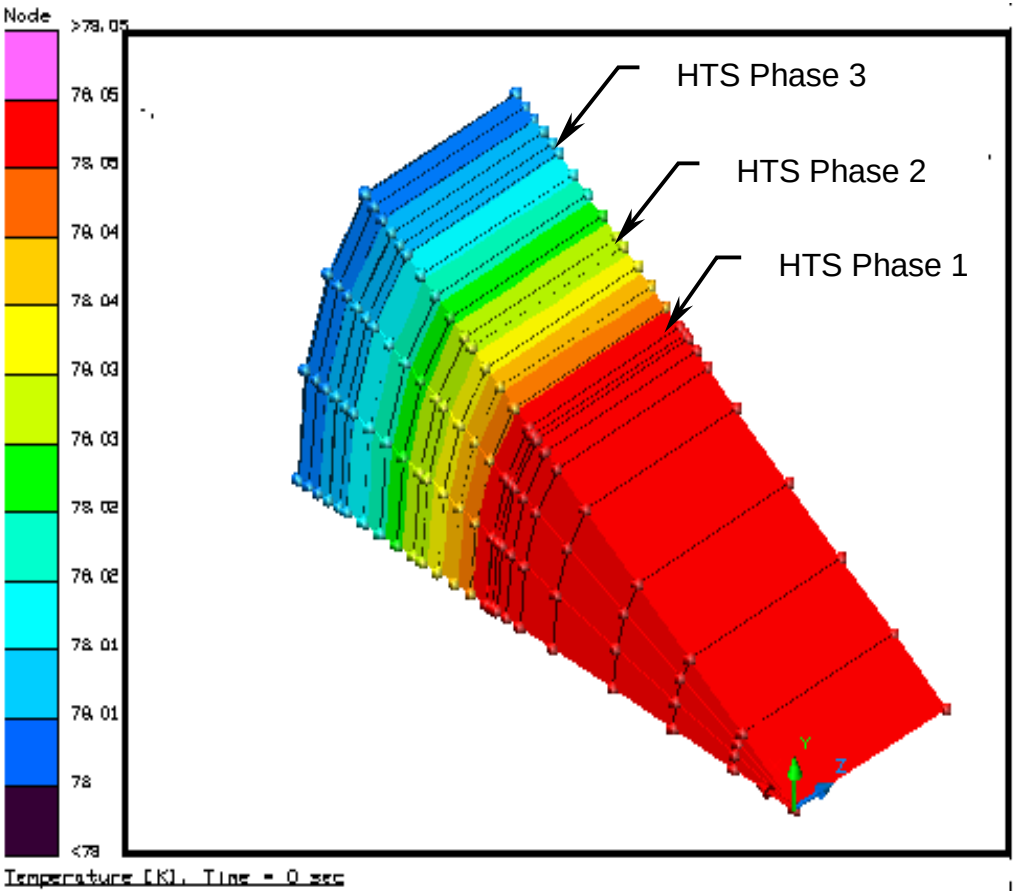
- **Open LN_2 bath**
- **DC test of the tri-axial cable was performed with a 25-kA, 15-V DC power supply.**
- **Critical current of 3.6 kA, 3.1 kA, and 2.8 kA for phases 1 to 3 were separately measured.**

Tri-axial cable heat load calibration for the calorimetric ac loss measurement



- Used previously developed calorimetric technique to measure the ac losses of the tri-axial cable.
- To calibrate the temperature rise for a known heating power, we used the DC characteristics of the HTS phase conductors.
- VI product gives the power input; a thermocouple measures the temperature rise.
- Temperature sensitivity about 10 mK

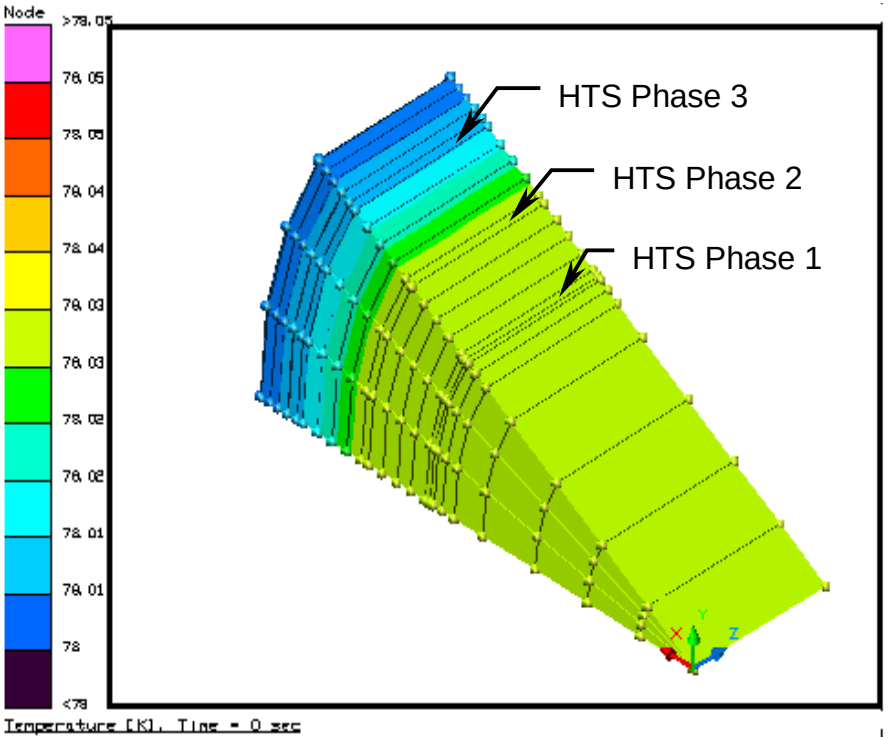
A finite element thermal model calculation was performed to clarify the heat load calibration



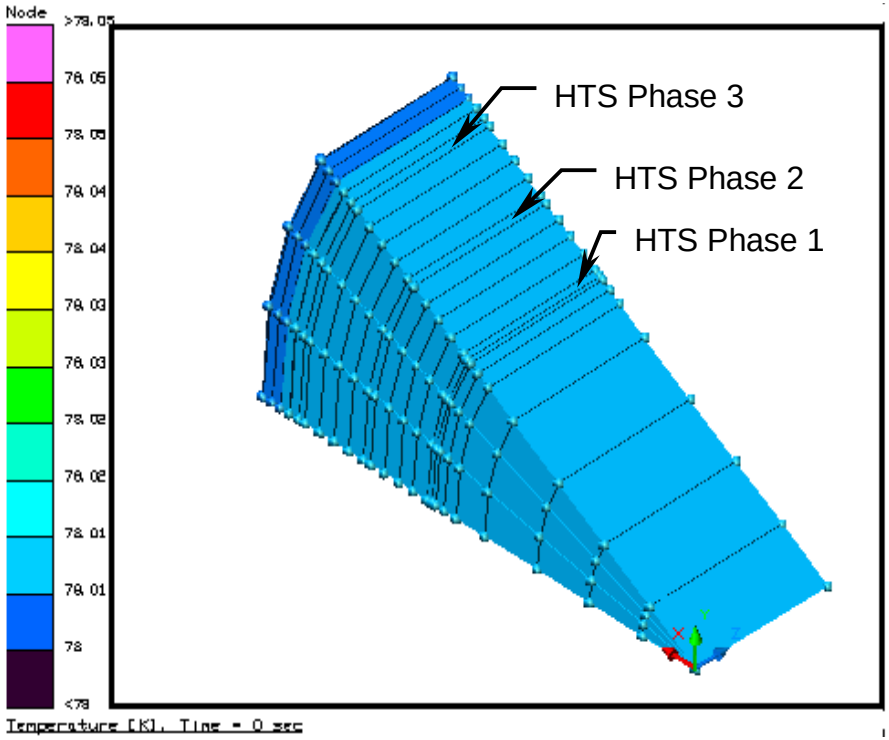
- **The nodes on the outermost surface of the Cu-shield layer were fixed at LN-temperature, all other external surfaces were considered adiabatic.**
- **Temperature profile was calculated for a heat load of 1 watt/m applied to phase 1.**

Tri-axial cable temperature profile of the cable with the same heat load of 1 watt/m on phases 2, 3

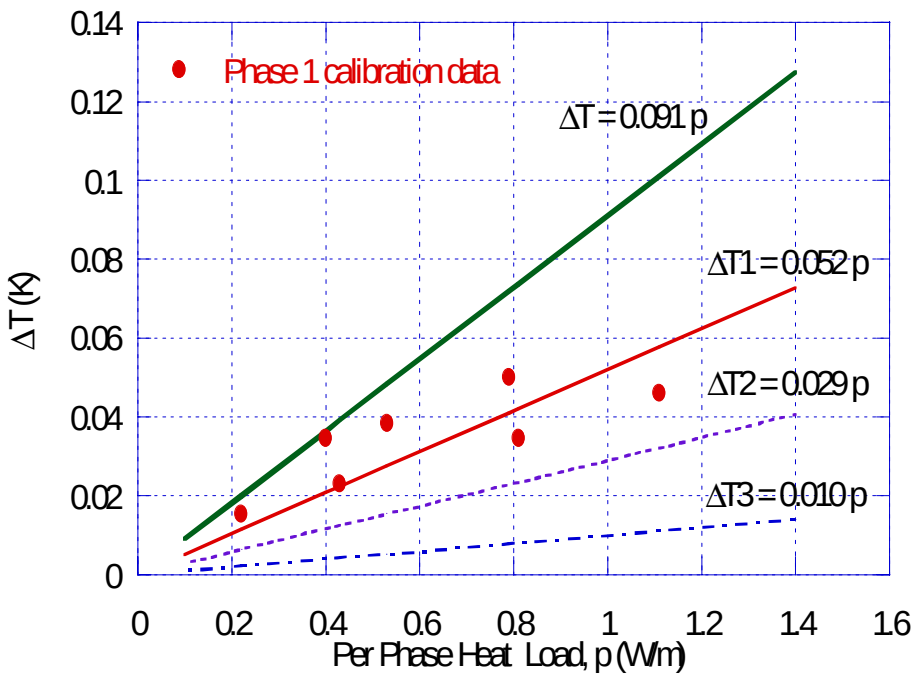
Phase 2



Phase 3

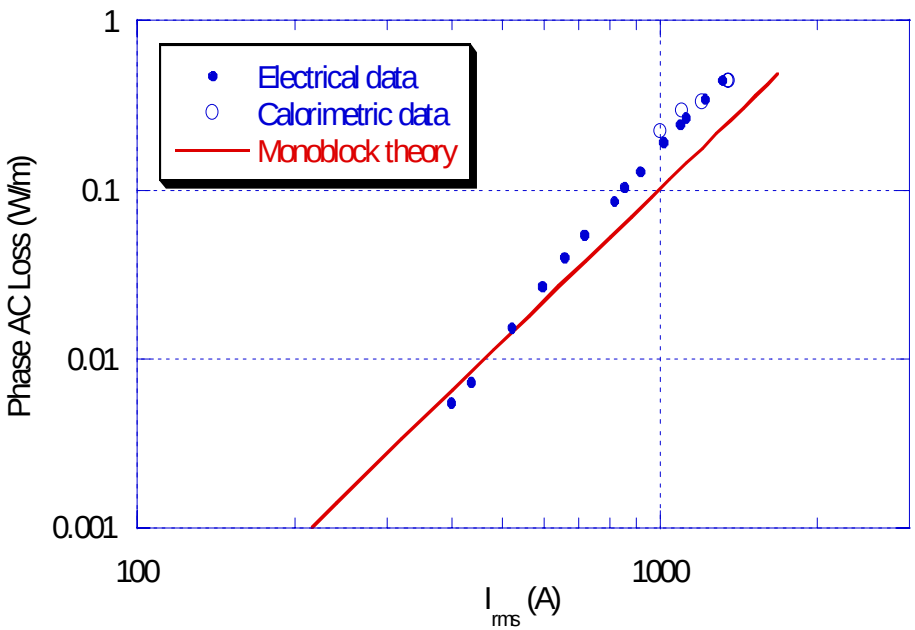


Tri-axial cable heat load calibration curves



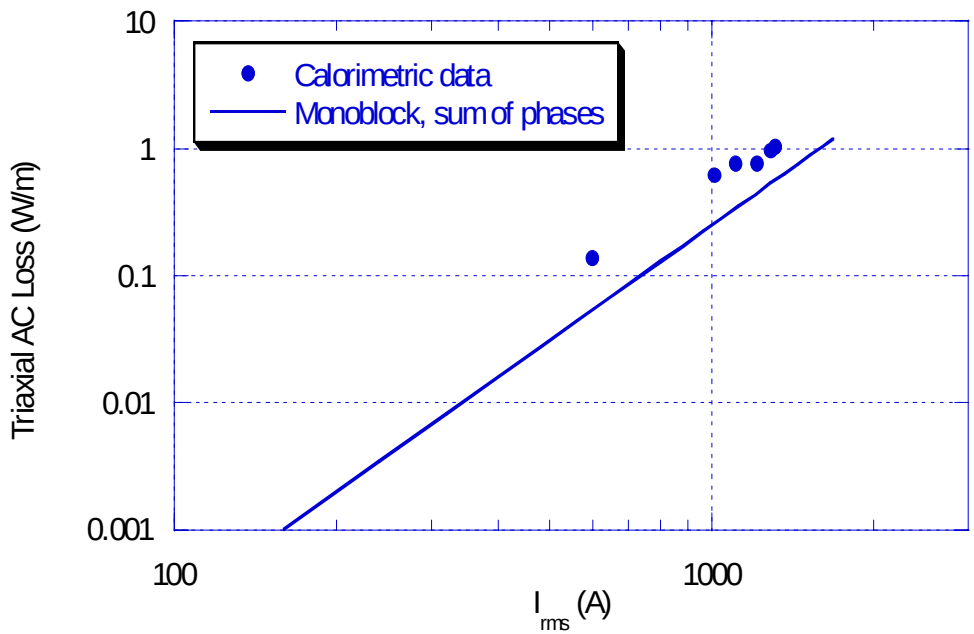
- **The effective thermal conductivity used to model the Cryoflex™ layers was adjusted to fit the dc calibration data of phase 1.**
- **Lower temperature rises were calculated for phases 2 and 3 as expected.**
- **ΔT_{tri} gives the temperature rise when the same heat load is applied simultaneously in all three phases.**

Tri-axial cable single-phase ac loss measurements



- **Both electrical and calorimetric techniques were used to measure the ac loss on each of the three phases separately.**
- **The two sets of data agree with each other surprisingly well.**
- **The experimental ac loss data is also in fair agreement with the simple monoblock theory.**

Tri-axial cable three-phase ac losses



- **The ac loss of the tri-axial cable was measured calorimetrically with equal currents of up to 1350 A on all three phases.**
- **The measured ac loss is in fair agreement with the sum of the three individual phase losses calculated by the monoblock theory.**
- **At the design current of 1250 A, the measured total ac loss of the tri-axial cable prototype is only about 1 watt/m.**

Tri-axial cable summary and conclusions

- **A 1.5-m long tri-axial HTS cable prototype was fabricated and tested for its superconducting properties.**
- **AC loss was measured both electrically and calorimetrically.**
- **Finite-element thermal modeling was performed to obtain a self-consistent calorimetric calibration.**
- **Individual phase ac losses show good agreement with the monoblock theory.**
- **The 3-phase ac loss data is close to that of the sum of three individual phases.**
- **There is no measurable, 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**

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** **(John Stovall, ORNL)**
- **FY 2001 Performance / FY 2002 Plans**
- **Research Integration**
- **Summary**

Termination model #2 passed all HV tests

- Passed ac withstand at 18 kV (2.5x operating field strength) for 30 min
- Passed impulse withstand (3 shots) at 113.8 kV, positive polarity
- Repeat 18 kV ac withstand
- Passed 110 kV BIL negative polarity impulse
- Impulse breakdown occurred at 156 kV in LN2
- PD inception studies in progress

Improved model cable verifies BIL capability

- Previous model cables used shield layers only on the ground side (i.e. between dielectric and ground), since the mandrel (HV conductor) is smooth
- A model cable (1.3-m) was made with shield and bedding tapes on both the HV and ground side
- PD inception at 20 kV, about 3 times the operating voltage.
- Impulse breakdown occurred at 206 kV, nearly 2x the required BIL
- Breakdown occurred at the beginning of stress cone
- No significant difference with previous model cables

Model cable aging - long term aging experiment

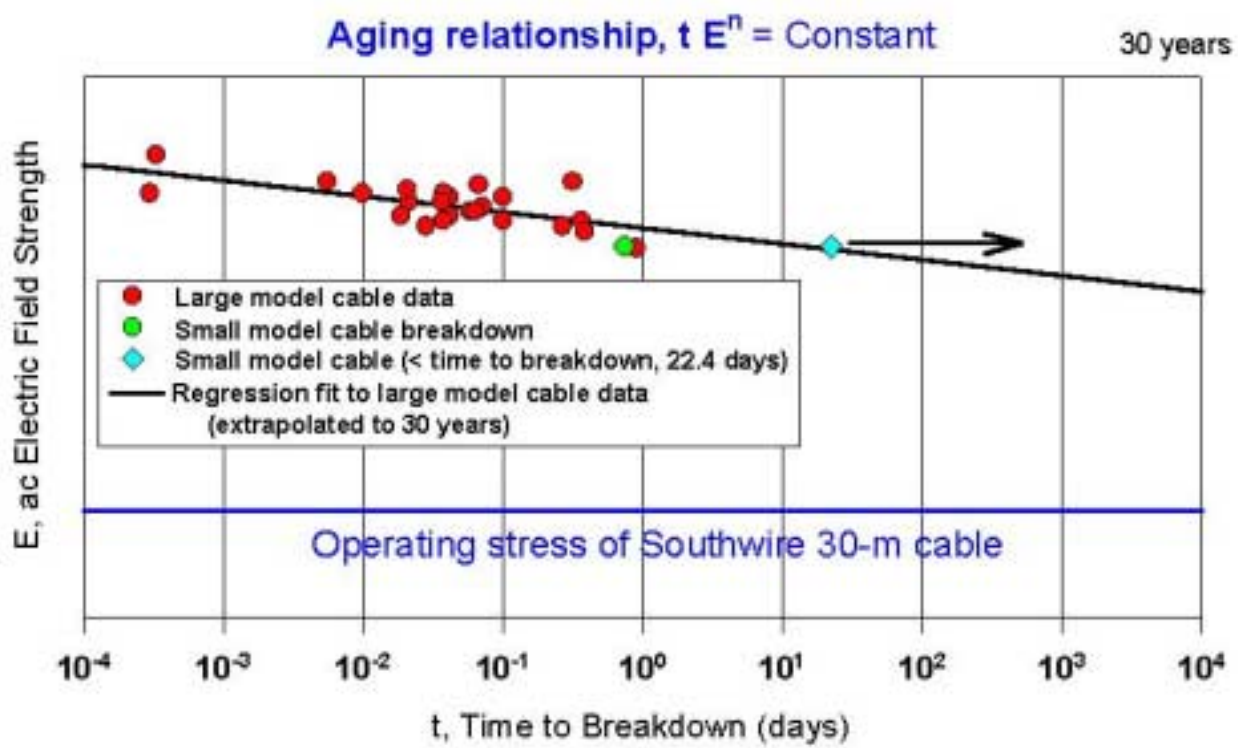
- New HV cryostat with automatic LN2 fill system permits aging studies to run for several days
- System uses both a low pressure and high pressure LN2 fill system unique at ORNL
- Small cables (0.6-m length) can be tested
- Model cable with half the insulation thickness of the 30-m cable ran at 8.3x the field strength for 537 h (22.4 days) without failure
- Ramp to breakdown of a similar cable occurred at 16x the operating field strength of the 30-m cable.

Model Cable Breakdown

- **Two model cable types: Large (1.2 m) for short term (< 1 day) aging dewar and small (0.6 m) for long term aging (> 1 day) dewar**
- **Table shows very little difference in the ramp-to- breakdown voltages of the two cable types (note that the insulation thickness in the cables used for these tests is less than the actual HTS cable)**
- **Future long term aging tests will be conducted with small model cables**

Model Cable Type	AC Breakdown Voltage (kVrms) at 77K	Std. Dev. (kVrms)	Weibull probability (at 62.3%) (kVrms)
Large (1.2 m)	52	13	58
Small (0.6 m)	56	6	---
All cables	53	11	58

Cryogenic Dielectric Model Cable Aging Studies: Short and long term tests



ORNL FY 2001 Performance

FY 2001 Plan

- Evaluation of 30-m cable operation and performance
- Research and development and testing of cable splices

FY 2001 Performance

- Over 8,500 hours of operation
- Critical current measurements show robust superconductor
- Current transient test shows response to over-current
- Neutral current testing shows effect of external circuit
- Unmanned operation (6/01)
- 5-m cable splice successfully tested
  - Rated voltage for >8 hours
  - 18-kV for 30 minutes
  - BIL above 110 kV
  - 11X fault currents

ORNL FY 2001 Performance

FY 2001 Plan

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

FY 2001 Performance

- Improved termination design reduces complexity
  - Rated voltage for >8 hours
  - 18-kV for 30 minutes
  - BIL above 110 kV
  - 11X fault currents
- Aging test further defines lifetime of cryogenic dielectric
- Thermal insulation testing by NASA (collaborative partner)

ORNL FY 2001 Performance

FY 2001 Plan

- ORNL will assist Southwire with the design and analysis of an HTS cable system for siting in a large urban area with a utility partner.

FY 2001 Performance

- Partnership with AEP established
- Challenging HTS cable application identified and evaluated
- SPI proposal prepared and submitted (Southwire, AEP, ORNL, PHPK, NST, ICE, 3M)
- Proposals under evaluation by DOE

Change in Plans During FY 2001

FY 2001 Plan

- **Added task to investigate the characteristics of tri-axial, cold-dielectric HTS conductors**

FY 2001 Performance

- **Completed testing of first 1.5 m tri-axial conductor. Results are positive.**

ORNL FY 2002 Plans
Oct. 1, 2001 to Sept. 30, 2002

- **ORNL will work with Southwire to improve the overall design and capabilities of the HTS cable system.**
  - **Bend testing of a 5-m HTS cable with flexible cryostat,**
  - **Design, construction, testing and analysis of 5-m tri-axial HTS cable including 3-phase terminations,**
    - **Continued development of the pressurized termination**
  - **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.**

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 2001 progress is evidence of well functioning team.**
  - **5-m cable research 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**
  - **Future joint development project under consideration**
- **NKT energized their 3-phase superconducting cable demonstration in May 2001 at Copenhagen Energy substation AMK.**
  - **2000-A, 36-kV, 30-m**
  - **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

- **14 presentations and 12 publications during the year**
  - **Four technical papers presented at the "Applied Superconductivity Conference, ASC 2000", in September 2000 and published in *IEEE Transactions on Applied Superconductivity,* March 2001.**
  - **IEEE Power Engineering Society Winter Meeting in January 2001.**
    - **Panel presentation and paper**
  - **Article published in Superconductor & Cryoelectronics, Winter 2000**
  - **Six technical papers presented at the CEC-ICMC 2001 in July 2001 and to be published in *Advances in Cryogenics***
    - **Four - Southwire and ORNL authorship**
    - **Two - NASA, Dynacs, and ORNL authorship**
  - **EEI, Transmission, Distribution & Metering Spring 2001 Conference**
    - **May 6-9, 2001, Seattle, Washington**
    - **Two presentations, one by Southwire and the other by ORNL**
  - **IEEE, Power Engineering Society, Insulated Conductors Committee**
    - **Fall 2000 Meeting, St. Petersburg, FL, Oct. 29 - Nov. 1**

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**

- **Awards**
  - **Federal Laboratory Consortium for Technology Transfer, Southeast Region**
    - **Excellence in Technology Transfer Award, Nov. 7, 2000**
    - **High Temperature Superconducting Power Cables**
  - **2000 Georgia Technology Leadership Award**
  - **2001 Georgia Engineering Excellence Grand Award**
  - **ORNL project team awarded "Engineer of Year" for UT-Battelle.**

Summary

- **FY 2001 goals have been achieved**
  - **30-m HTS cable has over 8500 hours of flawless operation**
    - **Cable remains robust and is running unmanned**
  - **Cable design and testing develops the needed technology base**
    - **5-m cable testing of splices shows ability to make long cable lengths**
    - **1.5-m tri-axial conductor testing shows merits of concept**
    - **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 August 1, 2001, the HTS cables have provided 100% of the customer load for 8500 hours