

# High Temperature Superconducting Cable



2000 Annual Peer Review

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



July 17-19, 2000  
Washington, DC



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



A Superconductivity Partnership Initiative (SPI) Project

## 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

- |                    |               |  |                  |
|--------------------|---------------|--|------------------|
| • <b>Southwire</b> |               | • <b>Oak Ridge National Laboratory</b> |                  |
| John Armstrong     | Steve Owens   | Glenn Barber                           | Randy James      |
| Zack Butterworth   | Ron Martin    | Larry Baylor                           | Winston Lue      |
| Hugh Butler        | Sammy Pollard | Bob Benson                             | Patrick Martin   |
| Randy Denmon       | David Reece   | Jonathan Demko                         | Marshall Pace    |
| Dwain Gosdin       | Mark Roden    | Alvin Ellis                            | Vaughn Patania   |
| R. L. Hughey       | Uday Sinha    | Paul Fisher                            | Isidor Sauers    |
| Gary Hyatt         | Jerry Tolbert | Chris Foster                           | Bill Schwenterly |
| Donnie Kittle      | Lewis Waters  | Mike Gouge                             | Dennis Sparks    |
| Kim Knuckles       | Nick Ware     | Robert Hawsey                          | John Stovall     |
| David Lindsay      |               |  |                  |

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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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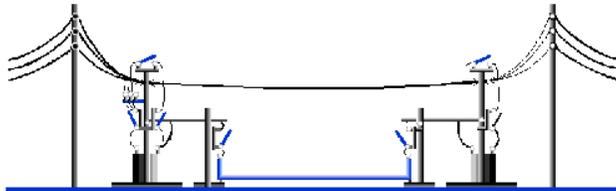
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## SPI Project Goal (February 1997)

### 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.



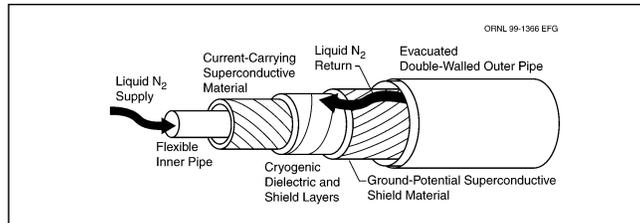
- Operation of 30-meter three-phase cable in **FY 2000** at Southwire Headquarters in Carrollton, Georgia.

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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**

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## 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 |

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### 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



**PHPK, Inc.**

← 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



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## Dedication Ceremony - Feb. 18, 2000

Georgia Governor and Energy Secretary

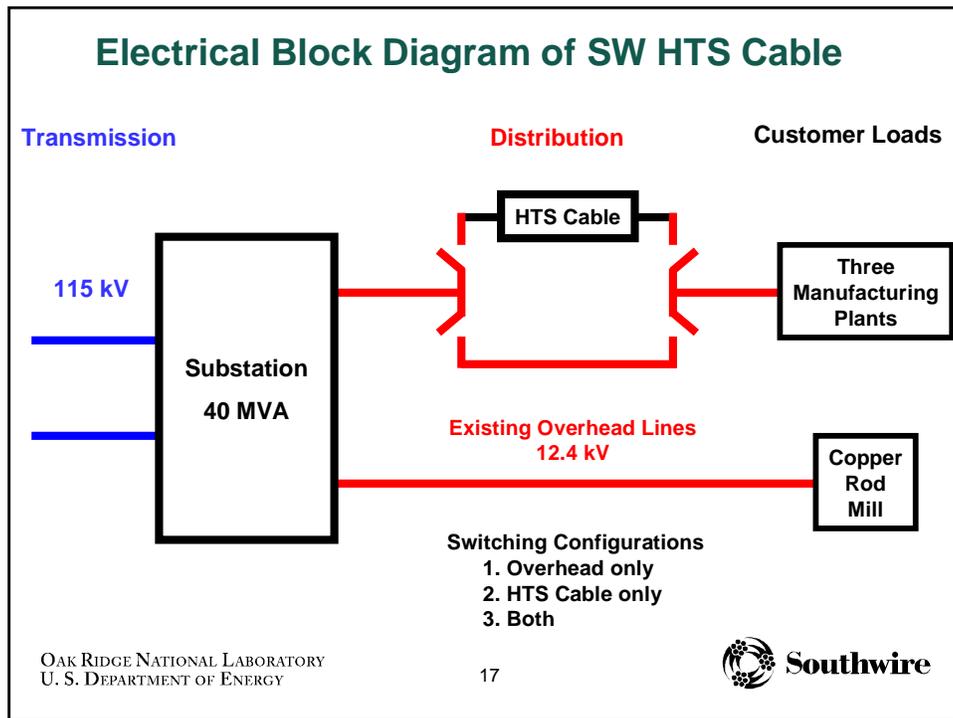


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*A Superconductivity Partnership Initiative (SPI) Project*



### 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

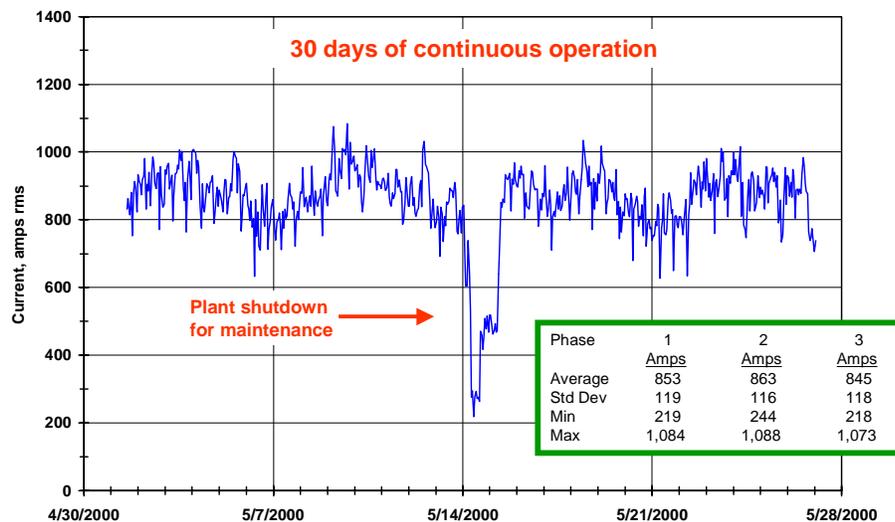


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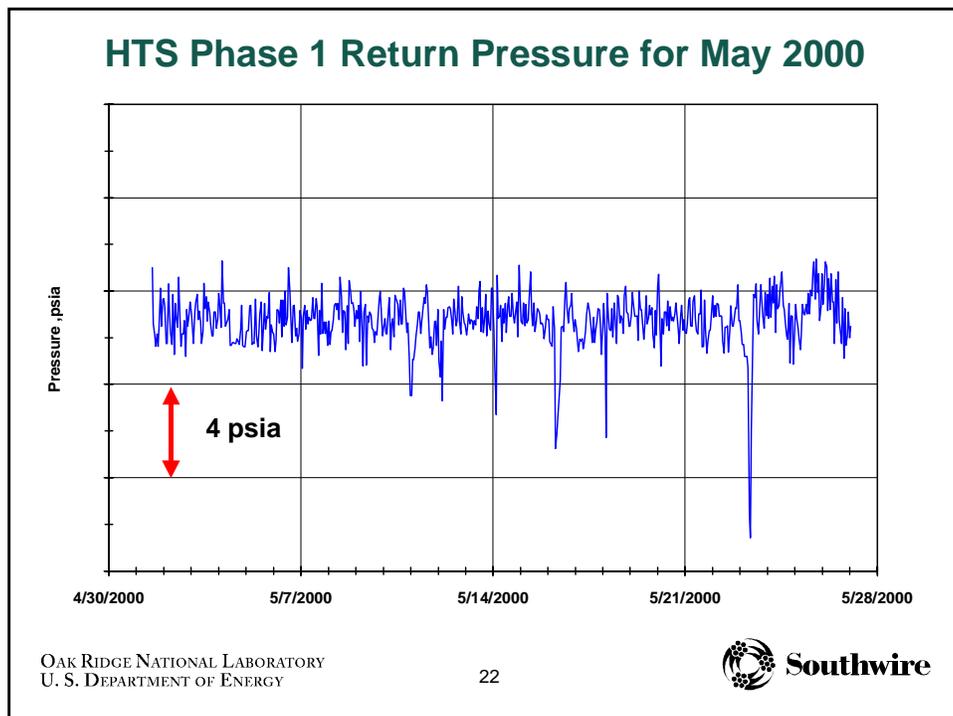
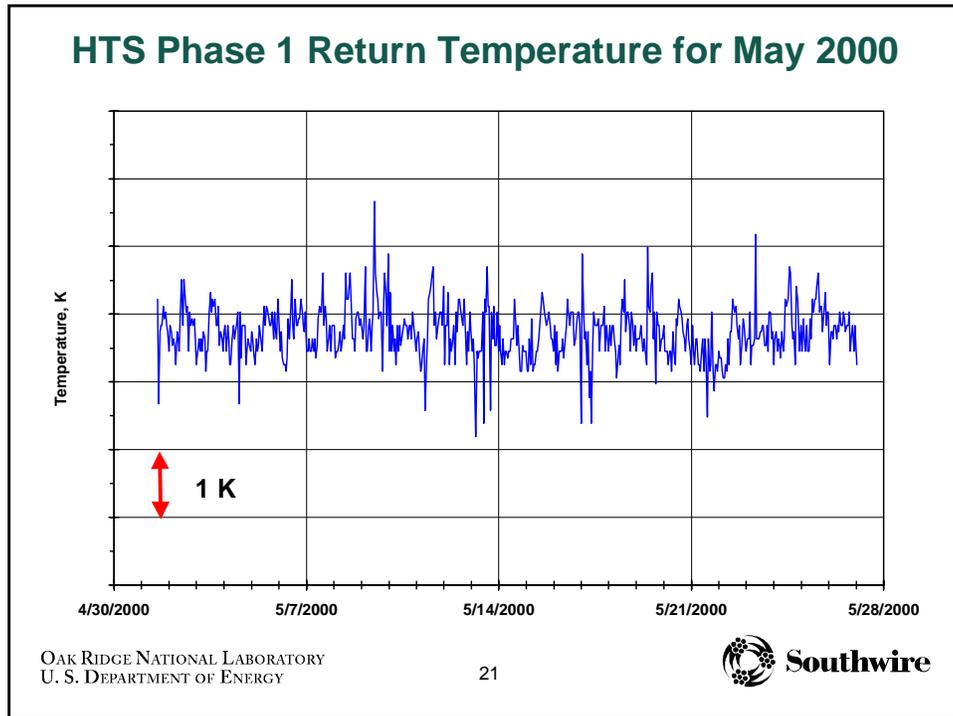
## HTS Phase 1 Current for May 2000

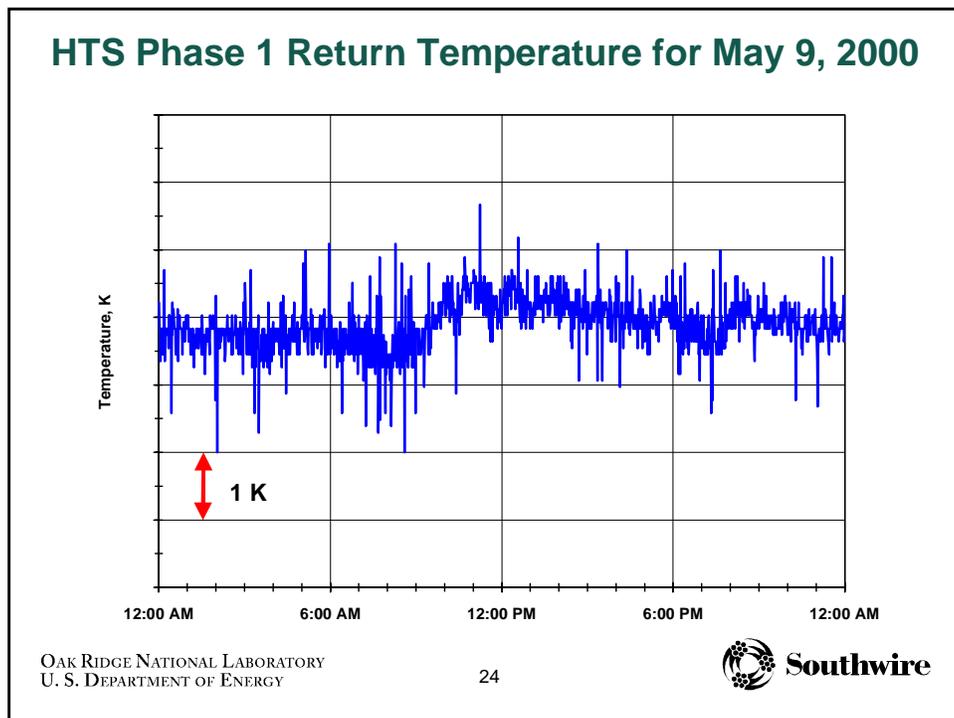
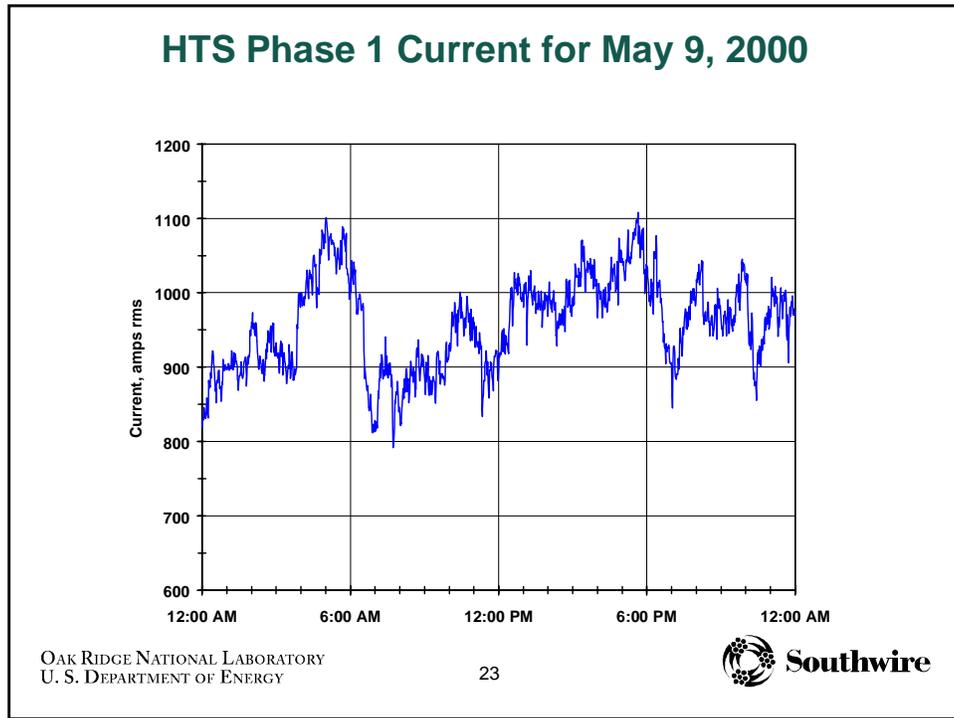


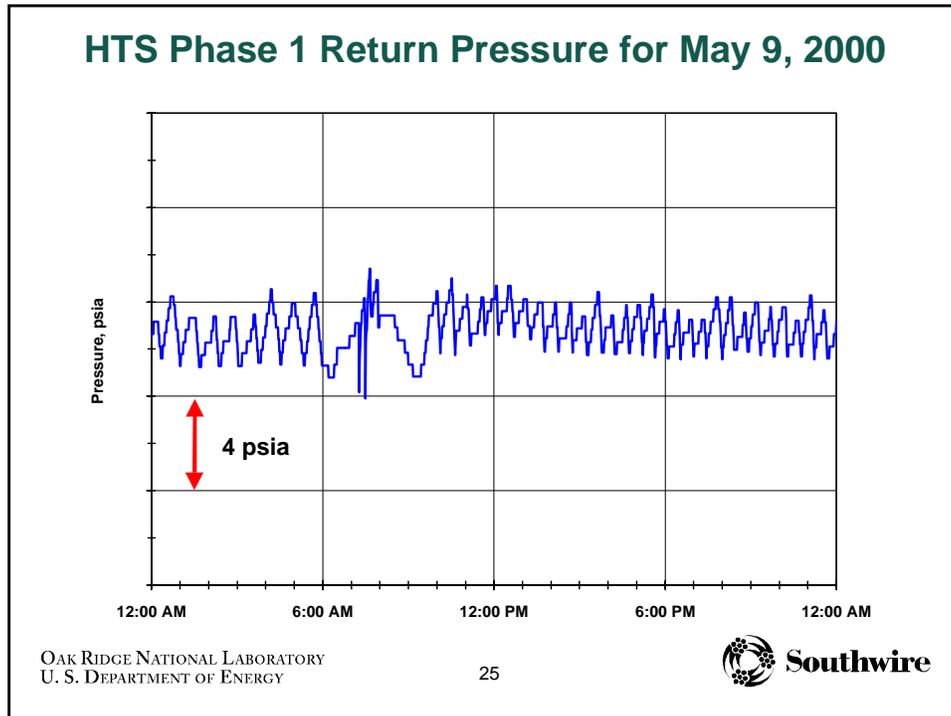
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**This field demonstration has successfully shown the utility application of superconducting cables at distribution voltages and high currents.**

• **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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  - 5-m Cable Research
  - Component Development
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- **FY 2000 Performance / FY 2001 Plans**
- **Technology Integration**
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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
<b>Measured</b>	<b>1.815</b>	<b>1.739</b>	<b>1.265</b>
<b>Calculated</b>	<b>1.778</b>	<b>1.778</b>	<b>1.207</b>
<b>Difference</b>	<b>2.1%</b>	<b>-2.2%</b>	<b>4.8%</b>

### Inductance - nH / m

	Phase 1	Phase 2	Phase 3
<b>Calculated</b>	<b>31.4</b>	<b>31.4</b>	<b>38.2</b>

**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.

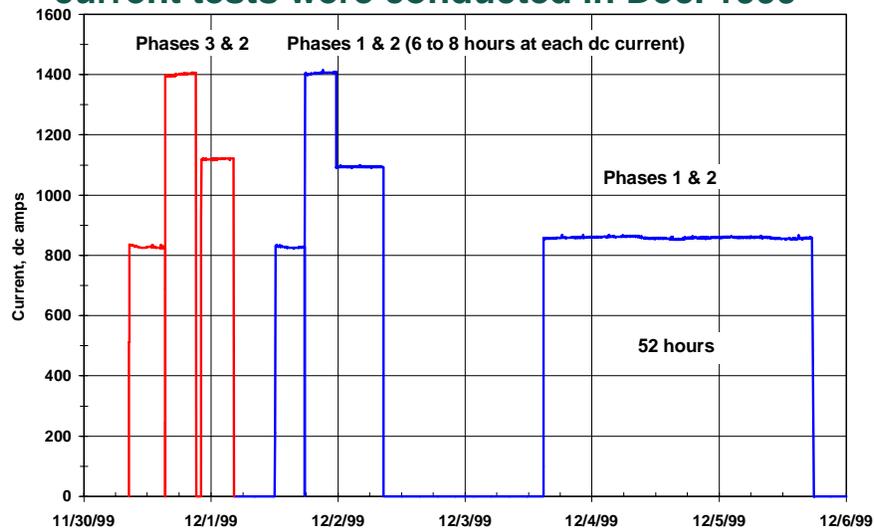


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### Off-line average, rated, and emergency dc load current tests were conducted in Dec. 1999

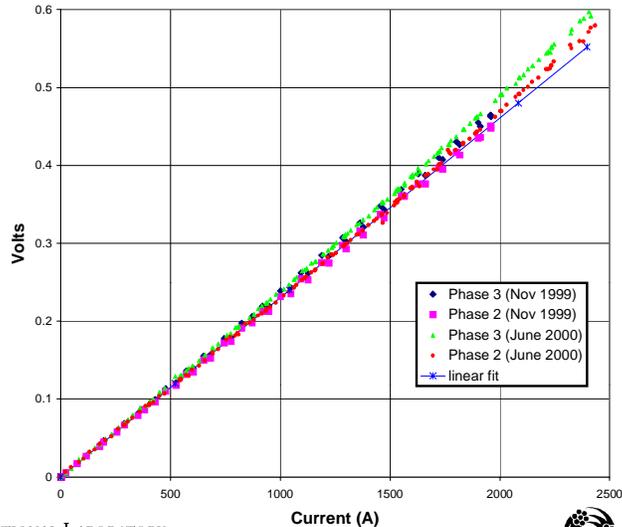


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### DC V-I curves in Nov. 1999 and June 2000 indicate no change in 30-m cable performance

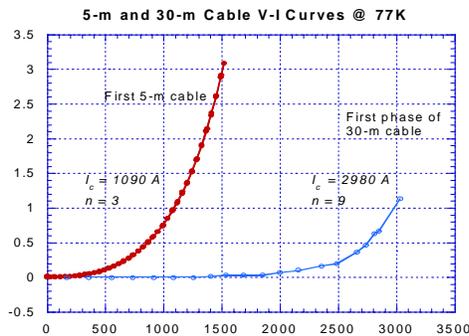


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### Testing of 30-m HTS Cables at Carrollton



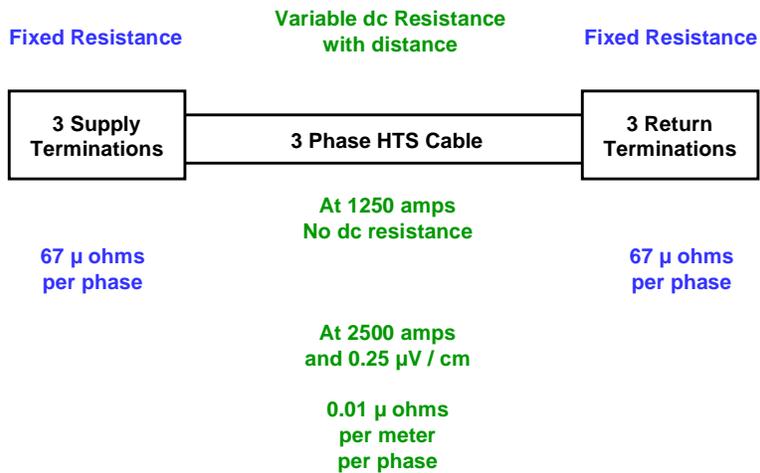
- Testing was performed on the power and shield conductors in the cable cryostat with boiling liquid nitrogen cooling.
- Performance was as expected from the individual tape properties.

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## End-to-end cable dc resistance has been measured

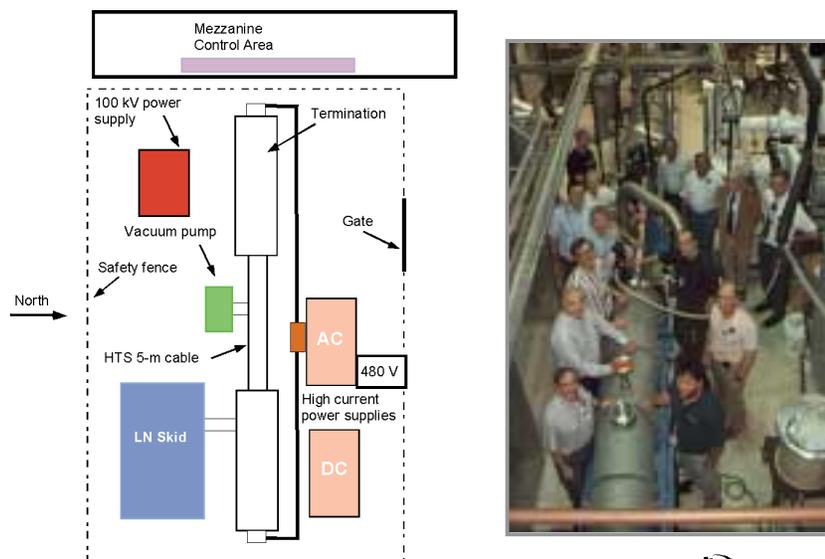


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## 5-m cable research facility at ORNL



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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



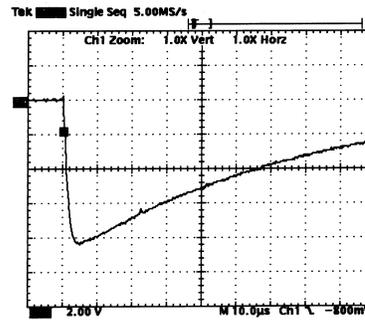
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### 5-m HTS cable #2 and terminations were impulse tested to ~90 kV

- 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



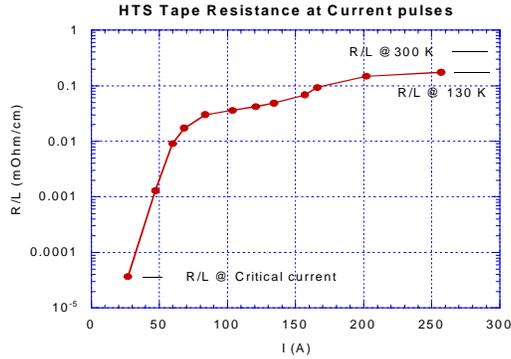
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## Over-current testing of single HTS tapes

- 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

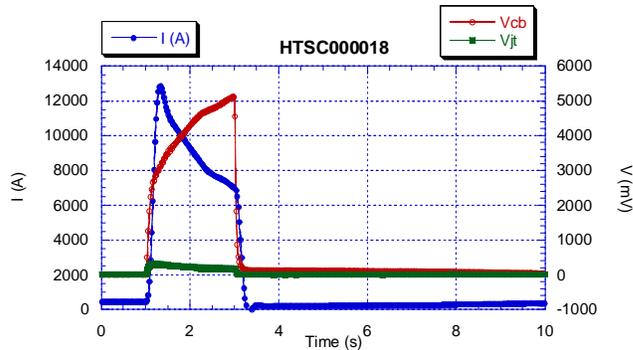


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## Successful short circuit (10x) test of 5-m HTS cable



- 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.

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## 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

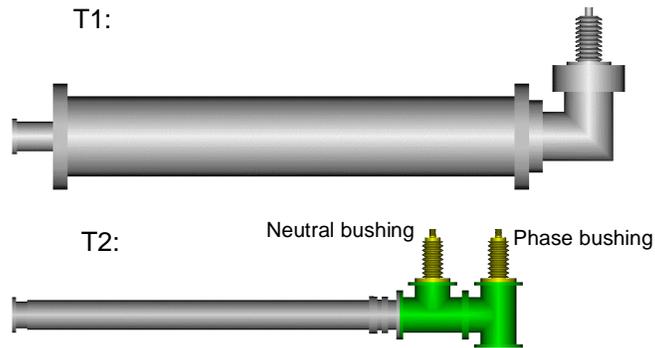
- An innovative new termination has been developed and refined
  - the design uses liquid / gaseous nitrogen at few to 10 bar pressure
  - the inner and shield conductor cold bushings are eliminated
  - the vacuum pumping system, system pump-down and leak checking from the previous vacuum design T1 are 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.

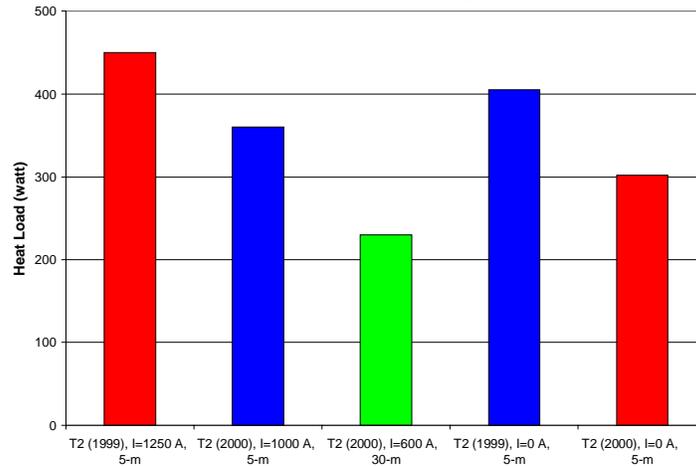
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## Heat load of terminations has been reduced

Each termination has two leads - phase and neutral

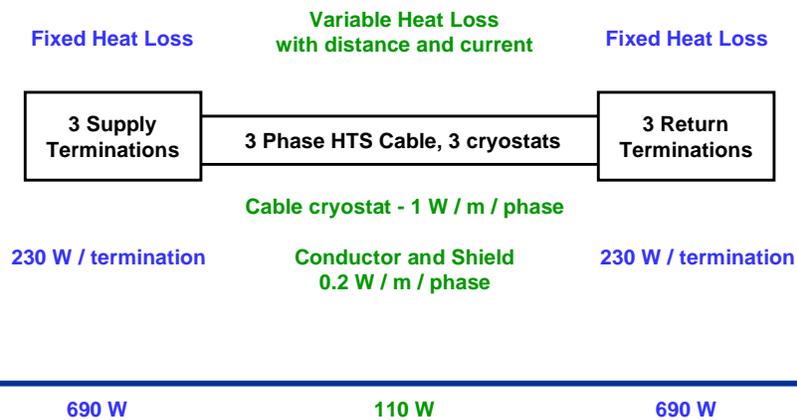


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## Cable system heat loss has been measured



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.

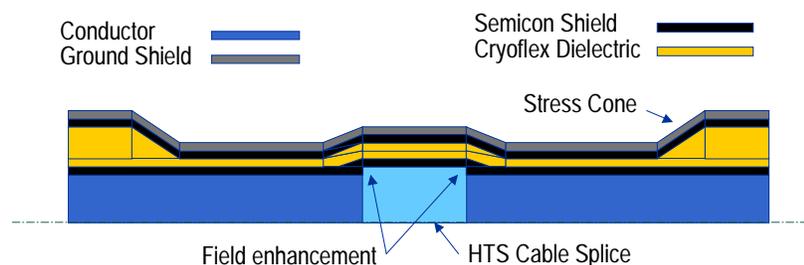
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## A model cable successfully tested the dielectric splice design

- 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  $\mu$ s )



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## 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



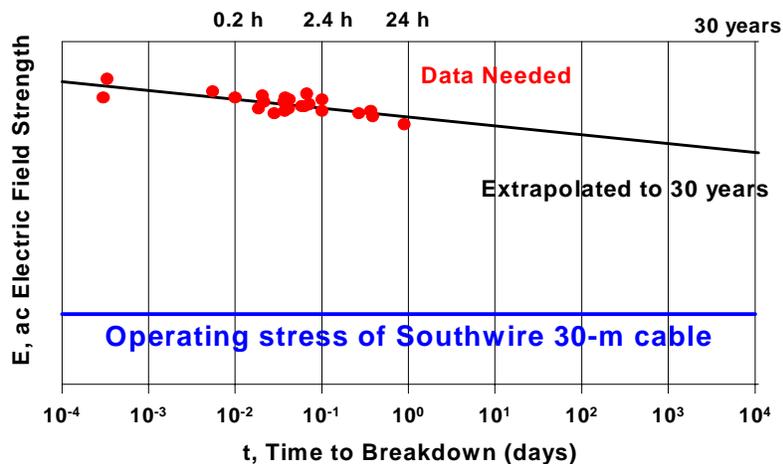
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## Cryogenic dielectric model cable aging studies are determining cable lifetime

Aging relationship,  $t E^n = \text{Constant}$



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## 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

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## 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

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## 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.**

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## 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

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## 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](http://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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## World's First Industrial Field Test of HTS Cable Delivers Power To Industrial Customer



*A Superconductivity Partnership Initiative (SPI) Project*