High Temperature Superconducting Cable

2000 Annual Peer Review

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

Southwire

ornl

July 17-19, 2000
Washington, DC

Oak Ridge National Laboratory
U. S. Department of Energy

UT-BATTELLE

World's First Industrial Field Test of HTS Cable Delivers Power To Industrial Customer

Presentation Outline

- **Southwire Activities** (David Lindsay, Southwire)
  - Introduction
  - 30-m Cable Installation
  - 30-m Cable Operation
- **FY 2000 Results**
  - 30-m Cable Off-Line Testing (Mike Gouge, ORNL)
  - 5-m Cable Research
  - Component Development
  - Cryogenic Dielectrics Research (John Stovall, ORNL)
- **FY 2000 Performance / FY 2001 Plans**
- **Technology Integration**
- **Summary**

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Project Participants at Southwire and ORNL

- **Southwire**

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

- **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

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Other Project Participants

- **Argonne National Laboratory**
- **EURUS - Plastronic**
- **Georgia Transmission**
- **IGC Superpower**
- **Southern Cal Edison**
- **Southern Company**
- **Subcontractors and Consultants**

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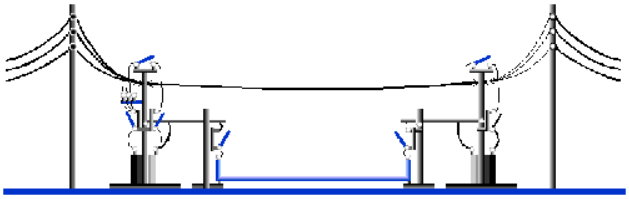
SPI Project Goal (February 1997)

First U.S. Industrial SPI Cable Installation

- **At the end of the three 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.**



- Operation of 30-meter three-phase cable in **FY 2000** at Southwire Headquarters in Carrollton, Georgia.

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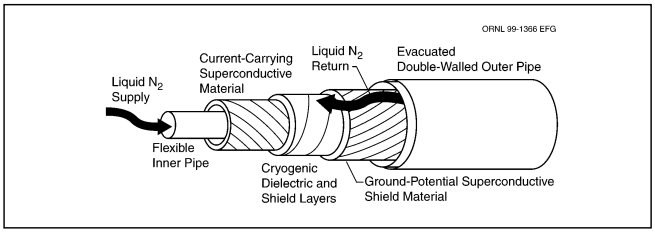
Cable Cross Sectional View



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

Southwire Project Status

- **FY 2000 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**

HTS Cable Site Progress

← Under construction, as shown last year

In operation this year →

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Cables Installed - 8/24/99

← Site ready for cable installation

Phase 3 set in place →

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Cryogenic System Delivered - 9/2/99

← As delivered

Installed and operational →

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Termination Assembly - 9/23/99

← Assembly in progress

Assembly completed →

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System Testing Oct. - Dec. 1999

- **Cryogenic system acceptance and testing**
- **Off-line electrical testing of superconducting cables**
- **Circuit breakers and protection system**

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Cables First Energized on January 5, 2000

Phase 3

Phase 2

Phase 1

Electrical Control and Protection Panel for HTS Cables

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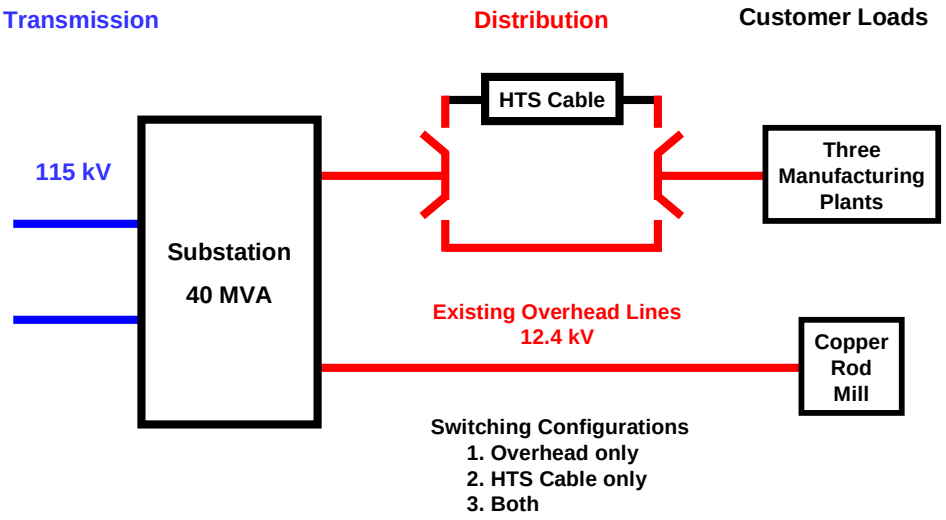
Computer (PLC) Controlled Cryogenic System

Dedication Ceremony - Feb. 18, 2000

Georgia Governor and Energy Secretary

Electrical Block Diagram of SW HTS Cable



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Substation

- **Two way transmission feed**
  - **one from Yates Power Plant**
  - **one from Bremen switchyard**
- **40 MVA**
  - **Two 20 MVA matched unit, non regulating, transformers**
  - **115 kV high side / 12.4 kV low side**
- **Two 12.4 kV feeders out**

Switchyard is part of Integrated Transmission System and provided by Georgia Power

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Two 12.4 kV Feeders Exiting Substation

- **Southwire feeder (left)**
  - **HTS cable on SW feeder**
- **Copper Division Southwire feeder (right)**
- **Both 1033.5 ACSR (aluminum conductor steel reinforced)**
- **12.4 kV protection on Southwire feeder is a vacuum breaker with a re-closing relay set for three shot before lock out.**
- **Symmetrical 3 phase fault current is around 14,000 amps at 12.4 kV**

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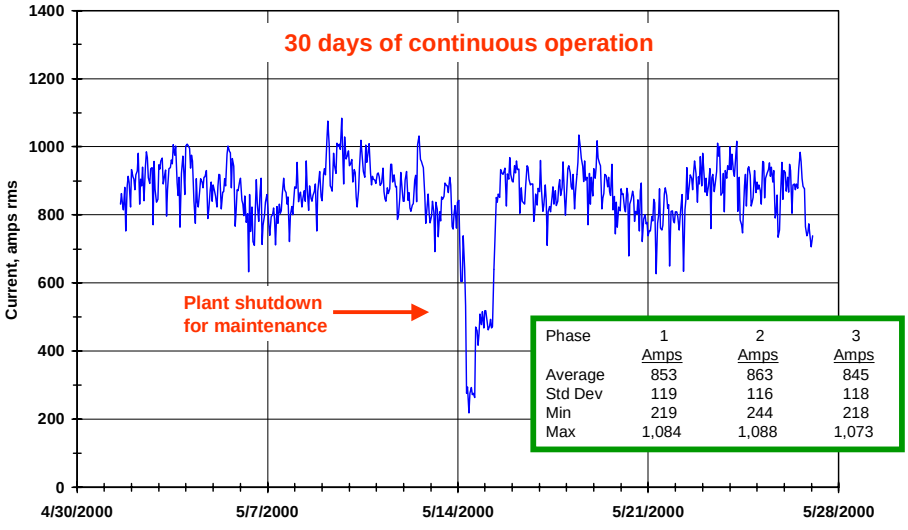
HTS Phase 1 Current for May 2000



Phase	1 Amps	2 Amps	3 Amps
Average	853	863	845
Std Dev	119	116	118
Min	219	244	218
Max	1,084	1,088	1,073

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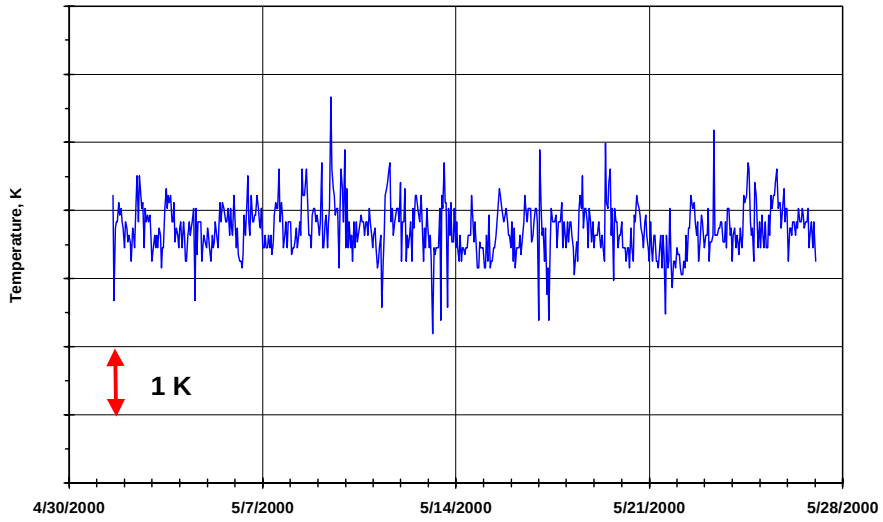
HTS Phase 1 Return Temperature for May 2000



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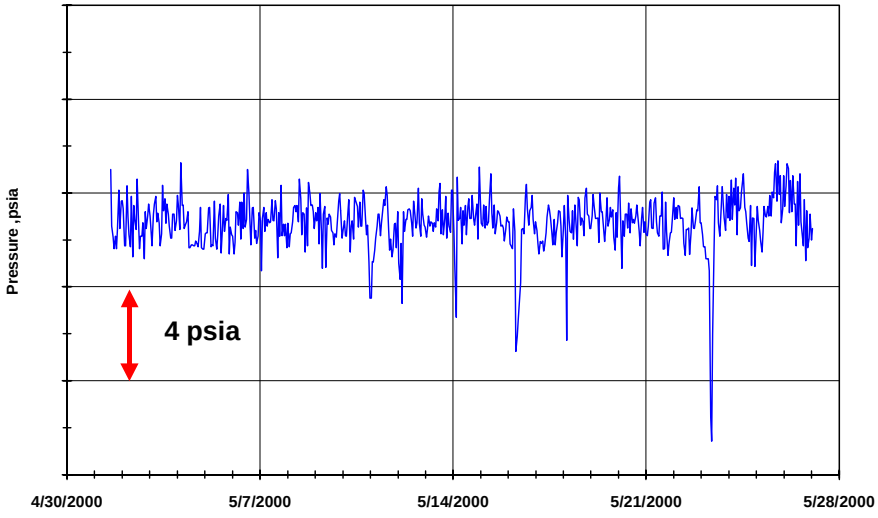
HTS Phase 1 Return Pressure for May 2000



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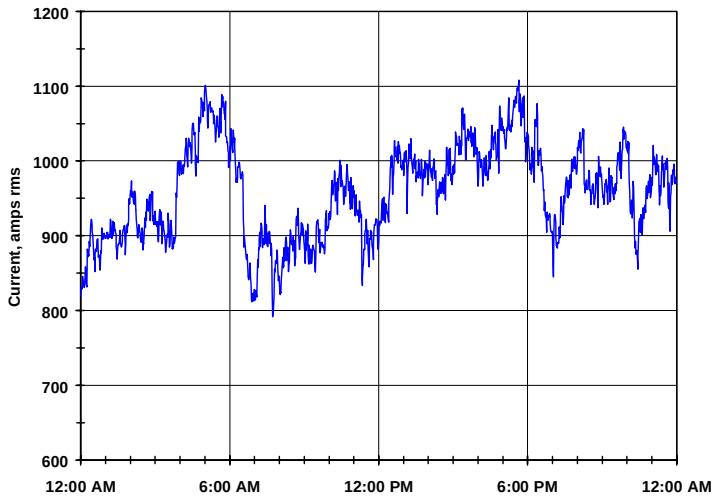
HTS Phase 1 Current for May 9, 2000



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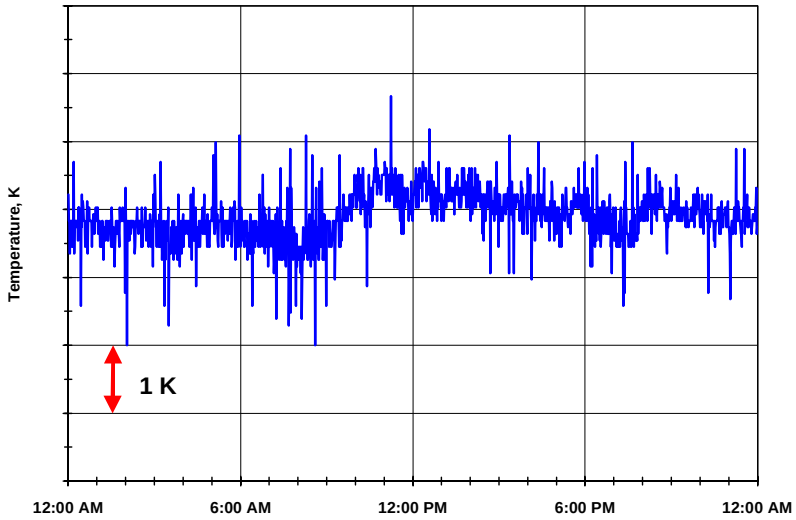
HTS Phase 1 Return Temperature for May 9, 2000



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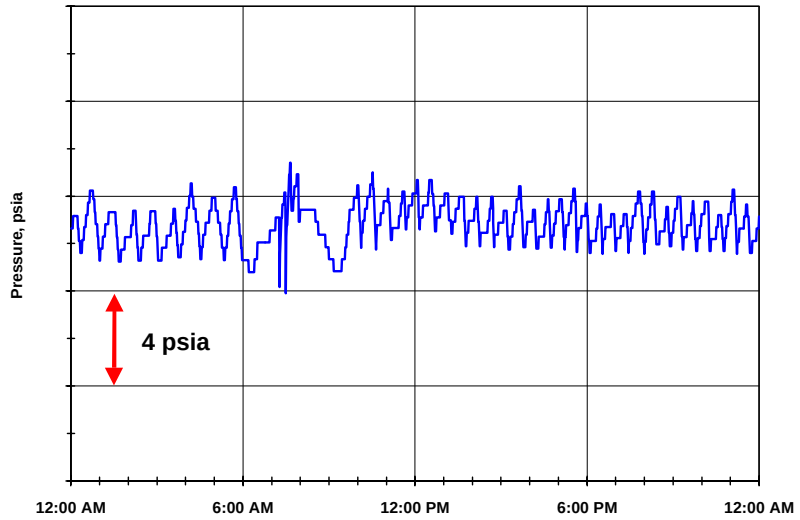
HTS Phase 1 Return Pressure for May 9, 2000



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This field demonstration has successfully shown the utility application of superconducting cables at distribution voltages and high currents.

- **Potential utility applications**
  - **Substation to customer**
  - **Substation to substation**
  - **Extended substation bus**
  - **Substation express feeder**
  - **Generating unit to step-up transformer**

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FY 2000 Objectives for ORNL (from FY 1999 Peer Review)

- **Conduct cable bending and short circuit tests on the 5-m cables.**
- **Continue cryogenic dielectric aging tests.**
- **Assist Southwire with the final construction, installation, checkout, testing, and operation of the SPI 30-m, 3-phase HTS cable.**
- **Extend HTS cable capability in partnership with Southwire researchers by:**
  - developing a cable splice,
  - improving the cable cryostat cryogenic insulation,
  - design a cable termination for higher operating voltages, and
  - examine cryogenic dielectric system requirements for higher voltage HTS cables.

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FY 2000 Results

- **30-m Cable Demonstration (Southwire lead)**
  - **Assisted Southwire with assembly of 3-phase, 30-m cable (Aug-Oct 99)**
  - **Joint Southwire/ORNL effort in commissioning cable and cryogenics system (Sep-Dec 99)**
  - **Joint Southwire/ORNL effort in 30-m cable demonstration and tests (dc V-I, ac withstand, temperature and flow scans, etc.)**
- **5-m Cable Research (ORNL lead)**
  - **successful over-current tests (~10 x) on 5-m cable**
  - **impulse tested cable #2 and the terminations to ~ 90 kV (recoverable breakdown above 90 kV)**
  - **bent 5-m cable and tested**

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FY 2000 Results (continued)

- **HTS Cable Component Development**
  - **design improvements to pressurized termination:**
    - **heat loss reduced**
    - **more robust to ambient conditions**
  - **collaboration with NASA Kennedy Space Center Cryogenics Test Bed on low thermal loss, flexible cryostats.**
  - **have designed and fabricated a 5-m cable with a splice**
    - **developed and successfully tested model dielectric tape splice**
    - **will test cold dielectric cable splice next month at ORNL**
  - **cryogenic dielectric aging tests underway**
  - **YBCO quench and stability studies**

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ORNL supported the 30-m, 3-phase, HTS cable demonstration at Southwire

First use of HTS cables in an industrial application

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ORNL assisted Southwire with the assembly of 30-m HTS cable terminations in Sept. 1999

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Commissioning the 30-m cryogenic system Sept. - Oct. 1999

- acceptance testing at Southwire in September 1999.
- commissioning in Oct-Nov 1999
- support of software development for manual and automatic control functions
- system is quite reliable: minor equipment problems with some components: cryogenic valve actuator, control air compressor

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Off-line testing of 30-m cables

- High voltage withstand
- DC voltage/current tests
  - Nov. 1999
- DC current load test
- DC voltage/current tests
  - June 2000
  - to determine cable performance after 6 months of operation, after 4 to 6 cool-down and warm-up cycles, and under variable loading

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High Voltage Withstand Test - 11/19/99

- **Voltage held for 30 minutes on each phase to test cable dielectric system.**
  - **Phases 1 and 2 maintained at 166% of rated voltage without breakdown.**
  - **Phase 3 maintained at 230% of rated voltage without breakdown.**

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Measured and Calculated Capacitance

Capacitance - nF / m

	Phase 1	Phase 2	Phase 3
Measured	1.815	1.739	1.265
Calculated	1.778	1.778	1.207
Difference	2.1%	-2.2%	4.8%

Inductance - nH / m

	Phase 1	Phase 2	Phase 3
Calculated	31.4	31.4	38.2

Above values result in surge impedance for 30-m cable of about 4 ohms.

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V-I curve & DC current load tests Nov./Dec. 1999 and June 2000

- **Voltage versus current (VI curve) was measured to determine the resistance of the superconducting cables and terminations.**
- **DC load current tests simulated**
  - **average,**
  - **rated, and**
  - **emergency loading of superconducting cables.**

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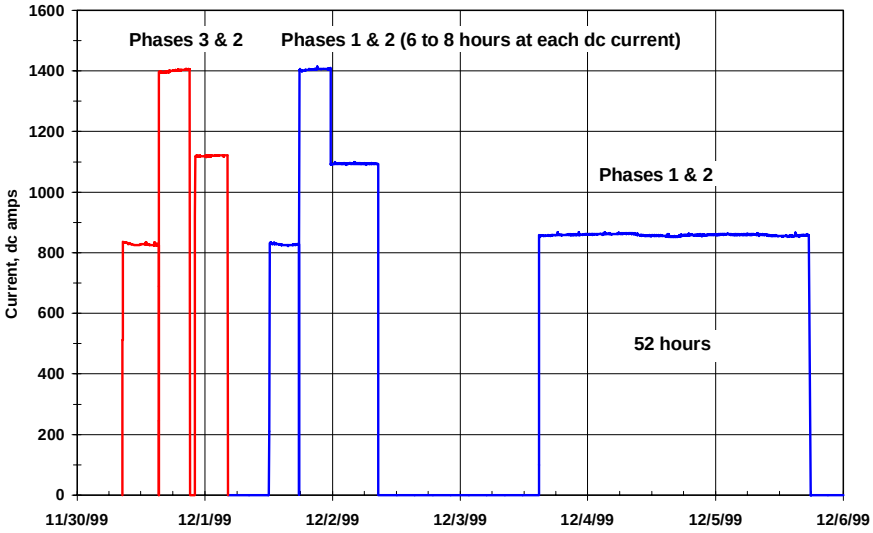
Off-line average, rated, and emergency dc load current tests were conducted in Dec. 1999



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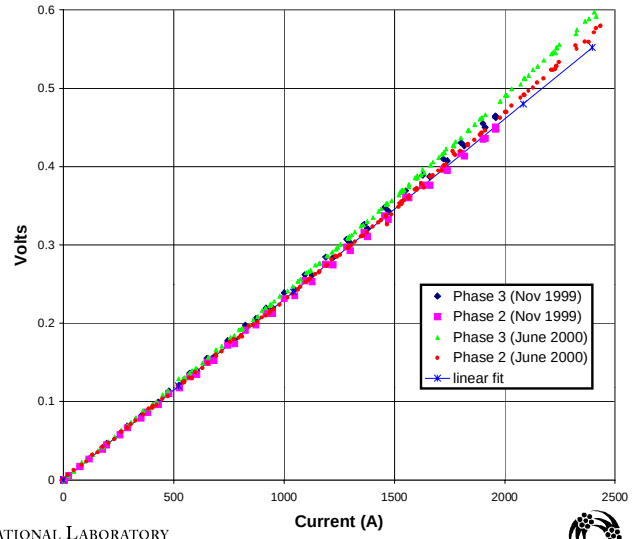
DC V-I curves in Nov. 1999 and June 2000 indicate no change in 30-m cable performance



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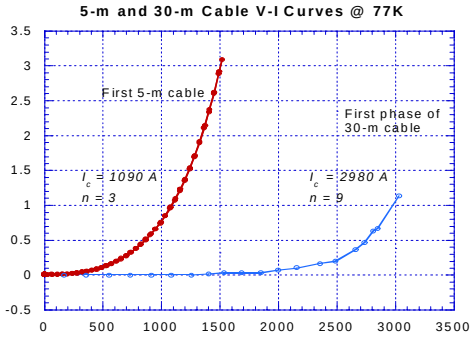
Testing of 30-m HTS Cables at Carrollton



- **Testing was performed on the power and shield conductors in the cable cryostat with boiling liquid nitrogen cooling.**
- **Performance was as expected from the individual tape properties.**

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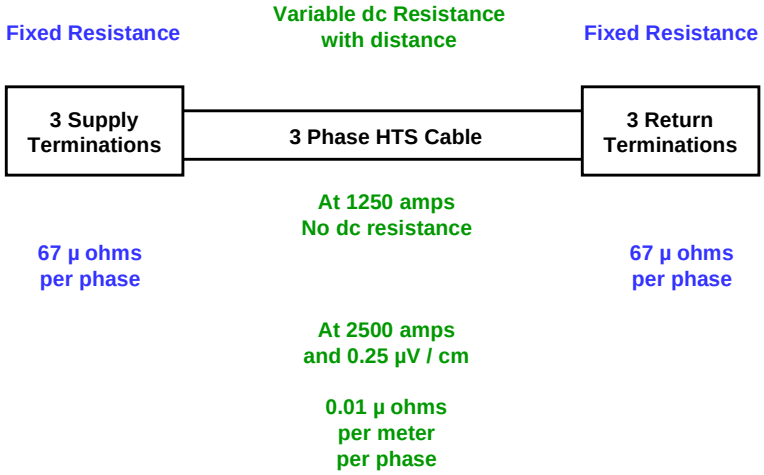
End-to-end cable dc resistance has been measured



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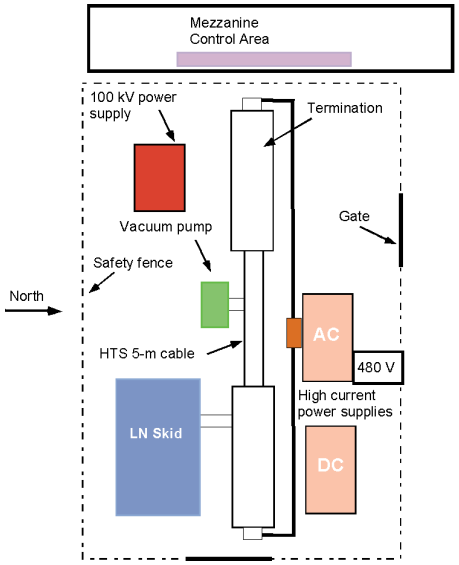
5-m cable research facility at ORNL



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5-m High Temperature Superconducting Cable Research Facility Status: July 2000

- **Facility upgrades complete**
  - **impulse power supply upgraded from 100 to 200 kV (BIL tests)**
  - **25,000 A pulsed dc power supply commissioned (short circuit tests)**
  - **pressurized terminations: improved cryogenic performance**
- **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**

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Facility upgrade - 200 kV impulse generator

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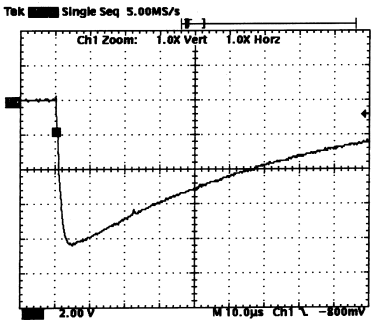
5-m HTS cable #2 and terminations were impulse tested to ~90 kV

- Requirement is 110 kV for distribution-class cable
- Breakdown above 90 kV does no insulation damage
- Cable can recover if test voltage reduced to < 90 kV
- Tests indicative of transient breakdown in long liquid nitrogen path
- No damage evident in system when disassembled
- Will next test with different cable



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Facility upgrade - 25,000 A, pulsed dc power supply for short circuit testing

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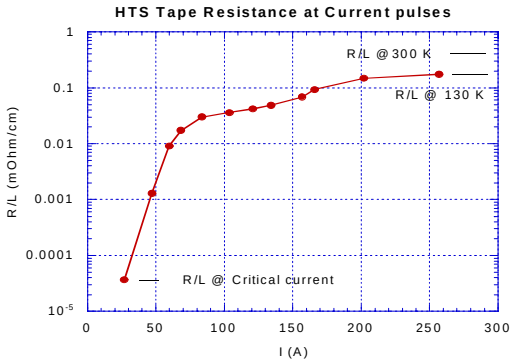
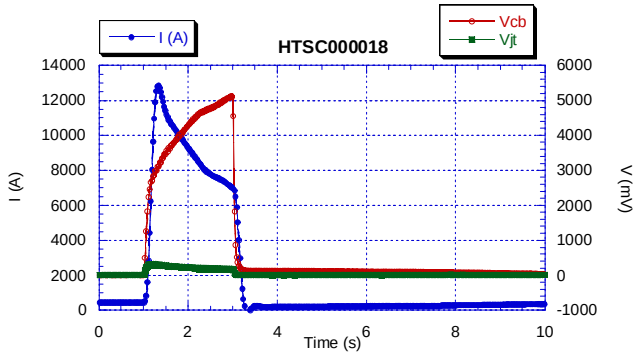
Over-current testing of single HTS tapes

- A fault current simulation test was performed on a single HTS tape wound on a rigid former.
- Tape was cooled in an open liquid nitrogen bath.
- Pulsed currents of up to 10 x the critical current applied for up to 3 seconds.
- At 10 times the design current (each tape @ ~ 120 A), the data showed that the HTS still carries a significant fraction of the total current



Successful short circuit (10x) test of 5-m HTS cable



- Figure shows HTS cable and joint voltage in response to a 12.8-kA, 2 sec over-current pulse to simulate a short to ground.
- Cable survived with no performance degradation over-currents up to 15 kA. Design current is 1.25 kA.

5-m HTS cable bending to simulate storage and shipment after manufacture

- **Bent 5-m cable #2 in both directions**
- **Tested cable after bending to determine dielectric system integrity**
  - **ac withstand test successful**

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Second generation pressurized termination (T2) developed

- **An innovative new termination has been developed and refined**
  - **the design uses liquid / gaseous nitrogen at 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 6/99 T2 prototype**

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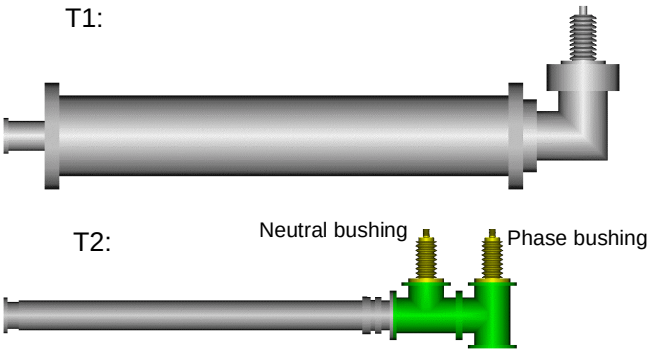
T2 (pressure termination) is more compact than T1 (vacuum termination)



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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 overcurrent to 13 kA for 2 s**
- **Performed an ac withstand test at 18 kV ac for 30 minutes.**
- **Impulse tested to ~90 kV.**
- **Measured heat loads and LN pressure drops.**

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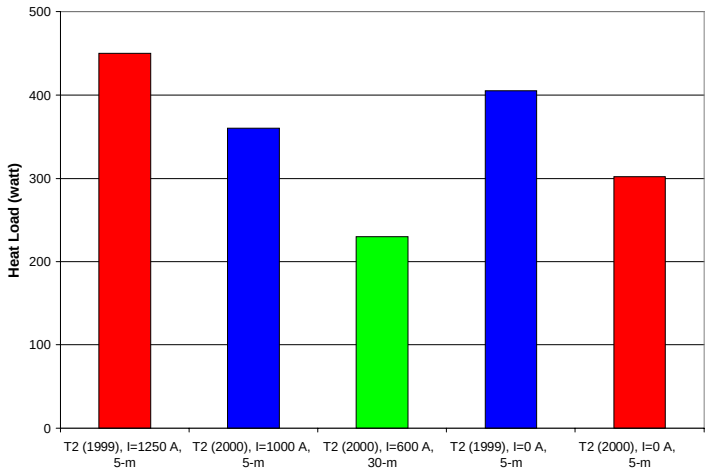
Heat load of terminations has been reduced

Each termination has two leads - phase and neutral



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Cable system heat loss has been measured

Fixed Heat Loss | **Variable Heat Loss with distance and current** | **Fixed Heat Loss**

3 Supply Terminations — **3 Phase HTS Cable, 3 cryostats** — **3 Return Terminations**

Cable cryostat - 1 W / m / phase

230 W / termination | **Conductor and Shield 0.2 W / m / phase** | **230 W / termination**

690 W | **110 W** | **690 W**

Heat loss (all 3 phases) for 30.5 meter cable and terminations at 600 amps is 1490 W.

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Simulated flexible cryostat testing is being conducted with NASA Kennedy Space Center

- Testing in progress on simulated flexible cryostat geometry.
- Goal is to design flexible thermal insulation with heat loads approaching rigid cryostat values.

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Splice Development and Testing

- A cable splice design has been developed.
- A model cable has successfully tested the dielectric splice design.
- A 5-m splice cable is being manufactured by Southwire for testing at ORNL.
- Future plans include testing a splice on the 30-m cable at Southwire.

Future location of splice at 30-m test site.

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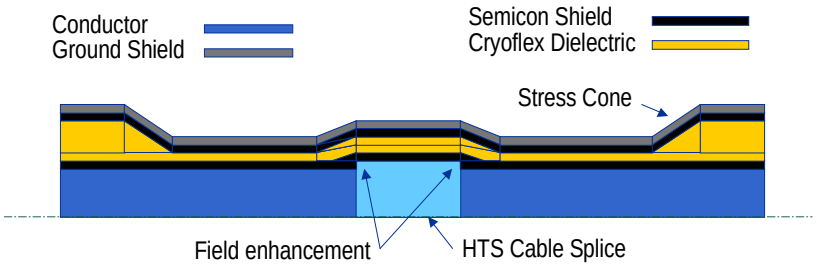
A model cable successfully tested the dielectric splice design

- 30 min. ac withstand at 2.5 x operating voltage (18 kV)
  - Partial discharge level less than 1 pC at 18 kV
- Passed ac voltage breakdown test (10 times rated)
- Passed 110 kV BIL impulse test (1.2 x 50 μs)



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Southwire

A small model cable dewar has been set up for and aging studies and partial discharge (PD)

- Dedicated system for aging studies and PD.
- Automated high pressure LN2 fill system installed
- An innovative partial discharge system has been developed for model cable aging studies
  - Used to isolate PD signals from cable test region and stress cones
  - Conventional PD detectors connected to HV bus have difficulty locating the source of PD

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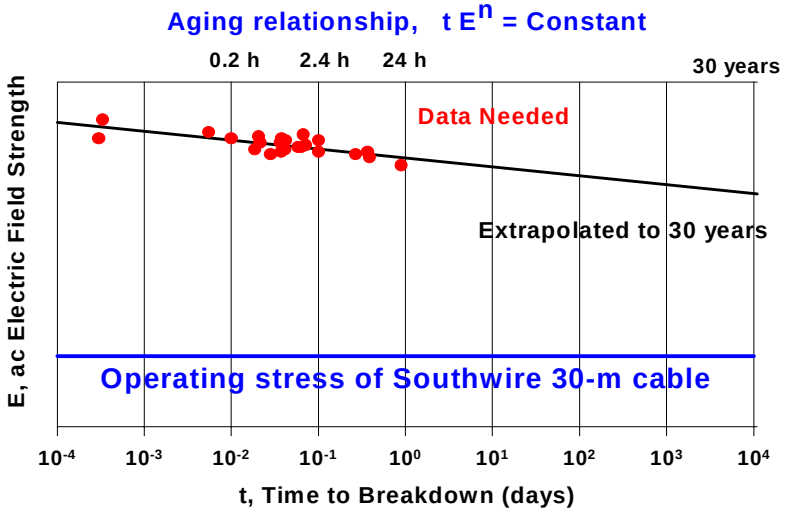
Southwire

Cryogenic dielectric model cable aging studies are determining cable lifetime



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Southwire

ORNL FY 2000 Performance

FY 2000 Plan

- Assist Southwire with the final construction, installation, checkout, testing, and operation of the SPI 30-m, 3-phase HTS cable.

FY 2000 Performance

- 30-m Cable Demonstration
  - New cable termination design improved performance
  - Heat load of HTS cable system estimated during operation
  - Voltage withstand test verified cable dielectric system and cable capacitance was measured
  - Dc load current tests tested conductors and cryogenic system operation off-line
  - Dc V-I testing verified health of main and shield cable conductors and measured end-to-end resistances (11/99 & 6/00)
  - Review of operational data has shown ways to improve system performance.

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ORNL FY 2000 Performance

FY 2000 Plan

- Conduct cable bending and short circuit tests on the 5-m cables.
- Continue cryogenic dielectric aging tests.

FY 2000 Performance

- Bent 5-m cable and tested dielectric - passed
- Successful short-circuit tests of 5-m cable, no degradation at 15 kA
- Impulse tested cable #2 and the terminations
- Measurements suggest dielectric “n” value is in acceptable range
- 30-m cable operating electric stress is very conservative

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ORNL FY 2000 Performance

FY 2000 Plan

- Extend HTS cable capability in partnership with Southwire researchers by:
  - developing a cable splice,
  - improving the cable cryostat cryogenic insulation

FY 2000 Performance

- HTS Cable Component Development
  - have designed and fabricated a 5-m cable with a splice
    - developed and successfully tested model dielectric tape splice
    - will test 5-m dielectric cable splice next month at ORNL
  - design improvements to pressurized termination:
    - heat loss reduced
    - more robust to ambient conditions
  - initiated collaboration with NASA Kennedy Space Center Cryogenics Test Bed on low thermal loss, flexible cryostat

Change in Plans During FY 2000

FY 2000 Plan

- Deferred due to utility interest in applications at distribution voltages and high currents.
  - design a cable termination for higher operating voltages, and
  - examine cryogenic dielectric system requirements for higher voltage HTS cables

FY 2000 Performance

- Added
  - YBCO quench and stability studies were initiated

ORNL FY 2001 Plans
Oct. 1, 2000 to Sept. 30, 2001

- **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.**

Technology 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 2000 progress is evidence of well functioning team.**
  - **5-m cable research at ORNL.**
  - **30-m cable installation at Southwire**
  - **30-m cable testing and operation at Southwire**

Technology 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.**
  - **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.**

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Technology Integration - Publications

- **Two papers were presented at "1999 Cryogenic Engineering and International Cryogenic Materials Conference," July 12-16, 1999, Montréal, Québec, Canada**
  - **5-m Single-Phase HTS Transmission Cable Tests**
  - **Cryogenic System For A High Temperature Superconducting Power Transmission Cable**
- **Four technical presentations/papers will be presented at the "Applied Superconductivity Conference, ASC 2000", in September 2000**
  - **Development and Testing of HTS Cables and Terminations at ORNL**
  - **Fault Current Tests of HTS Cable and Tape**
  - **Installation And Operation Of The Southwire 30-Meter High-Temperature Superconducting Power Cable (Invited Paper)**
  - **Practical AC Loss and Thermal Considerations for HTS Power Transmission Cable System**
- **ORNL Annual Report is available on the web**
  - **www.ornl.gov/HTSC/HTSPC-11.pdf**

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Summary

- **FY 2000 goals have been achieved**
  - **30-m HTS cable has been installed**
  - **30-m HTS cable is in operation**
- **ORNL has provided a breadth of expertise to Southwire**
  - **4 ORNL research division's have contributed this year**
  - **Have experimented with BSCCO tapes, 1-m, 5-m, 30-m cables, dielectric model cables, splice cables, cable joints, cryogenic systems**
  - **Have conducted a variety of tests: critical current, ac losses, ac withstand, voltage breakdown, impulse strength, partial discharge, short-circuit, dielectric aging, cryogenic heat loads**
- **The difficult transition from laboratory testing to a practical field application has been completed.**

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Southwire

World's First Industrial Field Test of HTS Cable Delivers Power To Industrial Customer