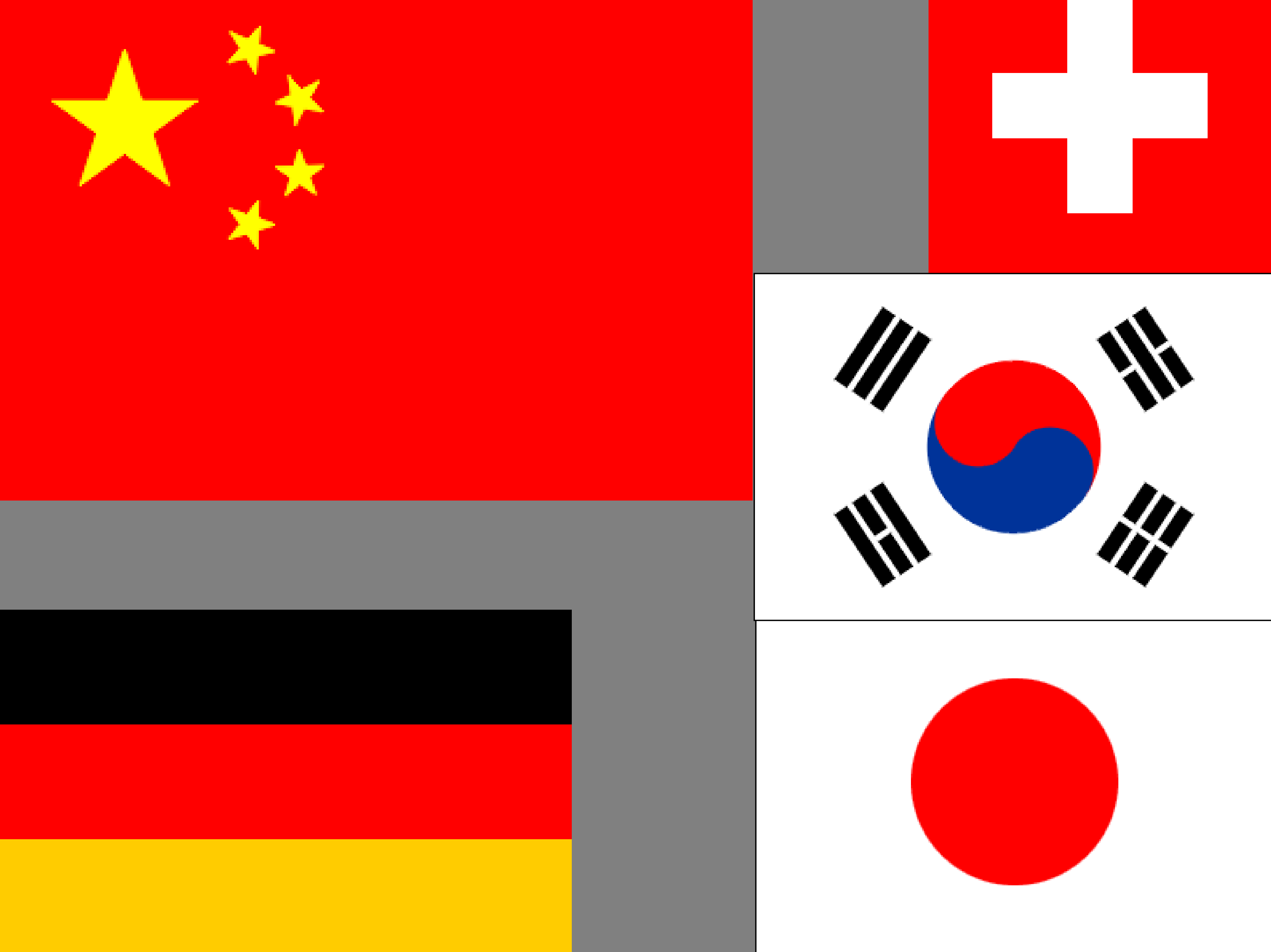


Xue Yuyang

Yao Ming


10 MILES
OF
TRACK, LAID
IN ONE DAY.
APRIL 28TH 1869

Overview of HTS Power Cable Projects in the United States

Paul M. Grant
EPRI Science Fellow (*retired*)
IBM Research Staff Member Emeritus
Principal, W2AGZ Technologies
w2agz@pacbell.net
www.w2agz.com

Symposium on HTS Cable Application
Kunming City, People's Republic of China
24 - 25 June 2004

It's Crowded Down There

"911"

"The Present Grid"

Wired Magazine, June 2001

27 July 1987

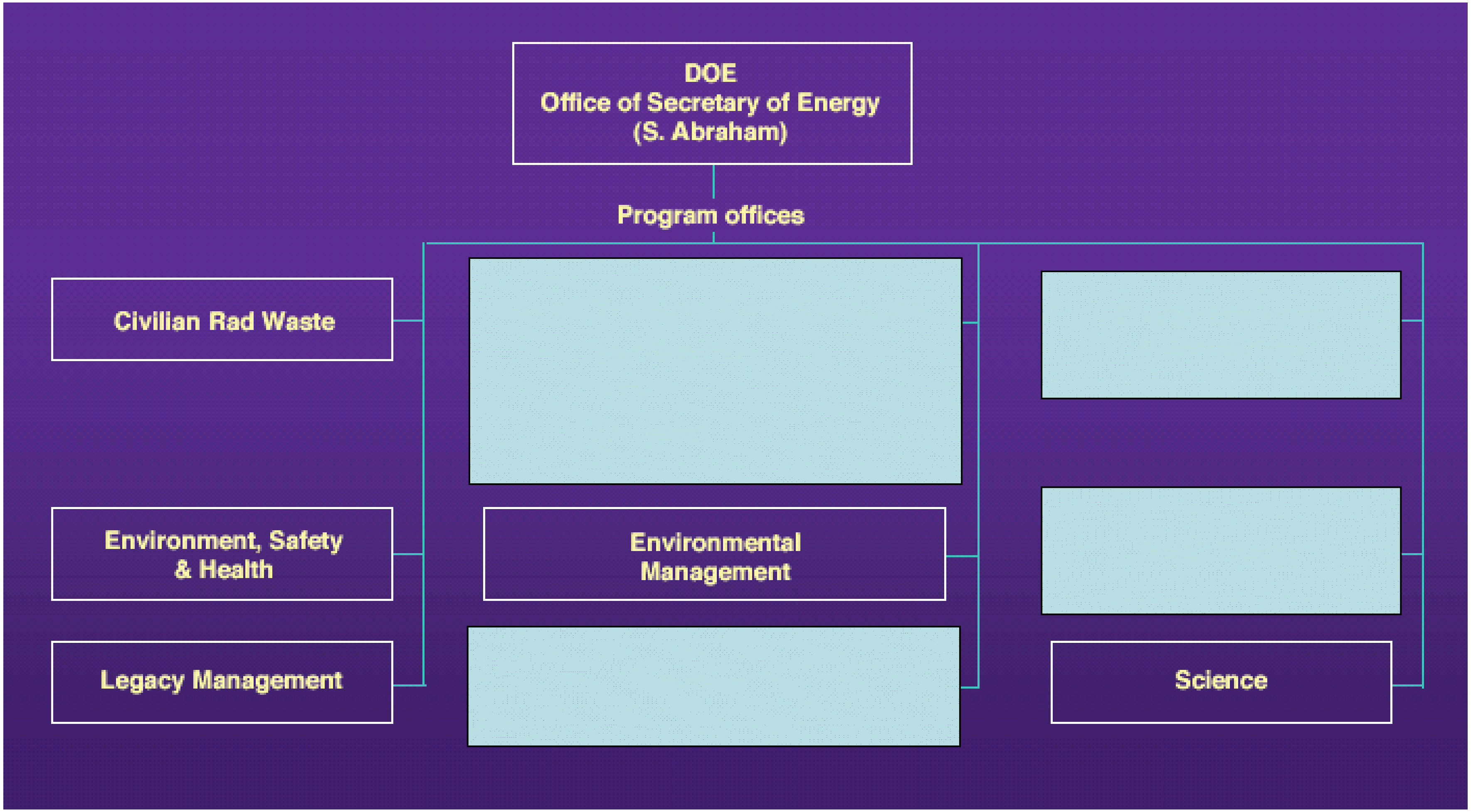
"White House Conference on Superconductivity"

Alan Schriesheim, Director of Argonne National Laboratory, demonstrates superconductivity to the President, Chief of Staff Howard Baker, Secretary of Defense Caspar Weinberger, Secretary of State George Shultz and Secretary Herrington.

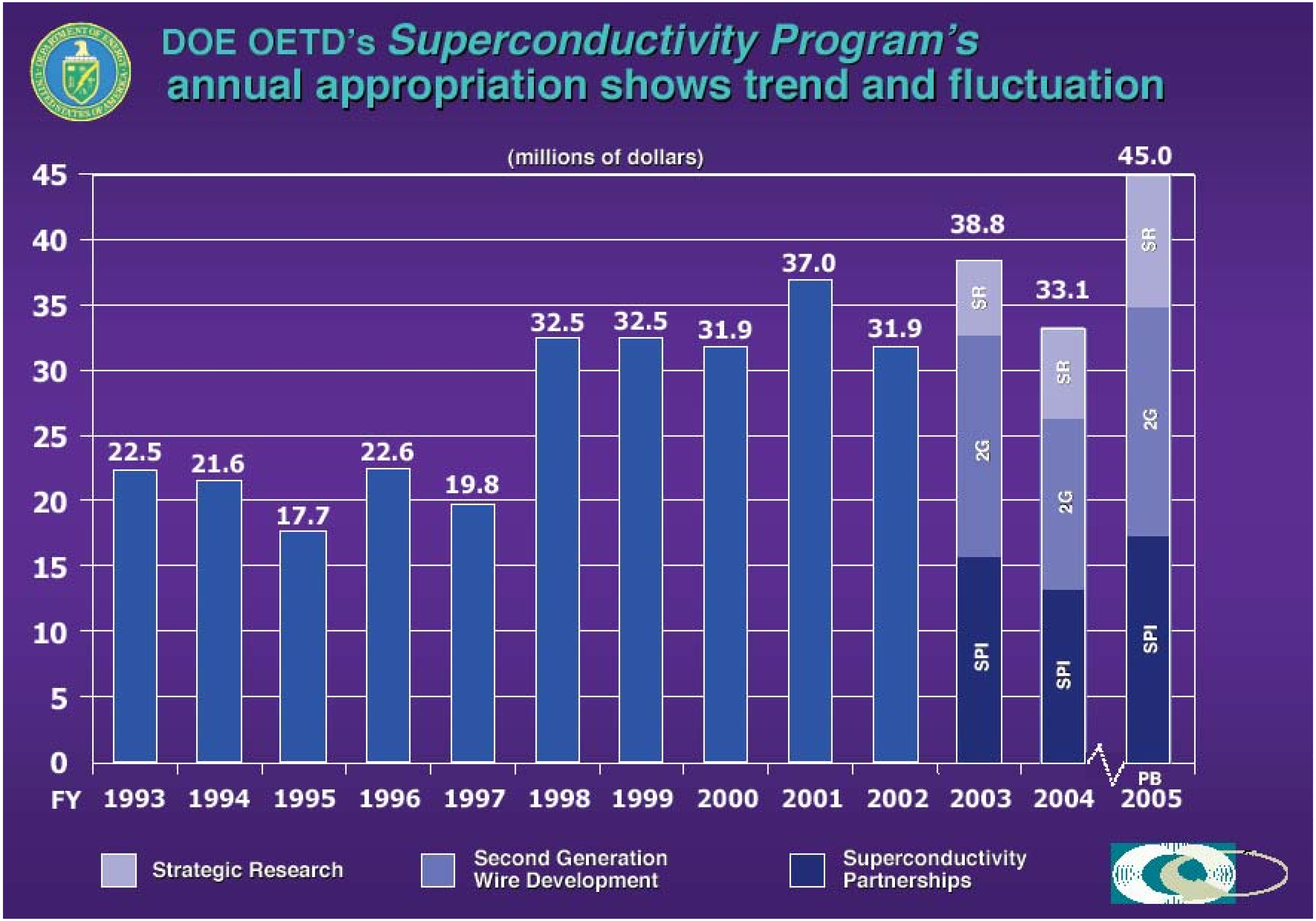
Thanks to…

• Jim Daley	USDOE/OETD
• Alan Wolsky	ANL (“Purple”)
• Bob Hawsey	ORNL
• Balu Balachandran	ANL
• Dean Peterson	LANL
• Alex Malozemoff	AMSC
• Steve Eckroad	EPRI

United States Department of Energy



OETD Budget


DOE OETD's *Superconductivity Program's*
annual appropriation shows trend and fluctuation
(millions of dollars)
45
40
35
30
25
20
15
10
5
0
FY 1993 1994 1995 1996 1997 1998 1999 2000 2001 2002 2003 2004 PB 2005
22.5
21.6
17.7
22.6
19.8
32.5
32.5
31.9
37.0
31.9
38.8
33.1
45.0
SR
2G
SPI
Strategic Research
Second Generation Wire Development
Superconductivity Partnerships

OETD Wire and SPI Strategic Plan

Year	Metric		HTS Motors		HTS Generators		HTS Transformers		
			Voltage	Power	Voltage	Power	Voltage	Power	
Fall 03			4kV	1.2 MW (2001)	4.16 kV	1.8 MW testing	13.8 kV	1.7 MW (2001)	
2004							24.9 kV	10 MW	
2005					13.8 kV	100 MW			
2006									
2007			4 kV	5 MW					
2008					13.8 kV	340 MW	138 kV	50 MW	
2009									
2010									
2012			6kV	5 MW	13.8kV	850 MW	345kV	340 MW	
2017									

EPRI/Pirelli Cable (1993 – 1998)

- Warm Dielectric (CD Design Study)
- 30 meters (eventually 50)
- 115 V, 1000 A (eventually 3000 A)
- Terminations + Joint + 90 Degree Bend
- Final test in Pirelli lab in Columbia, SC
- During final test, “blister/balloon” uncovered as an issue in Gen I HTSC tape manufacturing

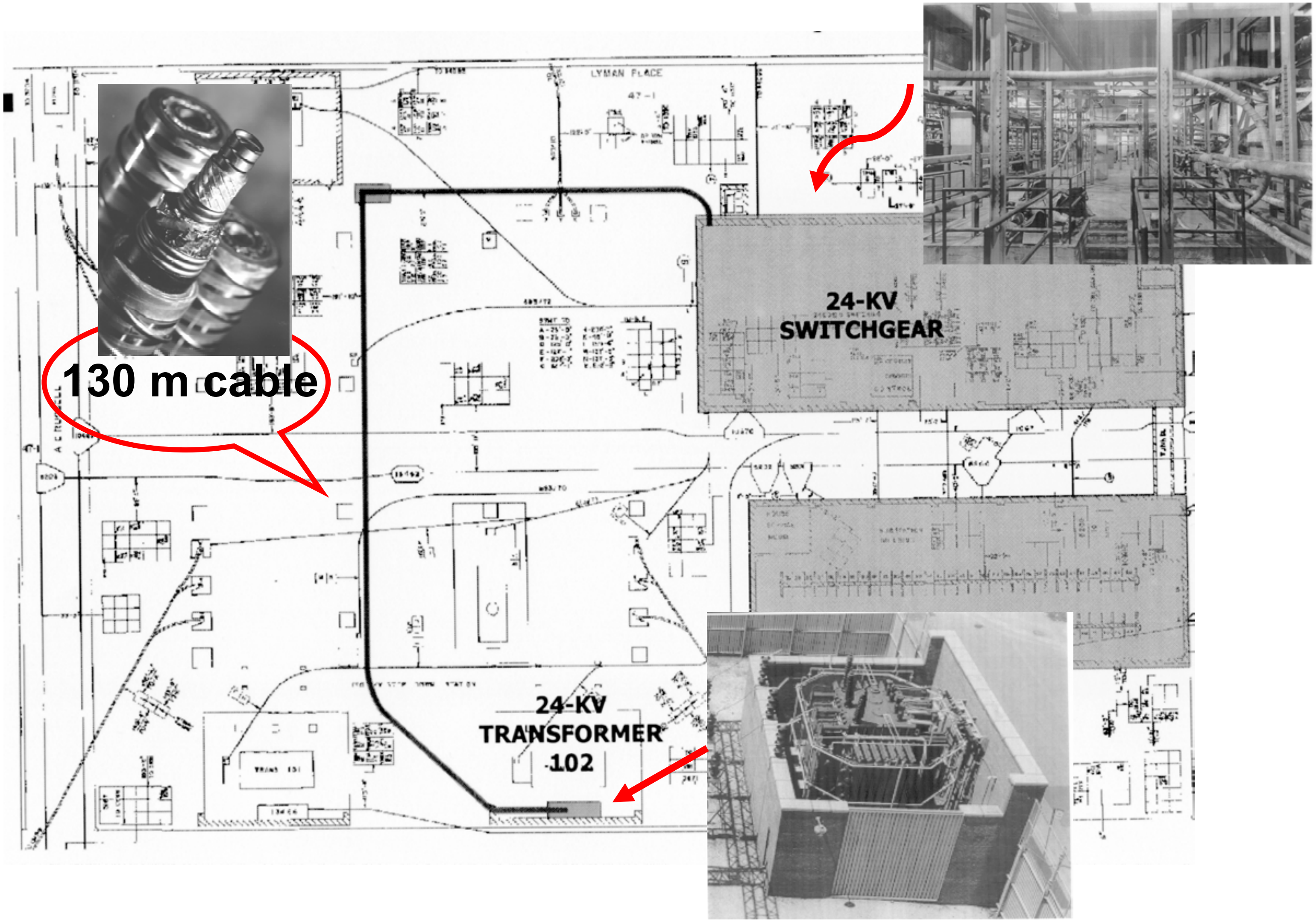
Southwire/Carrolton 30-m Cable

- 12.4 kV, 1.25 kA, 3 phase
- Cold dielectric
- IGC, NST Gen I tape
- n ~ 2-3

Detroit Edison Frisbee Project

- Cable Specs
  - 130 m, 24 kV, 3 ϕ, 3000 A_{rms}, LN_2
  - Substation Location, 4" Dia. Surface Ducts
- Advantage to Utility
  - 1:1 Overhead to Underground
  - Elimination of 120 kV Subtransmission System Due to Lower I^2R and CV^2 Losses
  - Utilize Existing 4" Conduit Infrastructure

Frisbie Layout



Detroit Edison Frisbie Cable

Why did it fail?

- Design based on proven warm temperature dielectric 50-m EPRI/Pirelli prototype
- Cable passed laboratory qualification test
- Tensile stress under pull < 30 % design
- Best evidence is stainless steel used for cryostat underwent hydrogen embrittlement when welded exacerbated by strain during pull.
- Resulting cracks degraded vacuum preventing HV operation
- LV ac operation at full current inferred hysteretic losses less than 1 W/m

HTS Cable Support Centers in the US

Current US Cable Projects

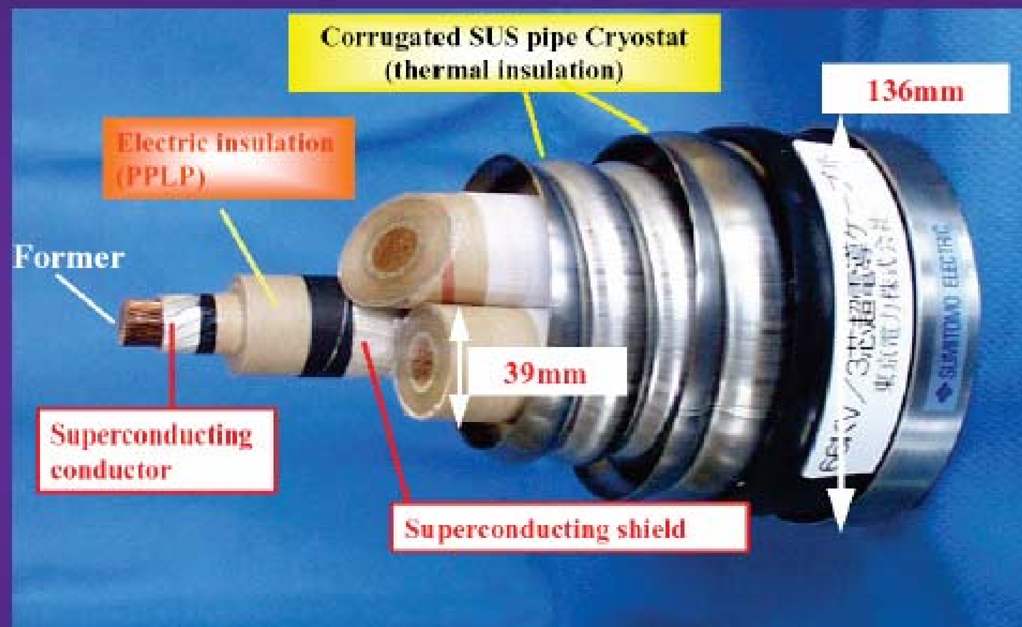
THREE NEW PROJECTS TO DEMONSTRATE HTS CABLE ARE UNDERWAY IN THE US

location	*team leader*
• Albany, N.Y.	IGC-SuperPower
• Bixby Substation, Ohio	Southwire
• Garden City-Newbridge, Long Island, N.Y.	AMSC

"Albany"

ALBANY TEAM* PLANS TO BUIILD AND DEMONSTRATE "3 CORE IN ONE CRYOSTAT" CABLE

- 3 phase AC
- each phase coaxial
- 0.8 kA
- 34.5 kV
- 48 MW
- 350 meter
- Bi-2223
- 1 splice



benefits from SEI's experience with TEPCO cable

* IGC-SuperPower, Sumitomo Electric, BOC, Niagara-Mohawk

"Albany"

- installation
- maintenance
- reliability
  fault durations
  8 cycles
  28 cycles
  80 cycles
- compatibility with rest of grid

future 30 m cable section having 2G conductor (8 km tape planned for delivery in '05)

route of project's 350 m Bi-2223 cable

"Albany"

Team:

SuperPower (Project Lead and 2G HTS Wire)

BOC (Cryogenic System)

Sumitomo Electric (Cable Production)

New York State Energy Research and Development Authority (Additional Funding)

Niagara Mohawk (Host Utility)

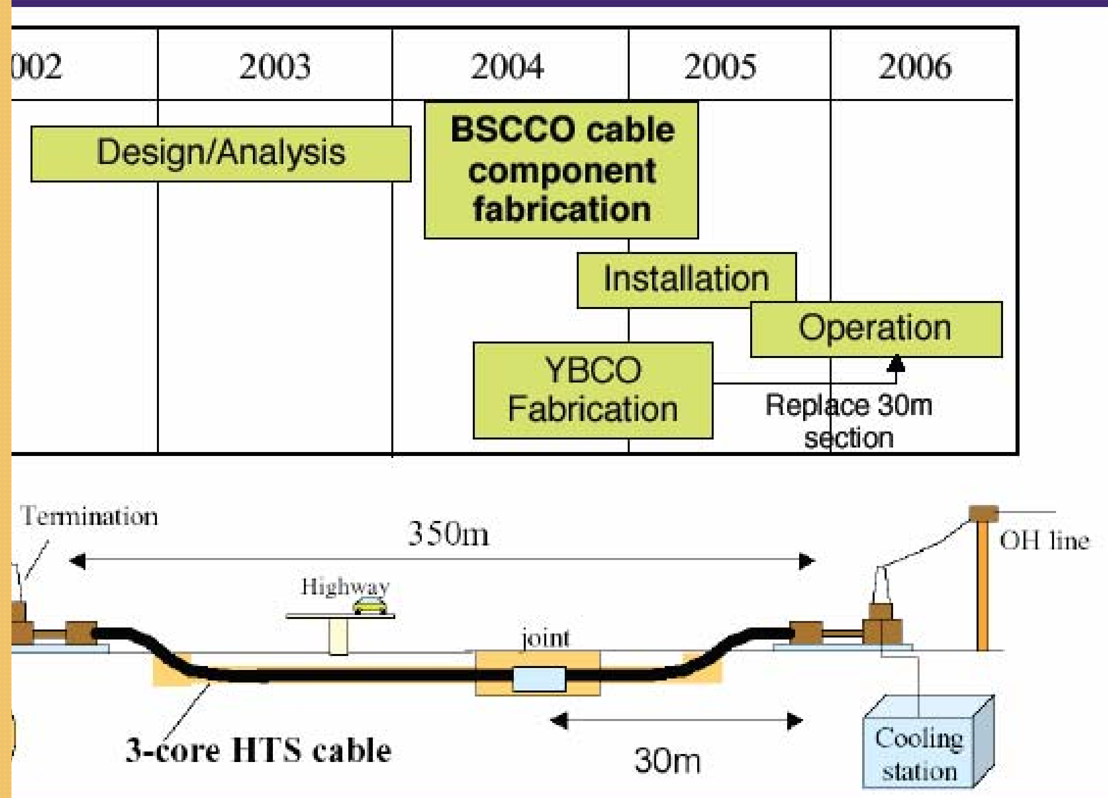
Period of Performance:

7/2003 - 5/2007

Cumulative Project Funding:

Private $12.86 Million (50%)
DOE $12.86 Million (50%)
Total: $25.71 Million

TEAM PLANS TO OPERATE CABLE IN 2006



"Long Island"

LONG ISLAND TEAM* PLANS TO BUILD AND DEMONSTRATE 3 COAXIAL PHASES

- 3 phase AC
- each phase coaxial
- 2.4 kA
- 69 kA during 15 cycle fault
- 138 kV
- 600 MW
- 610 meter
- Bi-2223
- 1 splice
- each phase has Cu shunt to increase Z during fault
- conventional cooling and pulse tube

AMSC design promises very low (& variable) impedance

* AMSC, Nexans, Air Liquide, Long Island Power Authority (LIPA)

"Long Island"

TEAM:

American Superconductor (HTS wire and project lead)

Nexans (cable manufacturing)

Air Liquide (Refrigeration system)

Long Island Power Authority (Host utility)

PERIOD OF PERFORMANCE:

3/2003-12/2006

CUMULATIVE PROJECT FUNDING:

Private $15.20 Million (50%)
DOE $15.20 Million (50%)
Total: $30.39 Million

D TEAM PLANS TO OPERATE CABLE IN 2005

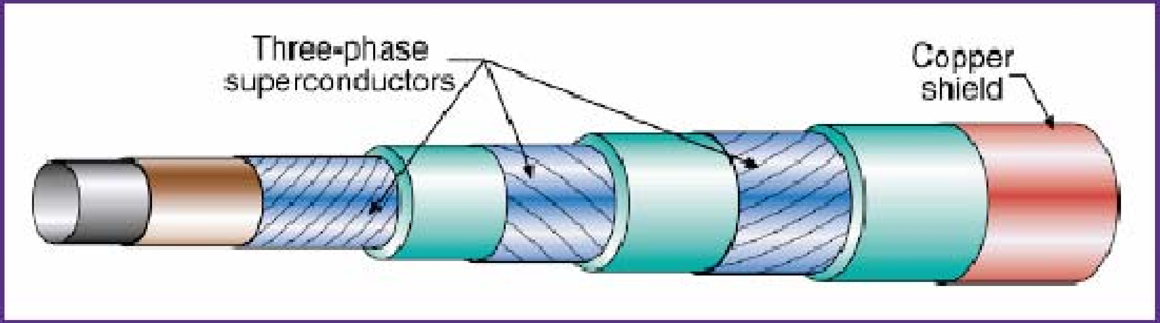
- locate in corridor now home to
  three conventional 138 kV cables
  one conventional 69 kV cable
  connecting two substations
- commission in 2005
- operate into 2006
- submit final report 2006

ST: by 2020, Long Island's Load Will Grow by 1.2 GW

"Bixby"

BIXBY, OHIO TEAM* PLANS TO BUILD AND DEMONSTRATE A TRIAXIAL CABLE

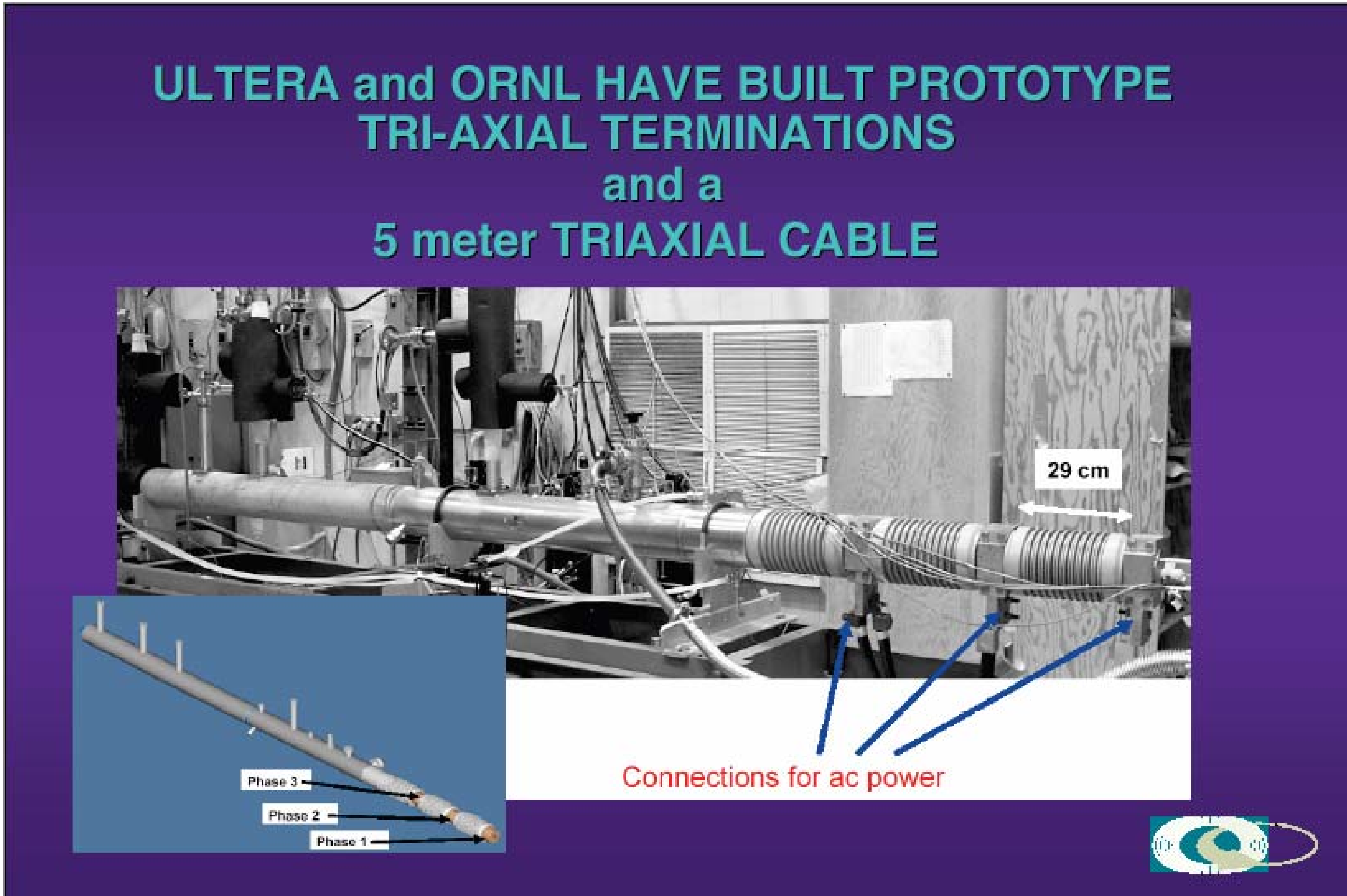
- 3 phase AC
- all in one cryostat
- 3 kA
- 13 kV
- 69 MW
- 300 meter
- Bi-2223



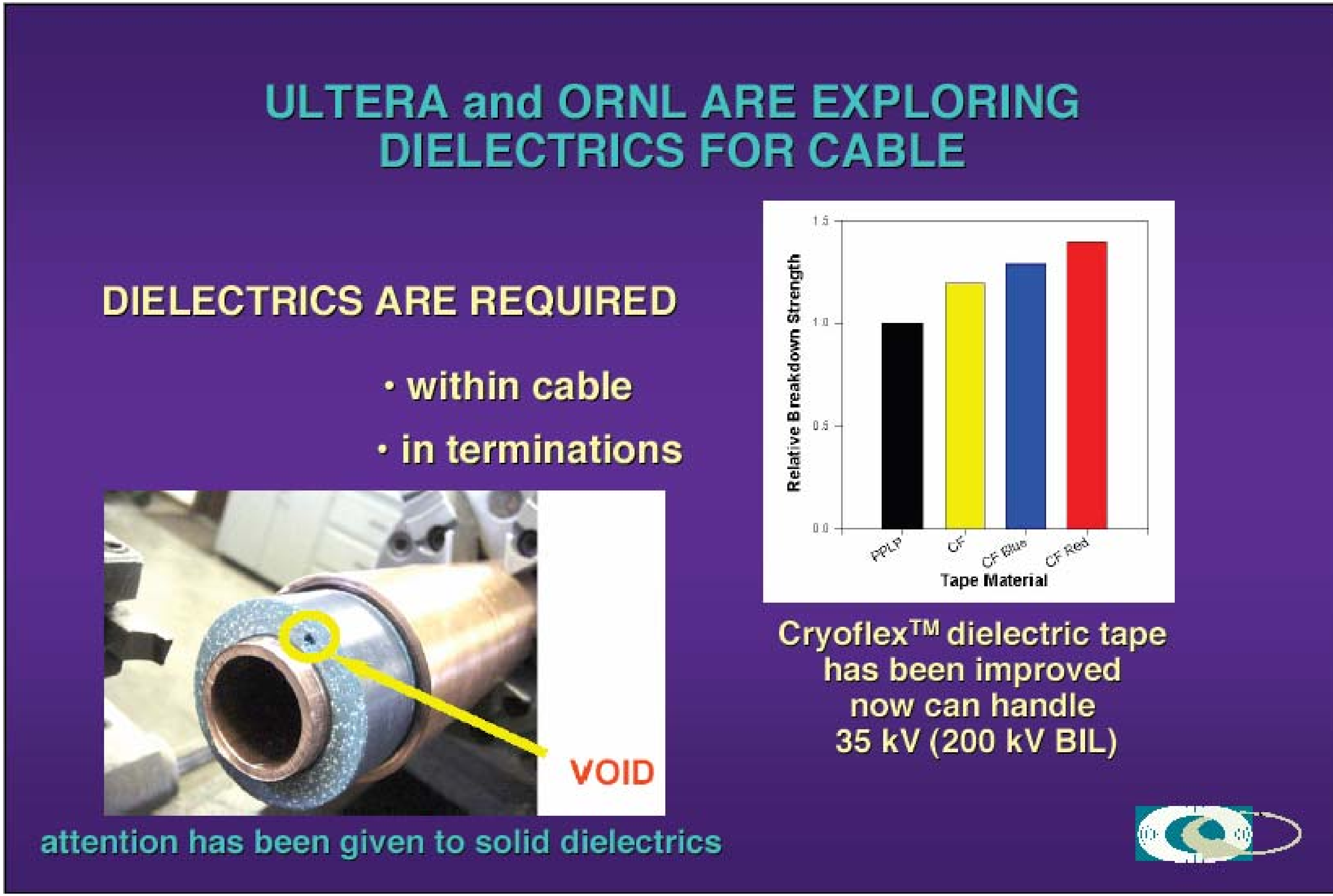
when compared to 3 coaxial phases,
tri-axial design promises reduced heat invasion
tri-axial design promises reduced need for HTS tape
unbalanced impedance no problem for lengths less than 10 km

* Ultera (Southwire&NKT), AMSC, ORNL, PHPK, American Electric Power

“Bixby”


ULTERA and ORNL HAVE BUILT PROTOTYPE
TRI-AXIAL TERMINATIONS
and a
5 meter TRIAXIAL CABLE
29 cm
Connections for ac power
Phase 3
Phase 2
Phase 1

"Bixby"


ULTERA and ORNL ARE EXPLORING
DIELECTRICS FOR CABLE
DIELECTRICS ARE REQUIRED
• within cable
• in terminations
VOID
attention has been given to solid dielectrics
1.5
1.0
0.5
0.0
Relative Breakdown Strength
PPLP
CF
CF Blue
CF Red
Tape Material
Cryoflex™ dielectric tape
has been improved
now can handle
35 kV (200 kV BIL)

"Bixby"

TEAM:

ULTERA (team leader)

American Electric Power (host utility)

Oak Ridge National Laboratory (supporting technology and research)

Integrations Concepts Enterprises (power controls)

PERIOD OF PERFORMANCE:

4/2002-7/2006

CUMULATIVE PROJECT FUNDING:

Private $4.32 million (50%)
DOE $4.32 million (50%)
Total: $8.65 million

TEAM PLANS TO OPERATE CABLE IN 2005

I-2 Bixby Substation, AEP, Columbus, OH

1Q, FY2005 (Oct-Dec04)
- Complete cable construction and off-site verification testing

2Q, FY2005 (Jan-Mar04)
- Begin delivery of cable system components to Bixby station

3Q, FY2005 (Apr-June05)
- All civil/electrical construction work by AEP completed
- HTS cable, cryogenic, and control systems installed

4Q, FY2005 (Jul-Sept05)
- On-site commission testing of all cable system components

1Q, FY2006 (Oct 2005)
- Energize cable system

US HTSC Conductor Development

Bi-2223 conductor ("gen 1")

- used in today's demonstration projects
- operated up to 83 K and in low magnetic field
- in 50 km quantities, AMSC offers for 135 $/kA-m
- price must be reduced greatly
  to offer an economic alternative to Cu or Al
  in most commercial applications
- DOE funding tapering off for Bi-2223

REBaCuO conductor ("gen 2" aka "coated conductor")

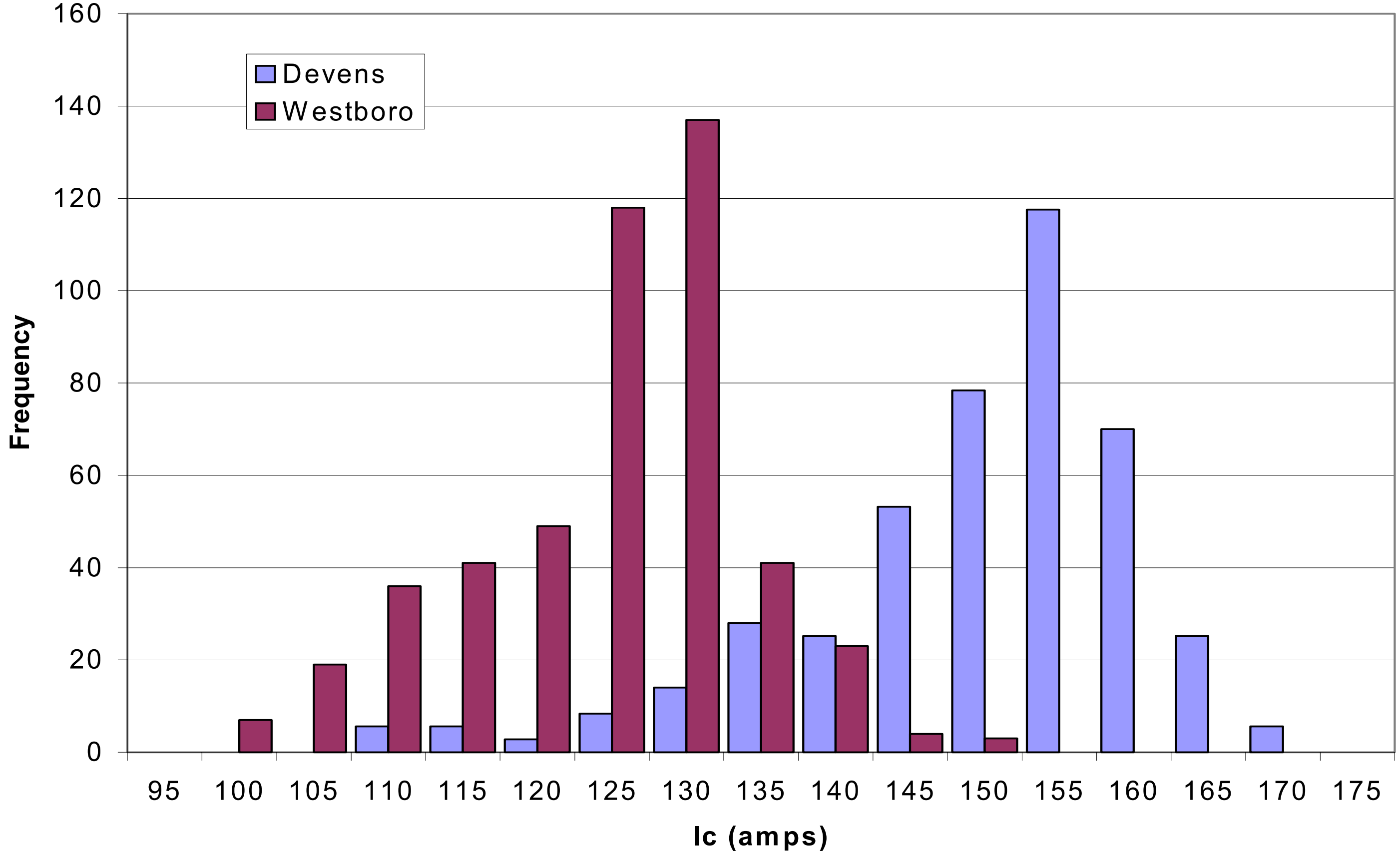
- to be used in 2006 demonstration project (30m cable)
  but not yet available in sufficient length
- expect to operate up to 83 K and in magnetic field > 2 Tesla
- hope that production techniques can yield conductor
  having price less than 50 $/kA-m
- DOE funding emphasizes REBaCuO tape

TWO US FIRMS ARE DEVELOPING HTS CONDUCTOR

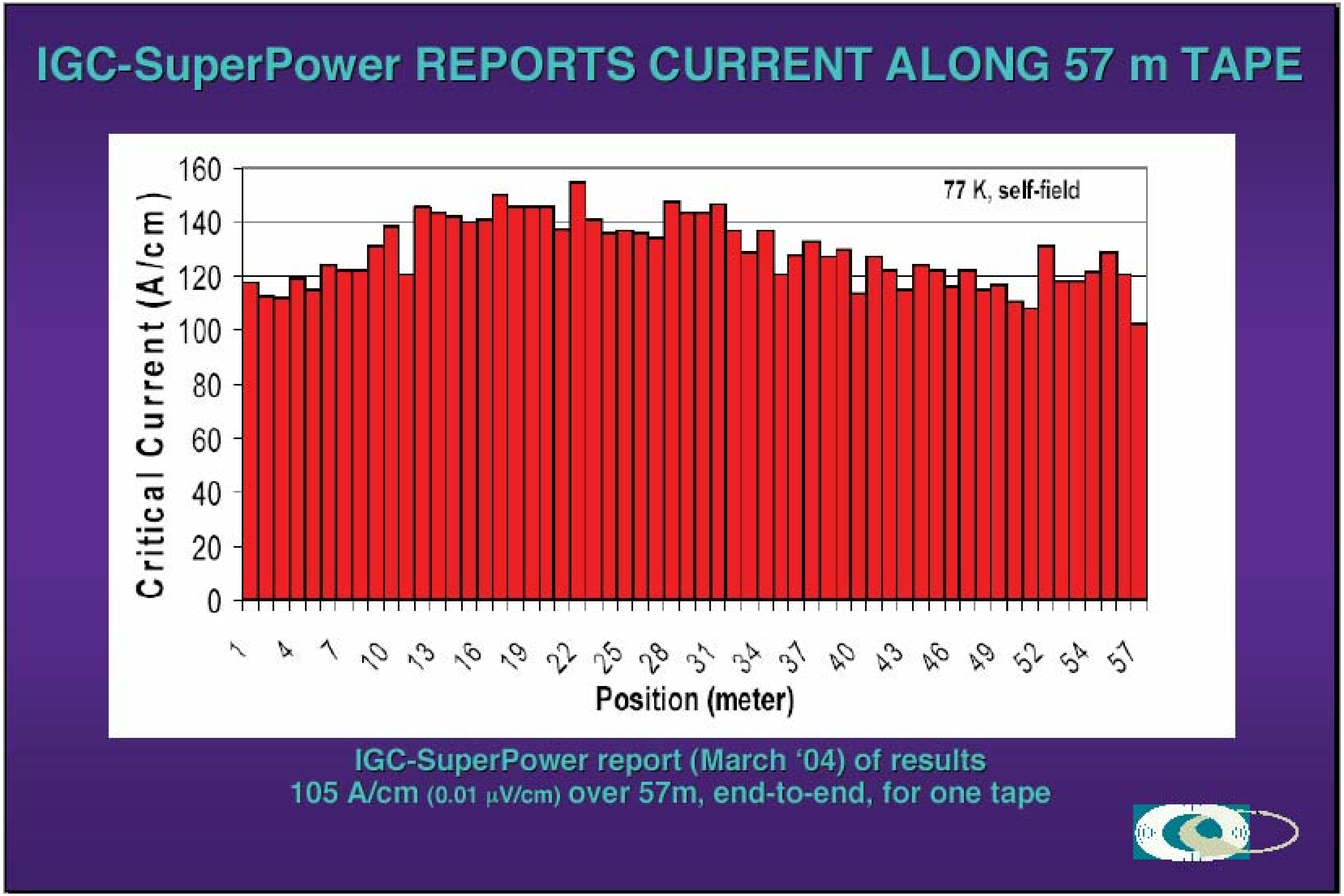
	American Superconductor		IGC-SuperPower
	Bi-2223 (gen 1)	REBaCuO (gen 2)	REBaCuO (gen 2)
some collaborators	ANL LANL U. of Wisconsin	ANL LANL ORNL SNL MIT U. of Wisconsin	ANL LANL

Stanford MgO IBAD

AMSC 1G (BSCCO-2223) Production Status

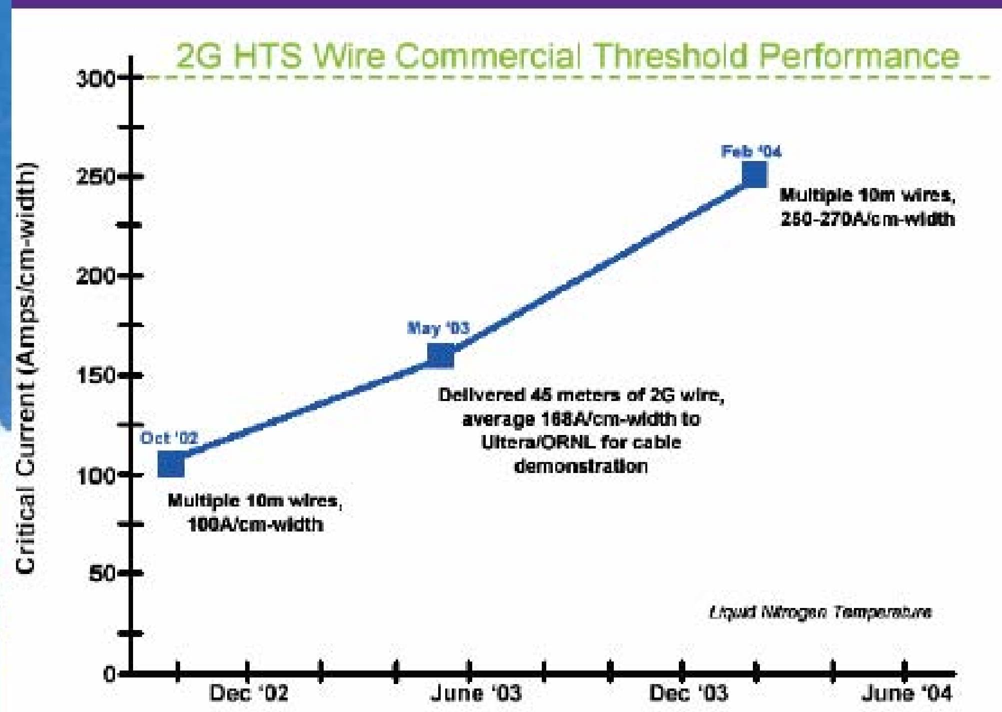


IGC-SuperPower Gen 2 MOCVD/IBAD Progress

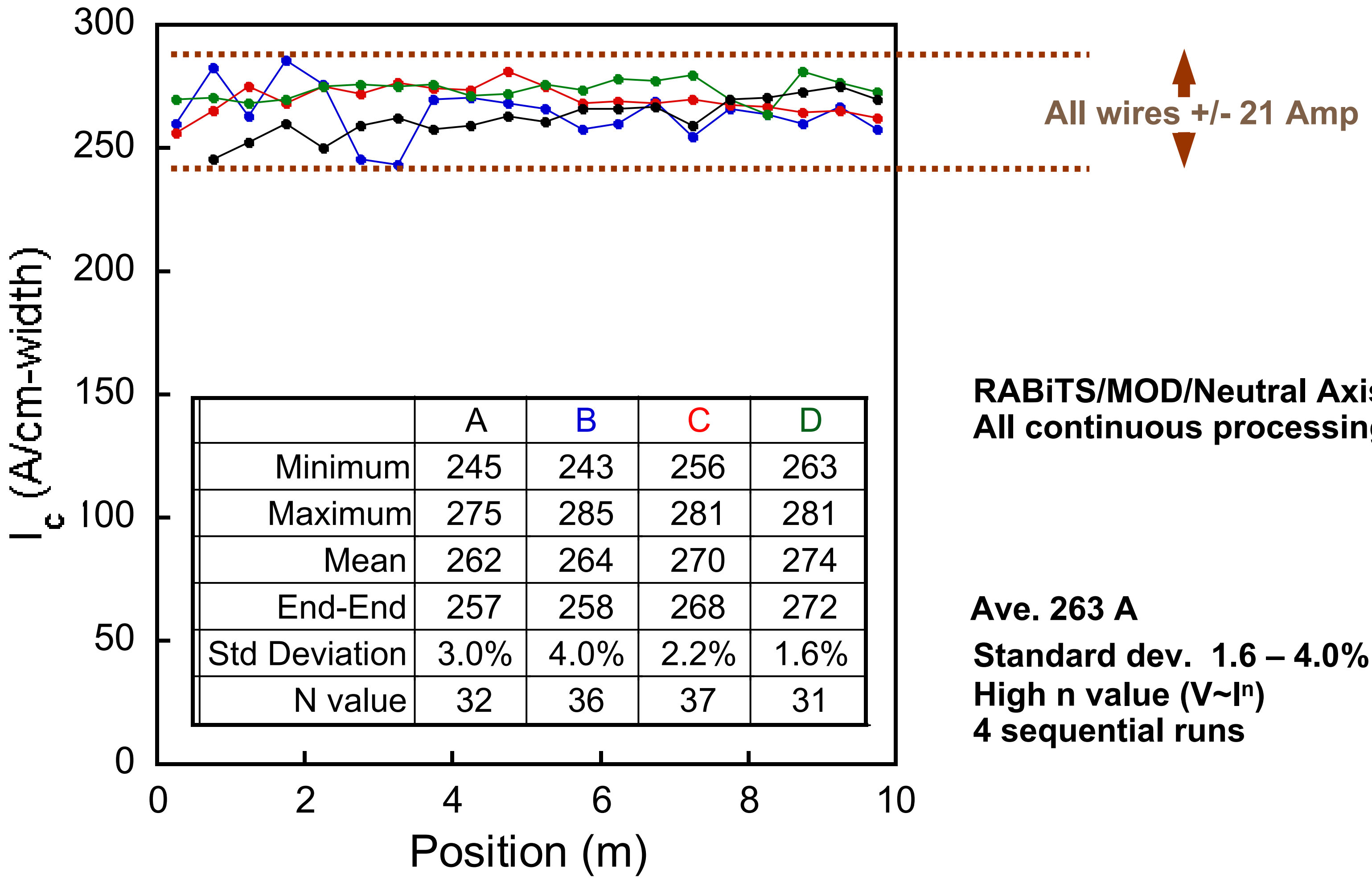


AMSC/ORNL/MIT Gen 2 "non-vacuum" Process

- RABiTS yields a textured metal substrate (Ni-W, Cu?)
- MOD adds buffer & conductor via liquid phase
- "nanodots" are added (proprietary process) to REBaCuO (Y_2O_3 $Y_2CU_2O_5$)



AMSC 2G RABiTS/MOD Status



	A	B	C	D
Minimum	245	243	256	263
Maximum	275	285	281	281
Mean	262	264	270	274
End-End	257	258	268	272
Std Deviation	3.0%	4.0%	2.2%	1.6%
N value	32	36	37	31

RABiTS/MOD/Neutral Axis
All continuous processing

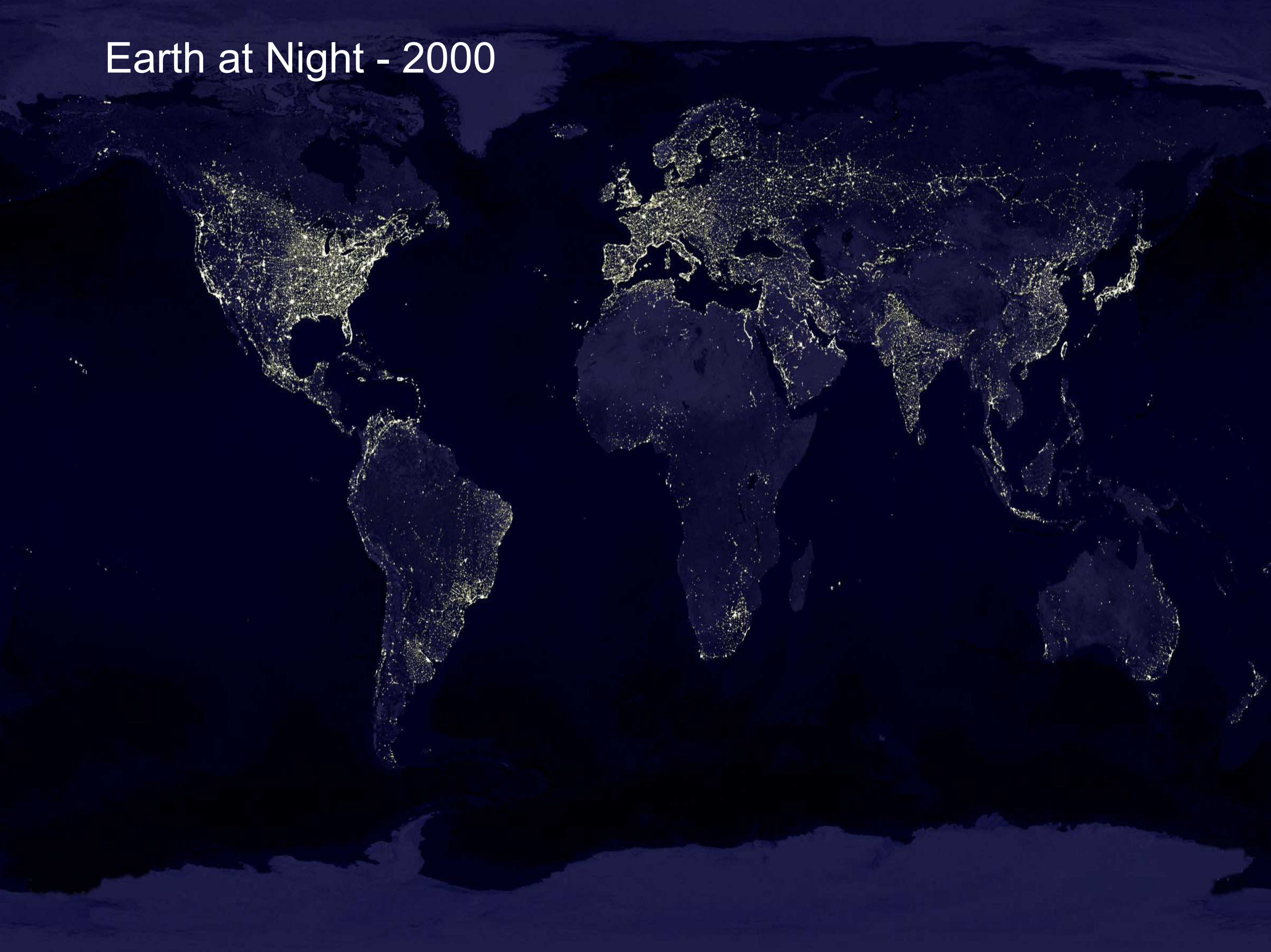
Ave. 263 A

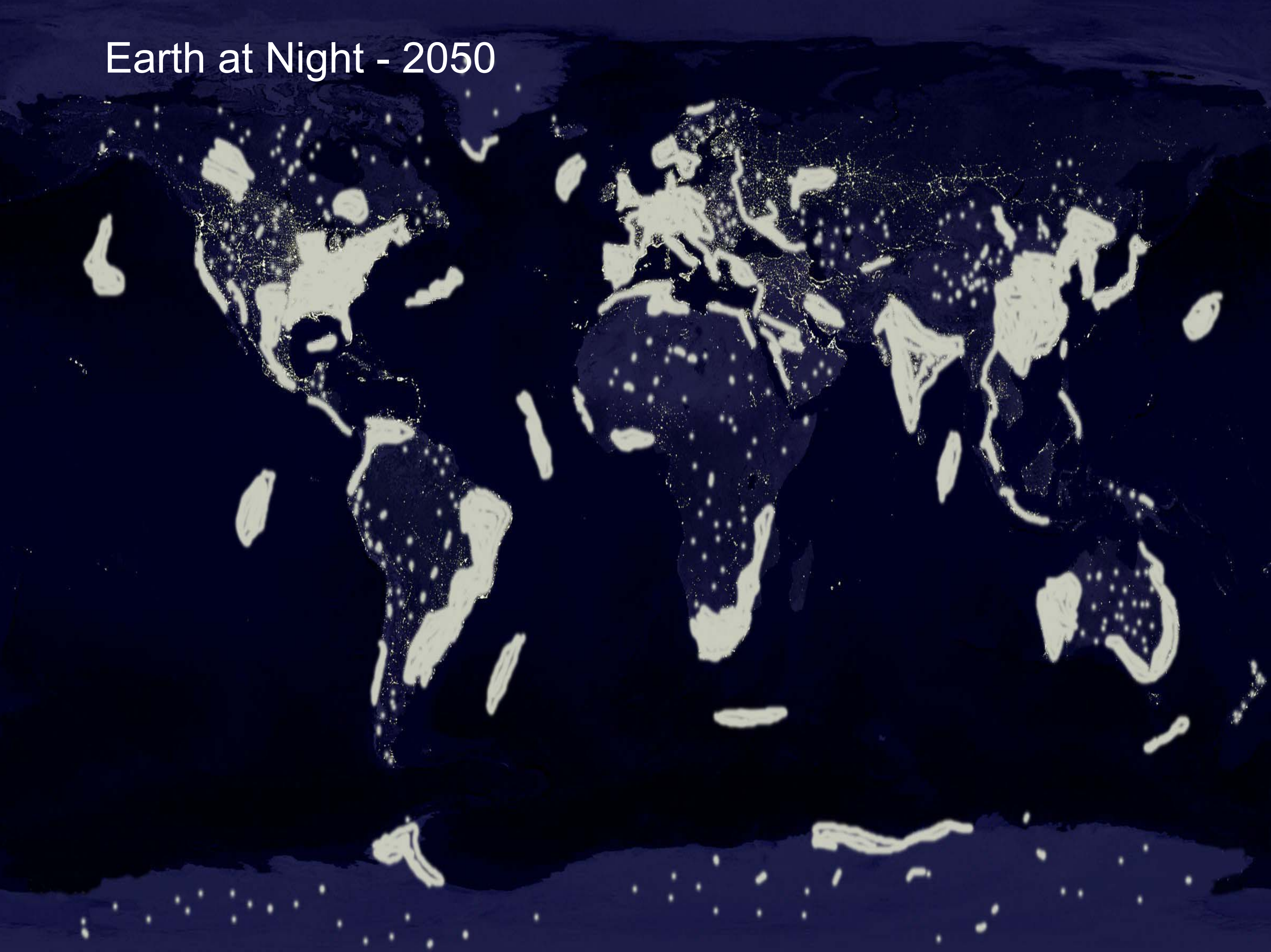
Standard dev. 1.6 – 4.0%
High n value ($V \sim I^n$)
4 sequential runs

The SuperGrid
An Energy Vision for the World of 2050

Chauncey Starr and Paul Grant

Earth at Night - 2000




Earth at Night - 2050




The 21st Century Energy Challenge

Design a communal energy economy to meet the needs of a densely populated industrialized world that reaches all corners of Planet Earth.

Accomplish this within the highest levels of environmental, esthetic, safe, reliable, efficient and secure engineering practice possible.

…without requiring any new scientific discoveries or breakthroughs!

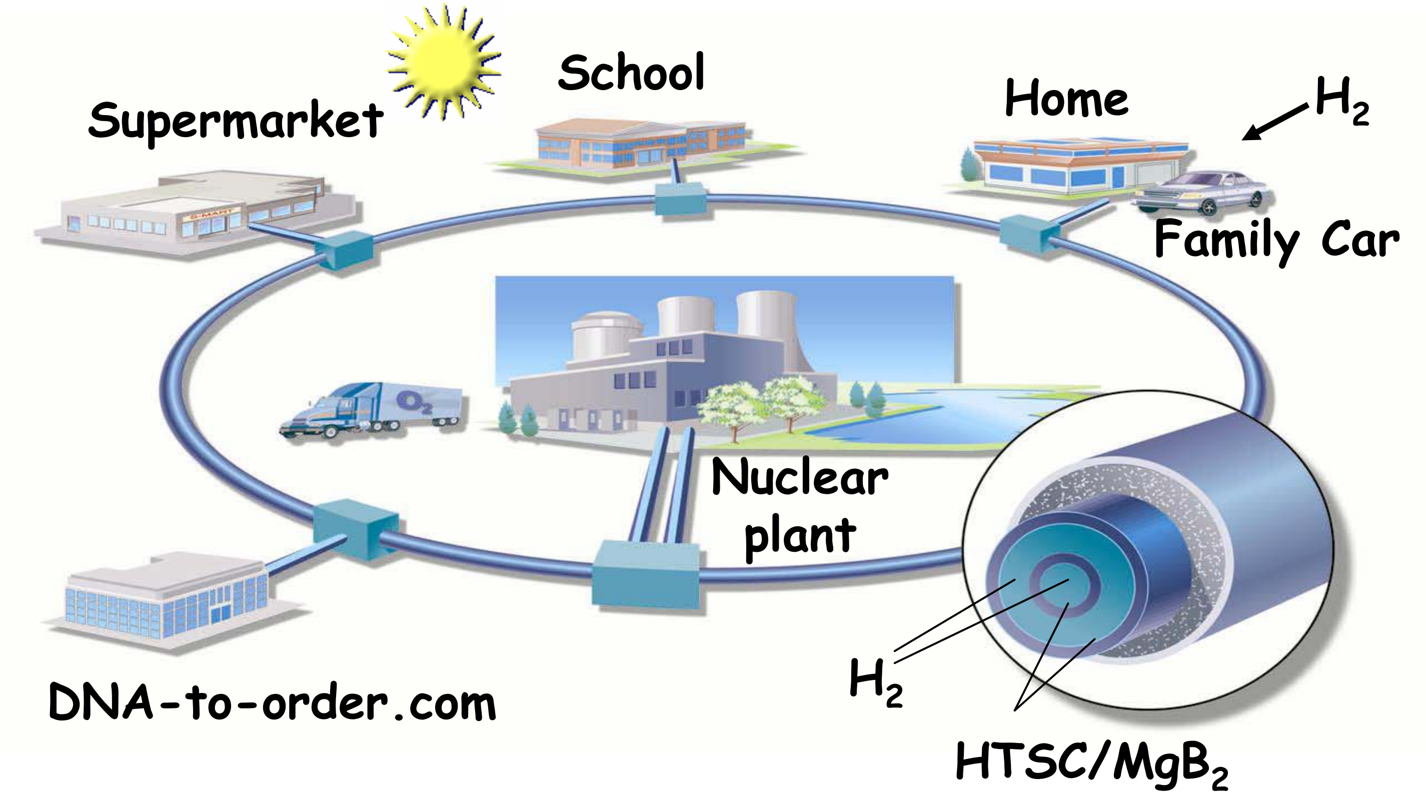
Its Solution

A Symbiosis of

Nuclear/Hydrogen/Superconductivity

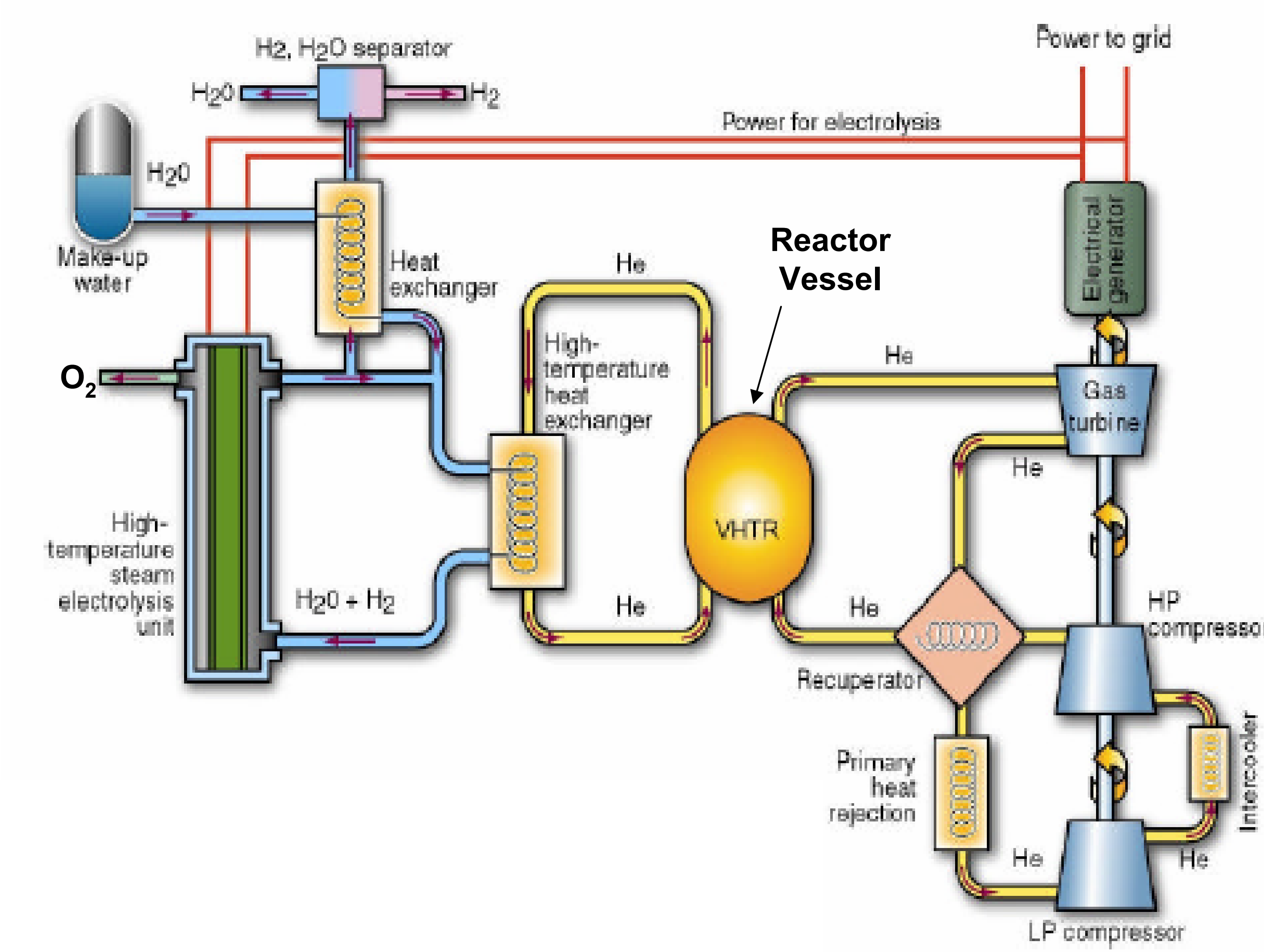
Technologies supplying Carbon-free, Non-Intrusive Energy for all Inhabitants of Planet Earth

SuperCity



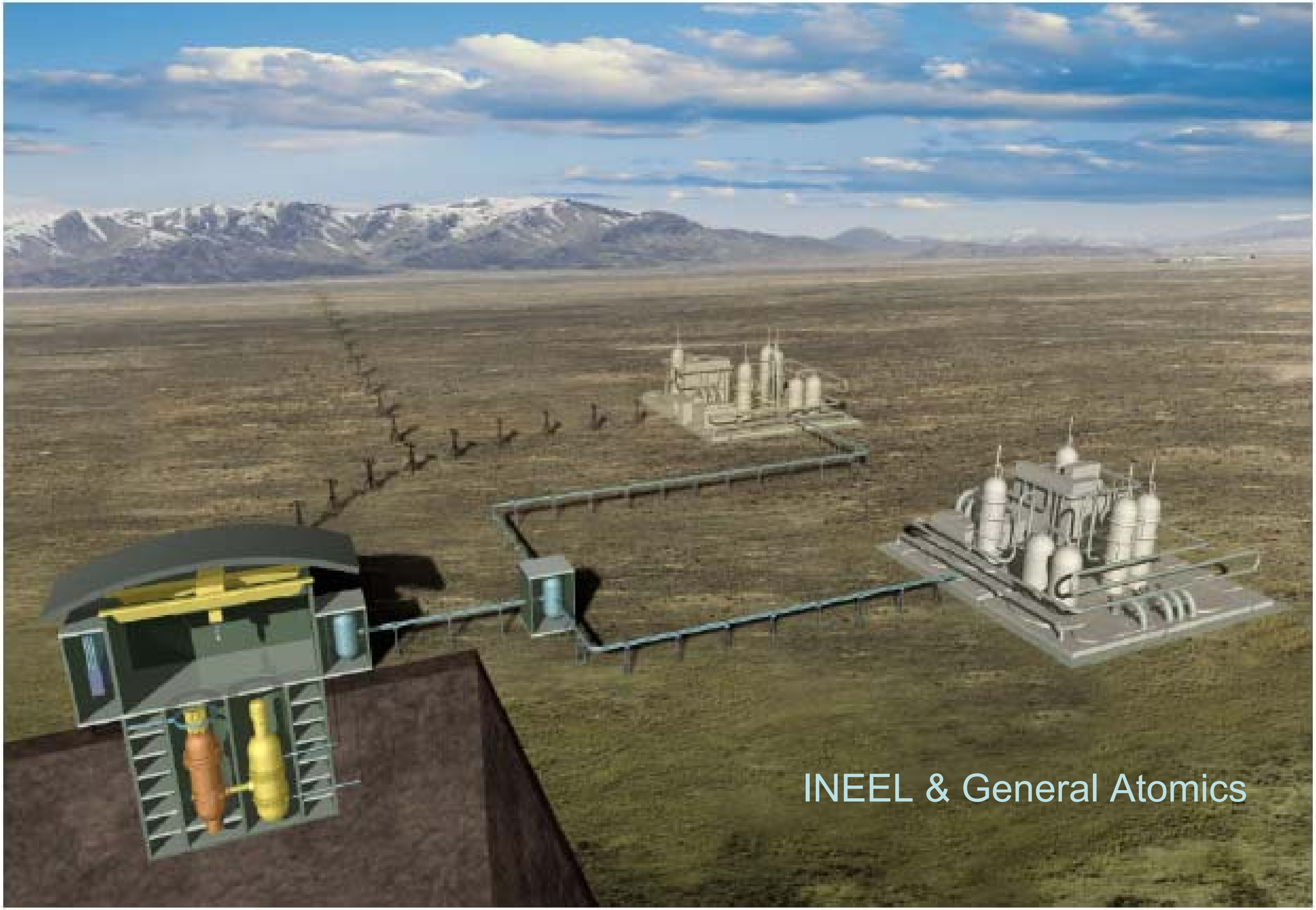
P.M. Grant, The Industrial Physicist, Feb/March Issue, 2002

Co-Production of Hydrogen and Electricity

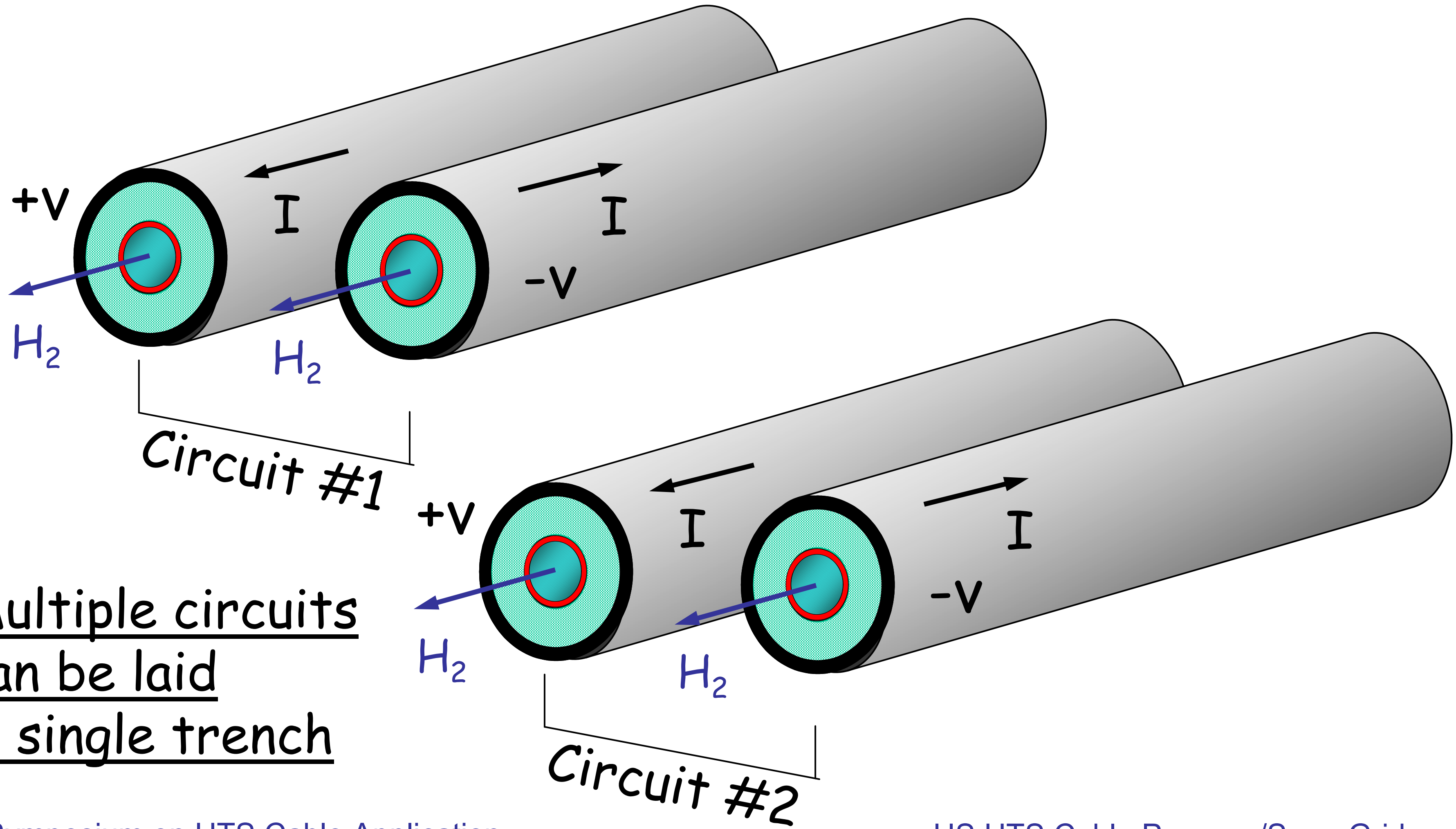


Source: INEL & General Atomics

Nuclear "Hydricity" Production Farm

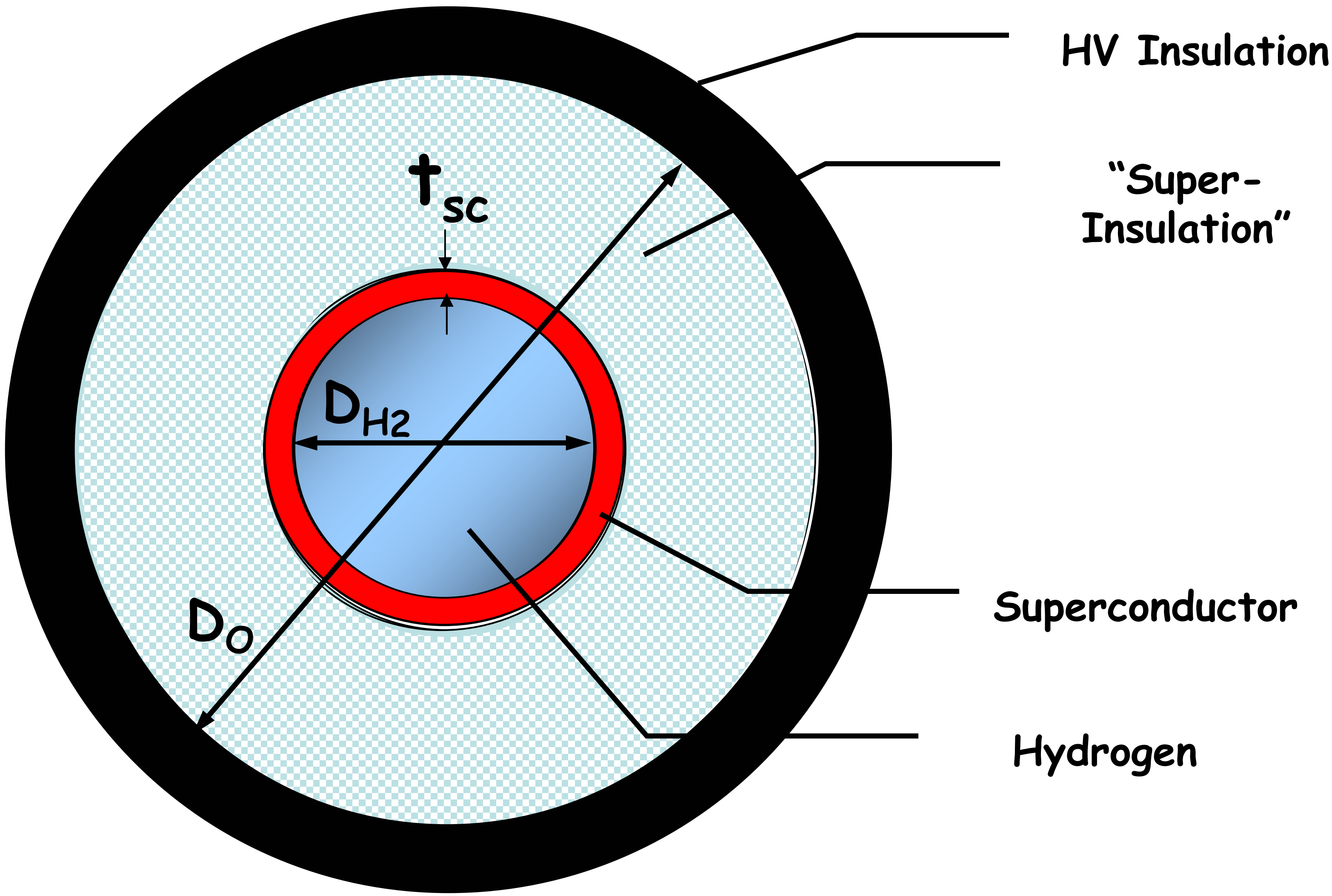


"Hydricity" SuperCables



Multiple circuits
can be laid
in single trench

SuperCable Monopole



Power Flows

Electricity

$P_{SC} = 2|V|IA_{SC}$, where

P_{SC} = Electric power flow
V = Voltage to neutral (ground)
I = Supercurrent
A_{SC} = Cross-sectional area of superconducting annulus

Hydrogen

$P_{H2} = 2(Q\rho vA)_{H2}$, where

P_{H2} = Chemical power flow
Q = Gibbs H_2 oxidation energy (2.46 eV per mol H_2)
ρ = H_2 Density
v = H_2 Flow Rate
A = Cross-sectional area of H_2 cryotube

Electric & H_2 Power

Electricity

Power (MW)	Voltage (V)	Current (A)	Critical Current Density (A/cm^2)	Annular Wall Thickness (cm)
1000	+/- 5000	100,000	25,000	0.125

Hydrogen (LH_2, 20 K)

Power (MW)	Inner Pipe Diameter, D_{H2} (cm)	H_2 Flow Rate (m/sec)	"Equivalent" Current Density (A/cm^2)
500	10	3.81	318

Thermal Losses

$W_R = 0.5\varepsilon\sigma\,(T^4_{amb} - T^4_{SC})$, where

W_R = Power radiated in as watts/unit area
$\sigma = 5.67\times10^{-12}$ W/cm^{2}K^4
T_{amb} = 300 K
T_{SC} = 20 K
ε = 0.05 per inner and outer tube surface
D_{SC} = 10 cm

W_R = 3.6 W/m

Radiation Losses

Superinsulation: $W_R^f = W_R/(n-1)$, where

n = number of layers

Target: W_R^f = 0.5 W/m requires ~10 layers

Other addenda (convection, conduction): W_A = 0.5 W/m

$W_T = W_R^f + W_A$ = 1.0 W/m

Heat Removal

$dT/dx = W_T/(\rho v C_P A)_{H2}$, where

dT/dx = Temp rise along cable, K/m
W_T = Thermal in-leak per unit Length
ρ = H_2 Density
v = H_2 Flow Rate
C_P = H_2 Heat Capacity
A = Cross-sectional area of H_2 cryotube

Take W_T = 1.0 W/m, then $dT/dx = 1.89\times10^{-5}$ K/m,
Or, 0.2 K over a 10 km distance

Remaining Issues

Current stabilization via voltage control

- AC interface (phases)
- Ripple suppression
- Charge/Discharge cycles

Remaining Issues

Power Electronic Discretes

- GTOs vs IGBTs
- 12” wafer platforms
- Cryo-Bipolars
  - Minority carrier concentration
  - Doping profiles

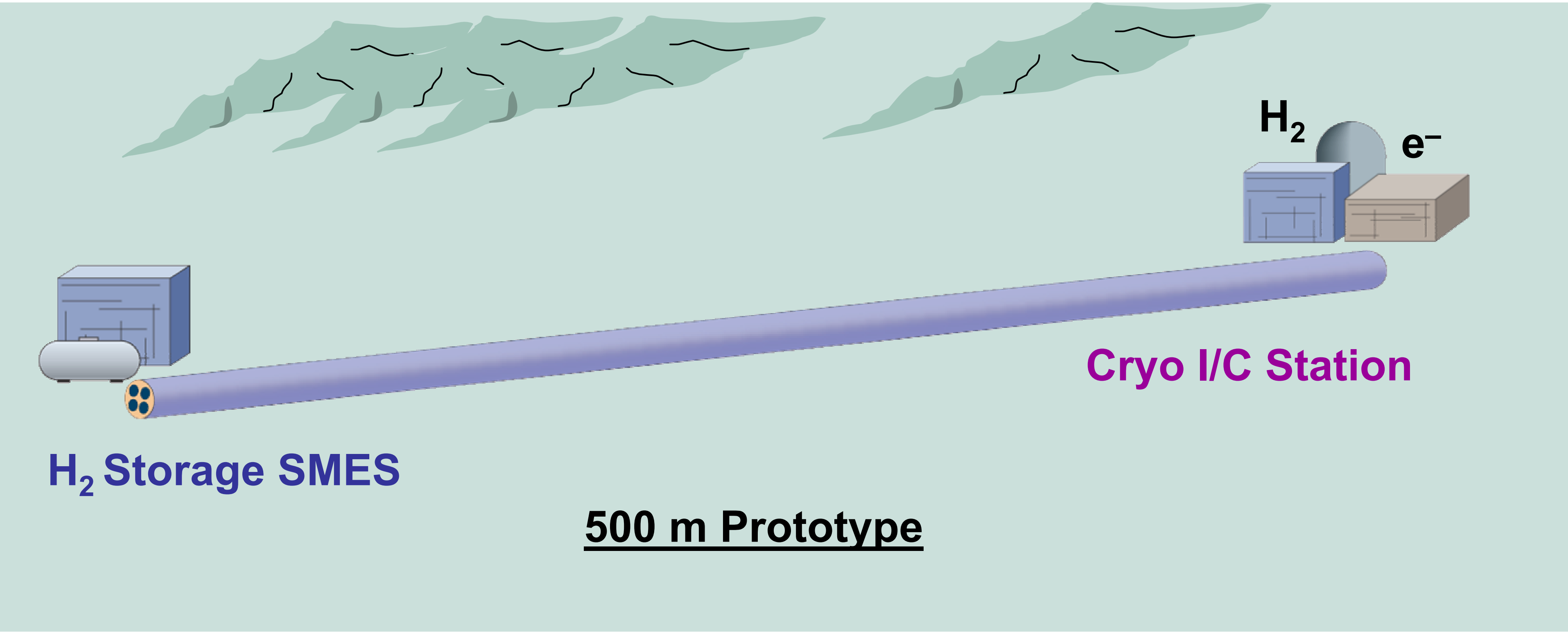
SuperCable H_2 Storage

Some Storage Factoids	**Power (GW)**	**Storage (hrs)**	**Energy (GWh)**
TVA Raccoon Mountain	1.6	20	32
Alabama CAES	1	20	20
Scaled ETM SMES	1	8	8

One Raccoon Mountain = 13,800 cubic meters of LH2

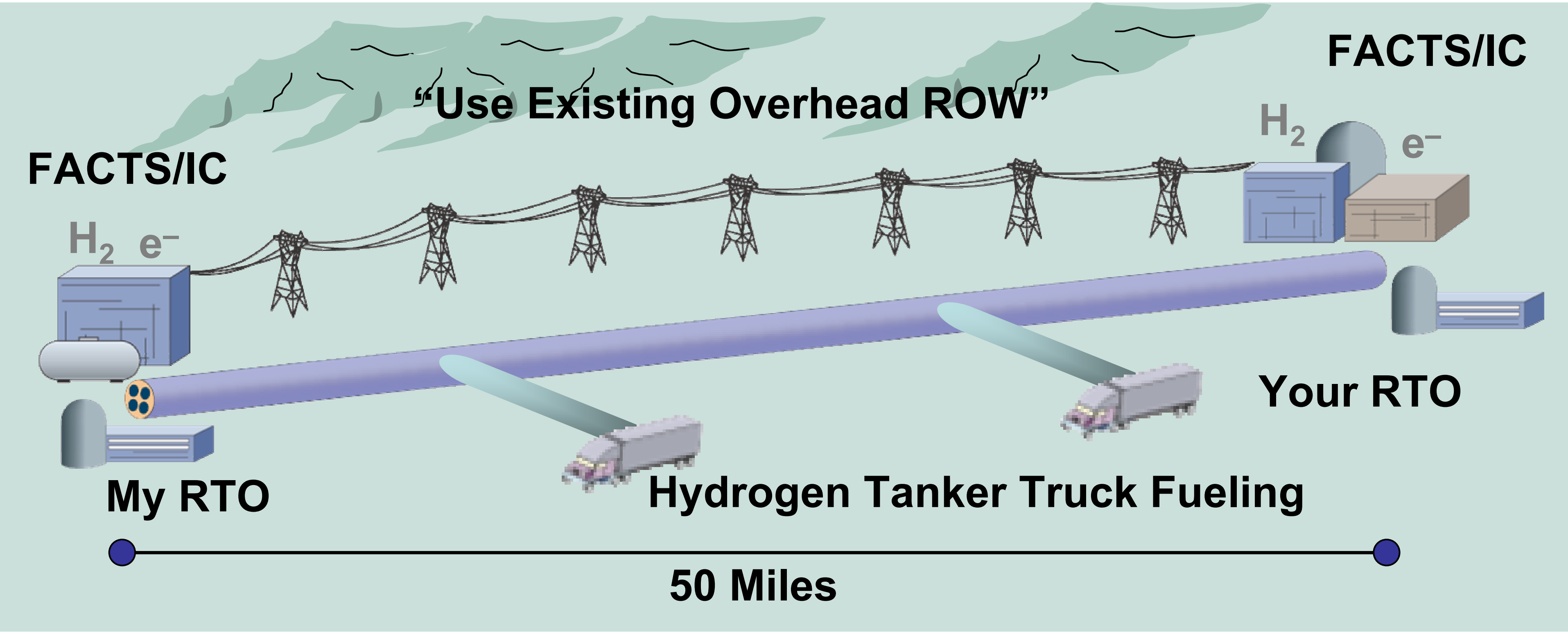
LH_2 in 10 cm diameter, 250 mile bipolar SuperCable
= Raccoon Mountain

SuperCable Prototype Project

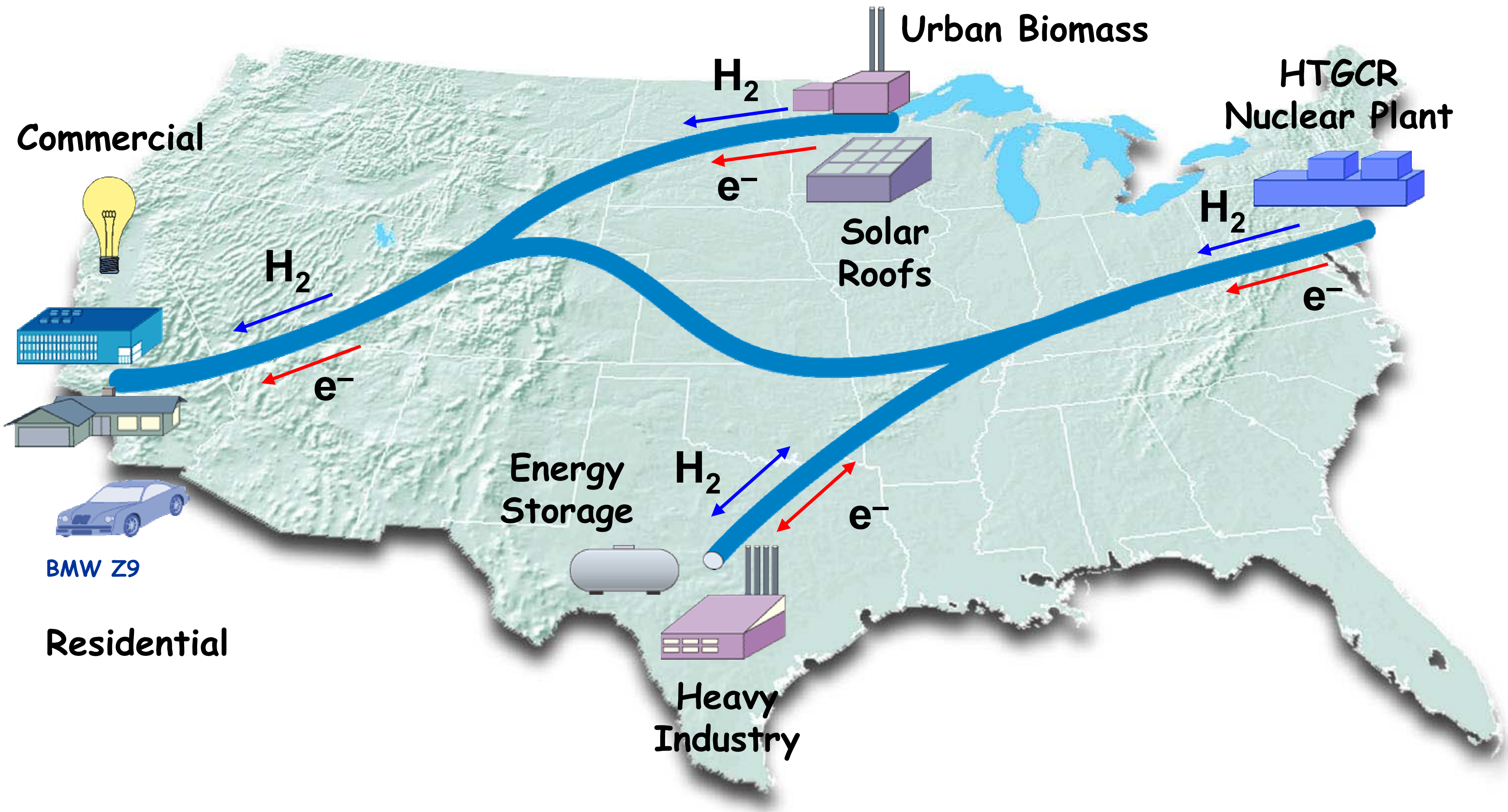


"Appropriate National Laboratory"
2005-09

RegionGrid Interconnection



North American 21st Century Energy SuperGrid



The Energy SuperGrid

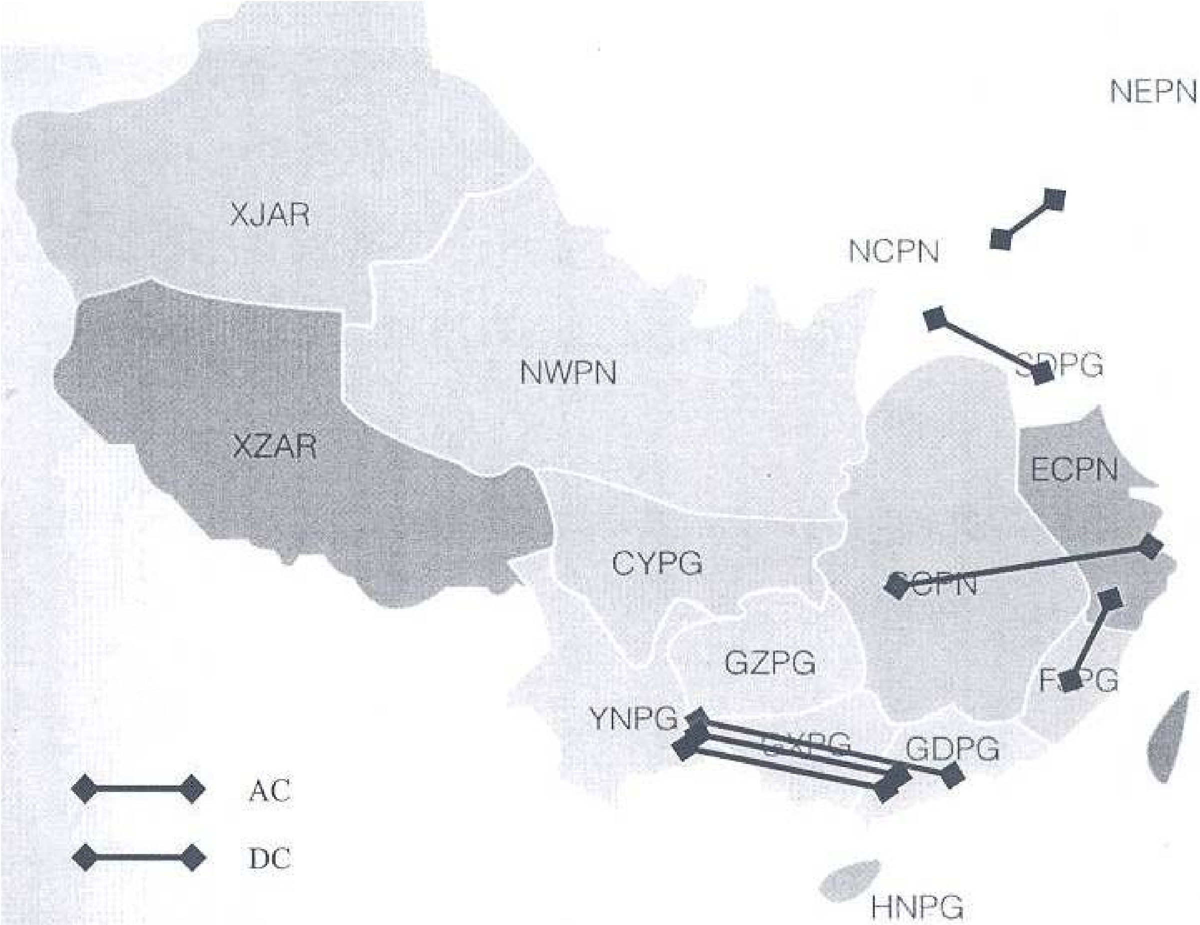
http://www.energy.ece.uiuc.edu/supergrid.htm.

A Workshop Sponsored by
The Lounsbery Foundation
&
EPRI

25 – 27 October 2004

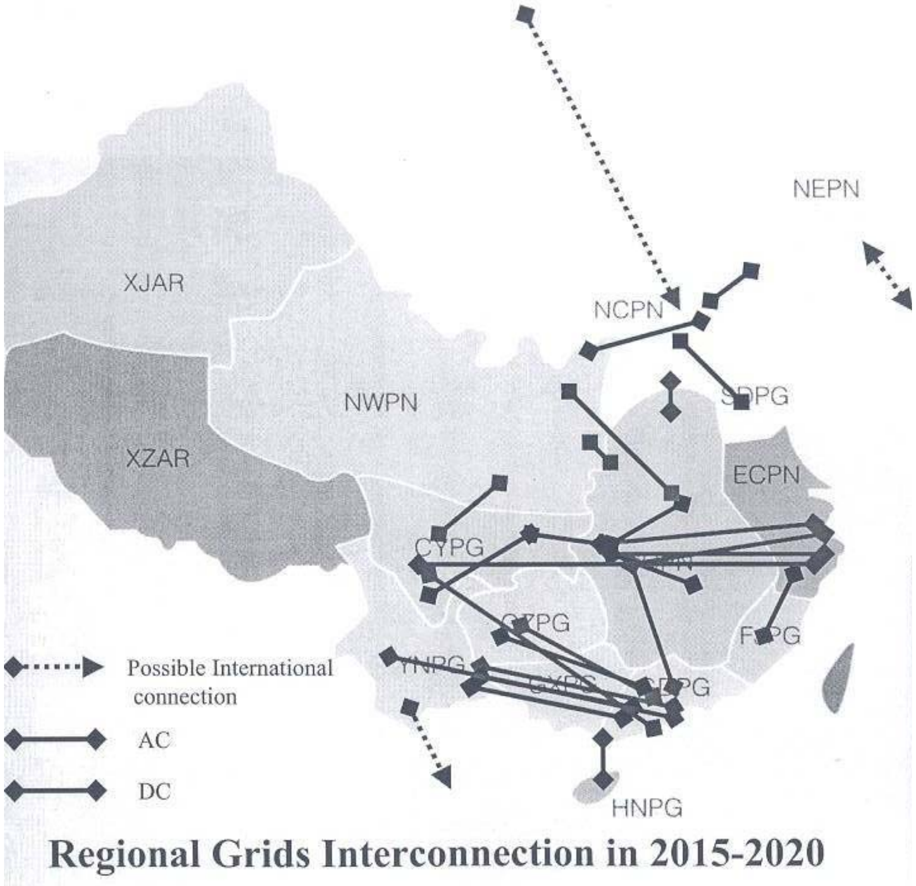
University of Illinois, Urbana – Champaign
Contact Tom Overbye for Details

China: Present



Regional Grids Interconnection in 2001-2002

China: 2015 - 2020



Will China Build the World's First SuperGrid?

"You can't always get what you want…"

"…you get what you need!"