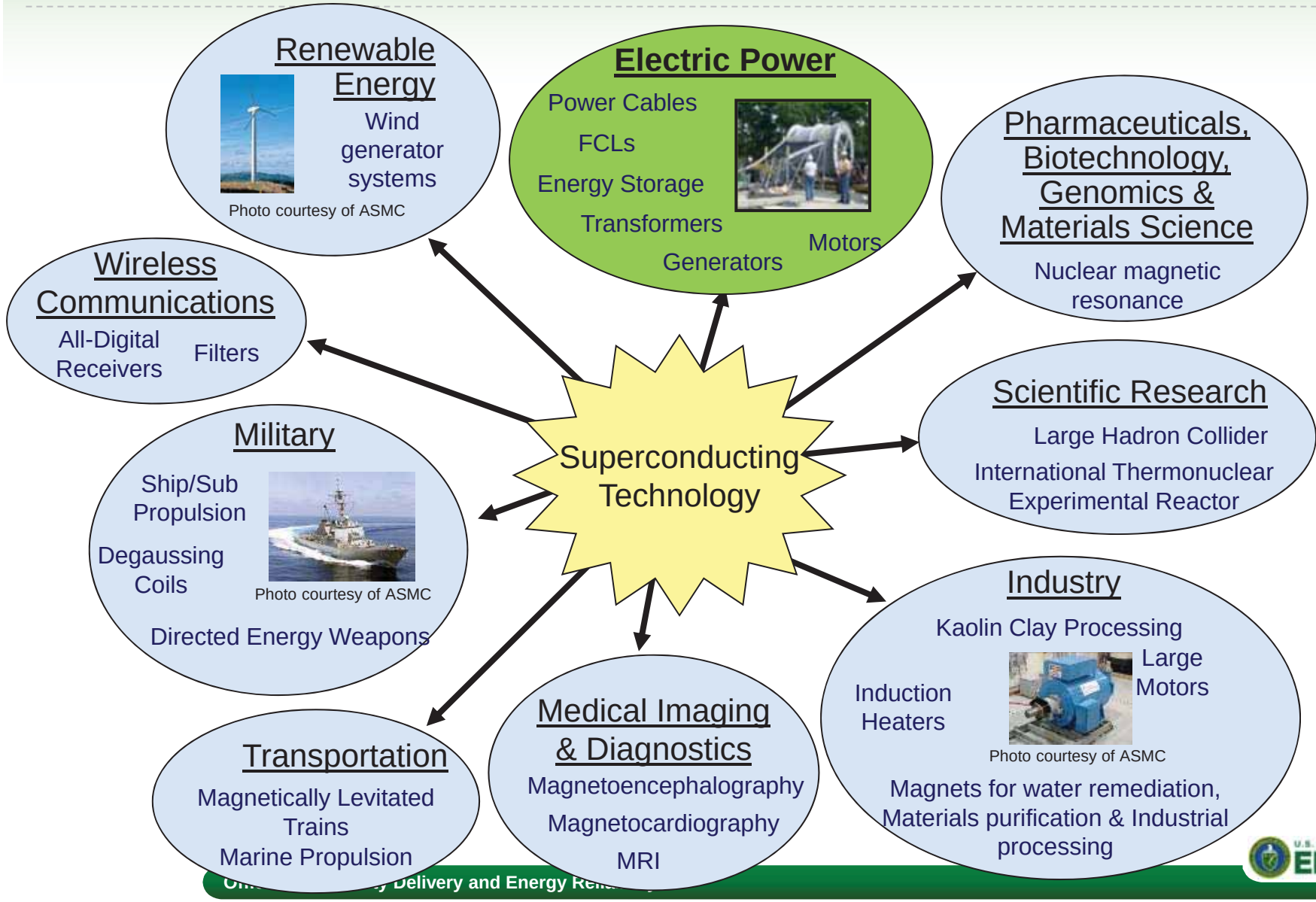
U.S. DEPARTMENT OF ENERGY | Office of Electricity Delivery and Energy Reliability

HIGH TEMPERATURE SUPERCONDUCTIVITY
A HISTORY OF SUCCESS

Materials Innovation for Next Generation T&D Grid Components
Oak Ridge National Laboratory
August 26-27, 2015

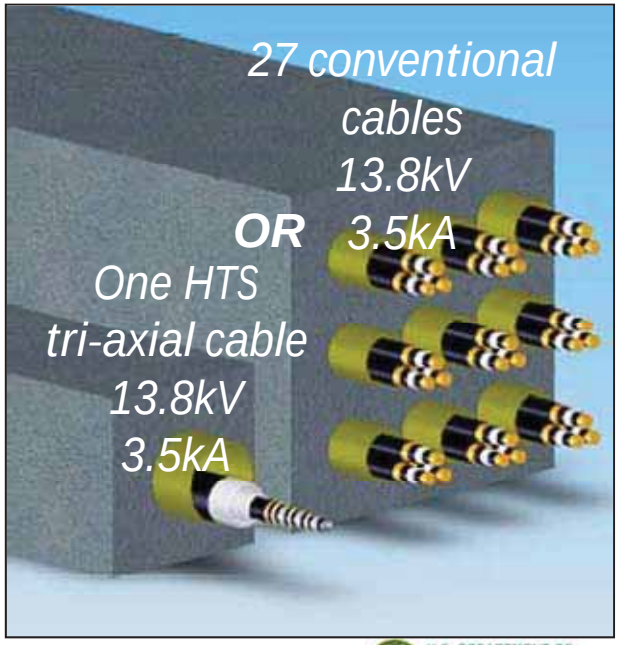
Debbie Haught

Many Applications That Utilize Electricity Can Benefit From Superconductivity



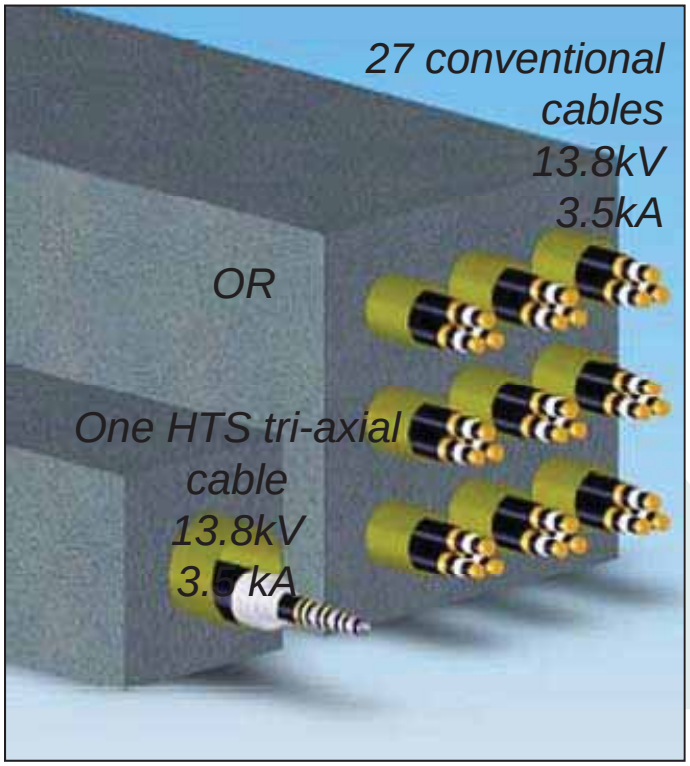
Why HTS for the Electric Grid?

- High Temperature Superconductors are the most efficient electricity carrier, reducing energy losses and carbon emissions
- HTS based devices such as cables, fault current limiters, transformers and energy storage devices are intrinsically smart, can limit overcurrents, and protect the grid from damage
- HTS cables can provide up to 10 times higher capacity than conventional cables and carry transmission power at distribution voltages
- HTS cables have reduced right-of-way requirements and can be readily permitted and installed in dense urban areas
- HTS fault current limiters improve system reliability when renewables and distributed generation are added to the electric grid



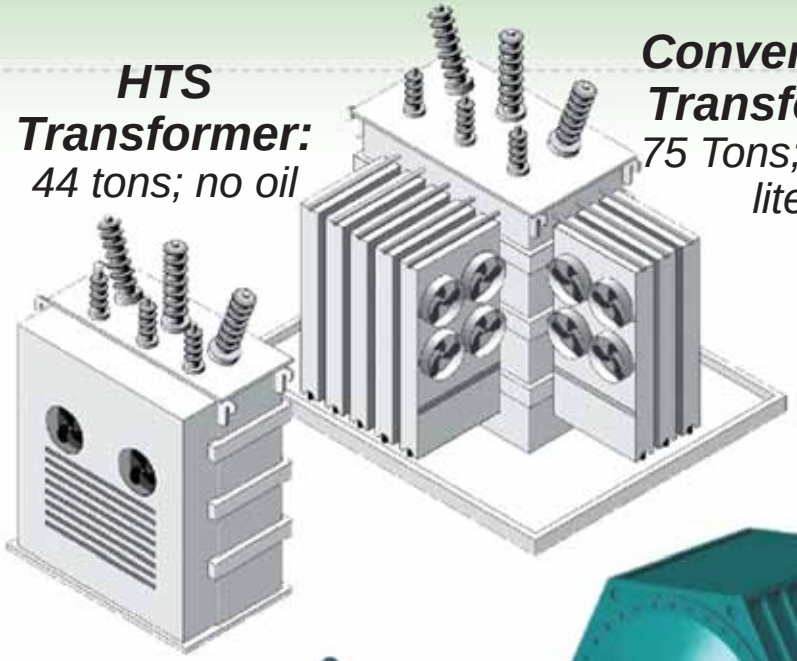
HTS vs. Conventional Equipment Comparison

Power Cables



HTS Transformer: *44 tons; no oil*

Conventional Transformer: *75 Tons; 23,000 liters of oil*



Conventional Motor

HTS Motor for Navy

One half the size and weight of conventional devices

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HTS Program Overview

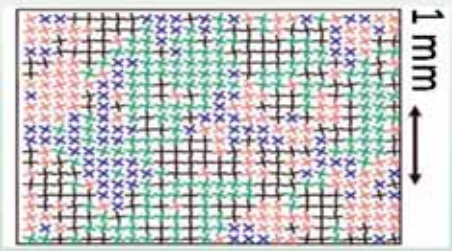
- HTS was discovered in 1986
- The Department of Energy's HTS research and development efforts began in 1988
  - Started developing useful forms of wire
  - Investigated material properties to make wire performance improvements
  - Successfully integrated wire into electric power applications
- The program formed three key R&D areas
  - **Wire Development**—improve the performance of superconducting wire while reducing manufacturing costs
  - **Strategic Research**—conduct the fundamental investigations necessary to support the wire and systems development
  - **Applications**—demonstrate the applicability and the potential benefits of superconductivity in electric power systems
- The program brought diverse stakeholders to develop HTS devices and systems with the advantage of a 50% cost-share with industry

Science to Energy: Textured template is the foundation of commercial 2G wires

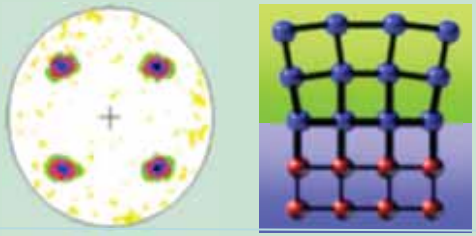
Basic Science

Realized that near-single crystal quality HTS is needed

Studied grain-to-grain current flow



Understood texture formation & multi-layered epi-film growth



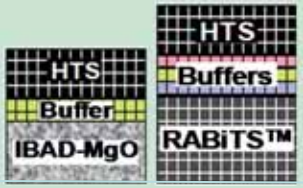
Applied Research

Near-single crystal quality 2G template by the KILOMETER

Rolling Assisted Biaxially Textured Substrate (RABiTS)

Ion-Beam Assisted Deposition (IBAD)

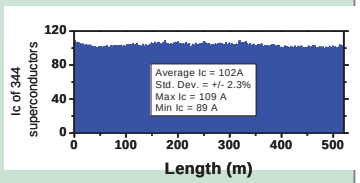
Multi-layered epitaxial buffer architecture

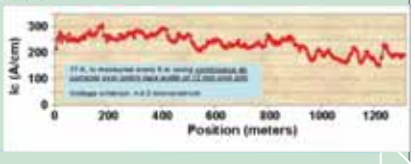


Manufacturing

Commercial wire with customers around the globe

- ✓ Licensed to SuperPower & AMSC as core wire technologies
- ✓ Commercial 2G HTS wire suppliers to the world

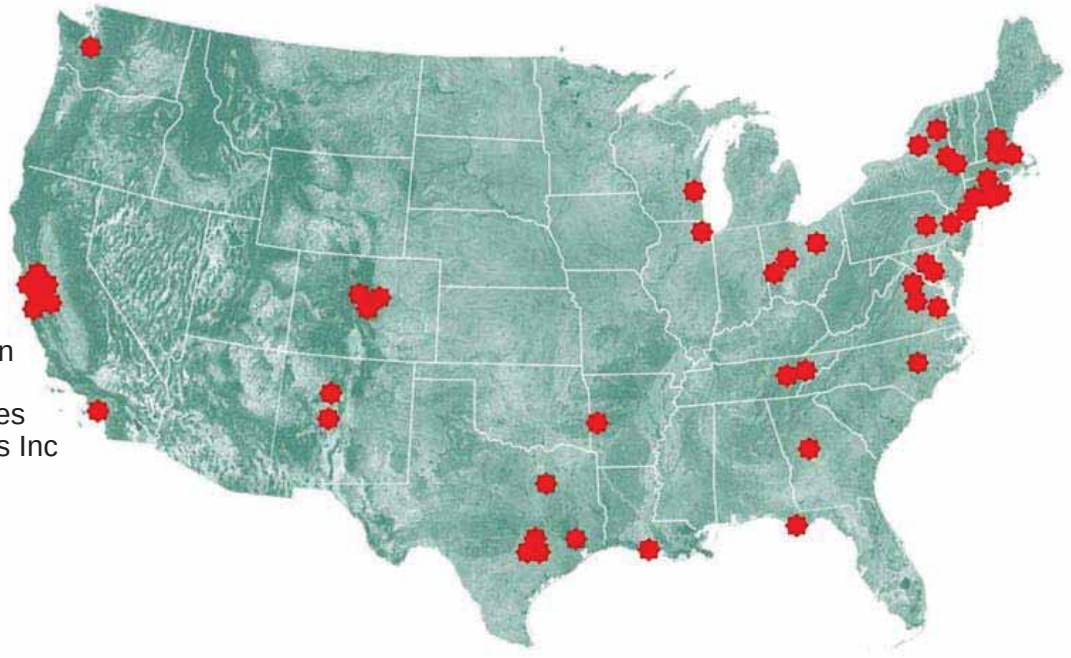


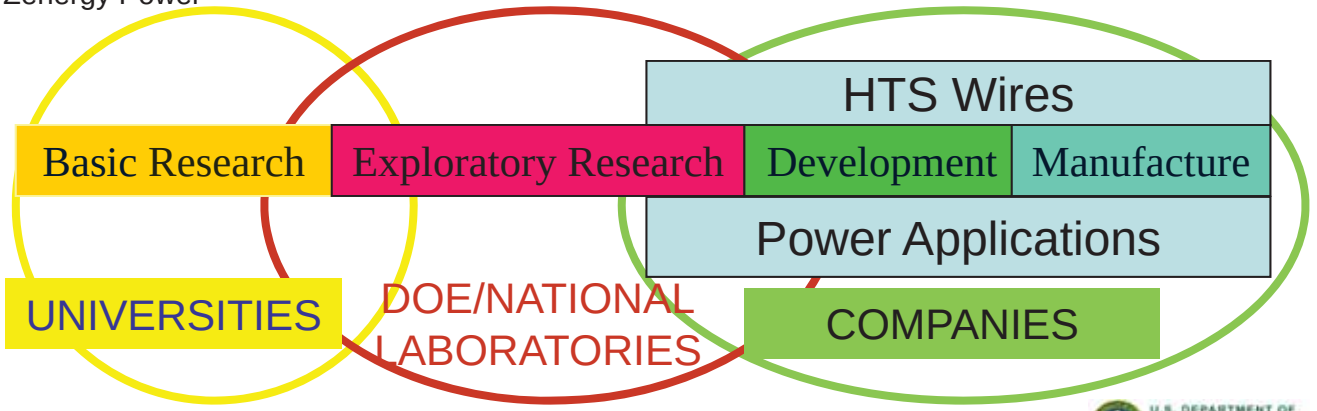


30x increase in current density over 1G HTS wire

Public – Private Partnerships Were Key to Success

Air Liquide
Air Products and Chemicals Inc.
American Electric Power
American Superconductor
Argonne National Laboratory
Brookhaven National Laboratory
Composite Technology Dev.
Consolidated Edison
Cryo-Industries of America Inc.
Delta Star Inc.
Directed Vapor Technologies
Dept. of Defense
Dept. of Homeland Security
Electric Power Research Inst.
Entergy
Florida State University
Long Island Power Authority
Los Alamos National Laboratory
Metal Oxide Technologies Inc.
Mipox International Corp.
National Grid
Nat'l Inst. of Standards & Tech.
National Renewable Energy Lab
Nissan Electric Co. Ltd.
Nexans
nkt cables Group
Oak Ridge National Laboratory
Oxford Superconducting Technology
Praxair
Sandia National Laboratory
Seattle City Light
Siemens Corporation
Southern California Edison
Stanford University
Sumitomo Electric Industries
Superconductor Technologies Inc
SuperPower
UES
ULTERA (Southwire)
University of Houston
University of Tennessee
Waukesha Electric
Zenergy Power





U.S. Federal Funding of HTS Research and Examples of Activities

Department of Energy

Office of Electricity Delivery and Energy Reliability
Office of Science – Basic Energy Sciences
Advanced Research Projects Agency – Energy

Demonstration projects for a range of electric power applications

Department of Defense

Air Force Research Laboratory
Army Research Laboratory
Naval Research Laboratory

Title III enabled US capacity for pilot production of second generation wire

Department of Homeland Security

Science and Technology Directorate

Resilient Electric Grid project for demonstration of a cable system for electric grid

Department of Commerce

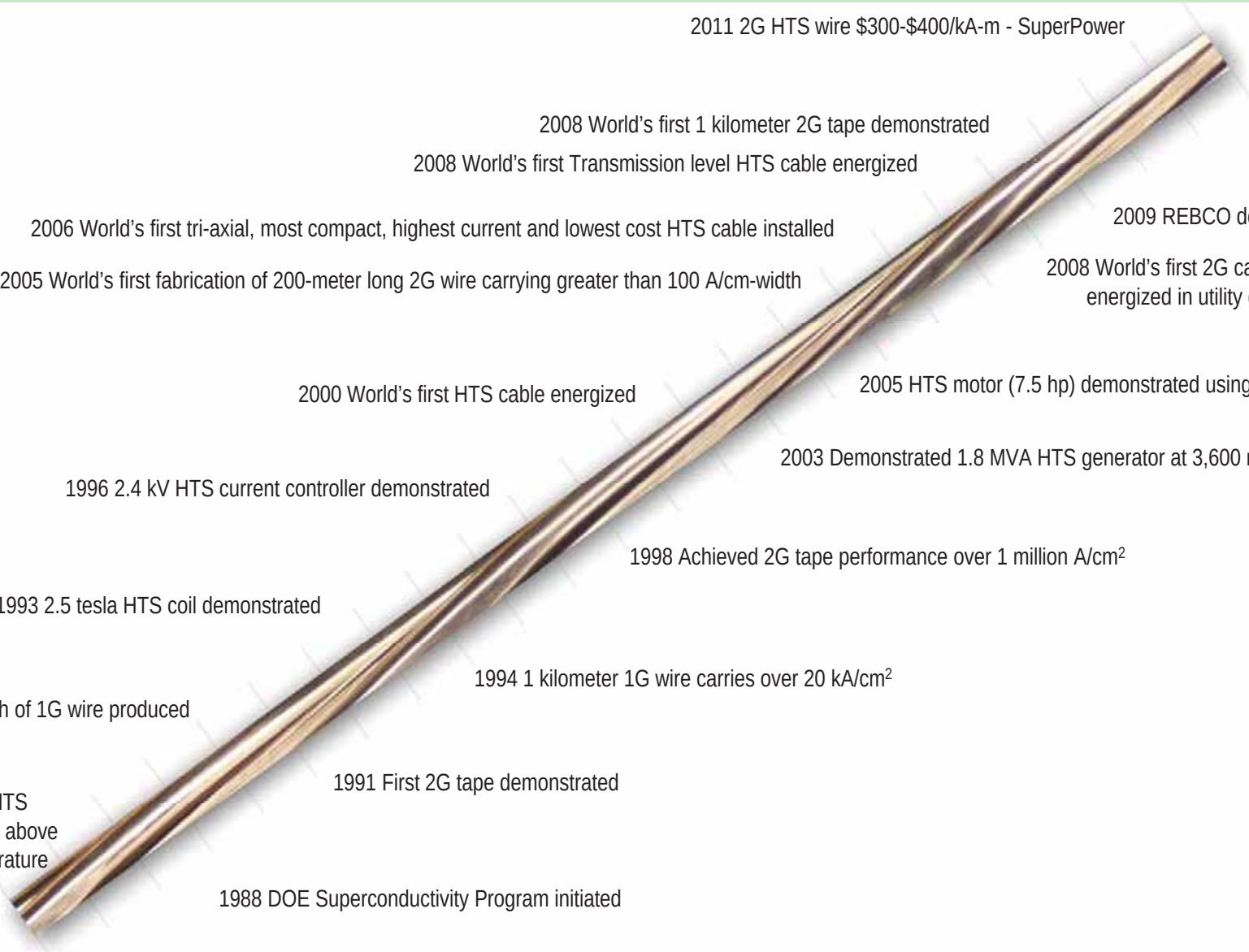
National Institute of Standards and Technology

Electromechanics enabled characterization of electromechanical properties of wire

Selected Program Achievements

- R&D100 Awards:
  - High performance superconducting wire (2010)
  - Large area near-single crystal substrate for semiconductors (2010)
  - Solution Deposition Planarization (2010)
  - Ultraconductus (2010)
  - SSIFFS: Structural single crystal faceted fiber substrate (2009)
  - MELCOT: Methodology to predict lifetime of Power line conductor-connectors operating at high temperatures (2009)
  - LMO buffer enabled IBAD-based superconducting wire (2007)
  - IBAD: Ion Beam Assisted Deposition (2003)
  - RABiTS: Rolling Assisted Biaxially Textured Substrates (1999)
  - Superconducting underground radio (1998)
  - Non-contact superconductor screening method (1989)
- 2010 R&D100 Innovator of the Year: Amit Goyal
- More than 150 patents by the National Labs; more than 20 have been licensed to industry
- Other major awards include:
  - FLC Excellence in Technology Transfer Awards (FLC Consortium)
  - Energy 100 Award (DOE)
  - Nano50 Award (NASA Nanotech Brief Magazine)
  - Micro/Nano25 Award (R&D Magazine)
  - Pride of India Gold Medal
  - E.O. Lawrence Award (DOE)
- Many program researchers are Fellow of professional societies, Editors of journals, Board members and Officers of societies and trade groups

HTS Technology Development



2011 2G HTS wire $300-$400/kA-m - SuperPower

2008 World's first 1 kilometer 2G tape demonstrated

2008 World's first Transmission level HTS cable energized

2006 World's first tri-axial, most compact, highest current and lowest cost HTS cable installed

2009 REBCO developed

2005 World's first fabrication of 200-meter long 2G wire carrying greater than 100 A/cm-width

2008 World's first 2G cable energized in utility grid

2000 World's first HTS cable energized

2005 HTS motor (7.5 hp) demonstrated using 2G wires

2003 Demonstrated 1.8 MVA HTS generator at 3,600 rpm

1996 2.4 kV HTS current controller demonstrated

1998 Achieved 2G tape performance over 1 million A/cm^2

1993 2.5 tesla HTS coil demonstrated

1994 1 kilometer 1G wire carries over 20 kA/cm^2

1990 10 meter length of 1G wire produced

1991 First 2G tape demonstrated

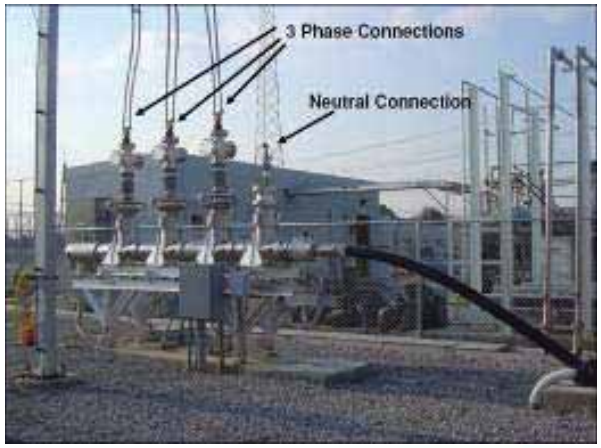
1987 YBCO, first HTS compound operational above liquid nitrogen temperature

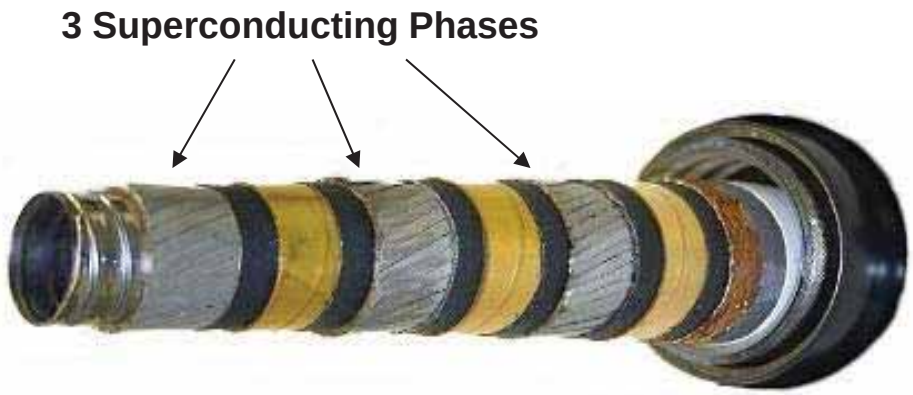
1988 DOE Superconductivity Program initiated

1986 First HTS discovery: lanthanum-barium-copper-oxide

Columbus HTS Cable Project

- 200 meters long; rated at 13.2 kV, 3 kA, and 69 MVA
- Served the equivalent of 36,000 homes
- Experienced fault events without any damage
- 6 years of operating time
- “Triax” design contains all 3 phases in one cable and uses ½ the amount of HTS wire compared to other designs





Ultera™
A Southwire / nkt cables Joint Venture

AEP

OAK RIDGE National Laboratory

PRAXAIR

American Superconductor

Albany HTS Cable Project

- 350 meters long; rated at 34.5 kV, 800 A and 48 MVA
- The world's first HTS cable-to-cable joint (required for long cable runs)
- World's first use of 2G wire in a utility device
- Served the equivalent of 25,000 homes
- Operated more than 6720 hours using 1G wire and additional 2400 hours using a 30 meter segment of 2G wire


3 phases in 1 common cryostat

SuperPower Inc.

nationalgrid

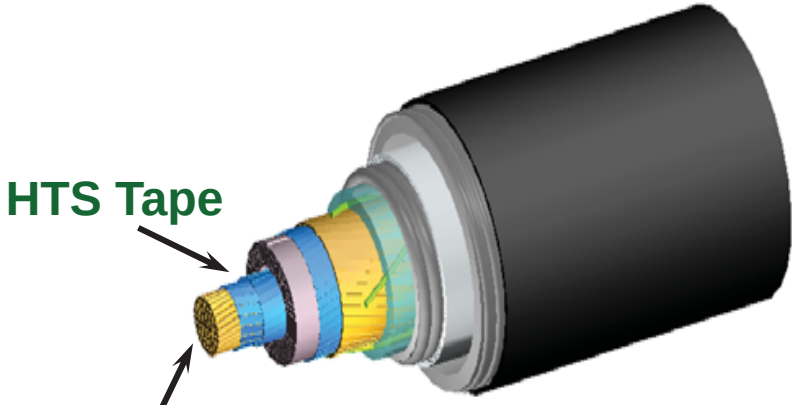
NYSERDA

Linde

SUMITOMO ELECTRIC

Long Island HTS Cable Project

- World's first transmission voltage HTS cable
- Was the world's longest HTS cable at 600 meters
- Design rating of 138 kV, 2.4 kA and 574 MVA
- Demonstrated a fault current limiting and fault current tolerant design
- More than 3 years of operating time for 1G cable
- Single phase of 2G cable installed in 2012



American Superconductor
REVOLUTIONIZING THE WAY THE WORLD USES ELECTRICITY™

LIPA
Long Island Power Authority

AIR LIQUIDE

Nexans

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DHS Resilient Electric Grid (Hydra) Project

Develop and Demonstrate Fault Current Limiting HTS Cable to protect critical urban power network infrastructure

- Phase 1- Develop inherently Fault Current Limiting Cable design
  - Passed all Industry Qualification tests and engineering studies
  - Con Edison approved for installation in urban power network
- Phase 2- System design, installation and 1-year operational demonstration
  - Site design, construction permitting and system design underway
  - Connecting two Con Edison 13.8kV substations
- Phase 3- Commercial Application which is a permanent, operational installation
  - Feasibility study with Commonwealth Edison (ComEd) underway to connect critical substations in downtown Chicago

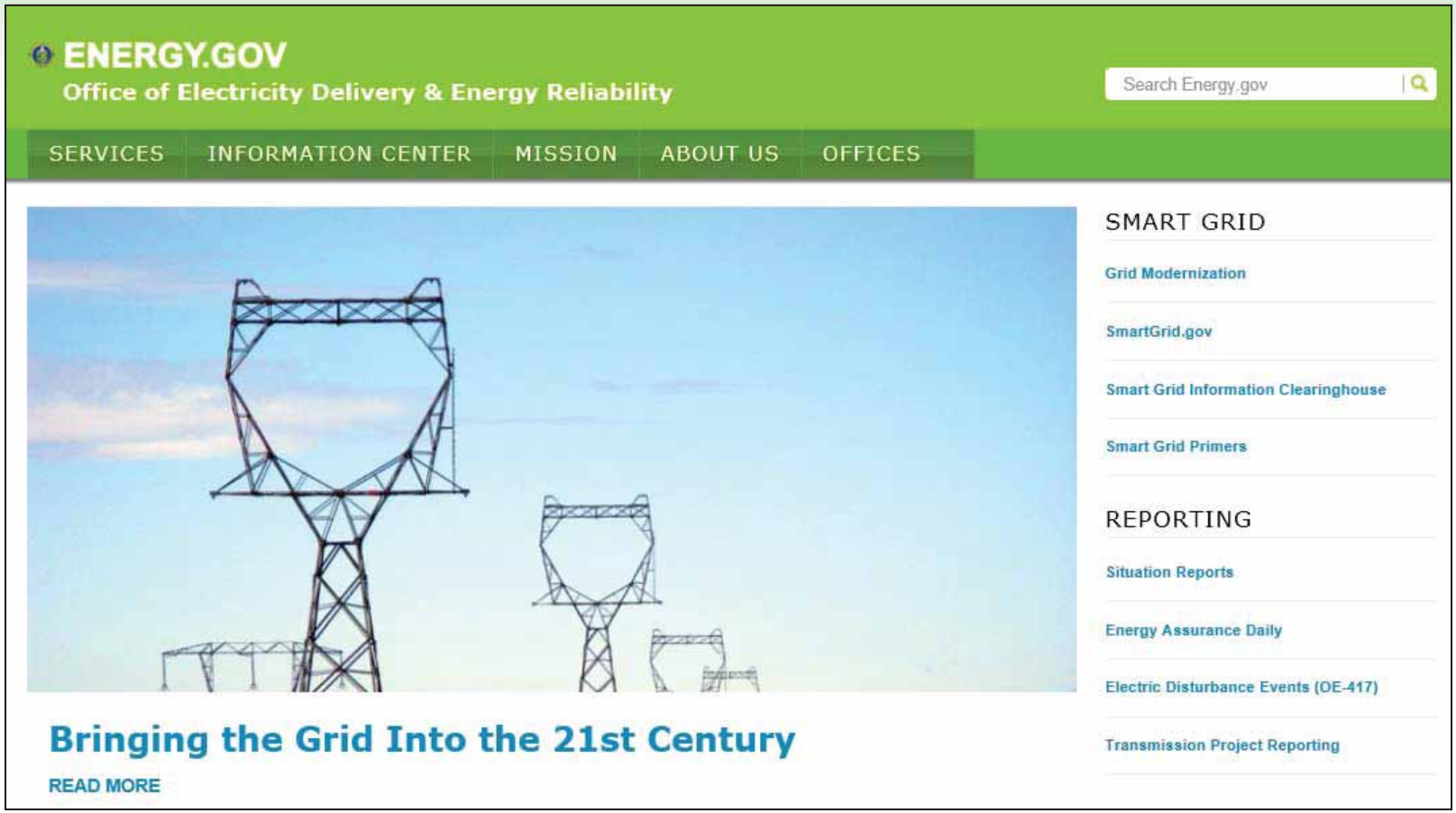
Prototype Cable in Type Test

Examples of Recent HTS US Activities

- DOE ARPA-E
  - High performance coated conductors for high field coil applications
  - Superconducting magnetic energy storage
- DOE EERE
  - Offshore wind turbine advanced drivetrain
- DOD
  - Ship protection systems
  - SBIR for conductor on round core cables for power transmission
- National Institute of Standards and Technology (NIST)
  - Advanced Superconductor Manufacturing Institute
- NASA
  - All electric aircraft using cryogenic motors and generators
- NY State Energy Research and Development Authority (NYSERDA)
  - Superconducting fault current limiter installed at a substation

The HTS Program Success Can be Used as a Model for Future Activities

- Applied R&D in advanced materials has the potential to improve the fundamental properties and capabilities of grid components
- Taking innovative materials and integrating them into grid scale devices takes time
- By understanding the fundamental characteristics of the materials, the HTS program helped to make significant wire improvements in performance and long length
- The Program also worked closely with industry to understand application specific needs
- Public private partnerships were key to success
- Close to using HTS in a commercial application
- Challenges remain for wider adoption



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