Status of Field Tests of HTS Electric Power Applications in the USA

Presented to Furukawa Electric Company

Nikko City, Japan

by

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*Managed by Lockheed Martin Energy Research for the U.S. Department of Energy under Contract DE-AC05-96OR22464

Outline

- **Introduction**
- **Status of HTS Wire Development in USA**
- **Field Tests Involving Oak Ridge National Laboratory using BSCCO Tapes**
  - Southwire 30-m Cable Project
  - Waukesha 5-MVA Transformer Project
- **Completed: Fault Current Controller**
- **3 New Projects Initiated by the U.S. DOE this year**
- **Conclusion**

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U.S. Department of Energy Superconductivity Program Goals

- **Performance**
  - Develop HTS wires with 100 times capacity of conventional copper/aluminum wires
  - Design broad portfolio of electric equipment based on HTS
    - 50% size of conventional units with same rating
    - 50% reduction in energy losses compared to conventional equipment
- **Cost**
  - Wire cost $0.01/ampere-meter
  - Equipment premium cost payback (efficiency savings) in 2 - 5 years of operation
  - Equipment total cost payback during operating life
- **ALL research involves High-Temperature Superconductors**

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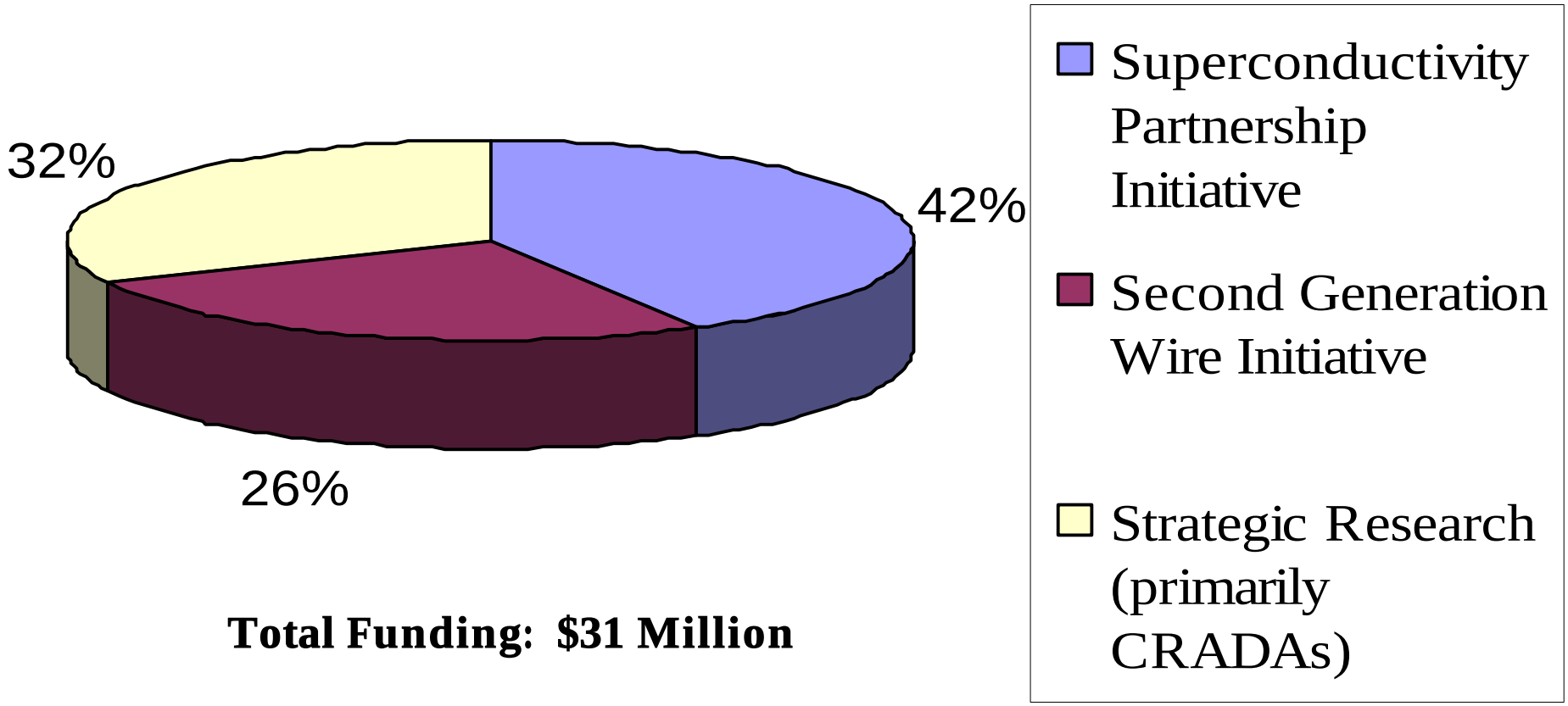
Department of Energy
FY 2000 Funding Breakdown



Total Funding: $31 Million

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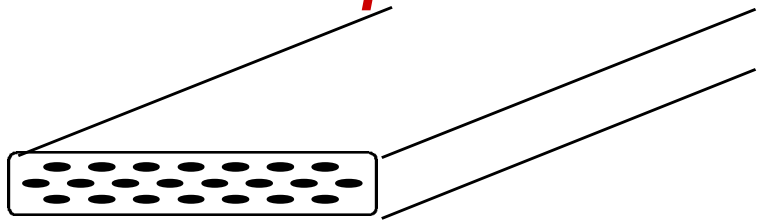
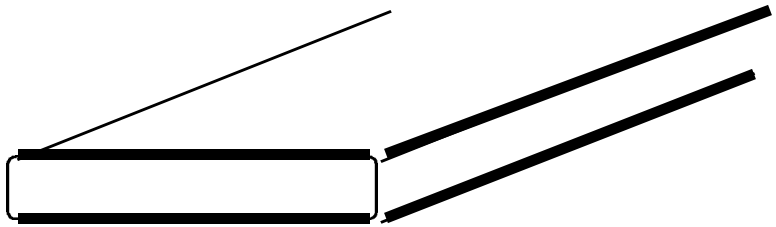
HTS Wire Technologies

"1st Generation": Bi-based powder-in-tube



- *pre-commercial level of development*
- *Long lengths with reproducible properties*
- *High field applications limited to low temperature (<30K)*

"2nd Generation": Biaxially aligned YBCO on metal tapes



- *Enabling properties for operation at liquid nitrogen temperatures*
- *Early development, only short lengths*
- *Unproved technology, economics, etc.*

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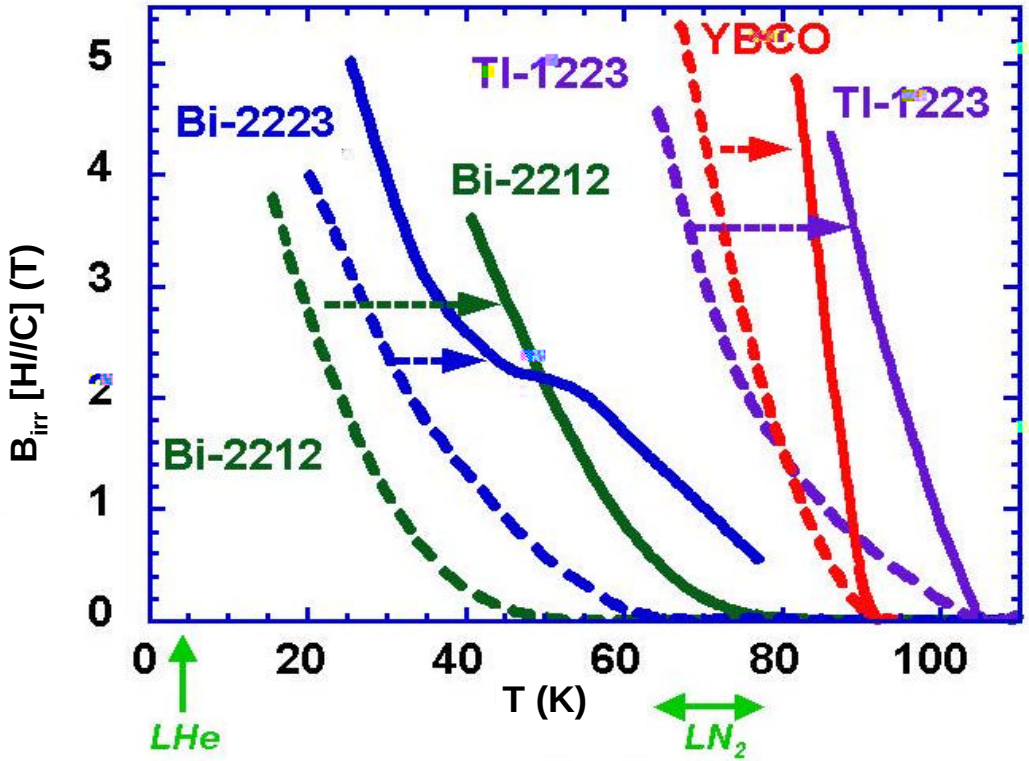
BSCCO-2223 Useful <30 K in Strong Magnetic Fields



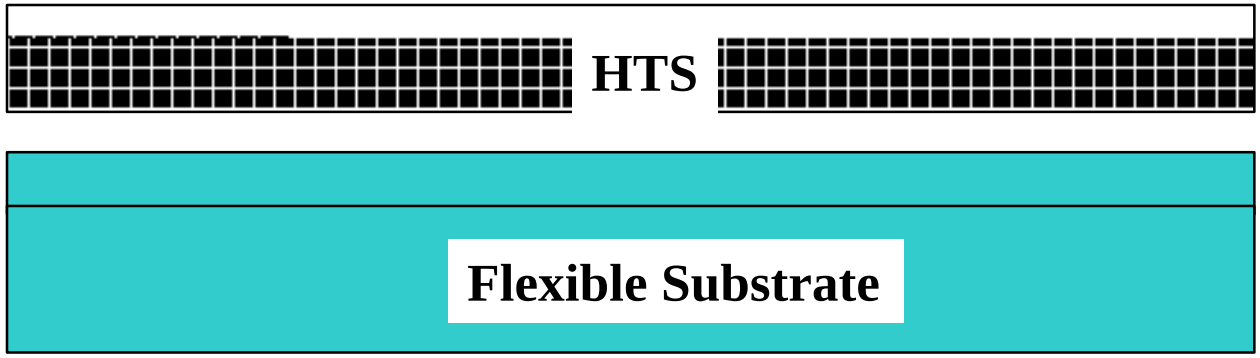
- **Critical current densities (J_c) of early $YBa_2Cu_3O_x$ (polycrystalline) samples were too low for practical applications:**
  - Polycrystalline HTS: 10^2 to 10^3 A/cm^2.
  - Epitaxial thin film on single crystal: ~10^6 A/cm^2 .

What is Needed to Obtain High J_c Flexible HTS Conductors for LN_2 In-Field Applications?

- **Need to use $YBa_2Cu_3O_x$.**
- **HTS on flexible substrate.**
- **Out-of-plane AND in-plane texturing of HTS.**

Present Approach:

- **Deposition of Epitaxial HTS on Textured substrates.**



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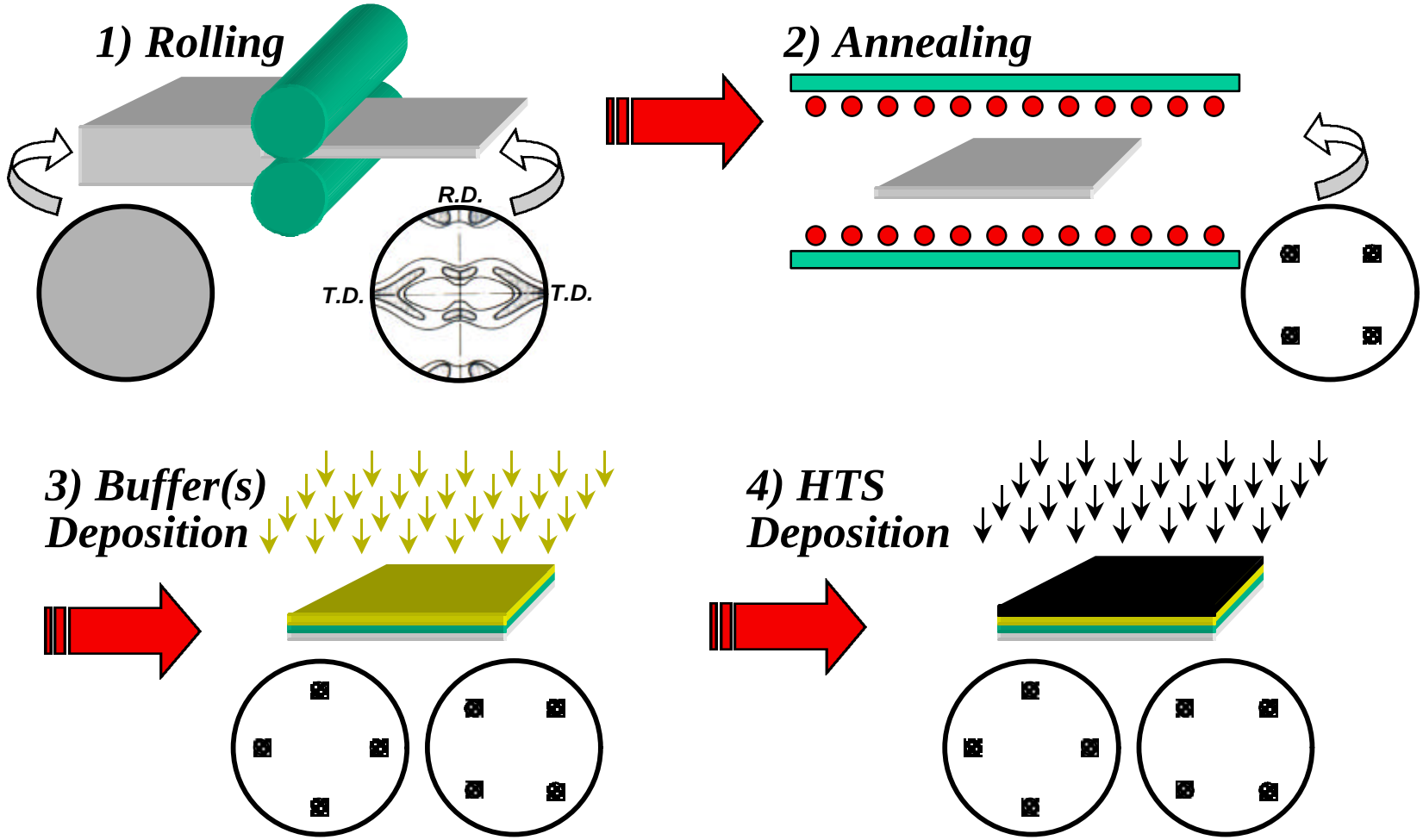
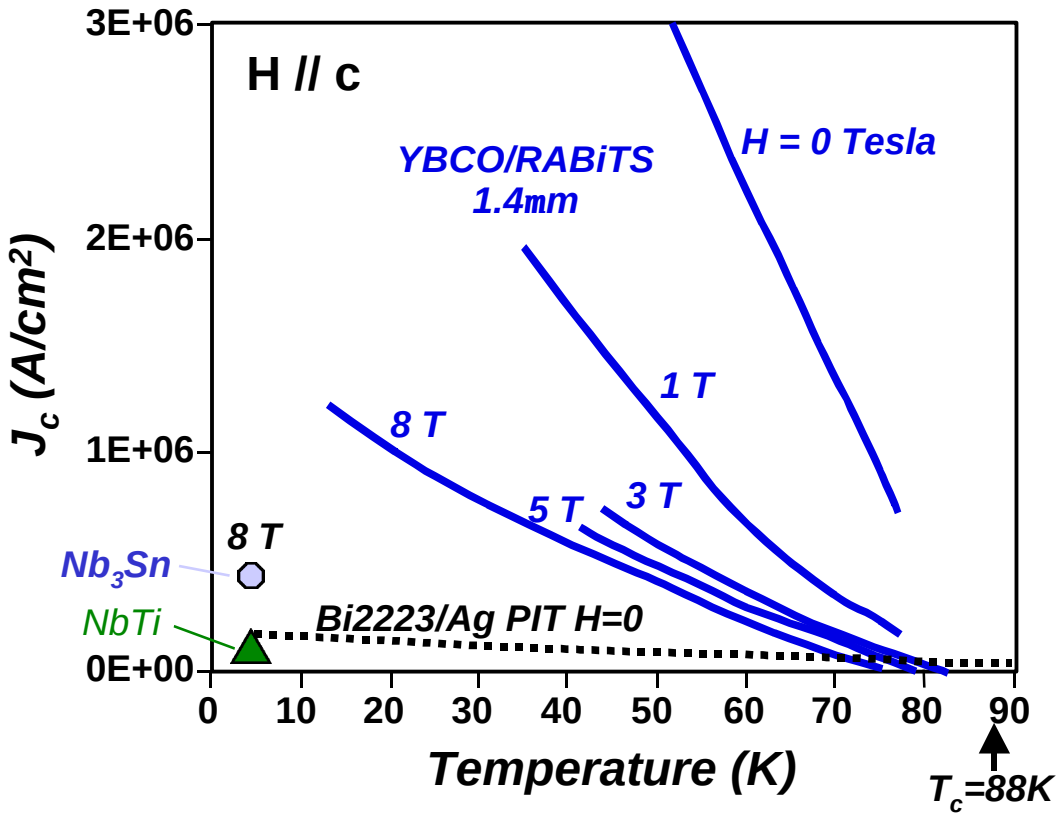
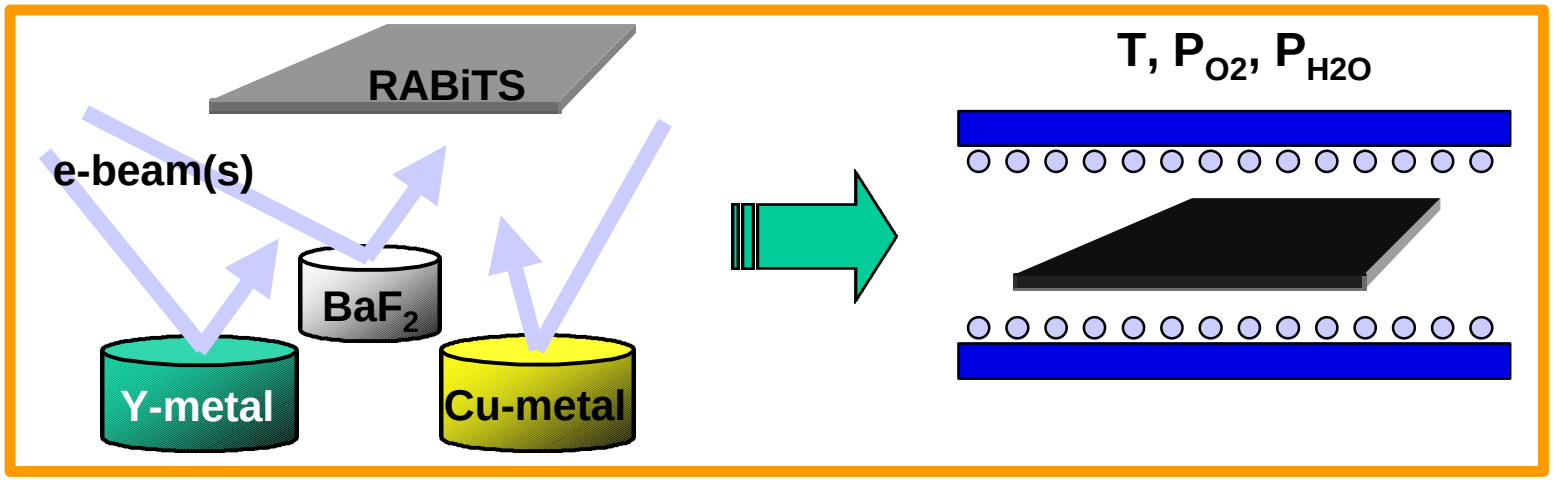
Rolling-Assisted Biaxially Textured Substrates



YBCO/RABiTS Show Large Enhancements as Temperature Decreases



Ex-situ Formation of YBCO by BaF_2 Precursor Offers Many Advantages



- **Advantages of ex-situ process:**
  - Deposition and formation steps are separated
  - Wider processing window - combination of temp, O_2 and H_2O partial pressures
  - "Adjustment" of precursor stoichiometry possible
  - Batch process.

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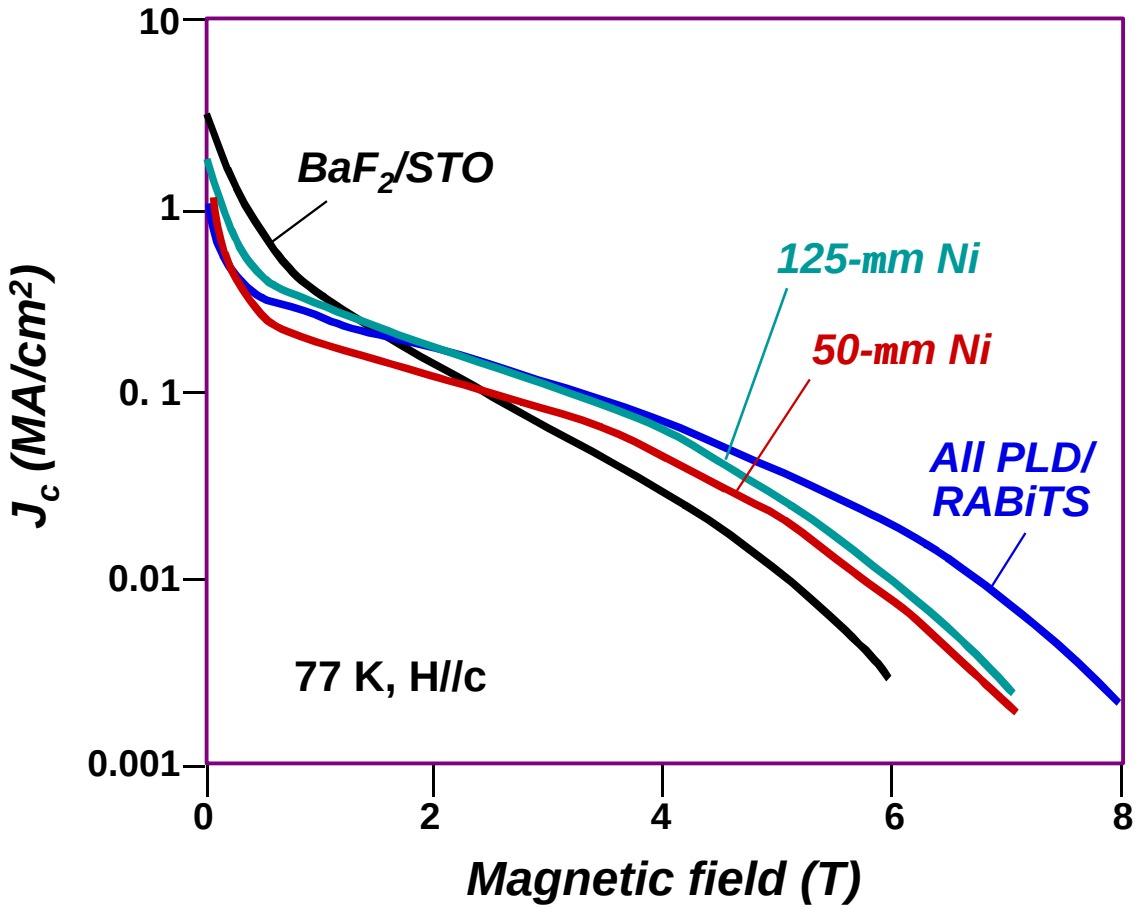
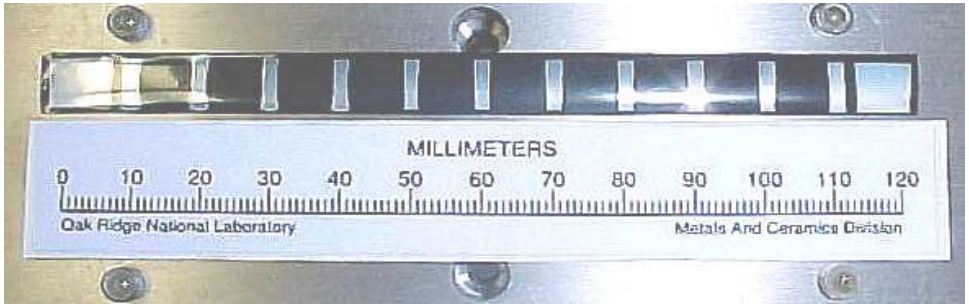
J_c of YBCO/RABiTS Processed by the BaF_2 Precursor Method is as Good as YBCO by PLD



YBCO Conductor Deposited by All-Moving Vapor Deposition and BaF_2 Conversion is Black, Shiny, and Uniform

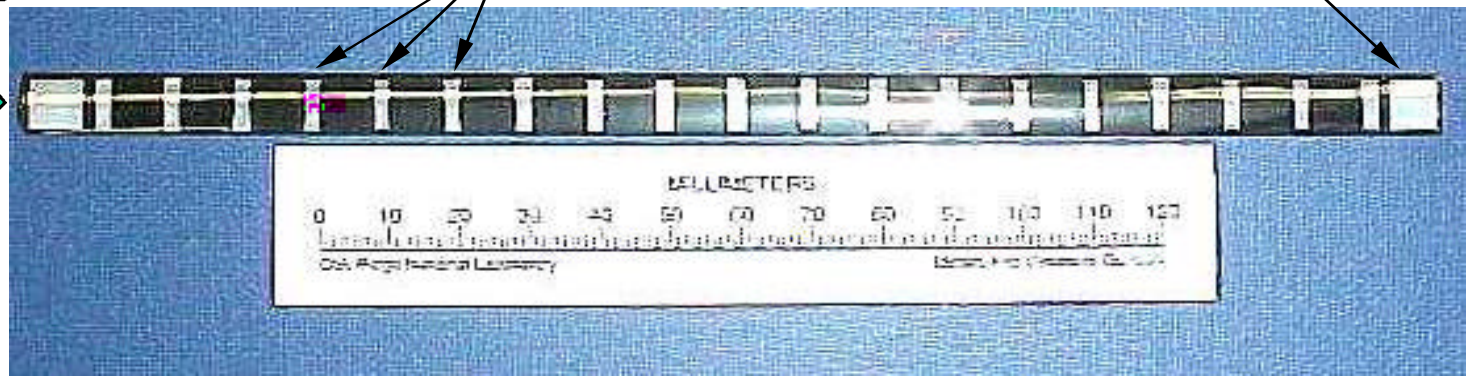
~12 cm



~20 cm

voltage taps @ 1 cm

current tap



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Private Companies to Scale Up YBCO Coated Conductors in the U.S.

Company	YBCO Deposition Approach	Substrate
3M	Reactive co-evaporation (in-situ and ex-situ processes)	IBAD, RABiTS
Oxford Superconducting	PLD (research)	RABiTS
MicroCoating Tech.	CCVD (open atmosphere CVD), also sol-gel*	RABiTS
EURUS Technologies	sol-gel*, others	RABiTS
American Superconductor	sol-gel TFA*	RABiTS
Intermagnetics General	PLD, MOCVD	IBAD

*non-vacuum *ex-situ* YBCO formation using post-anneal

National laboratories will conduct continuous processing research at <10-m lengths in 2000

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Projected Timeline for Coated Conductor Scale-up in USA

Pre-commercial Scale-up Phase- US Industry	Year	Estimated Budget ($M) per year for each Phase		
	99 00 01 02 03 04 05 06 07 08	Commercial	Government	Total
I Continuous Processing Feasibility & 1-m lengths		8.0	8.0	16.0
II 10-m piece lengths with lab-scale demonstration		12.0	12.0	24.0
III 100-m piece lengths and field tests using YBCO conductor in SPI		TBD	TBD	TBD
IV Pre-commercial production		TBD	0	TBD

U.S. Government and industry YBCO wire research is expected to cost $16 million in 2000.

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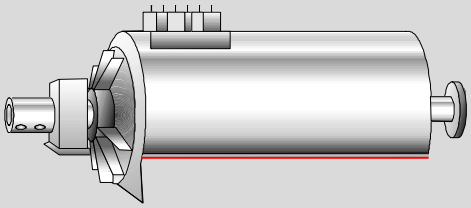
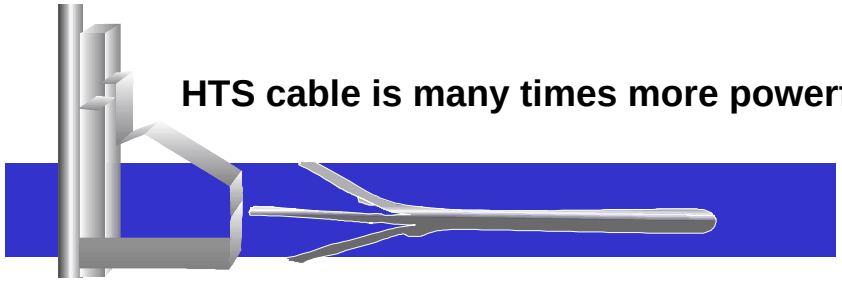
Potential to Impact Existing Technologies and Opportunities for Novel Applications

- **Significant efficiency benefits to the national electricity infrastructure.**

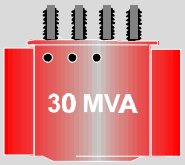


HTS motor is 50% smaller and lighter

. . .and losses are cut in half



HTS cable is many times more powerful



HTS transformers are nonflammable, less noisy, and do not use oil

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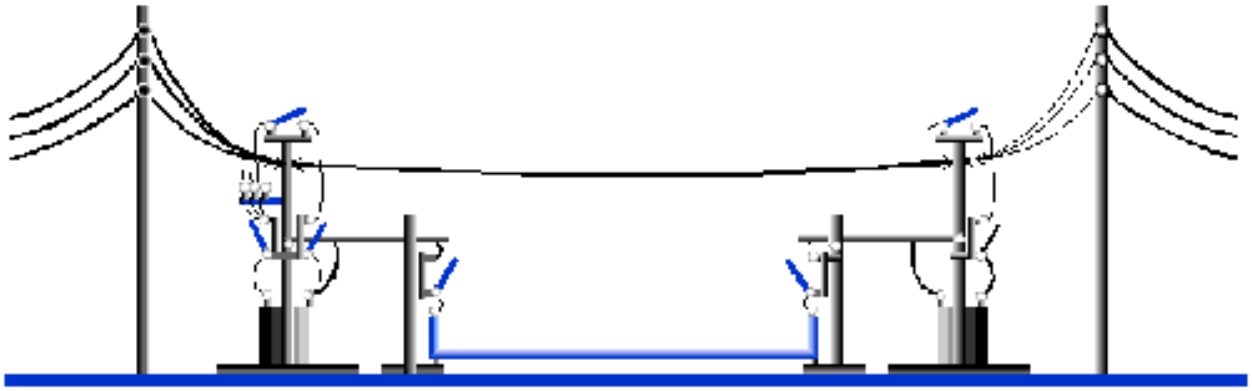
U.S. DOE Superconductivity Partnership Initiative
Project Goal: Southwire Cable
First U.S. Industrial SPI Cable Installation

- **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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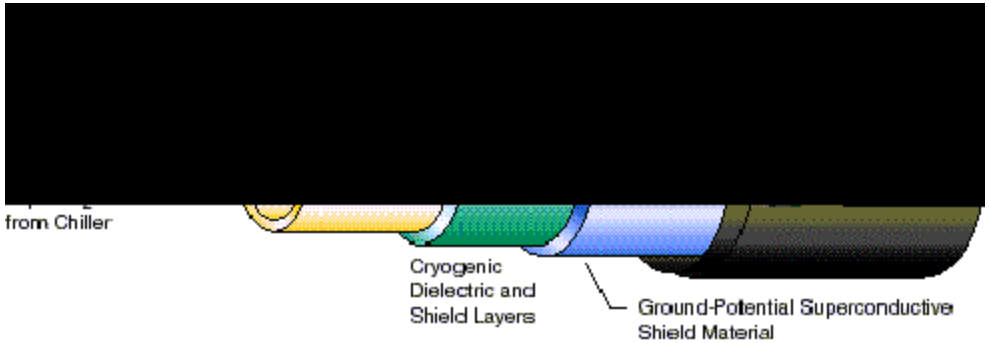
Cable Cross Sectional View



- **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

Project Participants

- **Southwire**

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

- **ORNL**

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

- **Subcontractors**
- **Consultants**
- **Electric Utility Partners (5)**

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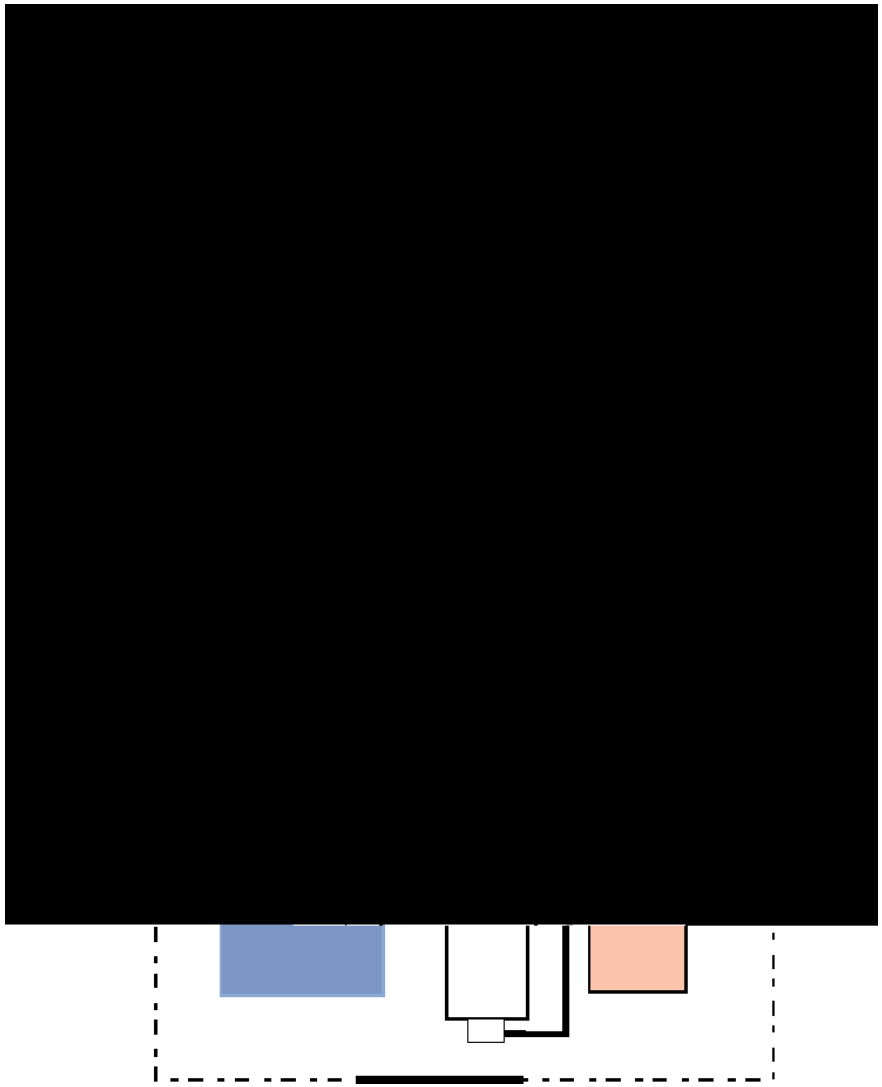
5-m Cable Research Facility at ORNL



1999 Test Program Results for 5-m HTS Cables 1 and 2

- **Have measured dc critical currents from ~72-82 K**
- **Characterized ac losses: of order 1 watt/m at operating temperature by standard electrical measurement**
- **Have tested cable integrity to 2.5 x operating voltage - 18 kV ac and ac currents up to 1400 A**
- **Have impulse tested 5-m cable #2 and terminations to 108-kV**

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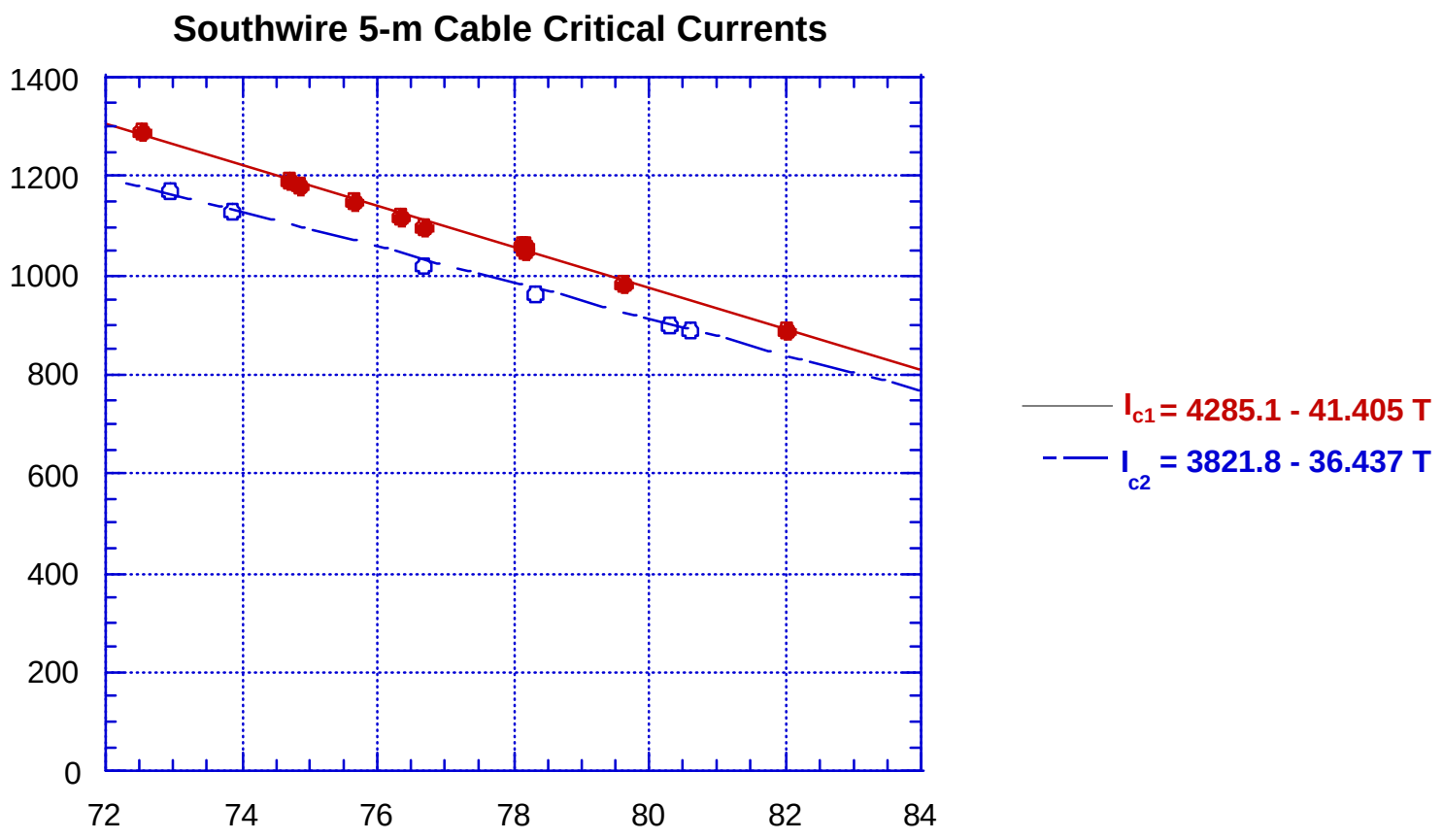
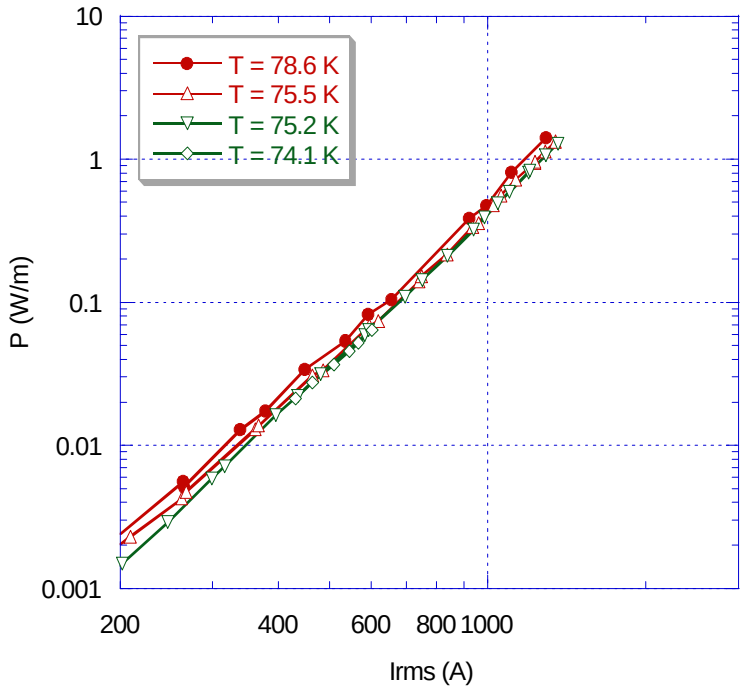
Critical Current of the HTS Prototype 5-m Cables

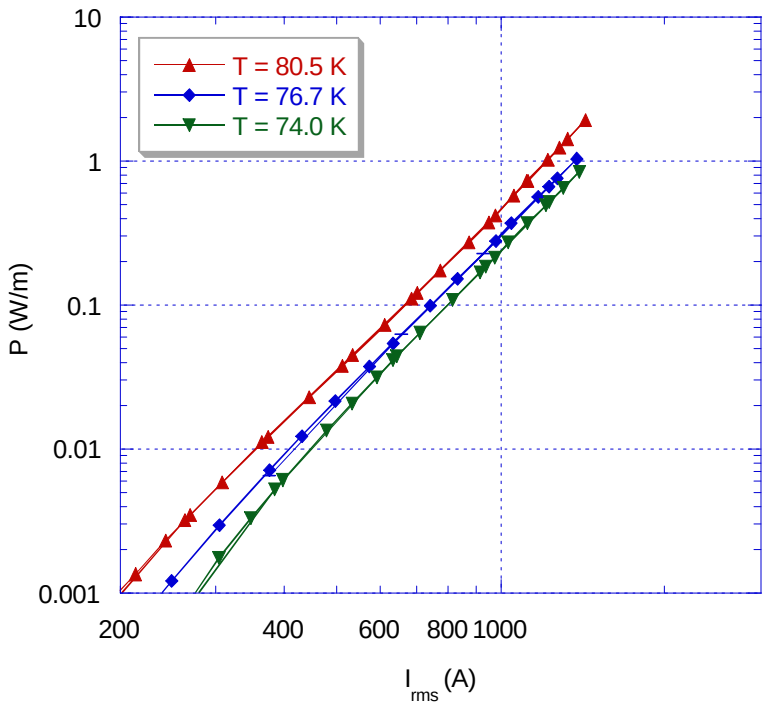


AC Losses of the 5-m HTS Cable

Cable 1

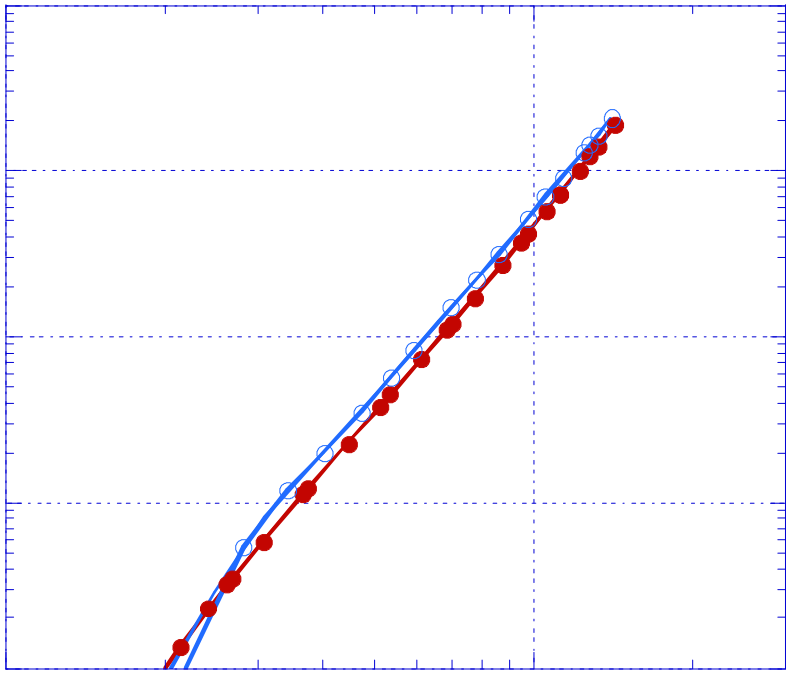


Cable 2

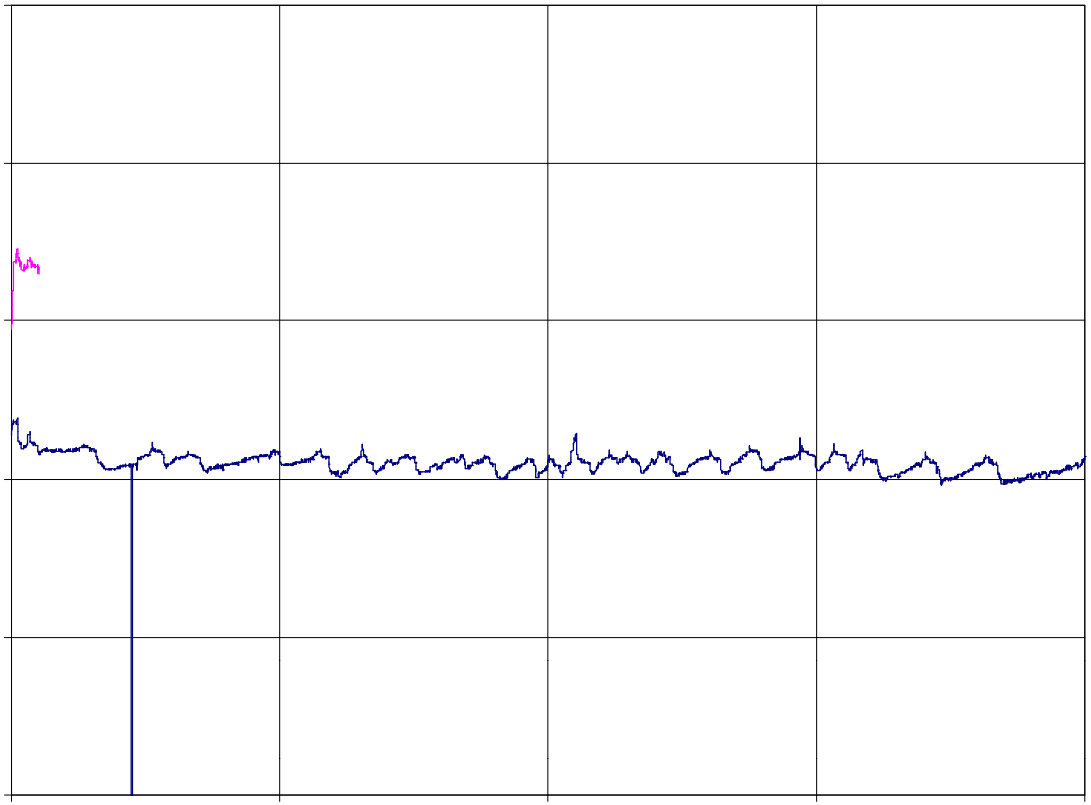


- **Loss rates of 0.8 -1.3 W/m were measured at the rated current of 1250 A rms (electrical measurement with Rogowski coil and lock-in amp)**

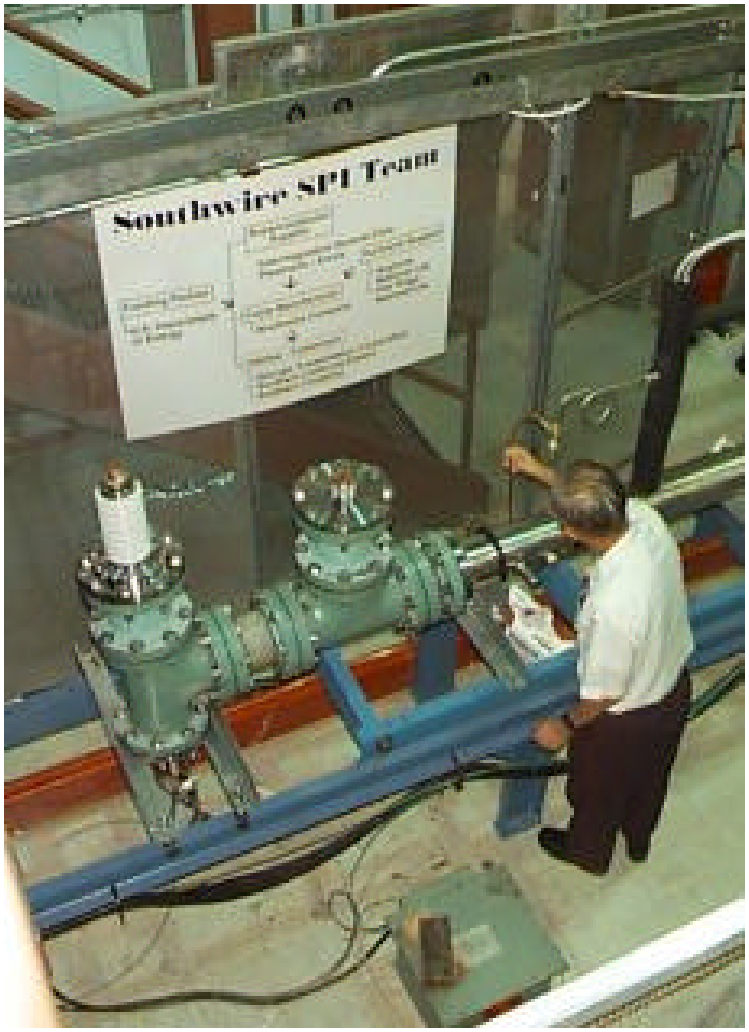
AC Losses Cable # 2: No Major Change with Time/Handling



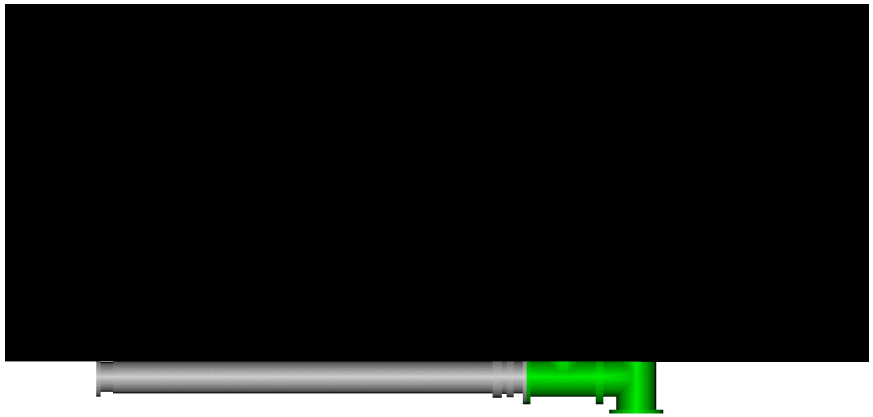
72-Hour Run: Cable #2



T2-Pressure Termination: ORNL Design



T2 is more compact than T1



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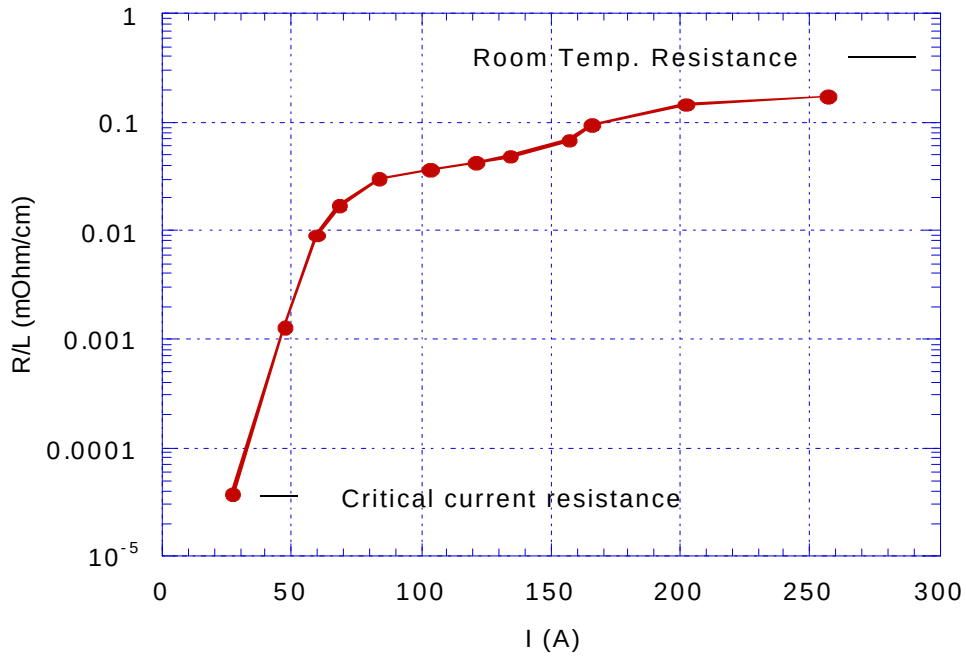
Over-Current Testing of Single HTS Tapes

- **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 x the design current (each tape @ ~120 A), the data showed that the HTS still carries a significant fraction of the total current.**



Site August 31, 1999, at Southwire

- Control House
- Switchgear ready
- Cables in place
- Nitrogen subcooler
- Overhead cables

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Site - August 31, 1999

- Solar sun shield
- Cable supports
- Nitrogen tank
- Termination carriage

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Termination Work - September 16, 1999

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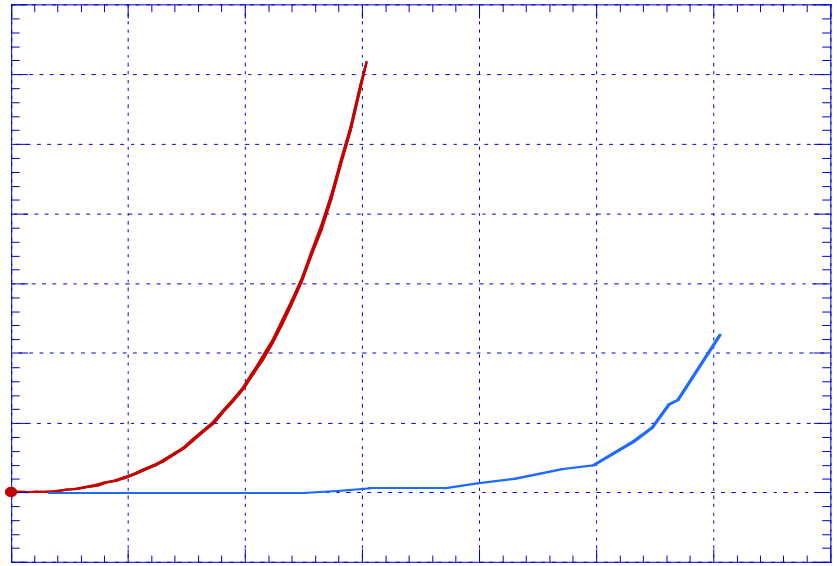
Testing of 30-m HTS Cables at Carrollton



- **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.**

Status - October 1, 1999

- Terminations complete by November 1999
- Power to site September 24, 1999
- Controls installed September 24, 1999
- Check-out all systems - November/December 1999
- Power up January 2, 2000!!!!

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HTS Transformers Will be Oil-Free

Today

Bank of 3 transformers on fire
May 1999, USA
Est. repair cost: $3 million

Tomorrow

Drawing courtesy of ASC

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Superconductivity Partnership Initiative: Waukesha Team to Demonstrate HTS Transformer

- **$6 million cost-shared project will result in installation of a 5/10 MVA, 26.4 kV HTS transformer at Waukesha's plant (on Wisconsin Electric's grid)**
  - will supply electricity to transformer manufacturing plant
  - greater efficiency, smaller unit
  - eliminates oil cooling, thus reducing fire and environmental hazards associated with oil-based systems
  - can be sited in high-density urban areas and inside buildings
  - more power per unit volume

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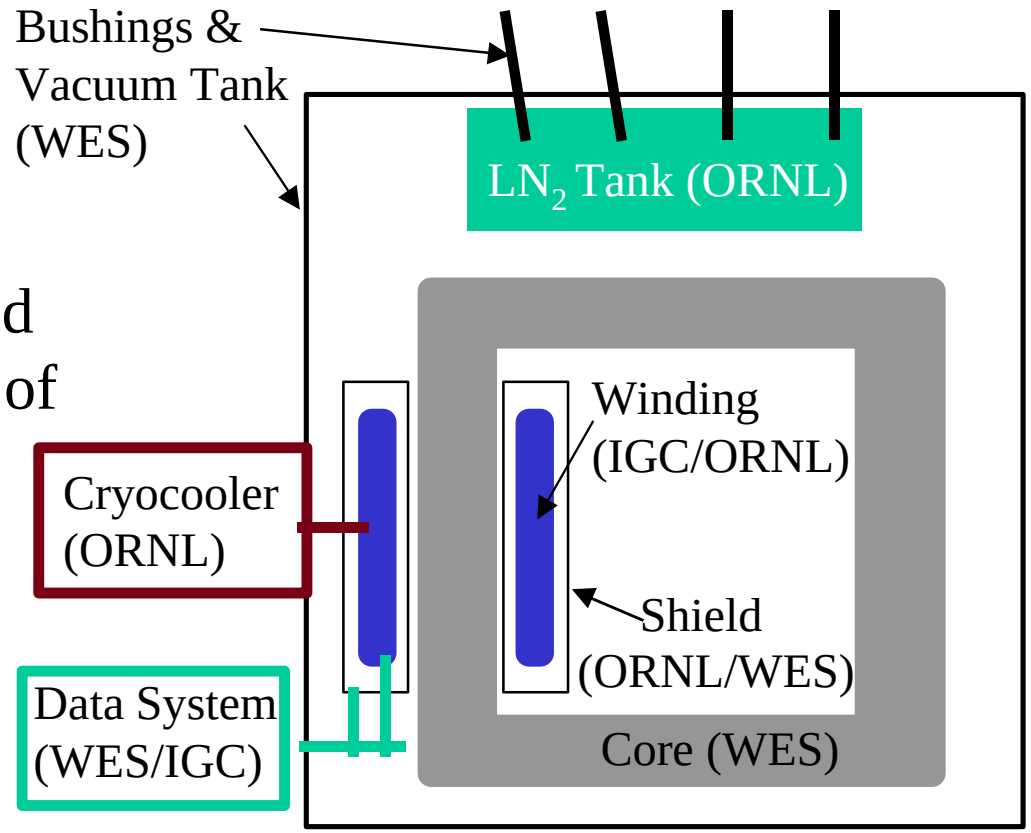
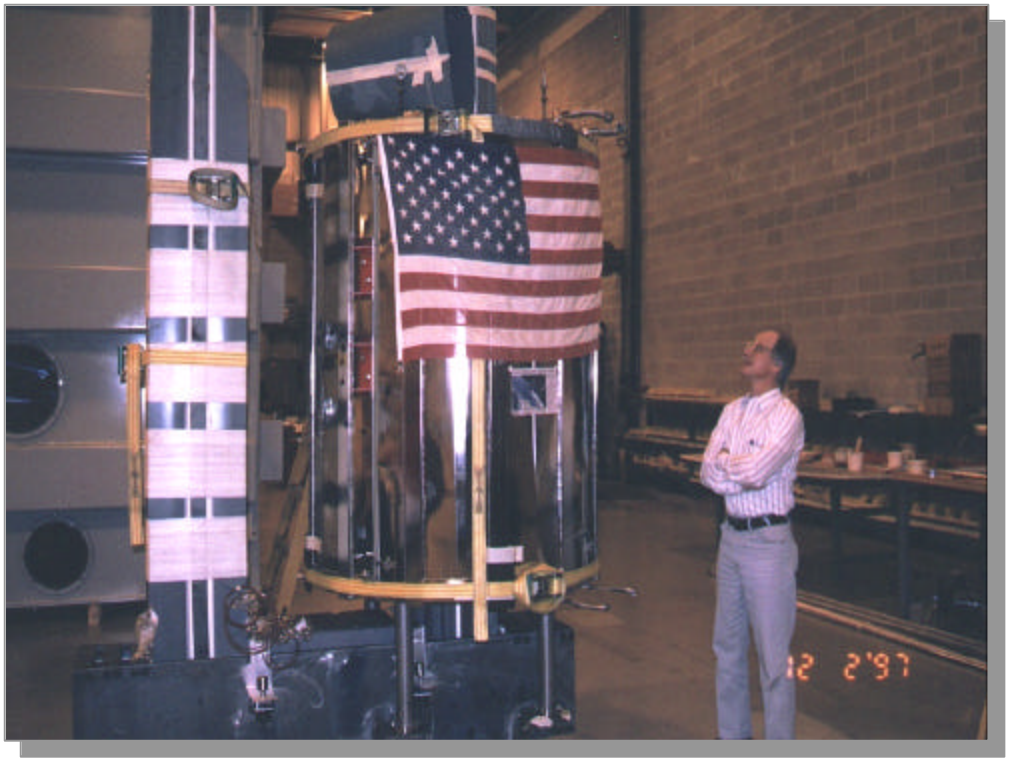
Waukesha 1-MVA Demo HTS Transformer

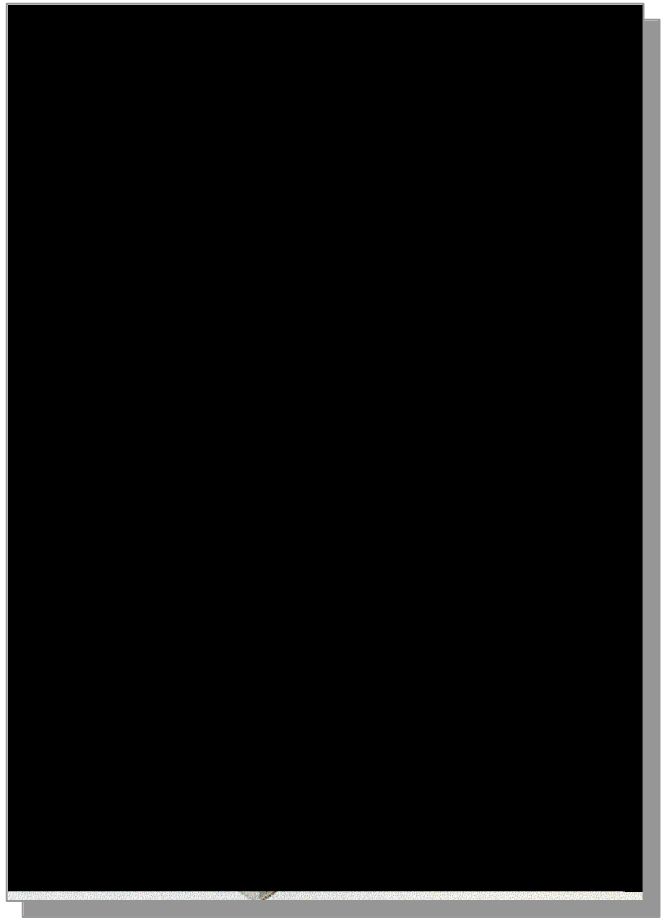
- 1-MVA, 1 phase
- HV=13.8kV, 72.5A
  LV=6.9kV, 145A
- Transformer is a test bed with core cross-section of a 30-MVA transformer
- HTS winding is cryocooled to ~25K
- Core at near room temperature



Pre-Commercial HTS Prototypes are Being Tested

Waukesha's Single-phase Demonstration HTS Transformer





3-phase HTS Transformer Concept

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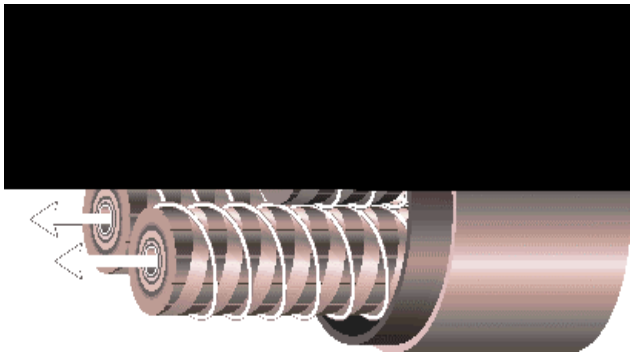
Superconductivity Partnership Initiative: Pirelli Team to Demonstrate HTS Cable

- **$5.5 million cost-shared project will result in installation of a 120-m, 3-phase, HTS transmission cable in Detroit Edison's Frisbie Substation by December 2000**
  - will replace three conventional circuits
  - can utilize existing cable conduits
  - 5x more power than conventional copper cables
  - reduces losses in electricity delivery
  - system, potentially saving over $6 billion annually nationwide



- **50-m cable successfully tested 1998 carrying 3,300 A dc.**

Superconductivity Partnership Initiative: Reliance Team to Demonstrate HTS Motor

- **$20 million cost-shared project will result in testing of a 1,000-hp HTS motor in 1999 and 5,000-hp HTS motor by 2001**
  - potential to replace large motors (>1,000 hp) for pump and fan drives for utility and industrial markets
  - more efficient than conventional motors, reduce losses by as much as 50%
  - smaller units
  - increase machinery efficiency beyond 98%
- **200 hp motor constructed and tested**
  - has exceeded design goal by 60%
  - HTS coil did not degrade under mechanical stresses

Advantages of HTS Motors

- **Lossless dc HTS coils produce higher motor air gap magnetic field**
  - results in smaller motor size
  - lower losses
- **Projected applications - Large motors (>1,000 hp) for pump and fan drives for utility and industrial markets. Motors will be powered by an adjustable speed drive.**
- **Expected benefits compared to conventional high efficiency motors**
  - HTS motors will be approximately half the volume
  - HTS motors will have half the losses
  - Lower life cycle costs

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Superconductivity Partnership Initiative: General Atomics Team Demonstrates HTS Fault Current Controller

- **Fault current controller for utility substations--Benefits**
  - react to and absorb unanticipated power disturbances
  - prevents loss of power to consumers and limits damage to utility grid equipment
  - increased safety, reliability, power quality
  - defer T&D system upgrades
- **2.4-kV current controller tested in 1995**
  - at Southern California Edison substation
  - prototype performed at 37% above specifications

Completed: 15-KV HTS Fault Current Limiter General Atomics Corporation - USA

- Completed June 1999.
- Tested at Southern California Edison's Chino Substation in June 1999.
- Three of the world's largest Bi-2223 coils (solenoids, 1- m outside diameter and 0.75-m long) produced by Intermagnetics.
- 35 K, a continuous dc current of 2,000 A as well as an ac pulsed current of 9,000 A.
- Tested in a single-phase mode because of a high voltage flash to ground in auxiliary equipment.
- A 70% fault reduction and a fast cycle breaker shutdown in single phase mode at 12.47 kV and 10 kA was achieved before the substation tests were terminated due to extremely hot weather.
- Trailer (shown at right) is now at Los Alamos National Laboratory.

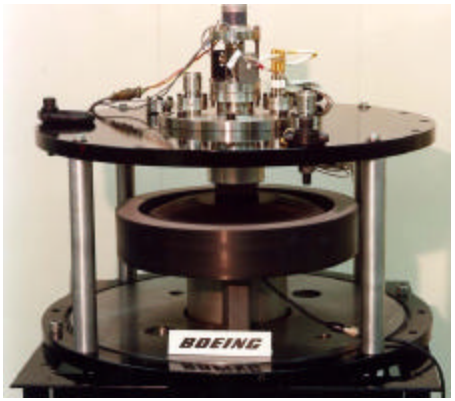
Photos courtesy IGC

New Superconductivity Partnership Initiative Projects Started by the US DOE in 1999

HTS Transformer #2 - ABB
Flywheel with HTS Bearings - Boeing
HTS Magnetic Separator - DuPont

Superconductivity Partnership Initiative: Boeing Team to Develop Flywheel Energy Storage System with Superconducting Bearings

- **$7.5 million cost-shared project will result in demonstration of a 10 kWh flywheel energy storage system with superconducting bearings for utility load leveling and power quality applications by 2001**
  - lower life cycle cost and maintenance than batteries
  - very low losses as compared to flywheels with conventional bearings
  - prevents power interruptions and increases power quality to consumers
  - applicable to utility, telecommunications, and other industrial markets
  - can be sited in high-density urban, environmentally sensitive areas, or inside buildings for distributed generation and storage
  - higher energy density than conventional storage technologies
  - provides energy for peak demand periods



- **Work started Spring 1999.**

SPI – DuPont Magnetic Separator
December 1998 - December 2001

Goal: To develop and build a one-quarter commercial scale reciprocating magnetic separator using an HTS magnet to demonstrate technological viability and assess cost competitiveness

Team: DuPont Company, Carpco, National High Magnetic Field Laboratory

Status: Conceptual design of the magnetic separator has been completed and design and component testing efforts are underway

Funding: Total Project Budget = $6.42M
DOE Share = $3.20M

Superconductivity Partnership Initiative: ABB Team to Study "Current Limiting" HTS Transformer

- **$0.6 million cost-shared project will result in study of a 10- MVA HTS transformer (to be installed at Southern California Edison for testing if Phase II funded)**
  - greater efficiency, smaller unit
  - eliminates oil cooling, thus reducing fire and environmental hazards associated with oil-based systems
  - can be sited in high-density urban areas and inside buildings
  - more power per unit volume
- **Contract executed 1999--- only PHASE I funded (a study period)**

Conclusion

- HTS has made surprising progress towards utility applications in 8 years of BSCCO wire availability
- Initial installations of various forms of electric equipment are being made around the world
- Prospects are good for initial market penetrations to be made over the next 10 years for cables, motors, transformers, and fault current controllers
- Power companies in the United States are involved in the DOE Superconductivity Partnership Initiative
  - **NEW PROJECTS EXPECTED IN 2001!**

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