Plain Talk about the Electric Power System

23-25 January 2007
Oglethorpe Power, Atlanta, GA

Advanced Transmission Technologies

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http://www.w2agz.com/pes07.htm

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Advanced Transmission Technologies

- Power Electronics
  - EE 101
  - Applications to FACTS, HVDC and Custom Power
- Superconductivity in Power Applications
  - Background Physics
  - Transformers, FCLs, Rotating Machinery
- The SuperGrid Vision
  - Nuclear + Hydrogen + Superconductivity

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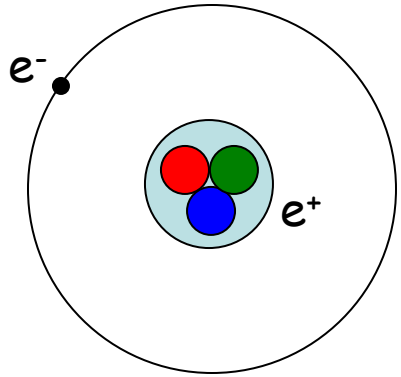
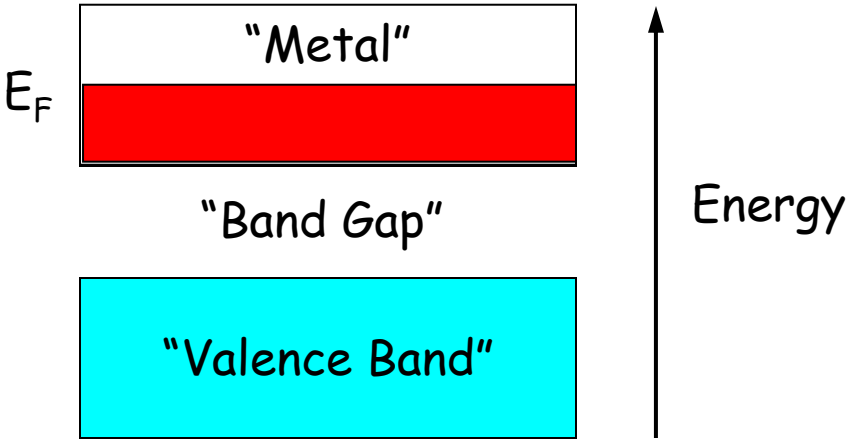
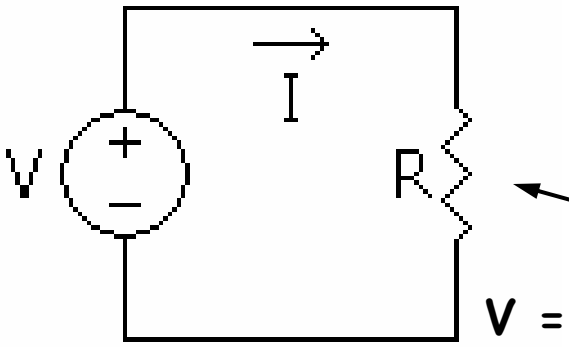
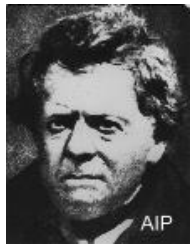
Physics of Electricity



Protium ^1H



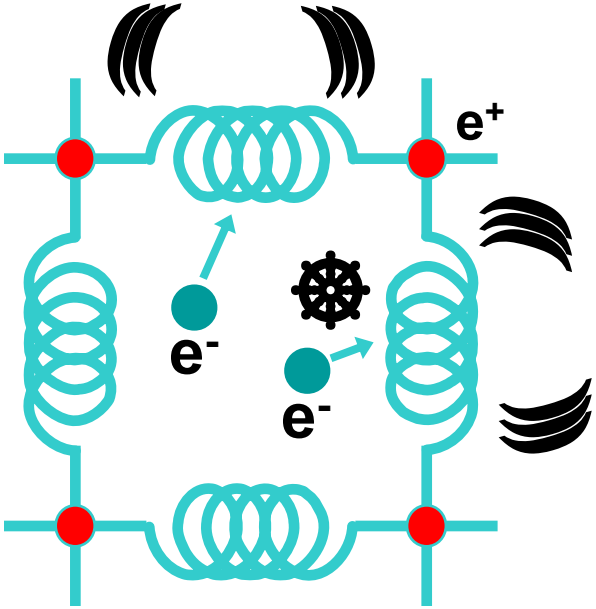




"Ohm's Law"

$V = I\,R(I,T)$

$P = I^2R$



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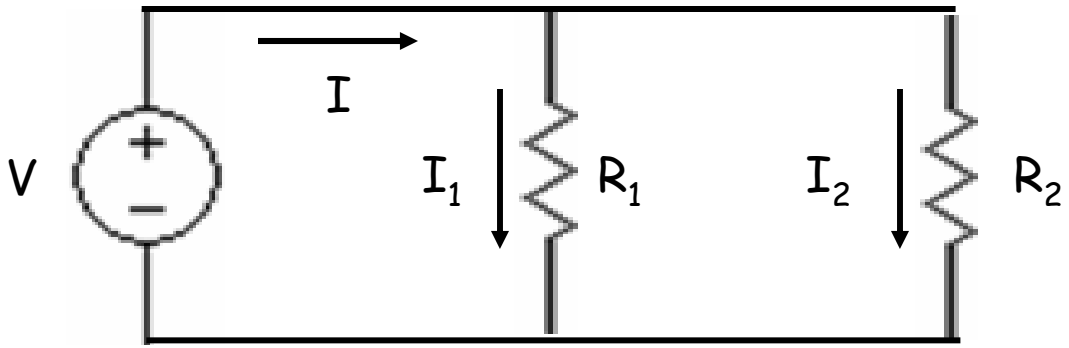
The Path of Least Resistance

A microcosm of the American Grid



If $R_1 > R_2$, Then $I_2 > I_1$ (Kirchoff's Law)

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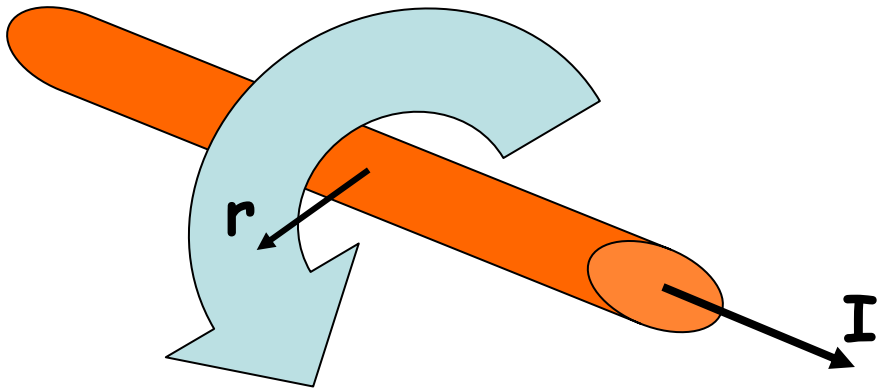
Those Magnetic Moments

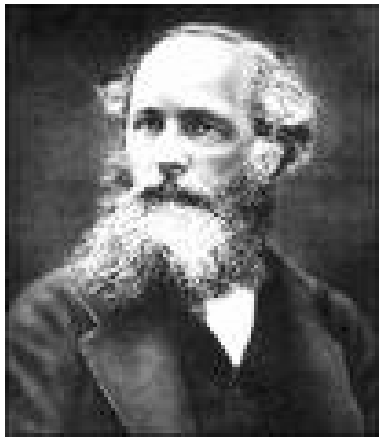
Ampere's Law



$$B \approx I/r$$

$$\nabla \cdot \mathbf{E} = 4\pi\rho$$
$$\nabla \cdot \mathbf{B} = 0$$
$$\nabla \times \mathbf{E} = -\frac{1}{c}\frac{\partial \mathbf{B}}{\partial t}$$
$$\nabla \times \mathbf{B} = \frac{1}{c}\frac{\partial \mathbf{E}}{\partial t} + \frac{4\pi}{c}\mathbf{J}$$

Maxwell's Equations



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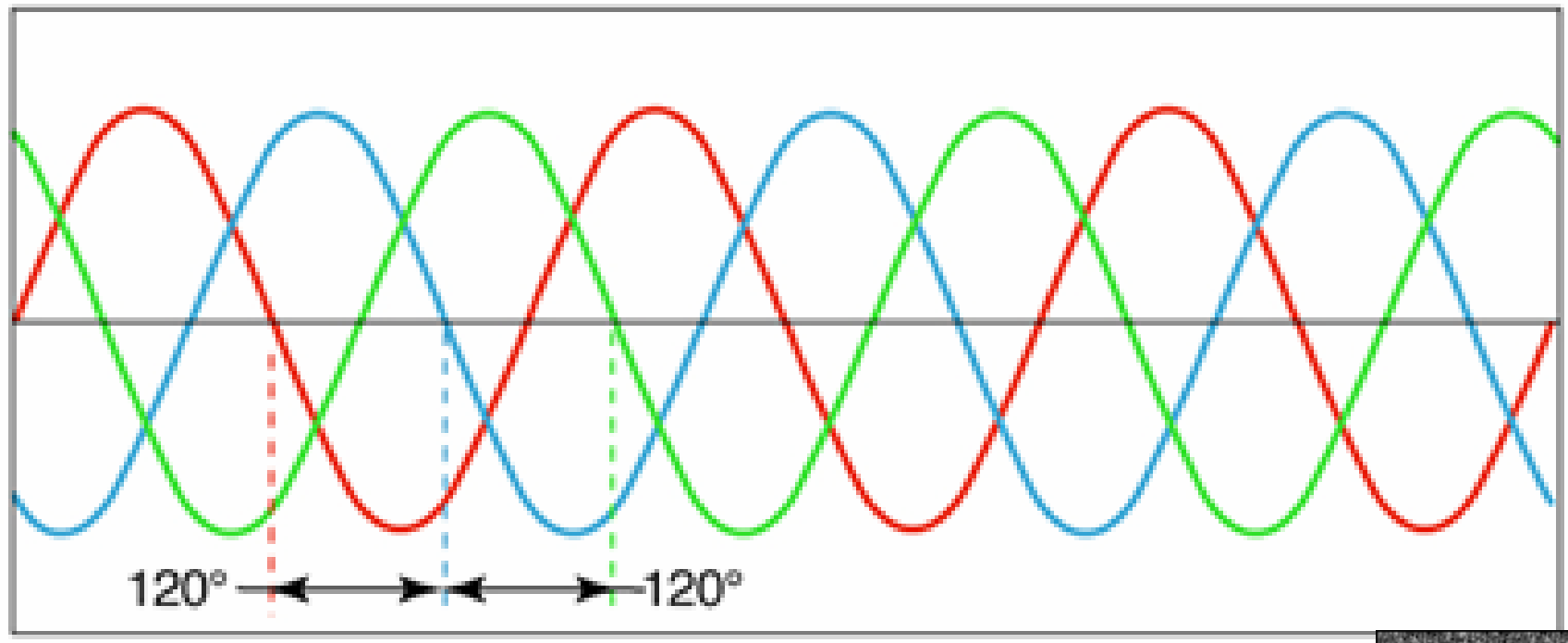
The Genius of Nicola Tesla: Alternating Current



The Polyphase ac System: Invented by Nicola Tesla to enable his concept of synchronous motors and generators, now used throughout the electrified world.

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ac and dc "The Story"

- Edison vs. Tesla
- ac won because ac can be transmitted with lower losses at high voltages, reducing I^2R dissipation
- dc is difficult to transform from a low voltage to a high voltage and back
- But maybe Edison won in the long run

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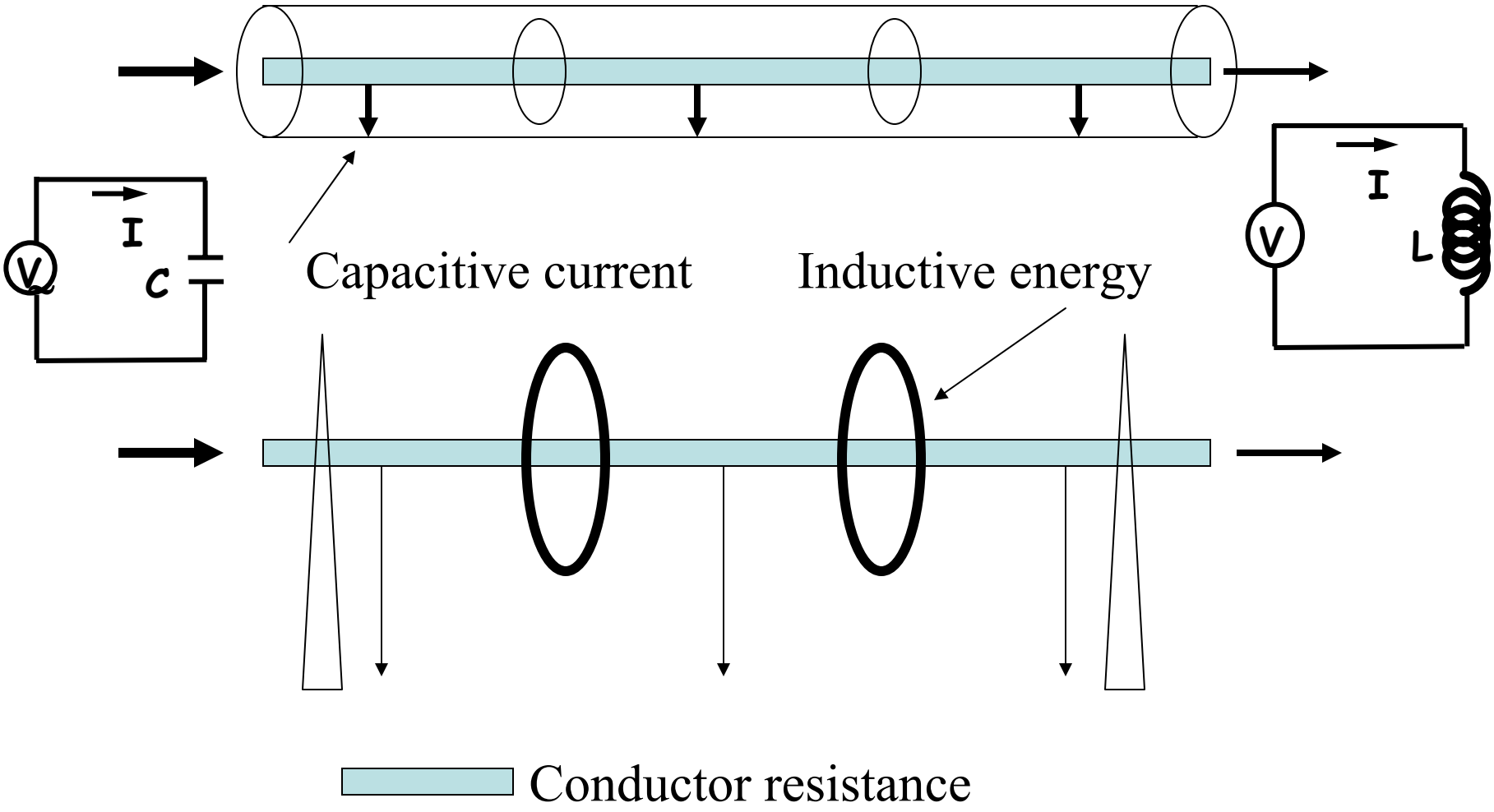
Cables & Lines



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Mechanical/Electrical Analogies

Mechanical	Electrical
Force/Pressure (F, P)	Voltage (V)
Velocity (v)	Current (A)
Friction (f)	Resistance (R)
Compliance (k)	Capacitance (C) (~ 1/k)
Inertia (Mass, m)	Inductance (L)
F = fv	V = IR (Ohm's Law)
P = Fv	$P = VI = I^2R = V^2/R$

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Physics of Power Flow

- dc transmission limited by V and R
- ac transmission limited by V and R and also the energy stored and released by associated electric (C) and magnetic (L) fields
  - Capacitive reactance limits length of underground cables to 20 – 30 miles
  - Inductive reactance and radiation limits length of overhead lines to $\lambda/4$ = 775 miles at 60 Hz

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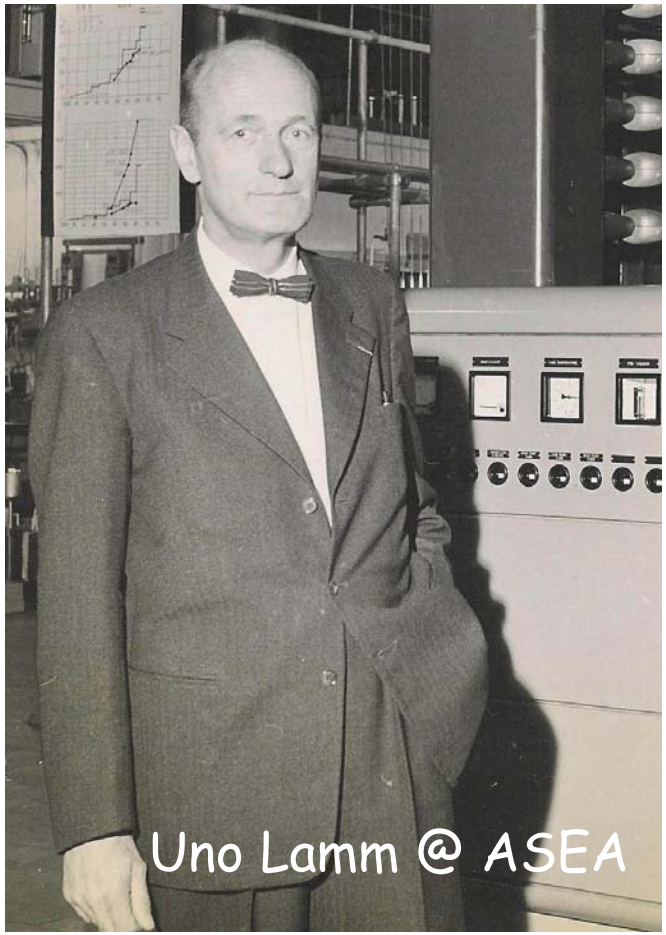
High Voltage dc

"Thyratrons"



Anode Porcelains & Mercury Cathode Tank

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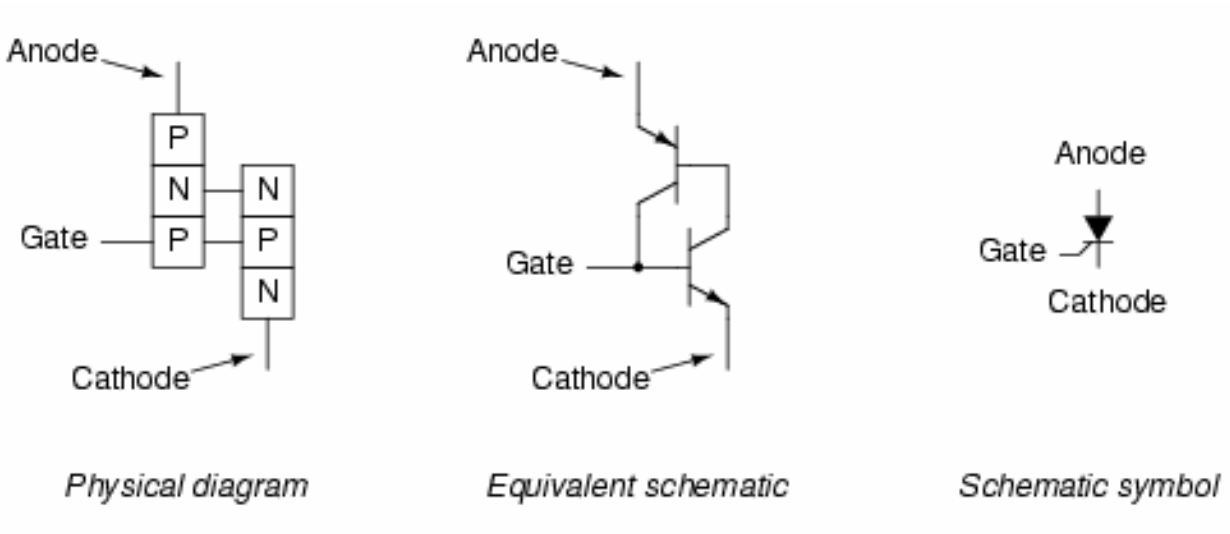
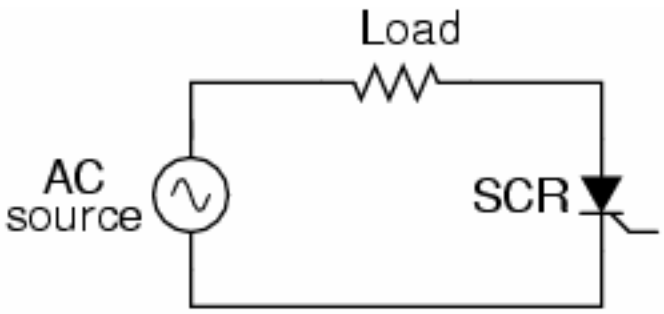
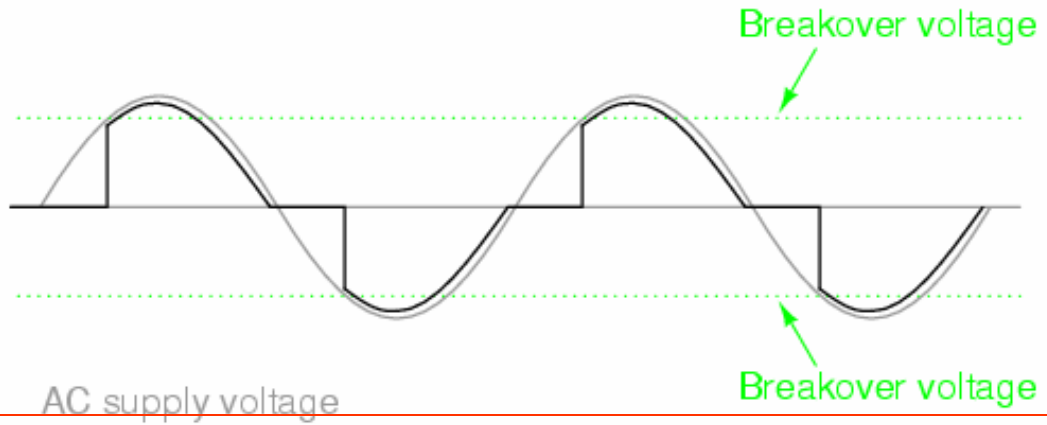
Thyristors, etc.







Thyristor-like discretes are the "pentiums" of all HVDC, FACTS and custom power applications

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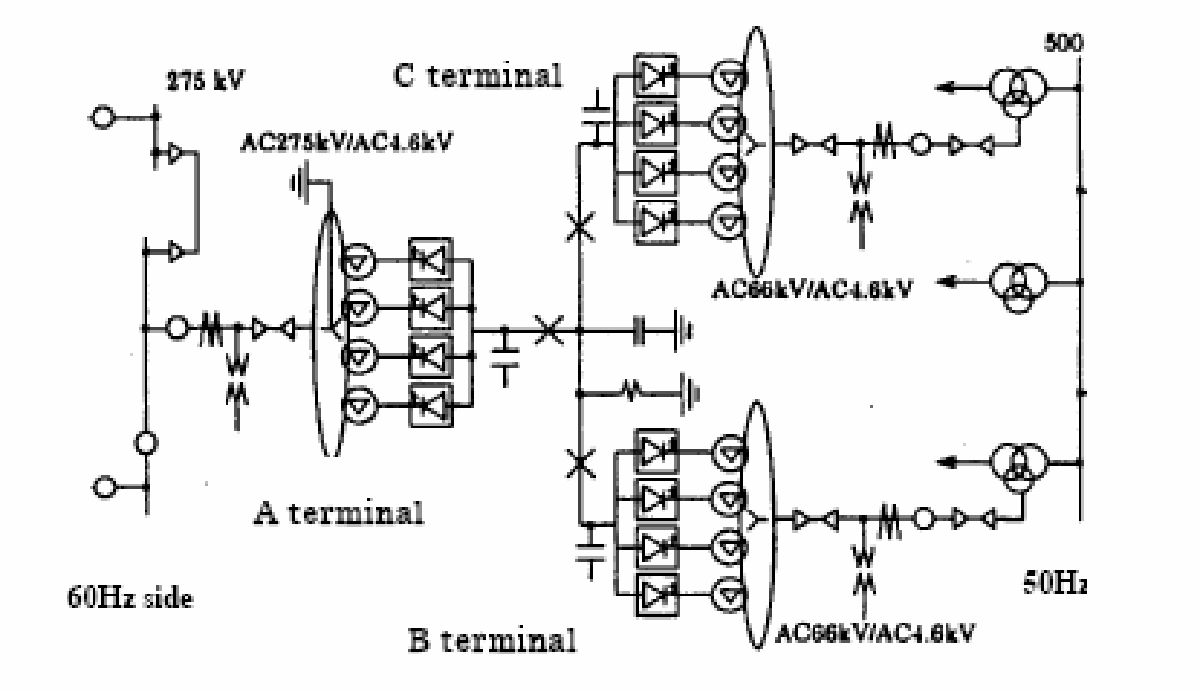
Application: BTB in Japan



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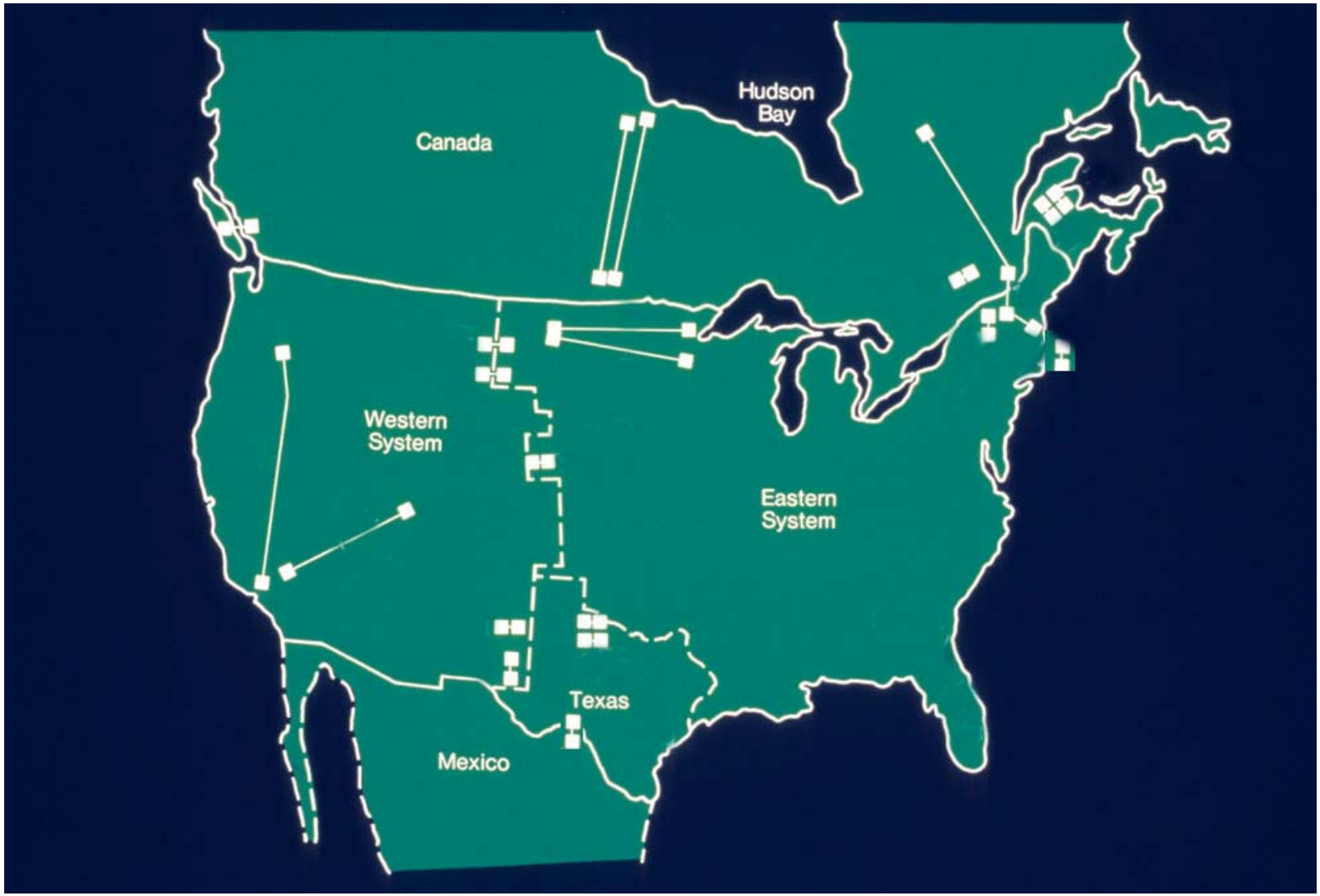
North American HVDC



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EMPIRE CONNECTION

Specifications

2-1000 MW HVDC Bipolar Circuits

- Circuit 1: 130 miles, Greene County → Bronx County
- Circuit 2: 140 miles, Albany County → New York County
- Each Circuit: +/- 500 kV, 1000 A Bipolar (2 cables ea.)

Financials

$750 M ($400 M "VC", $350 M "Futures")

Loan Payment (4%, 40 yrs, 750 M$) =	35 M$/yr
Labor, Overhead, Maintenance =	5 M$/yr
Tariff =	0.5 ¢/kWh
Profit (NOI) @ 50% Capacity =	4 M$/yr
Profit (NOI) @ Full Capacity =	48 M$/yr

Why didn't it go forward?

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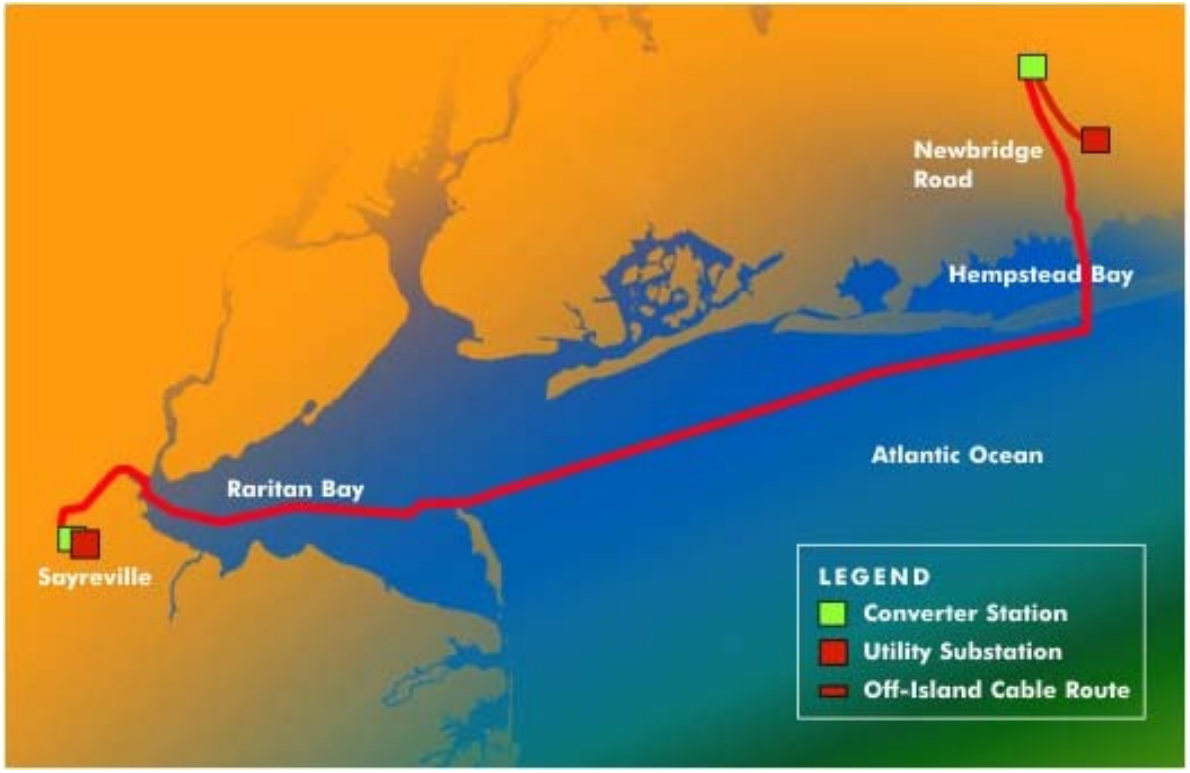
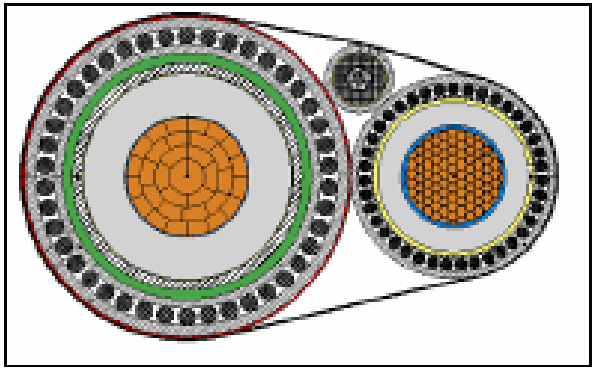
NEPTUNE Regional Transmission System™





HVDC Cable Cross-Section

Pirelli (Prysmian) Energy Cables

$190 M

Sayerville, NJ → Levittown LI, NY

- **600 MW (+/- 250 kV, 1200 A)**
- **65 miles (105 km)**
- **$400 M**
- **2007**

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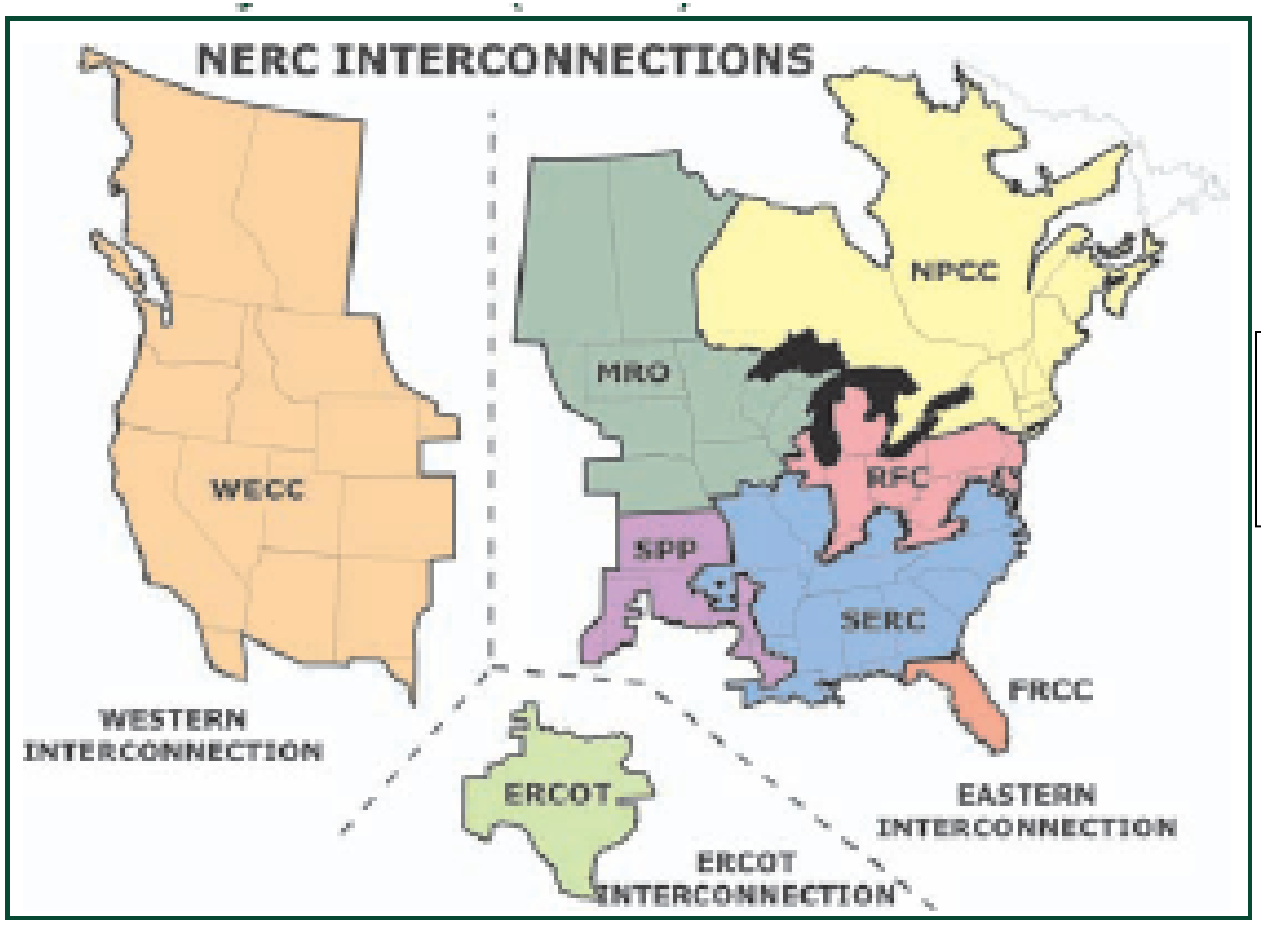
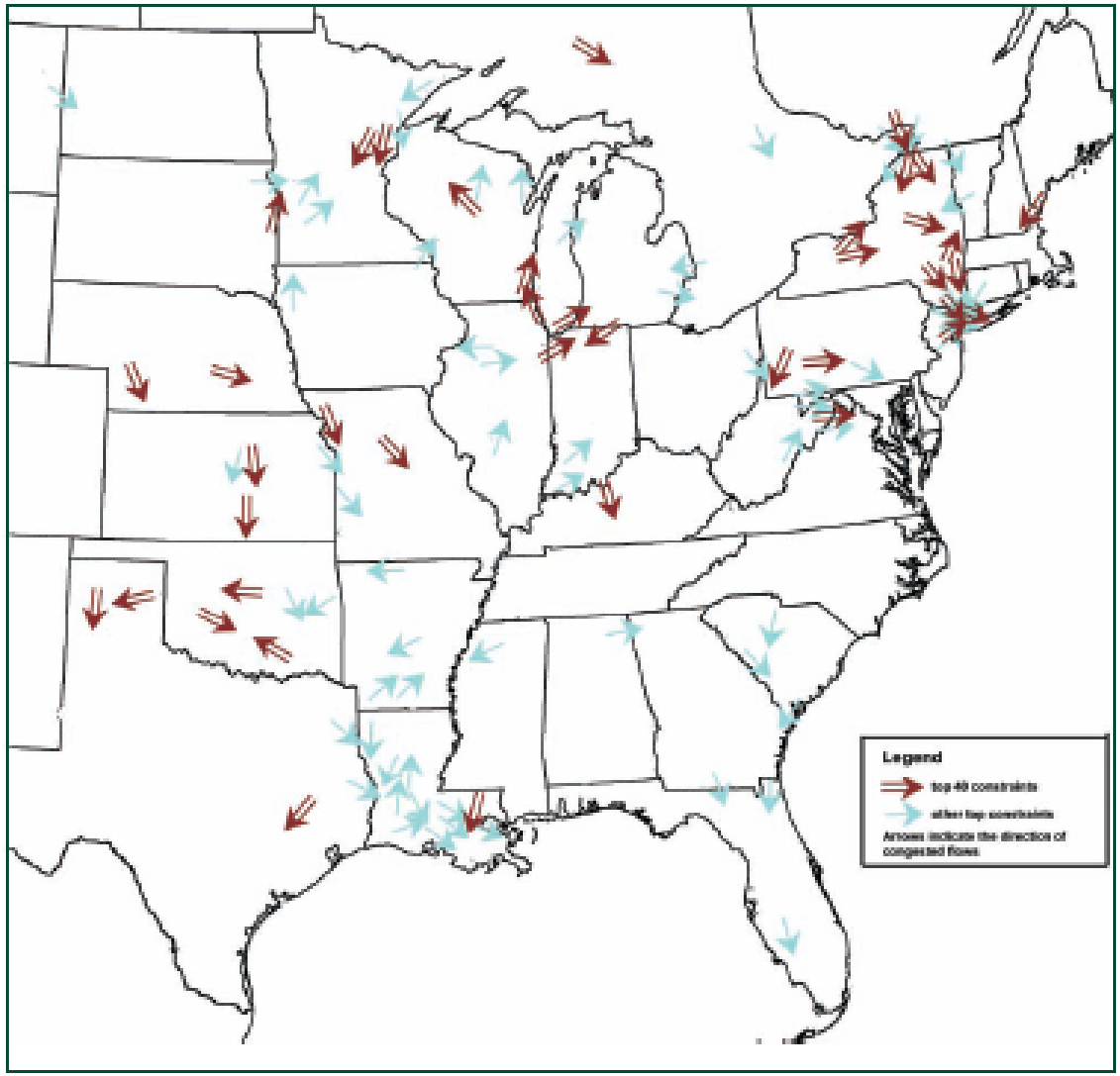
NERC Interconnects



Source: DOE 2006 National Electric Transmission Study

Projected 2008 Congested Paths in the Eastern Interconnection



Source: DOE 2006 National Electric Transmission Study

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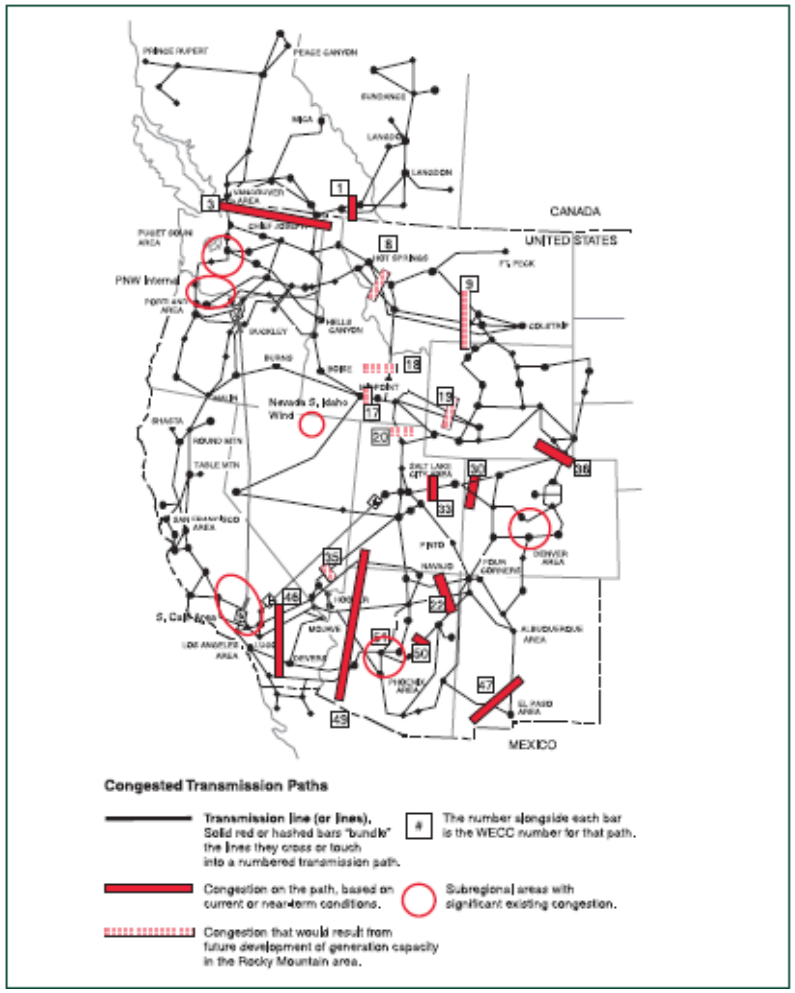
Western Interconnection



Source: DOE 2006 National Electric Transmission Study

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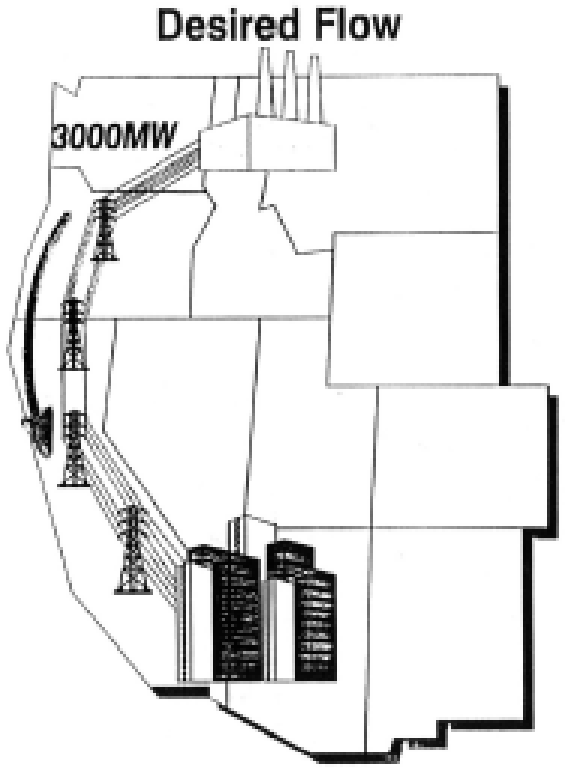
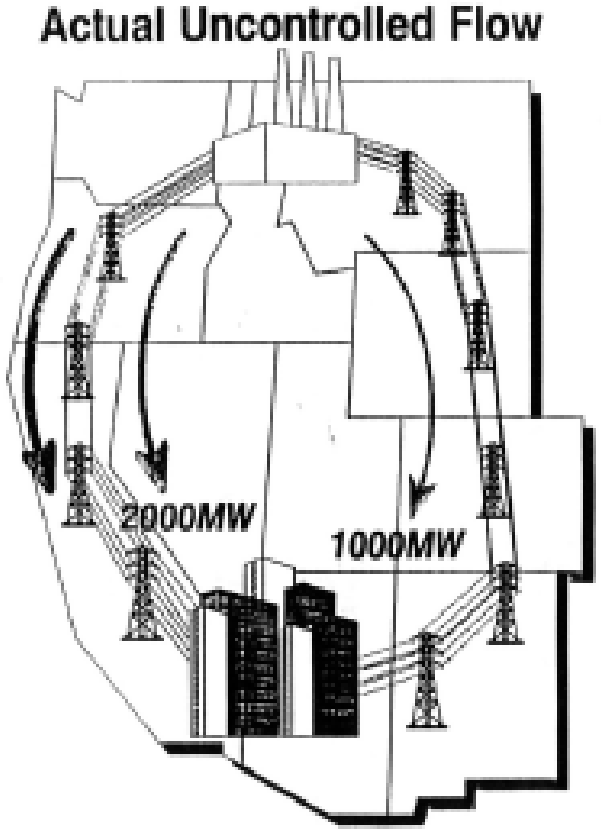
Real-Life Power Flows





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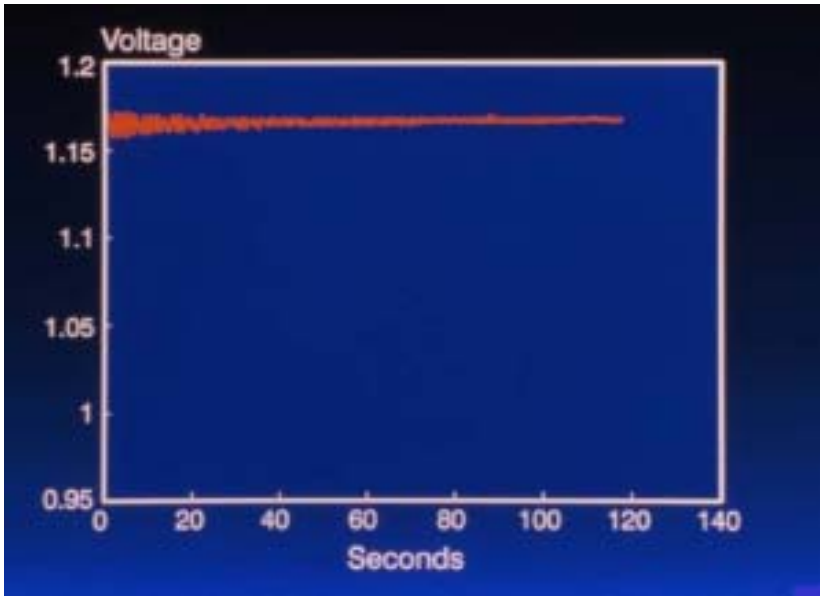
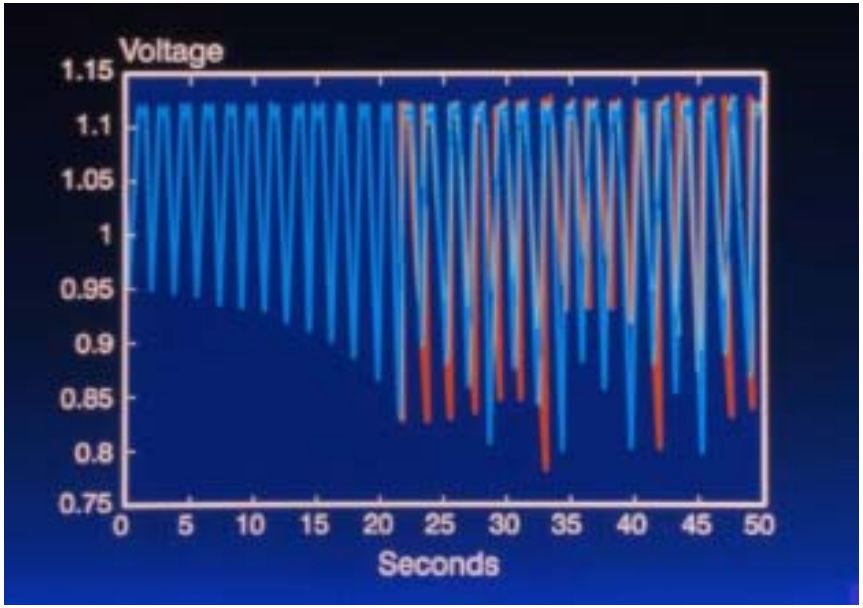
Chaos on the Grid





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Power Outrage

"We are sick and tired of them, and they had better change!"

Chicago Mayor Richard Daley on the August 1999 Blackout

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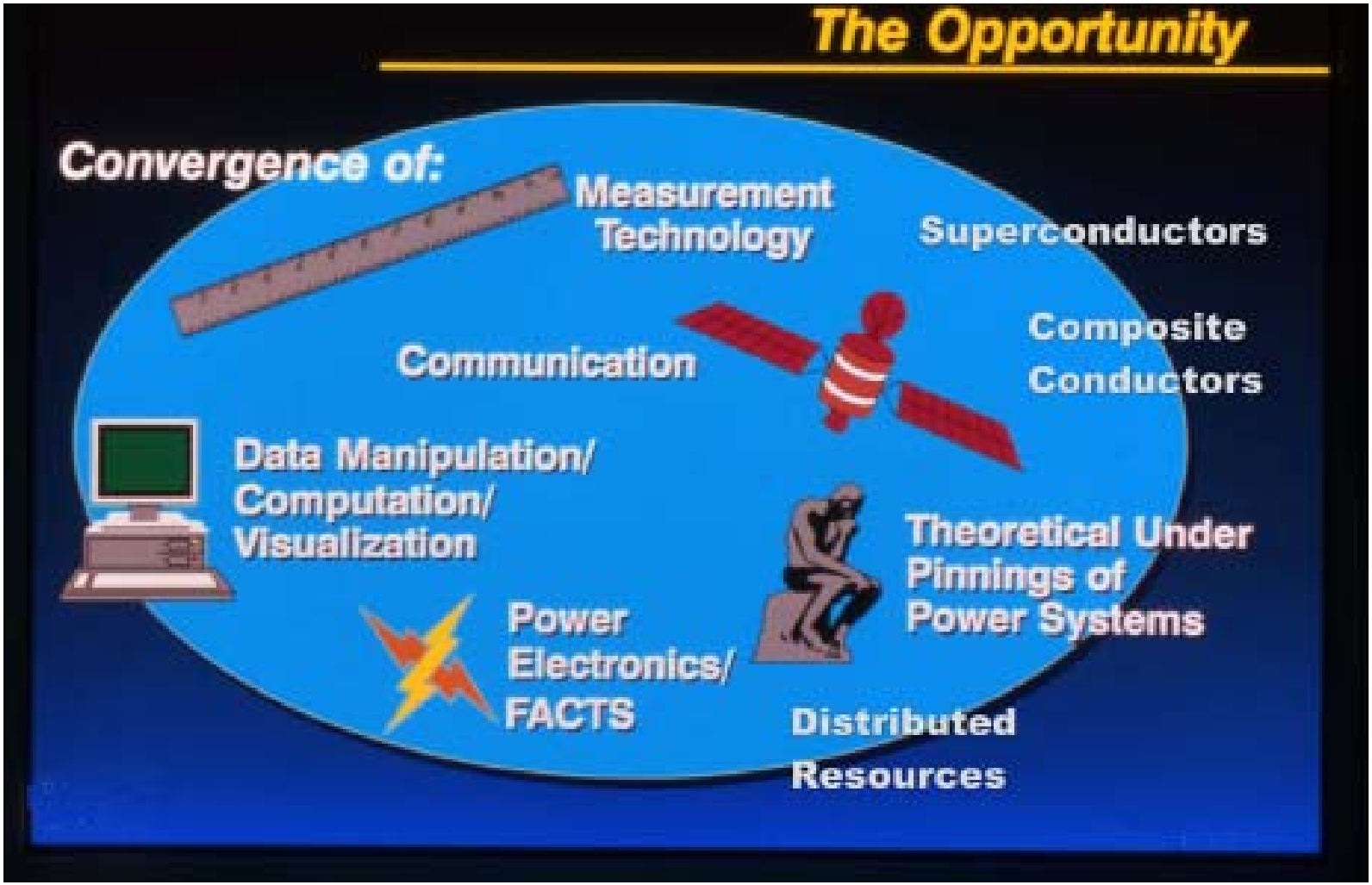
The Opportunity



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WAMS

ABB

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Do It!

- Buzz Words
  - GridWise
  - Intelligrid
  - Self-Healing Grid
  - Brilliant Grid
  - GridWorks
- It's not rocket science!
- It's good old Negative Feedback (Black, 1927)
  - Just like you have in your Bose headphones
  - Simply get rid of the noise
- Why not just do it?

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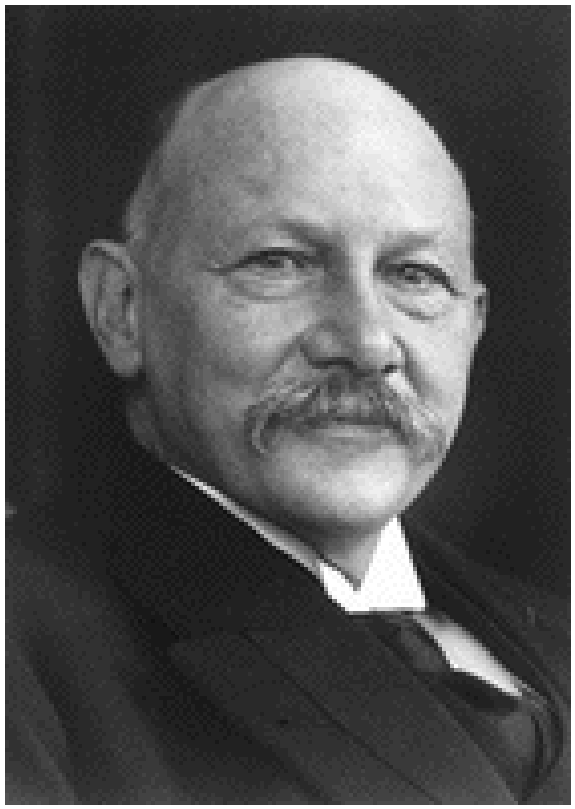
Fathers of Cryogenics

Dewar

CH_4	112 K
O	90
N_2	77
Ne	27
H_2	20
He	4.2



Kammerlingh-Onnes

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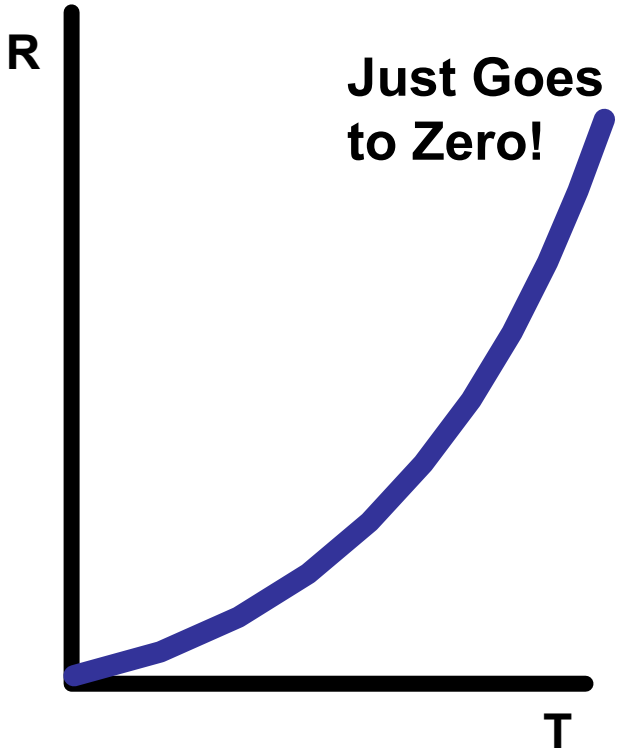
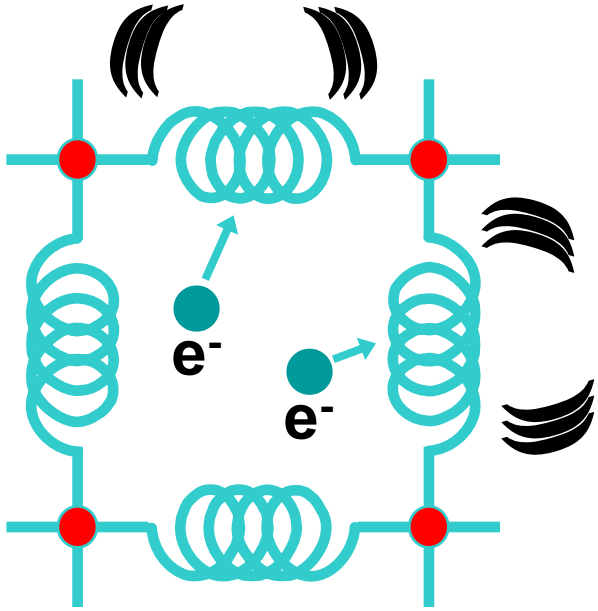
Models of Electrical Conductivity

The First Idea:





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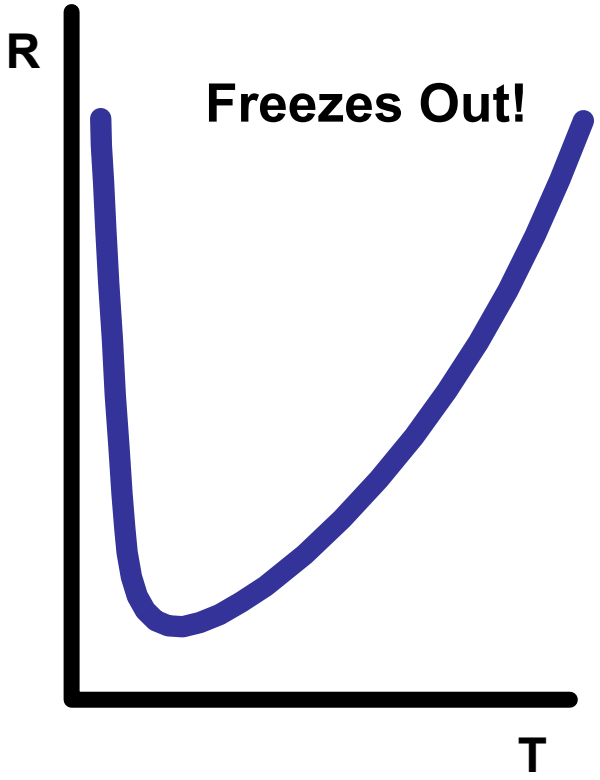
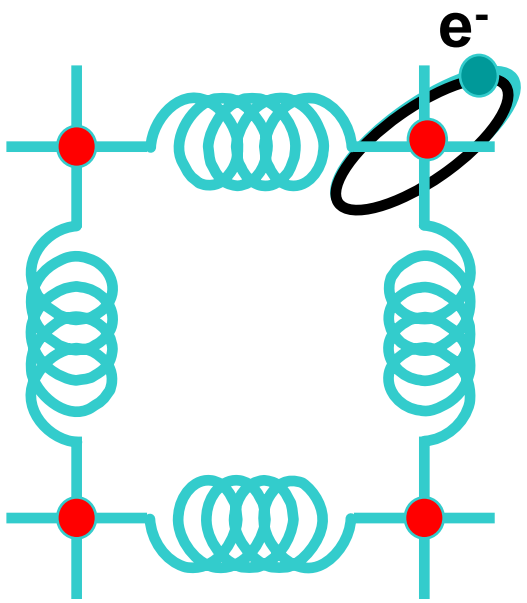
Models of Electrical Conductivity

The Most Popular:





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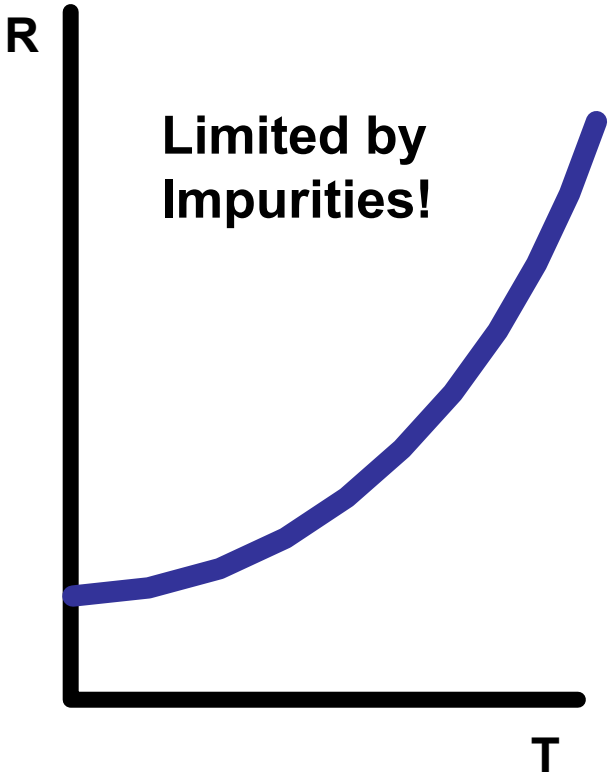
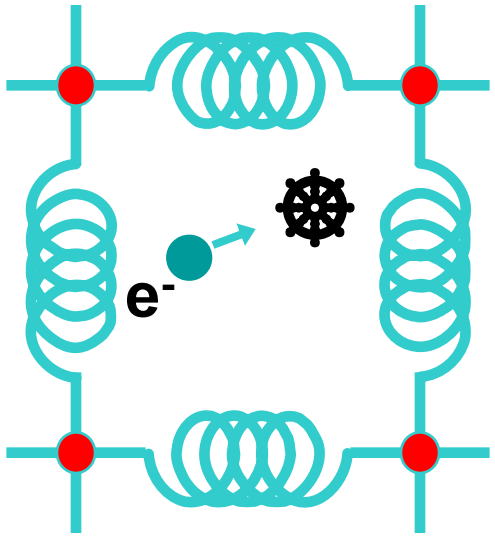
Models of Electrical Conductivity

Reality:





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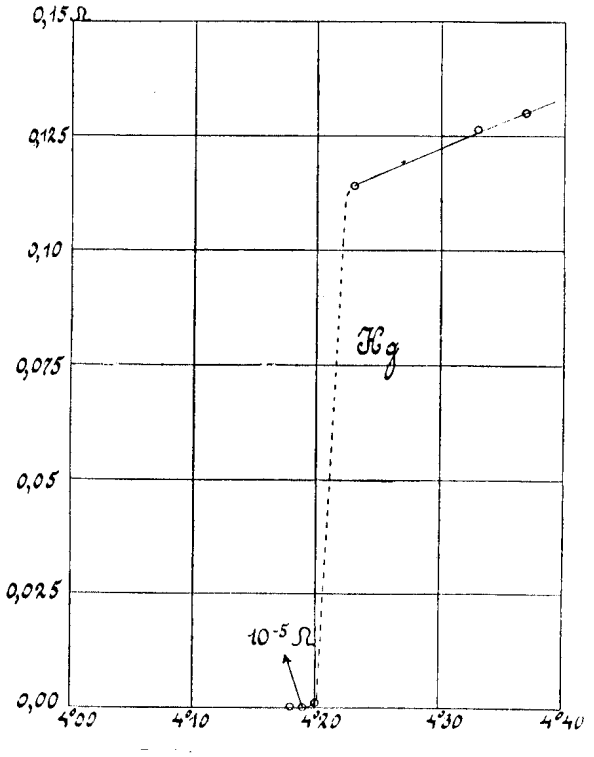
1911
A Big Surprise!



Thus the mercury at 4.2 K has entered a new state, which, owing to its particular electrical properties, can be called the state of *superconductivity*

H. Kamerlingh-Onnes (1911)

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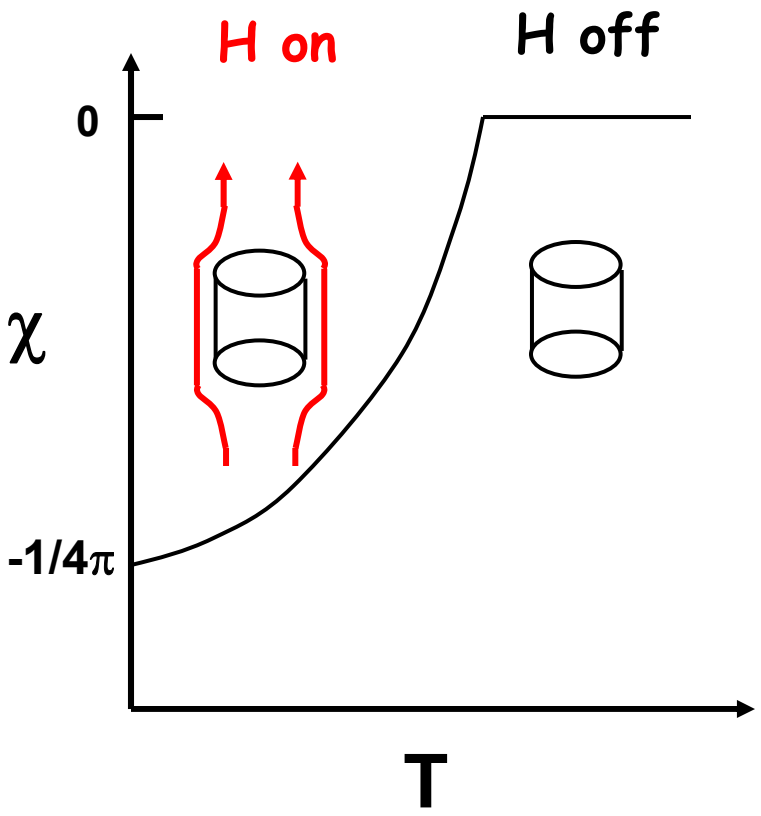
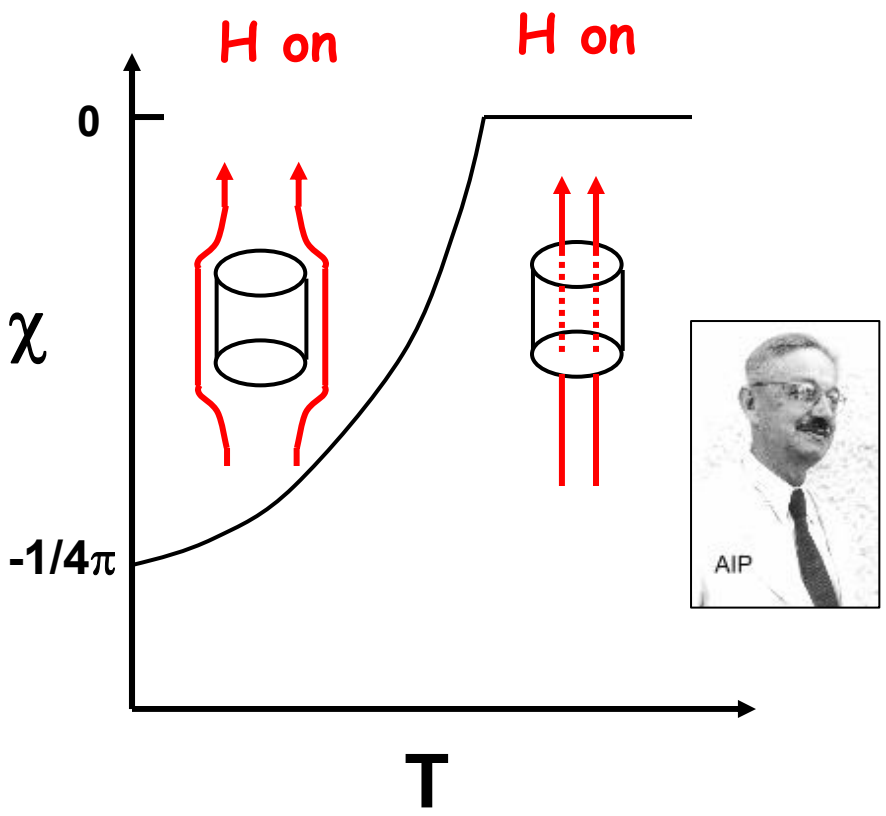
Magnetic Properties



Expected (Lenz' Law)



Weird ! (Meissner Effect)

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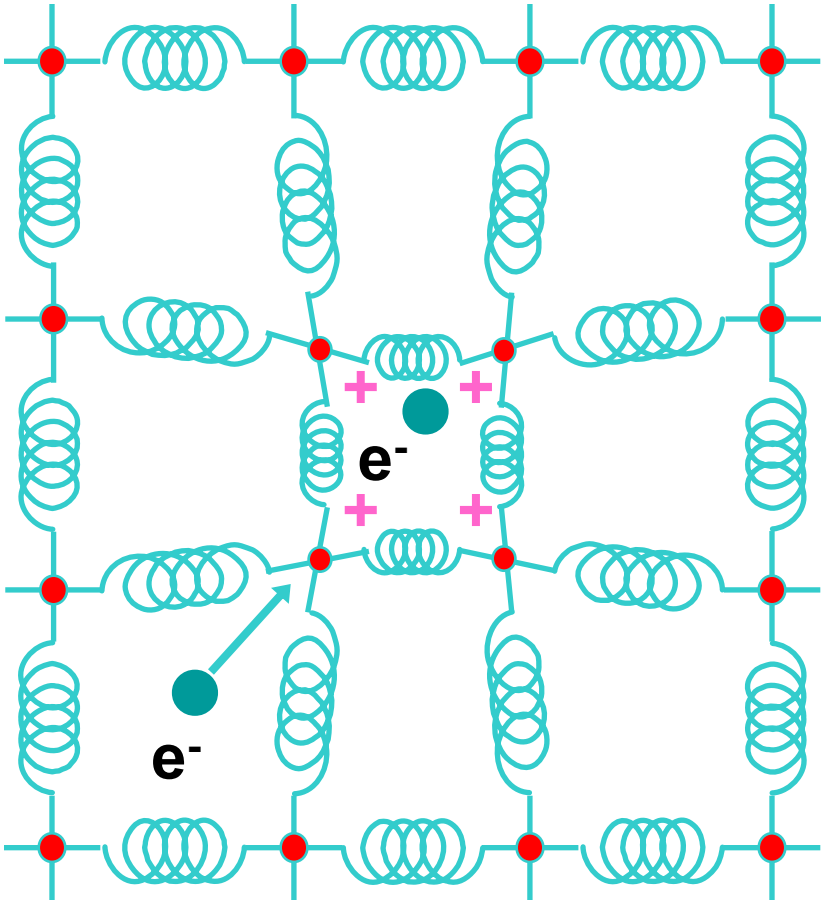
Physics of Superconductivity



Electrons Pair Off!

BCS Equation

$$T_C = 1.14\,\theta_D \exp(-1/\lambda)$$

$$\theta_D = 275 \text{ K},$$

$$\lambda = 0.28,$$

$$\therefore T_C = \underline{9.5 \text{ K}} \text{ (Niobium)}$$

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Important Numbers in Superconductivity

Transition Temperature, T_c	Way below 300 K
Critical Current Density, J_c	10^{-2} - 10^{6} A/cm^2
Critical Magnetic Field, H_c	10^{-4} - 10 T

NB! All these numbers depend on each other.

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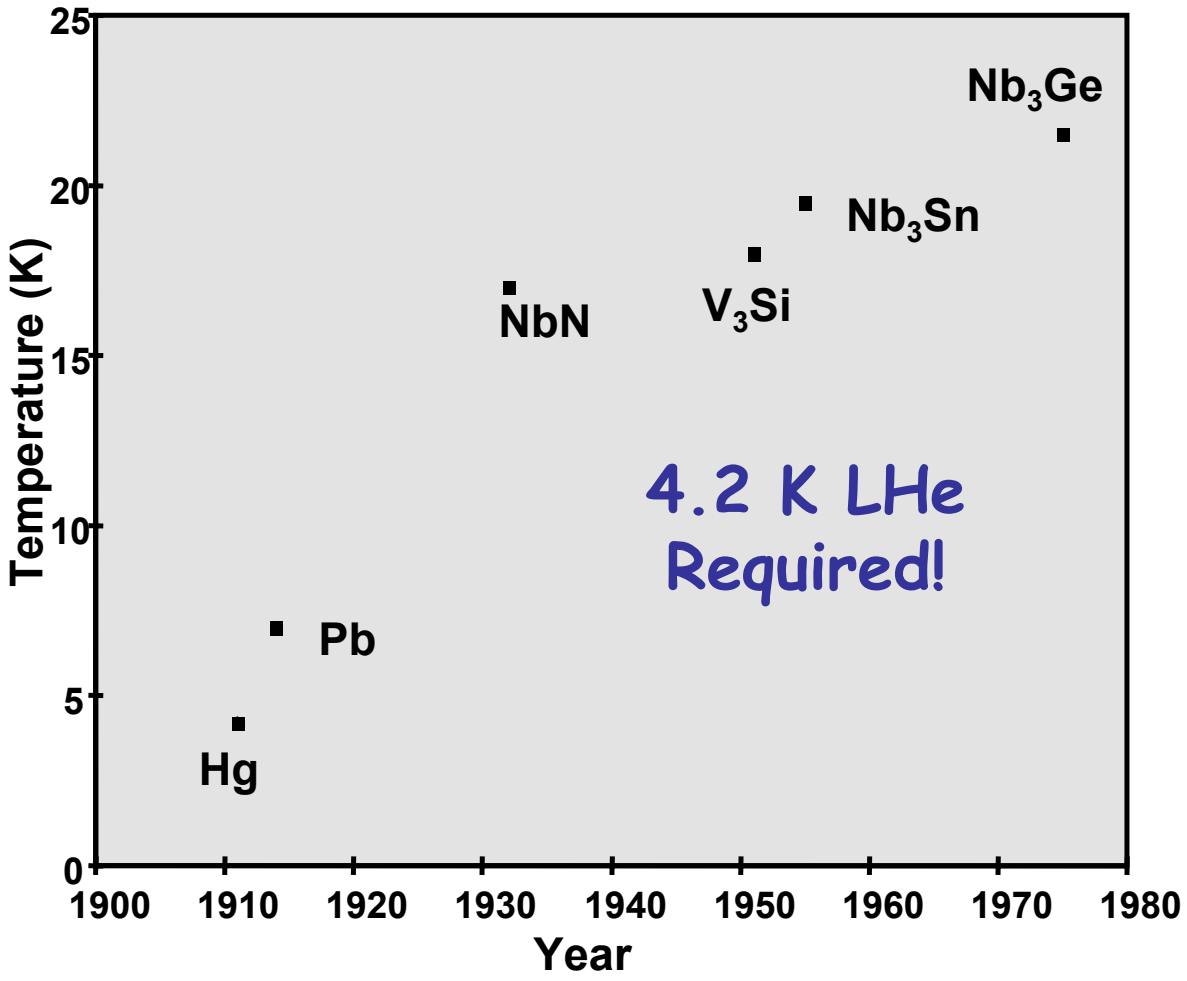
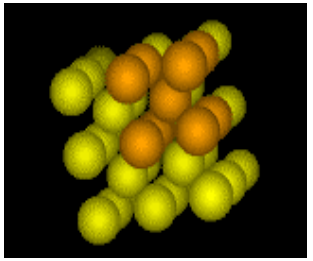
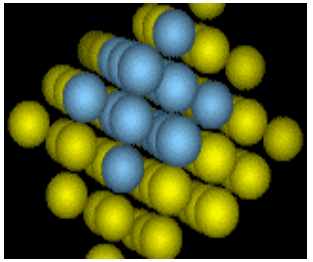
T_c vs. Year: 1911 - 1980







Cubic Metals

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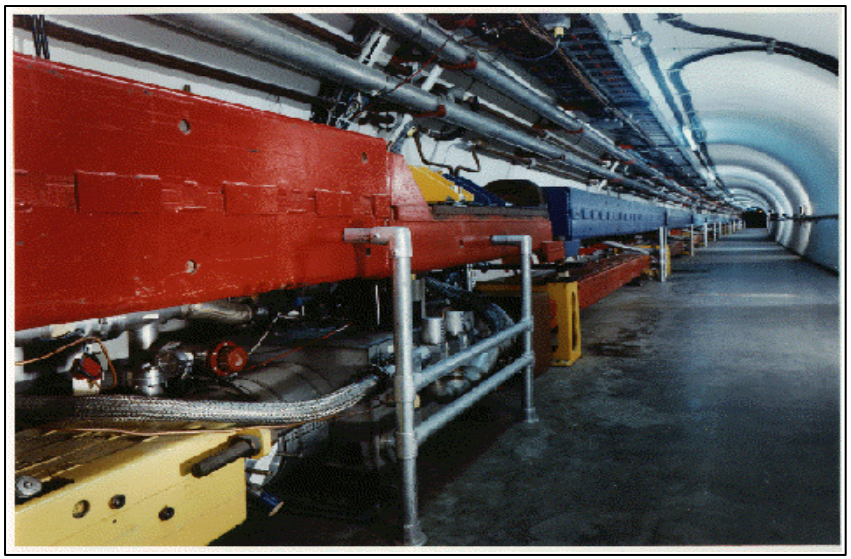
MRI & "Big Physics"

Magnetic Resonance Imaging
Philips



Tevatron
Fermi National Laboratory

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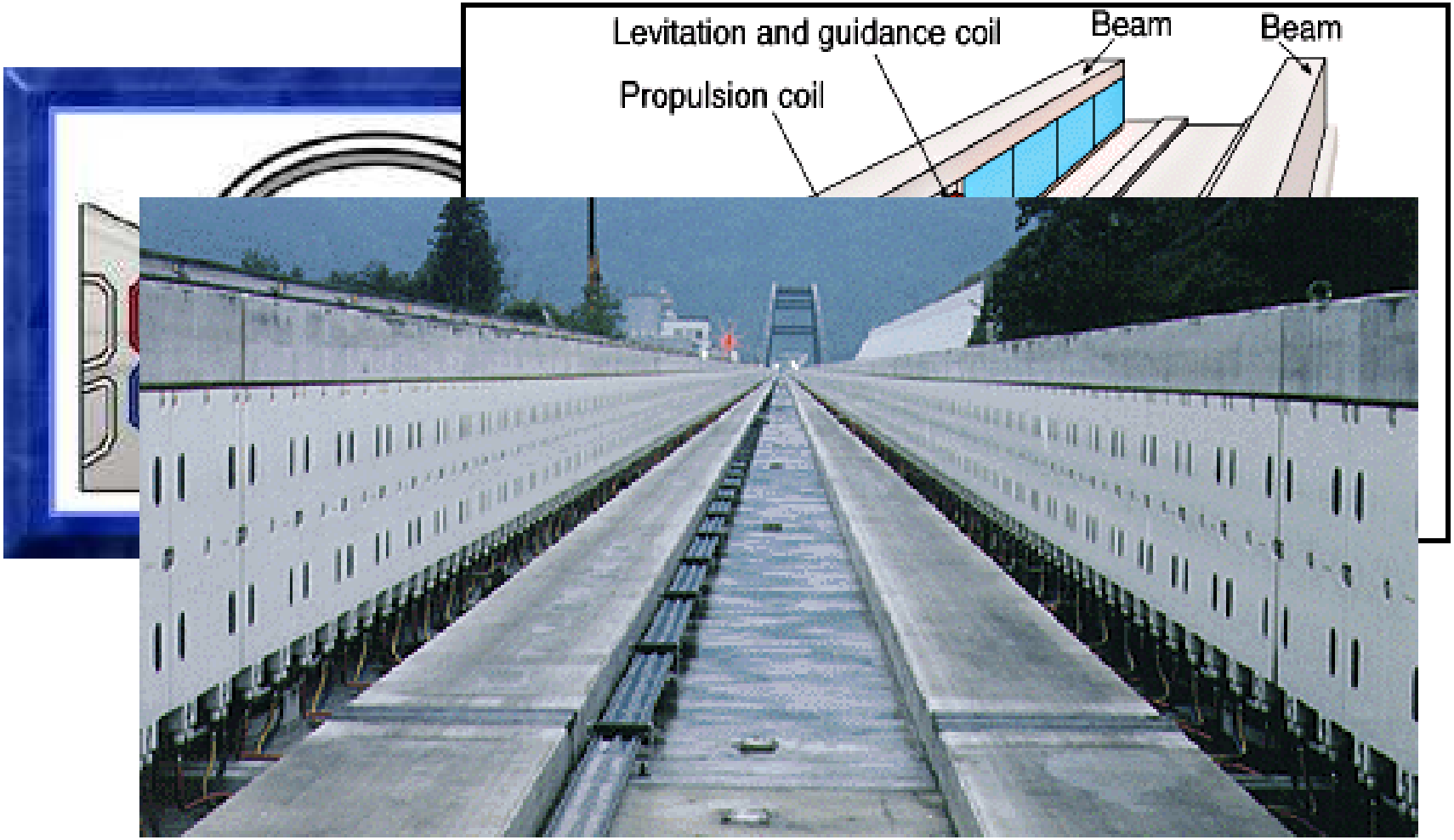
MagLev
Yamanashi Test Line



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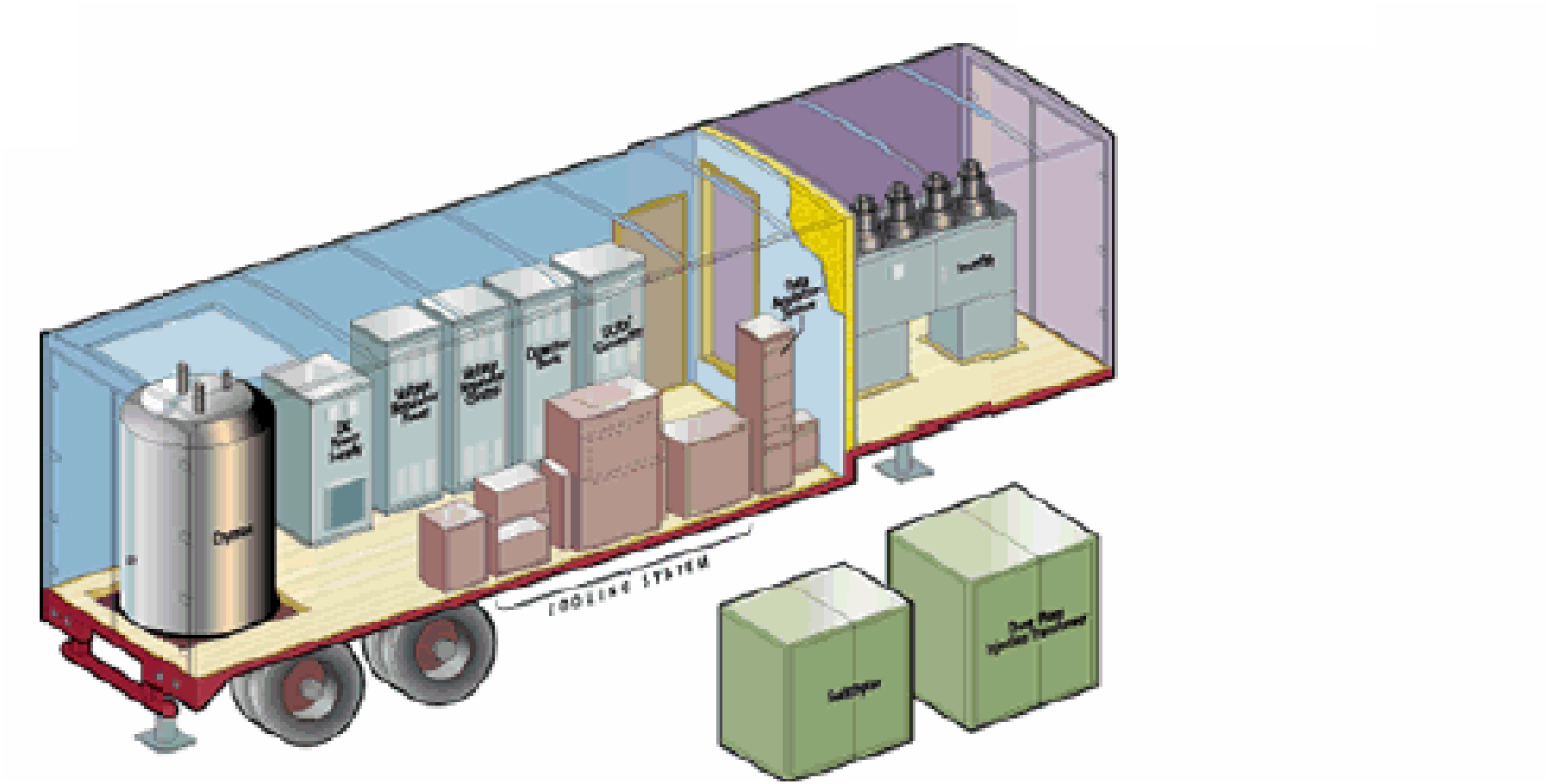
SMES

Superconducting Magnetic Energy Storage



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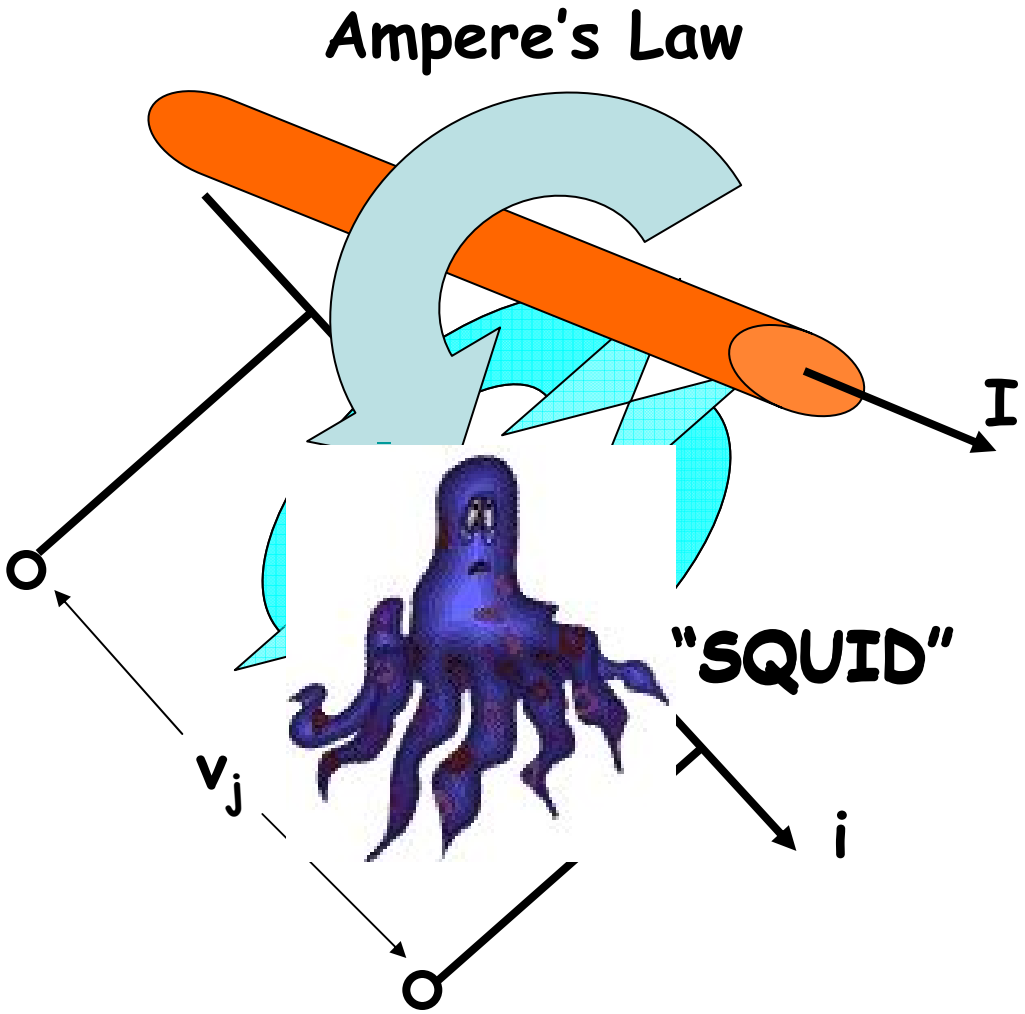
Superconducting Quantum Interference Device



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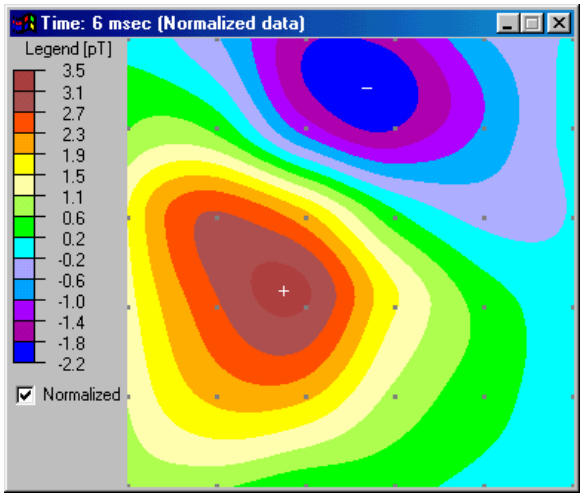
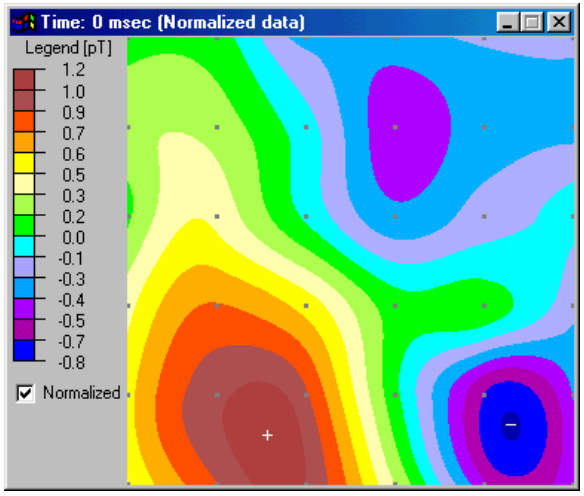
MagnetoTomaGraphy

MagnetoCardioGraphy

www.cardiomag.com



Healthy Heart



Ischemic Heart - Early Stages

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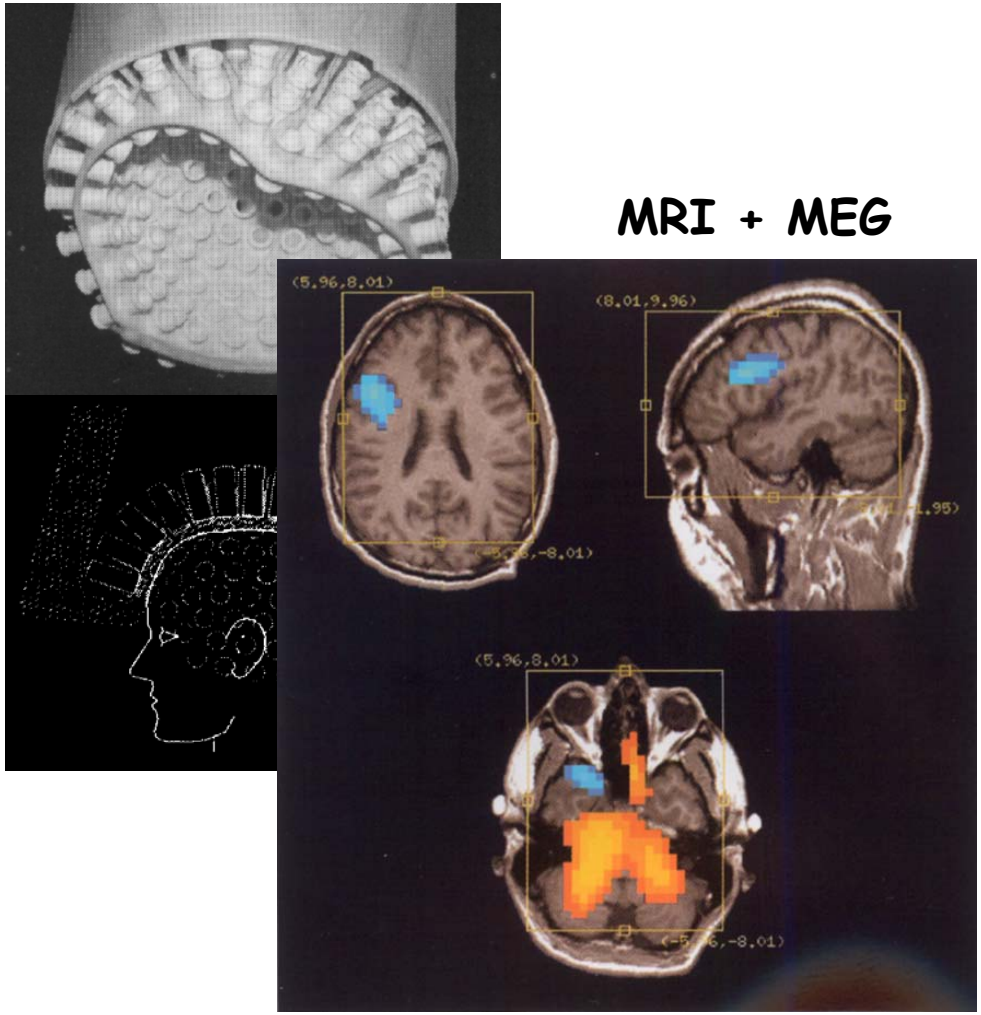
MagnetoTomaGraphy

MagnetoEncephloGraphy



MRI + MEG

Speech Center Pathologies

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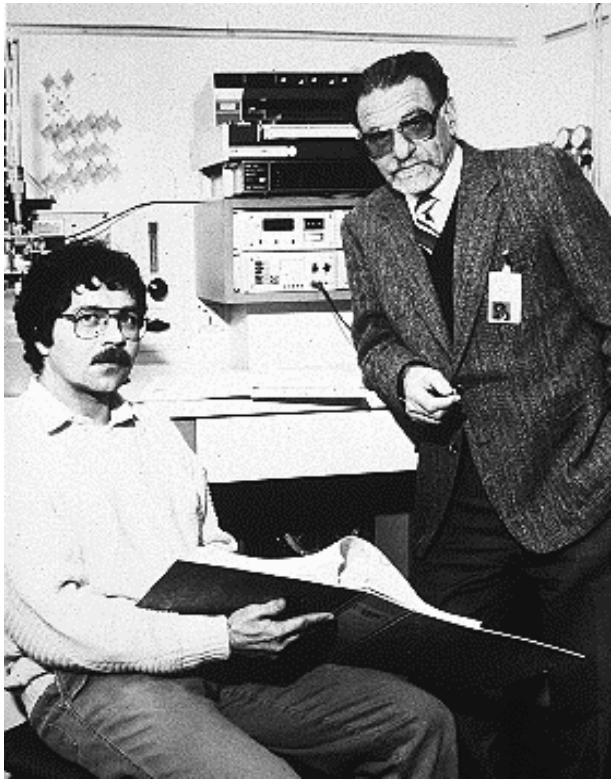
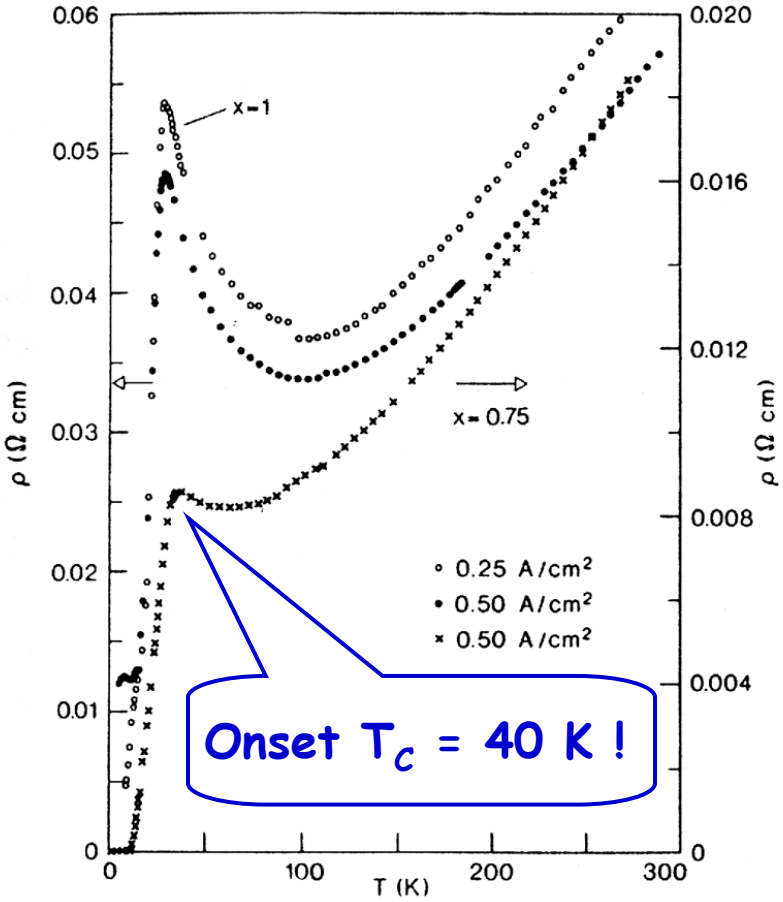
1986
Another Big Surprise!



Bednorz and Mueller
IBM Zuerich, 1986



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1987 "The Prize!"

Associated Press

J. Georg Bednorz, left, and K. Alex Müller after learning they had won the Nobel Prize in physics.

2 Get Nobel for Unlocking Superconductor Secret

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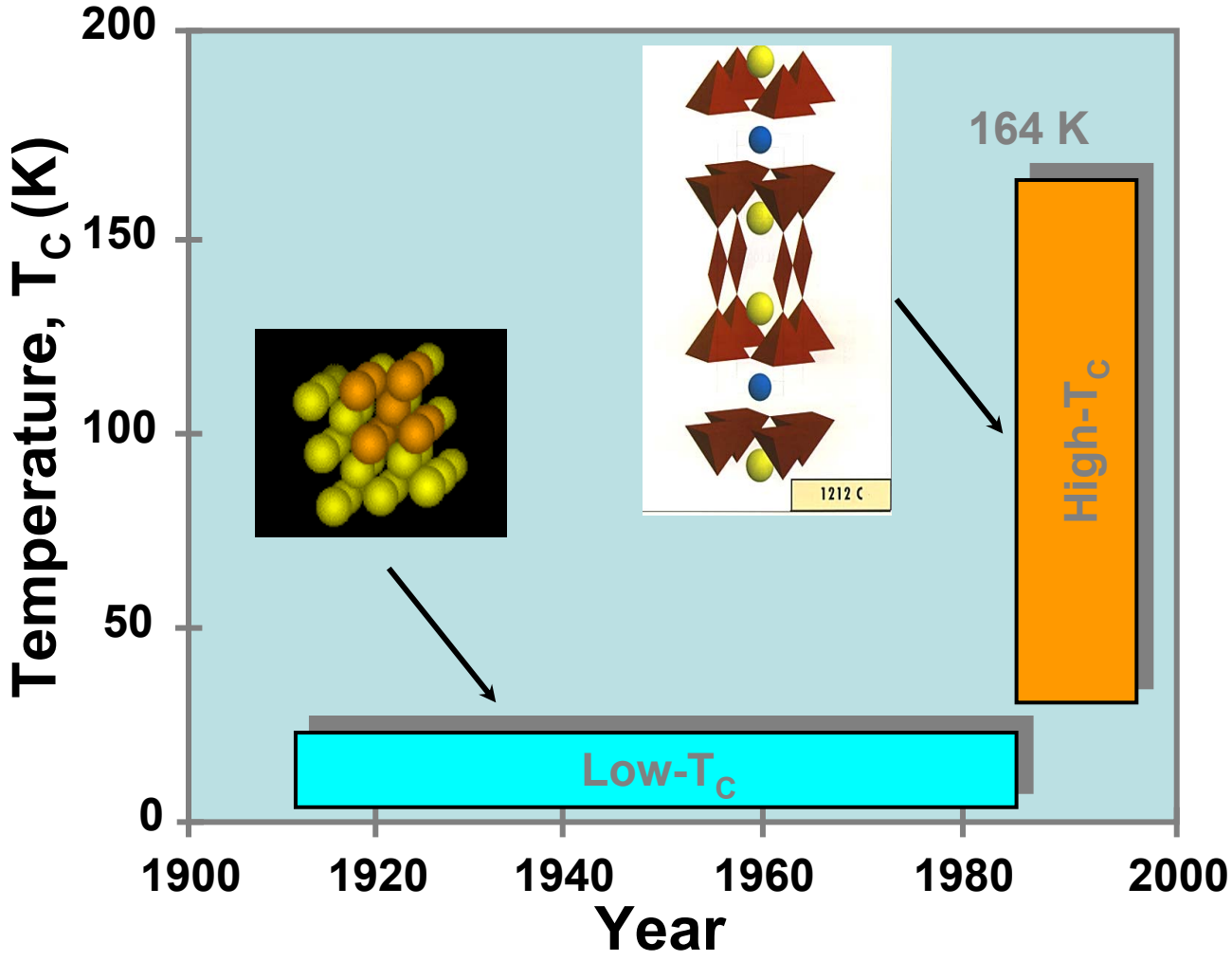
T_c vs. Year: 1911 - 1999



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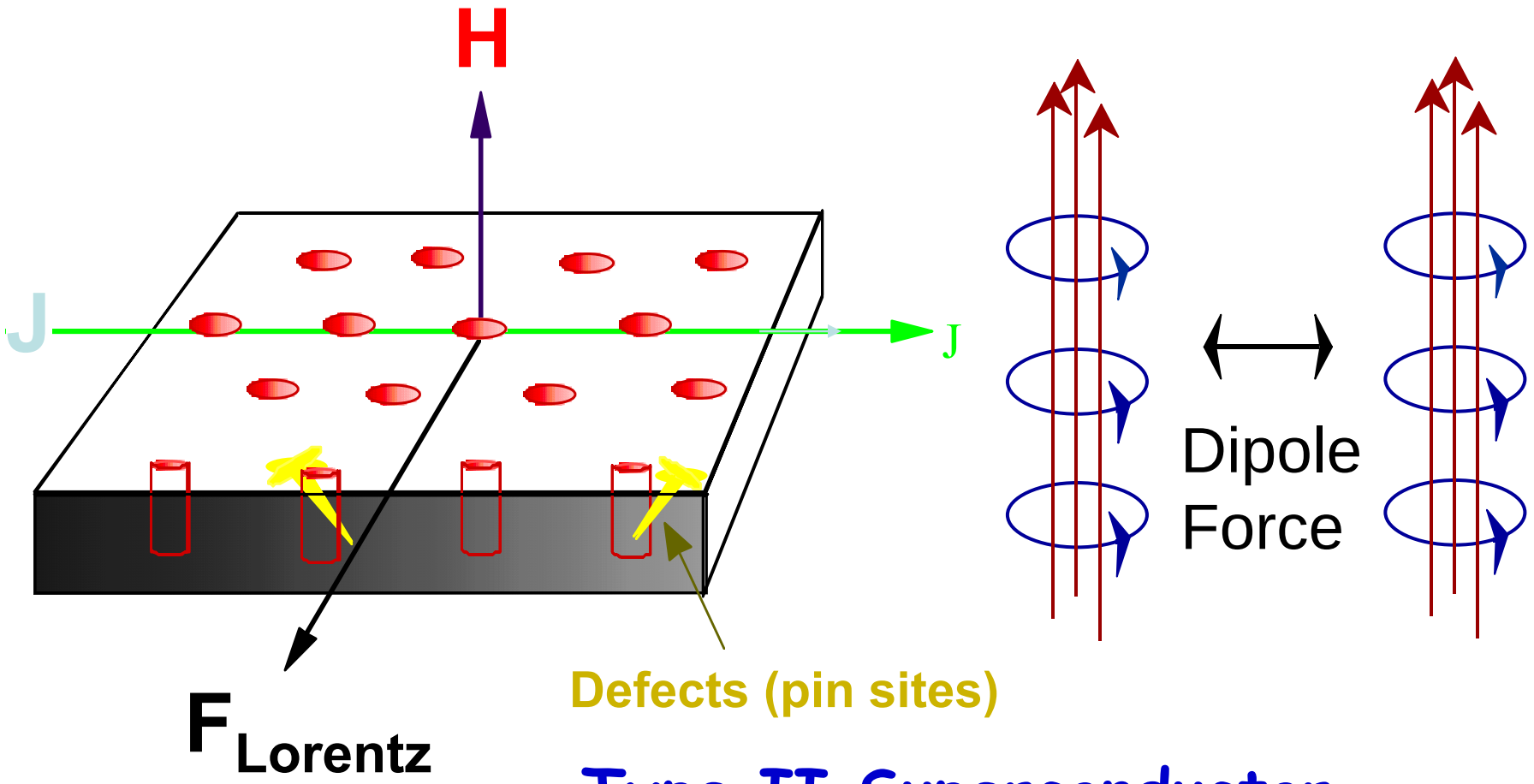
Abrikosov Vortex Lattice



Type II Superconductor in the Mixed State

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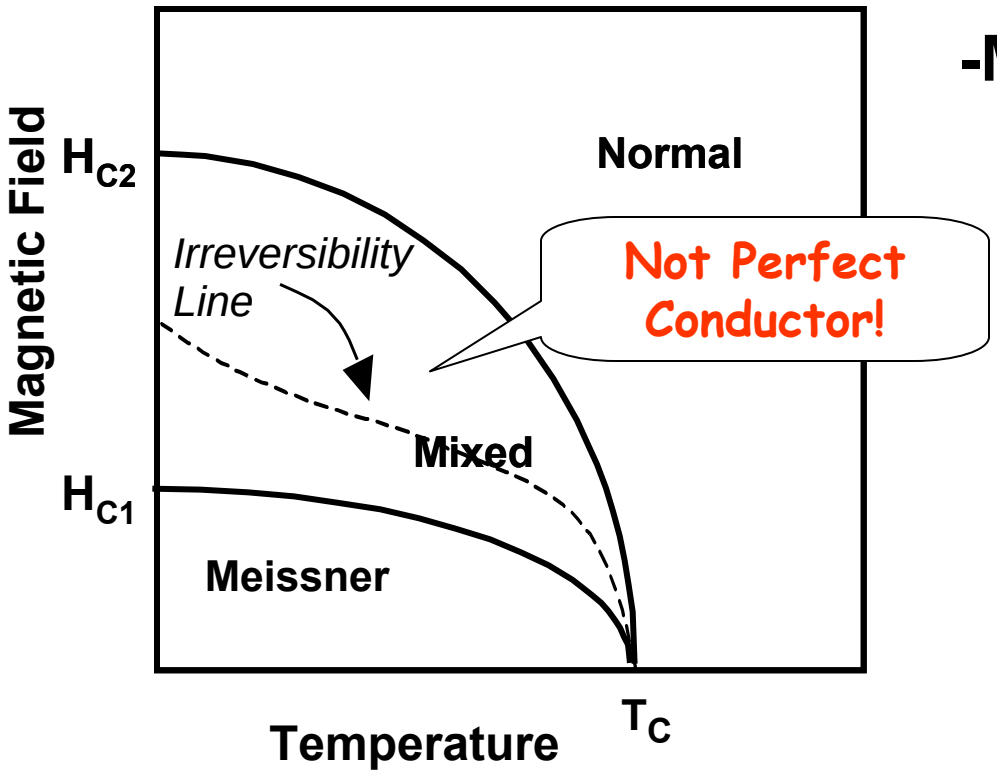
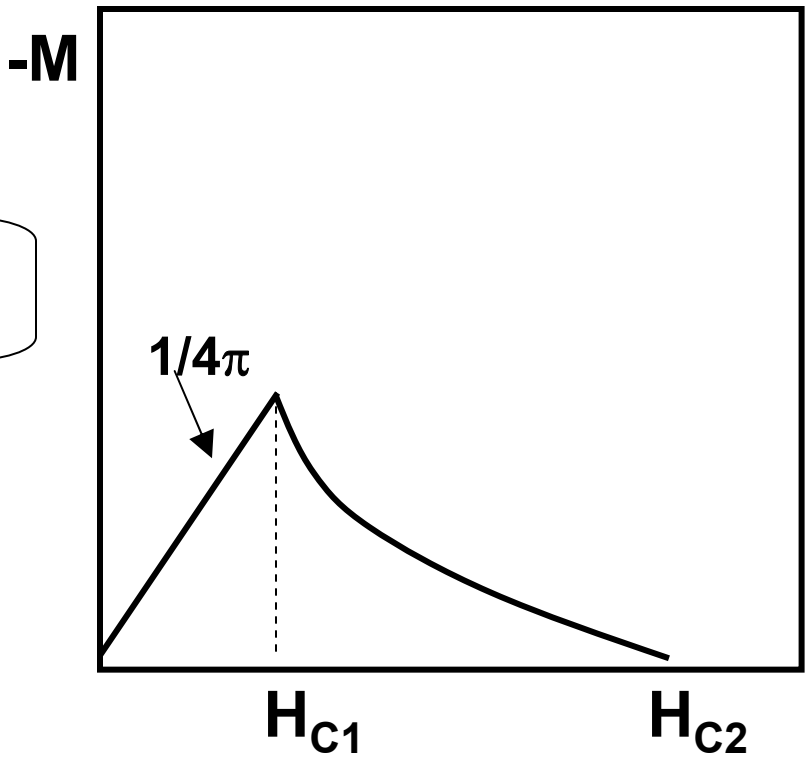
Type II Superconductivity





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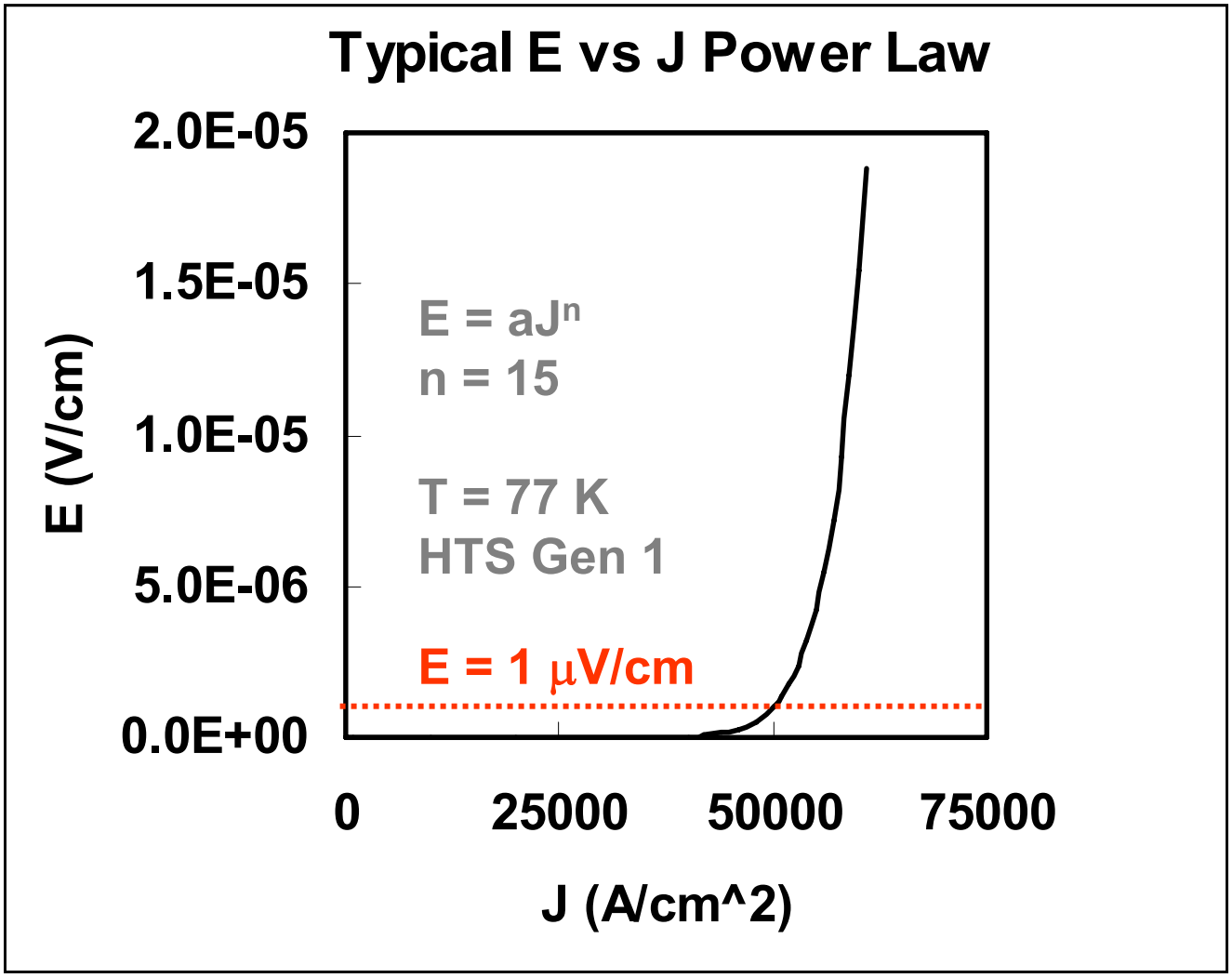
No More Ohm's Law



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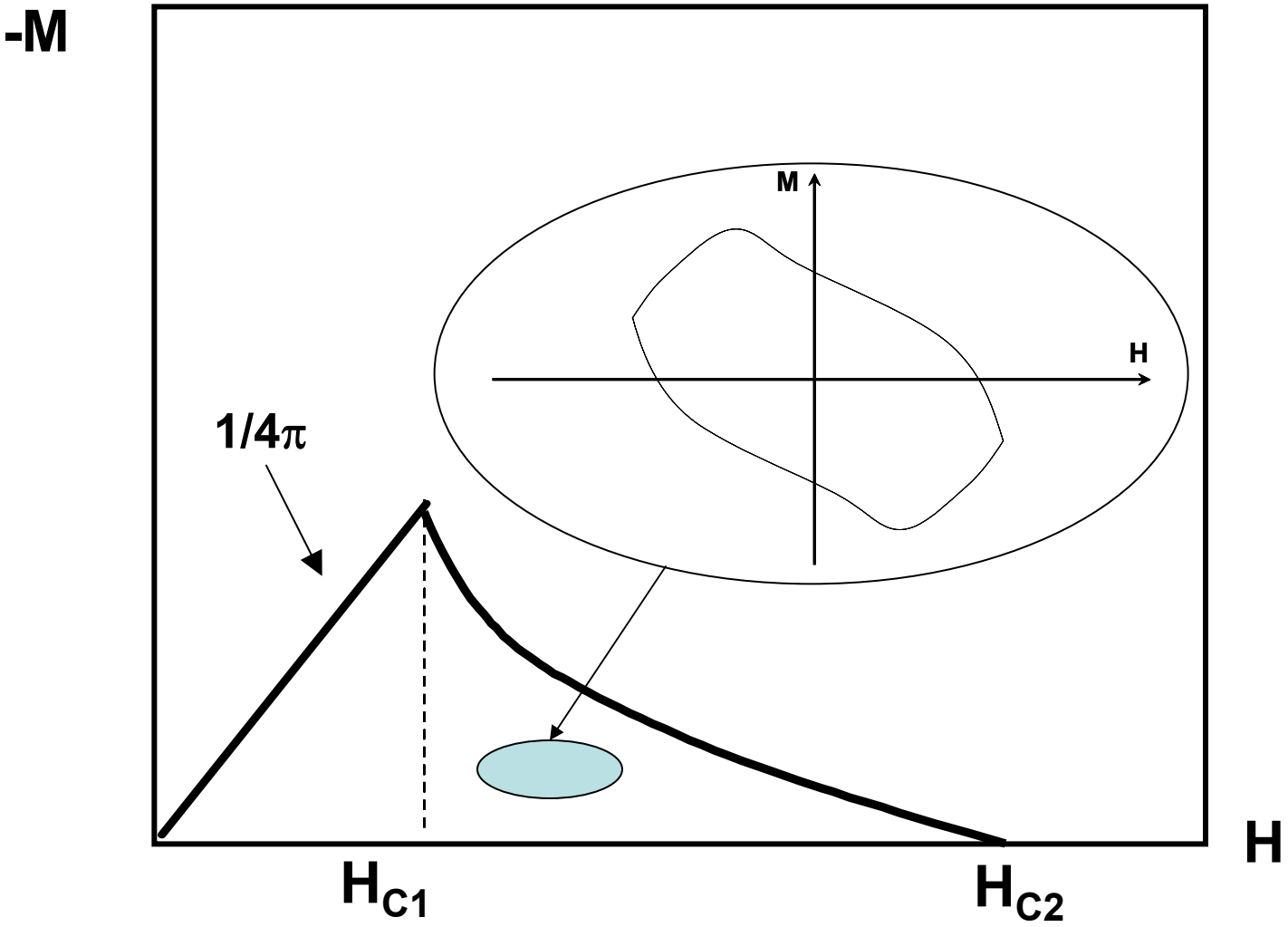
ac Hysteresis



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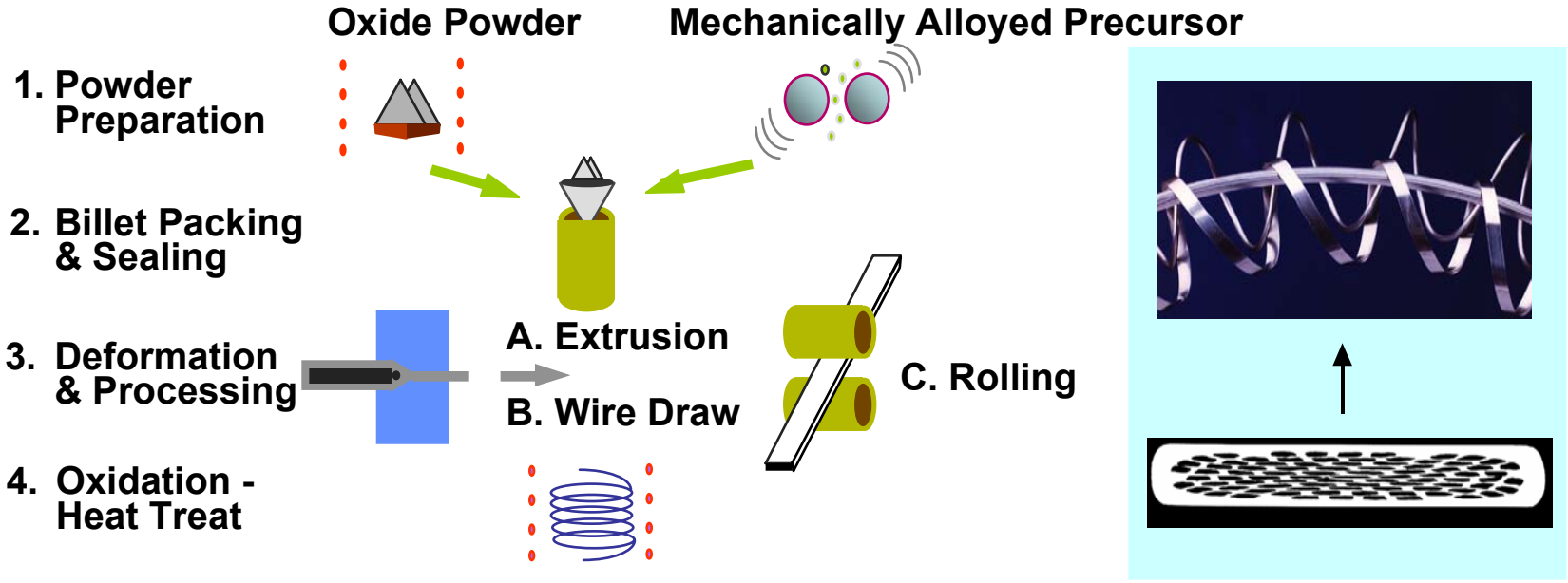
HTS OPIT/Ag Tape
Generation I

ASC Wire Forming Process



Wire is the Power Engineering commodity

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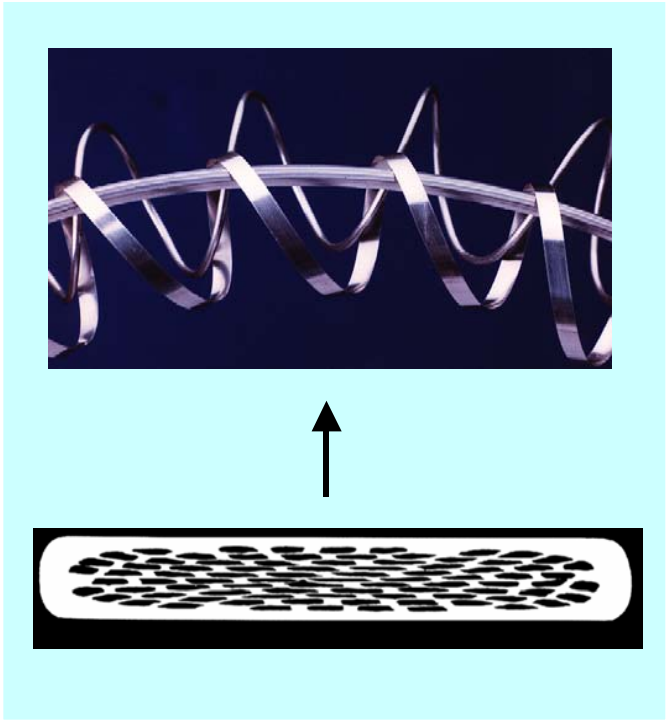
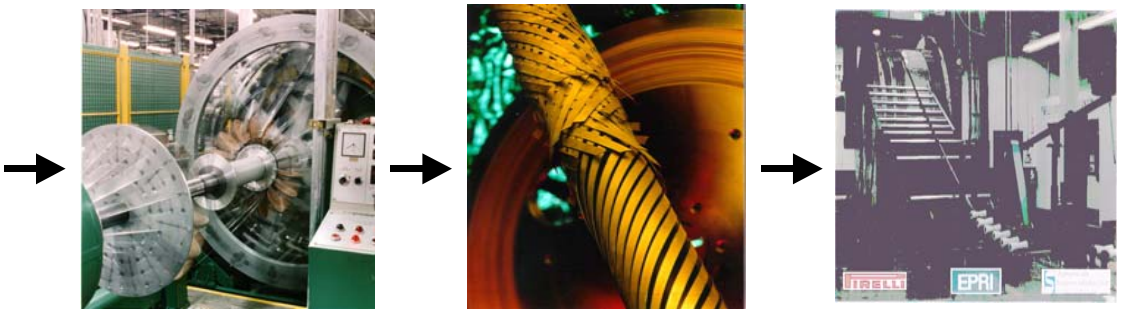
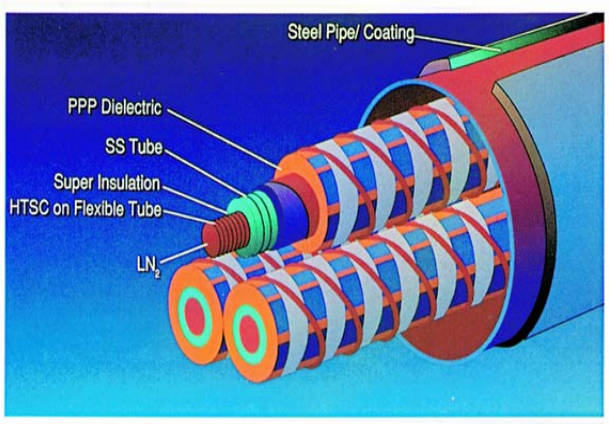
Wire-to-Cable







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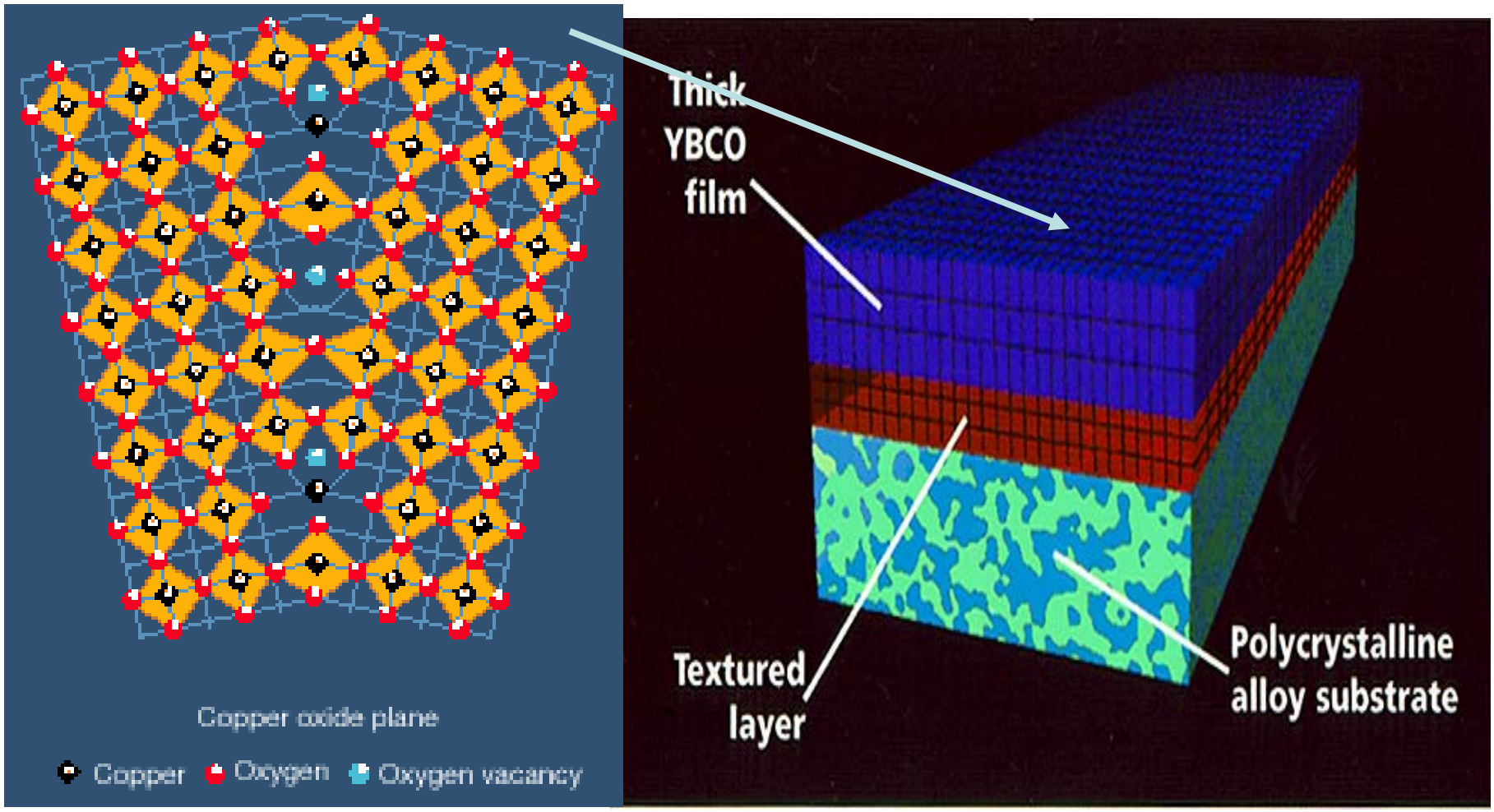
Coated Conductors
Generation II Wire



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Motors

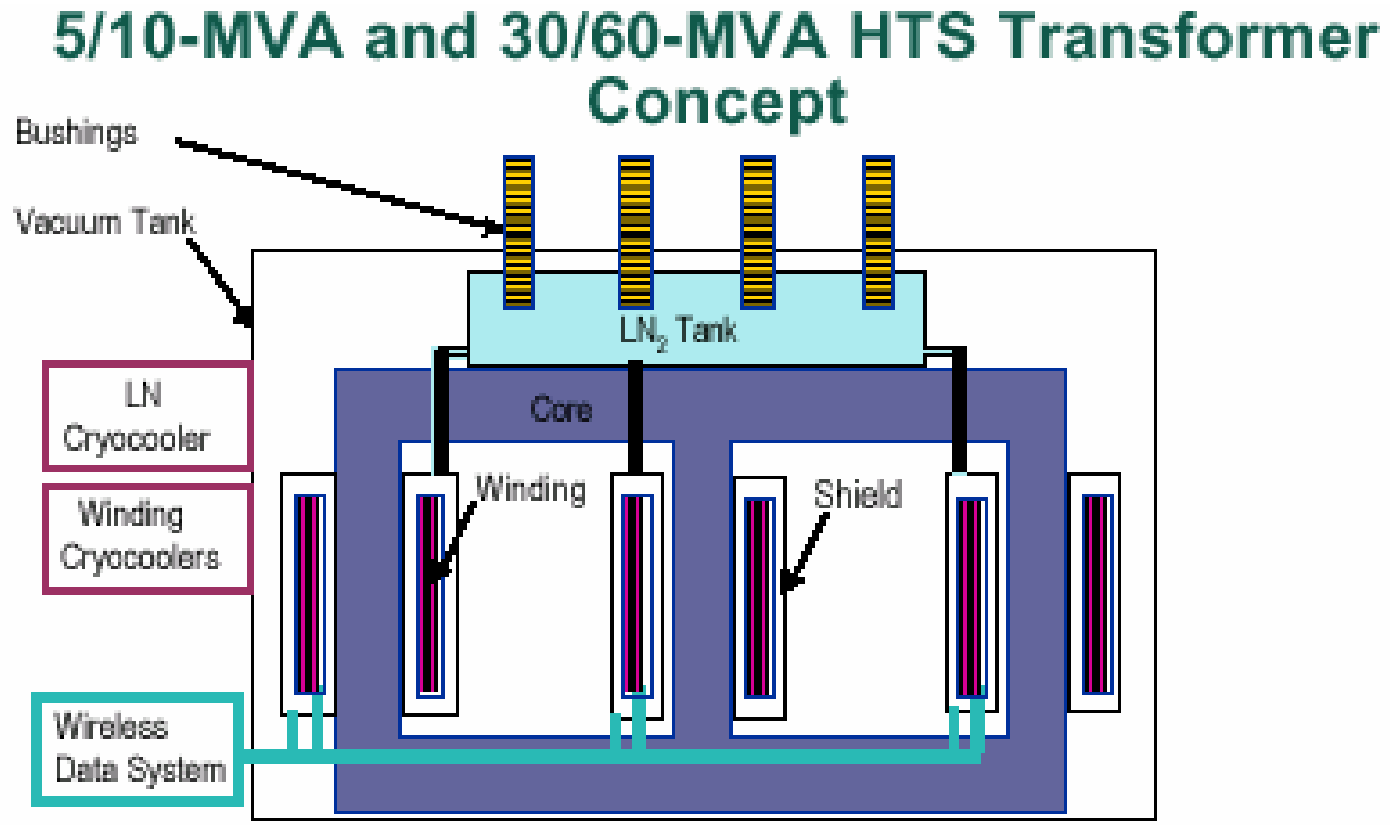
NAVY HTS
SUPERDRIVE

- 25,000 hp
- Small, Light (1/5 Conventional)
- High Power Density
- Quiet
- Robust

http://www.amsuper.com/navy.htm

Transformers

Waukesha, IGC, ORNL, DOE



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HTS Cables: They're Here!

12,400 Volts

1,250 Amps

3 Phase

Southwire Cable Plant
Carrolton, Ga.

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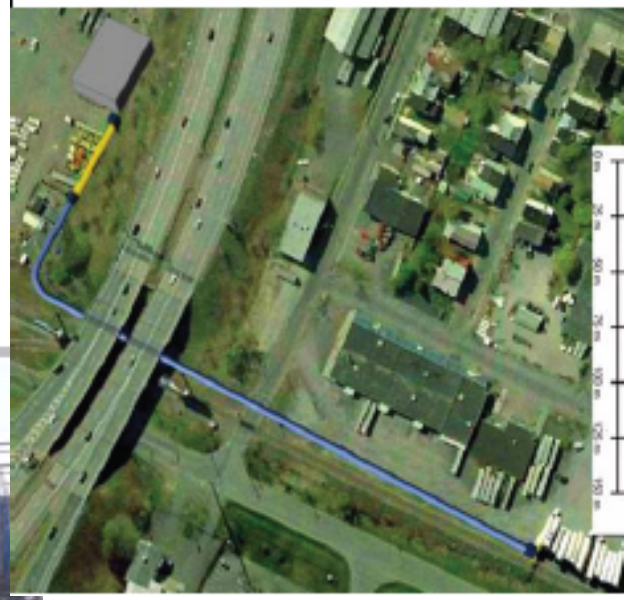
Albany Cable

- 350m long - 34.5kV - 800A_{rms} - 48MVA
- Cold dielectric, 3 phases-in-1 cryostat, stranded copper core design

Installed between two Niagara Mohawk substations

- Riverside-Menands
- Parallels new 34.5kV installation
- added to handle load growth



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AEP Bixby Cable

- Utility Partner = American Electric Power
- Location = Bixby Substation, Columbus, OH
- Voltage = 13.2 kV
- Load Rating = 3.0 kA_{rms} AC; 69 MVA
- Fault Current Rating = 20 kA_{rms}; ~57 kA_{peak}
- Cable Design = Triax
- Length = 200 meters
- Other Features = Splice
  Underground
  Multiple 90° Bends
- In Service August 2006

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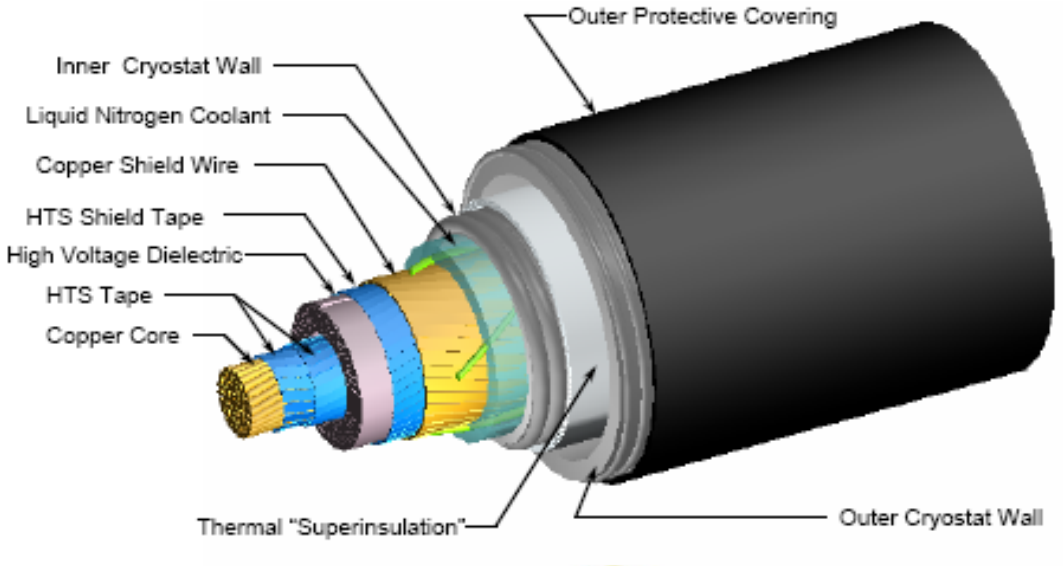
LIPA Cable

- Long Island Power Authority – Holbrook Substation
- Electrical Characteristics
  - Design Voltage/Current – 138kV/2400A ~ 574MVA
  - Design Fault Current – 51,000A @ 12 line cycles (200ms)
- Physical Characteristics
  - Length ~ 600m
  - HTS Conductor Length ~155km
  - Cold Dielectric Design



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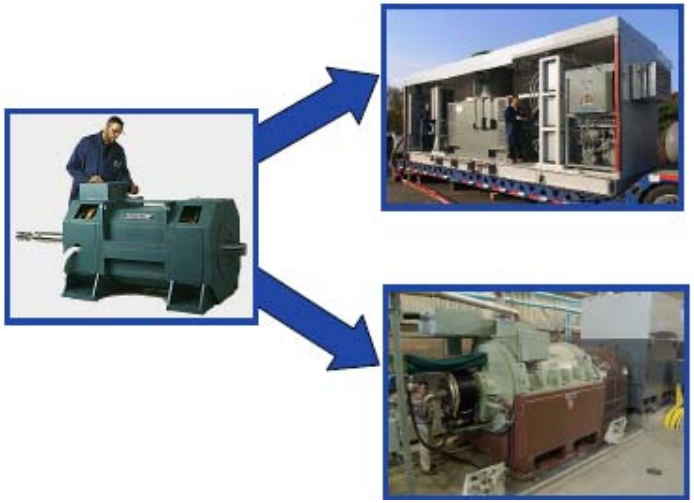
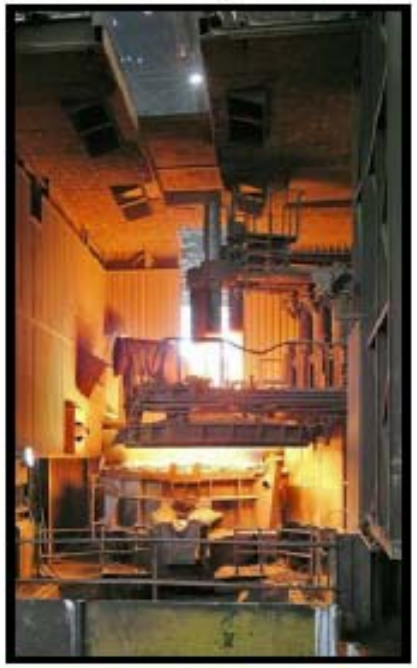
AMSC TVA SuperVAR





Rating	8 MVAR
Voltage	13.8 kV line to line
Ambient Temp	-30° to +40°C
Losses	1.7% rating at 8MVA
	Including 50kW 480V auxiliary power

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HTSC Utility Market

In the utility/energy market, the applications that appear to value performance attributes of HTS most are Fault Current Limiters and Synchronous Condensers.

10 More Years!

	Utility/Energy Market - Importance of Performance Attributes					
	Small & Light	High Power Density	Low Impedance	High Efficiency	High Field	Overall
Power Cable	●	●	●	●	○	●
Synchronous Condenser	●	●	●	●	●	●
Fault Current Limiter*	●	●	●	●	○	●
Industrial Motor	●	●	●	●	●	●
Utility Generator	○	○	●	●	●	●
Wind Generator	●	●	●	●	●	●
Transformer	●	●	●	●	○	●

Source: NCI Analysis, see Appendix: Value Propositions
* Fault current limiters also rely on the inherent quench properties of HTS.

NAVIGANT

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AMSC D-VAR

- "Orthogonal" to SMES…stores reactive power in an ordinary coil
- Great for intermittent generation…like wind

What does the "S" in AMSC now stand for?

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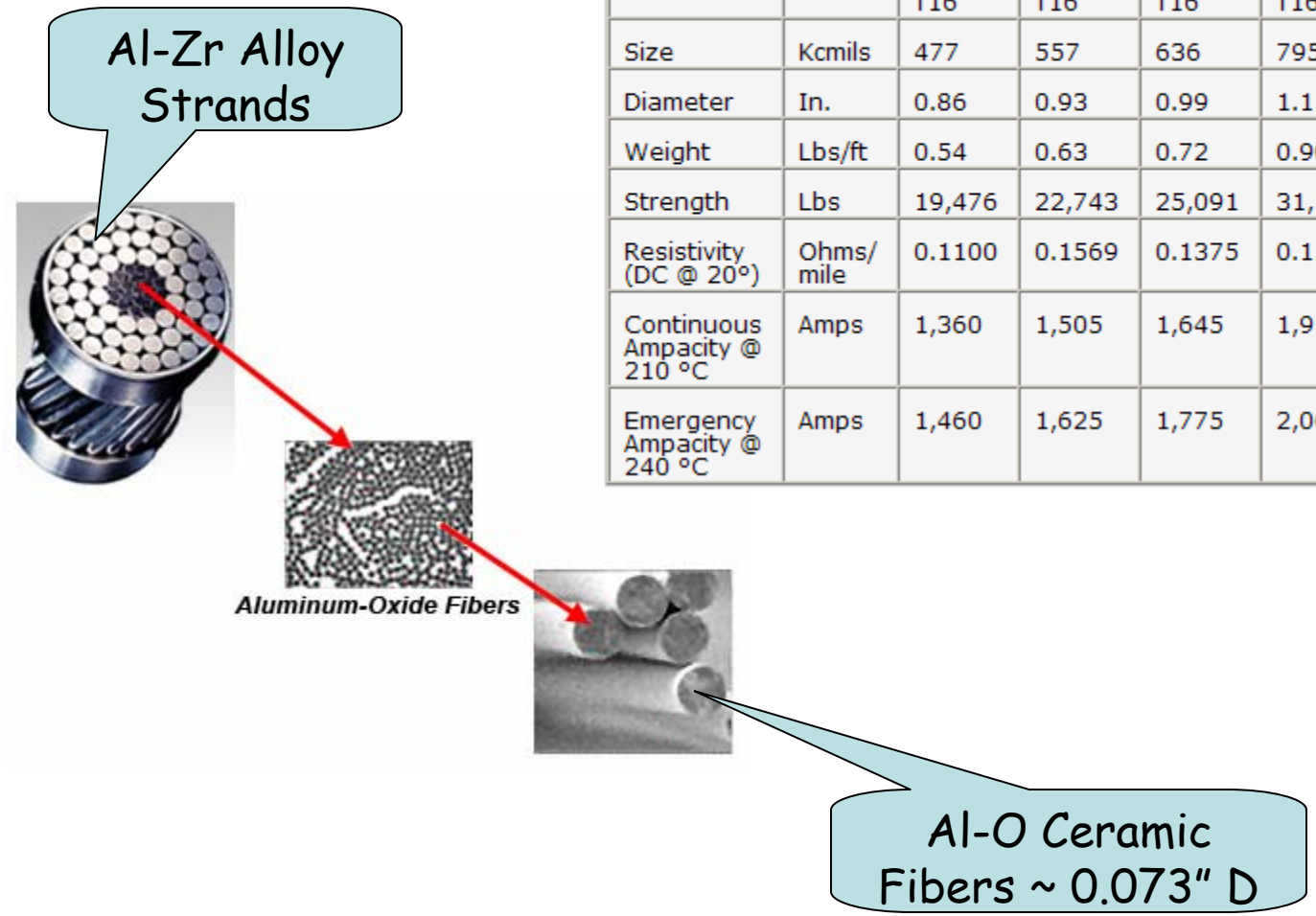
3M ACCR Conductor

Properties	Units	Conductors						
Name		477-T16	557-T16	636-T16	795-T16	954-T13	1272-T13	1590-T13
Size	Kcmils	477	557	636	795	954	1272	1590
Diameter	In.	0.86	0.93	0.99	1.11	1.20	1.38	1.54
Weight	Lbs/ft	0.54	0.63	0.72	0.90	1.04	1.39	1.74
Strength	Lbs	19,476	22,743	25,091	31,134	32,758	43,677	54,596
Resistivity (DC @ 20°)	Ohms/mile	0.1100	0.1569	0.1375	0.1100	0.0933	0.0700	0.0560
Continuous Ampacity @ 210 °C	Amps	1,360	1,505	1,645	1,910	2,130	2,585	3,000
Emergency Ampacity @ 240 °C	Amps	1,460	1,625	1,775	2,060	2,300	2,800	3,260



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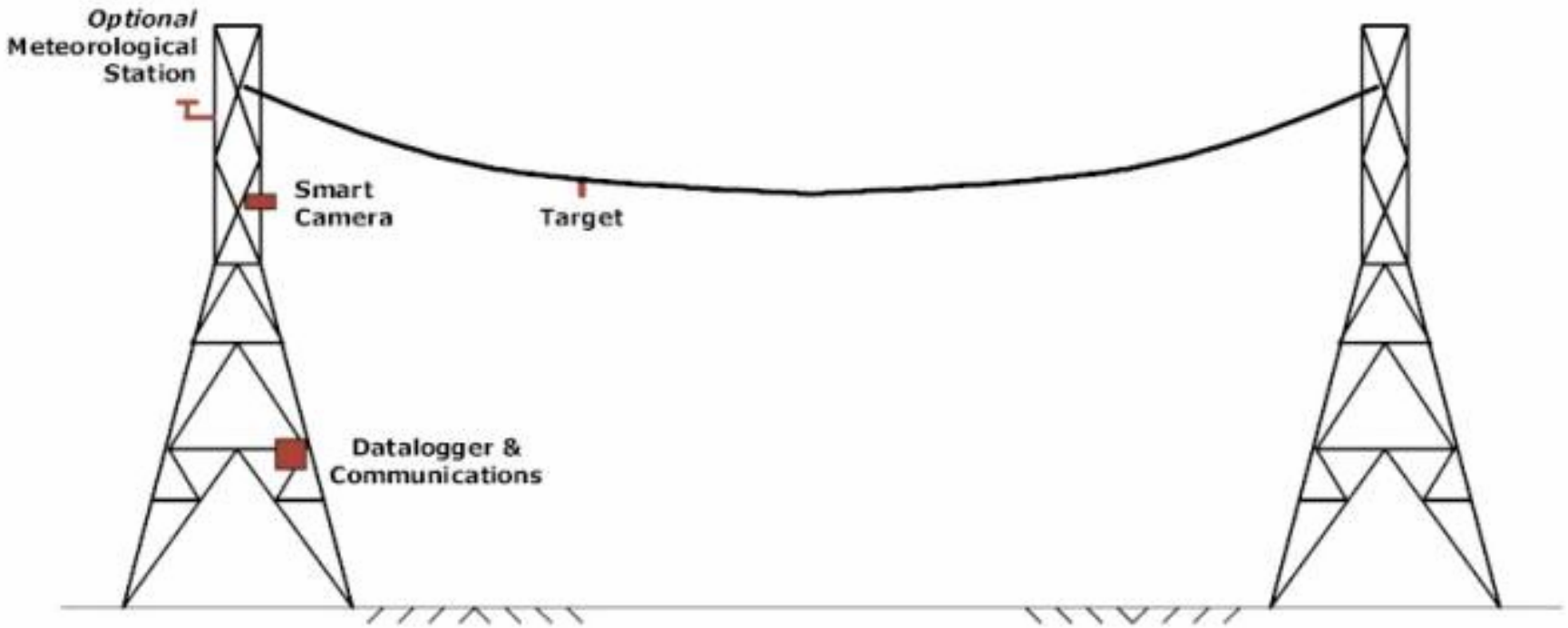
Sagometer

SAGOMETER™ SYSTEM COMPONENTS



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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!

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"Boundary Conditions"

- Givens
  - Energy Efficiency
  - Recycle Everything
- Off-the-Table: Eco-invasive Power Generation
  - All Fossils (CO_2 –forced climate change)
    - Carbon Sequestration
  - Baseline Renewables
    - Massive "Farms" – Wind, Solar, Biomass
- On-the-Table
  - Nuclear Fission Baseline Generation
  - Underground Energy Transmission Corridors
  - Solar Roofs
  - Urban/Agro Biomass

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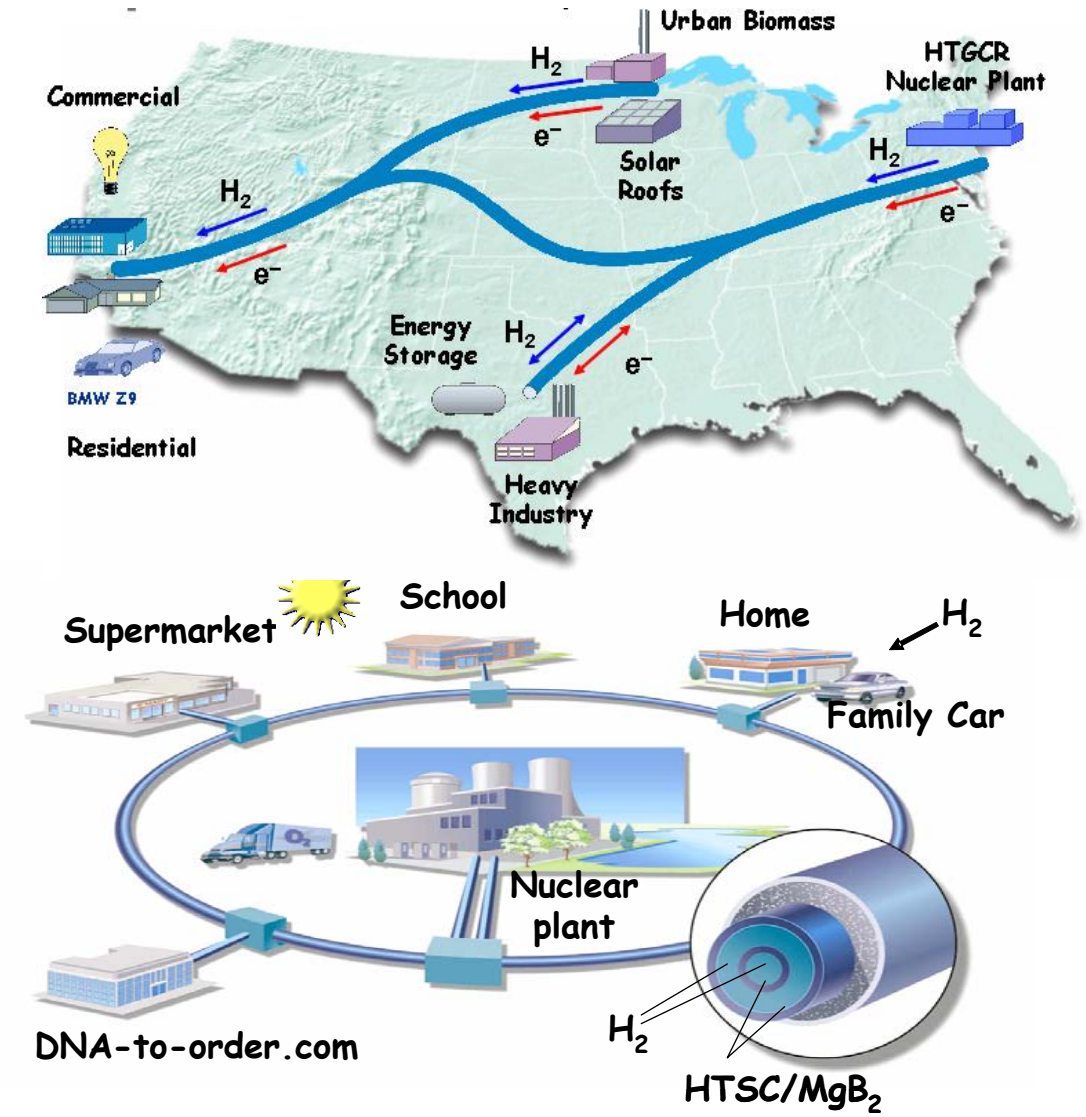
The Vision Concept



- Nuclear Power can generate both electricity and hydrogen – “Hydricity”
- Hydricity can be distributed in underground pipelines like natural gas
- The infrastructure can take the form of a **SuperGrid**
- …or a **SuperCity**

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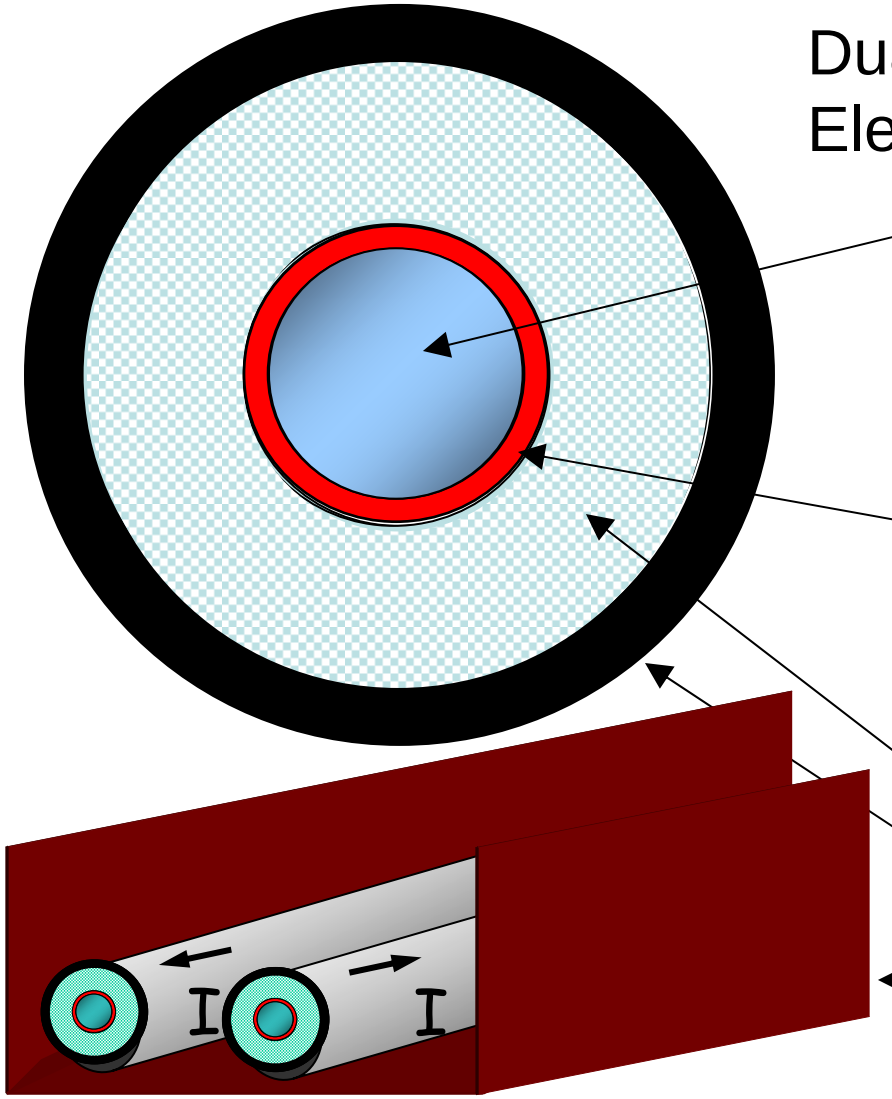
The Hydricity SuperCable

Dual Delivery of Hydrogen and Electric Power



Flowing liquid hydrogen or cold H_2 gas under pressure delivers power and also serves as the refrigerant to …

Enable the transmission of large amounts of electric power losslessly using superconductors

Thermal Insulation

Electrical Insulation

Enclosed in underground tunnel or trench

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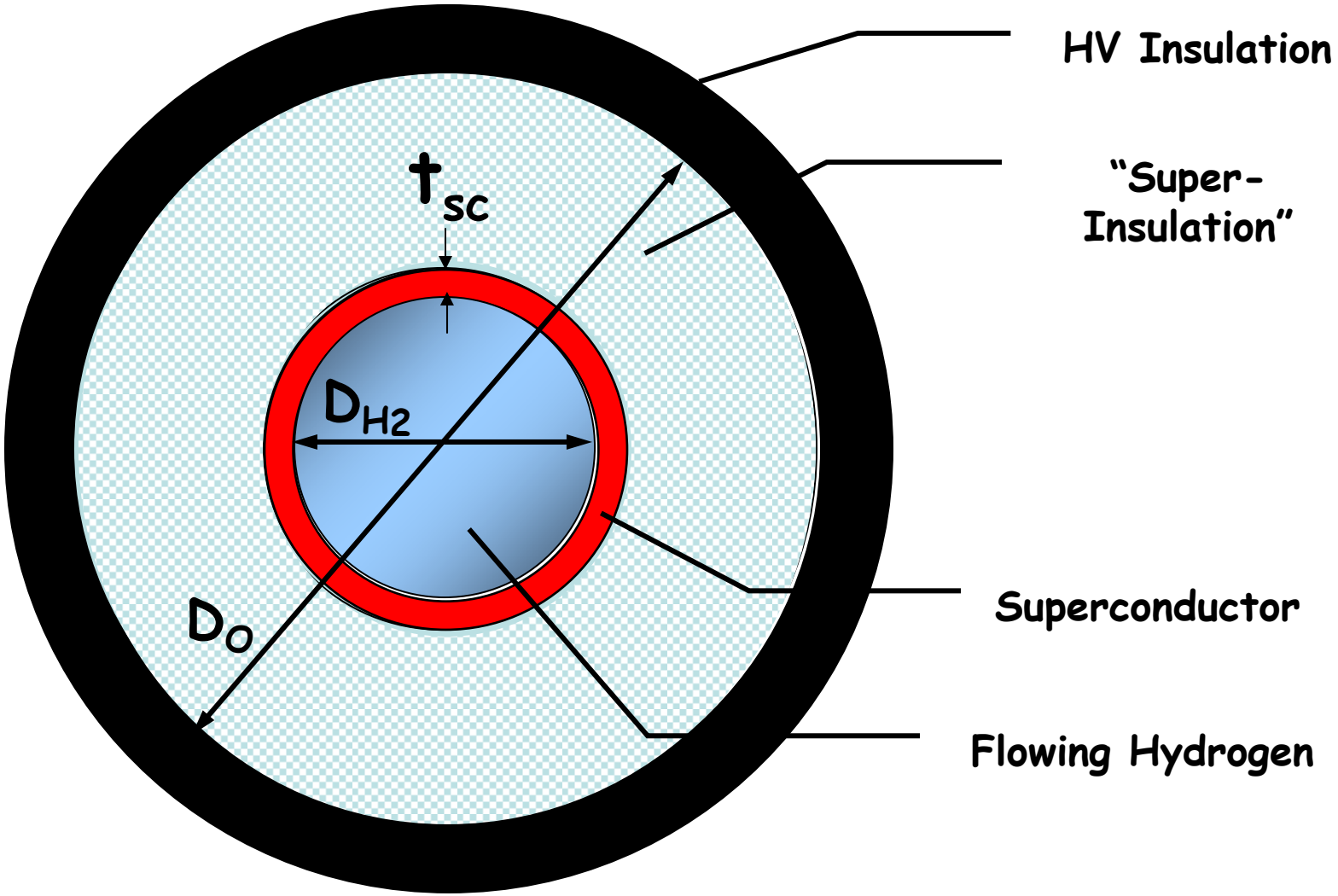
SuperCable Monopole



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Relative Power Flows

Electricity

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

P_{SC} = Electric power flow
V = Voltage to neutral (ground)
J = Supercurrent density
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

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Electricity (1000 MW) & Hydrogen (500 MW)

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

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The Hydrogen Economy

- You have to make it, just like electricity
- Electricity can make H_2, and H_2 can make electricity ($2H_2O \Leftrightarrow 2H_2 + O_2$)
- You have to make a lot of it
- You can make it cold, - 419 F (21 K)

P.M. Grant, "Hydrogen lifts off…with a heavy load," Nature 424, 129 (2003)

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The Hydricity Economy

Hydrogen for:

- Personal Transportation
- Storage of Electricity
- Industrial Thermal/Chemical Processing
- Residential/Commercial Heating

Electricity for:

- *Just about everything else!*

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Hydrogen for US Surface Transportation
"You have to make a lot of it"

Factoids & Assumptions

Daily consumption of gasoline and diesel by US cars & Trucks	8.6 Billion barrels/day
Effective Otto Cycle Efficiency (Useful conversion to drive chain)	25 %
Water Electrolysis Efficiency (Source Electricity-to-Hydrogen)	80 % (aggressive)
Fuel Cell Efficiency (Onboard Hydrogen-to-Electricity)	80 % (very aggressive)
Conversion/drive chain Efficiency	80 % (nominal)
Additional Electric Generation Plant Capacity for Hydrogen Vehicles	400 GW

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Hydrogen for US Surface Transportation: Generation by Renewable Electricity

Land Area Required to Supply by Renewables		
Technology	Area (km^2)	Equivalent
Wind	130,000	New York State
Solar	20,000	50% Denmark Death Valley + Mojave
Biomass	271,915	3% USA State of Nevada

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Diablo Canyon & Wind Power "Equivalent"

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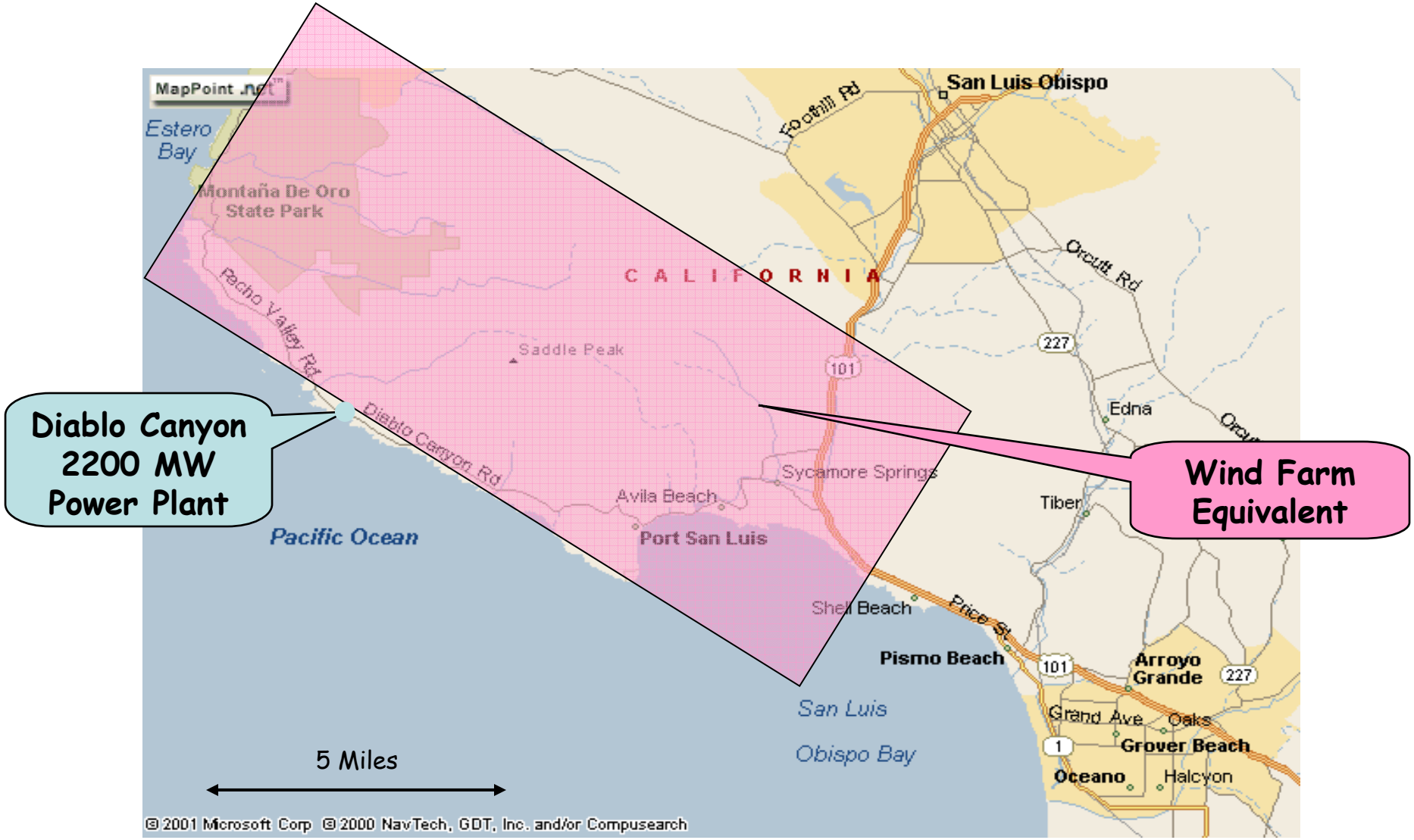
Nuclear_Power
California Coast Power



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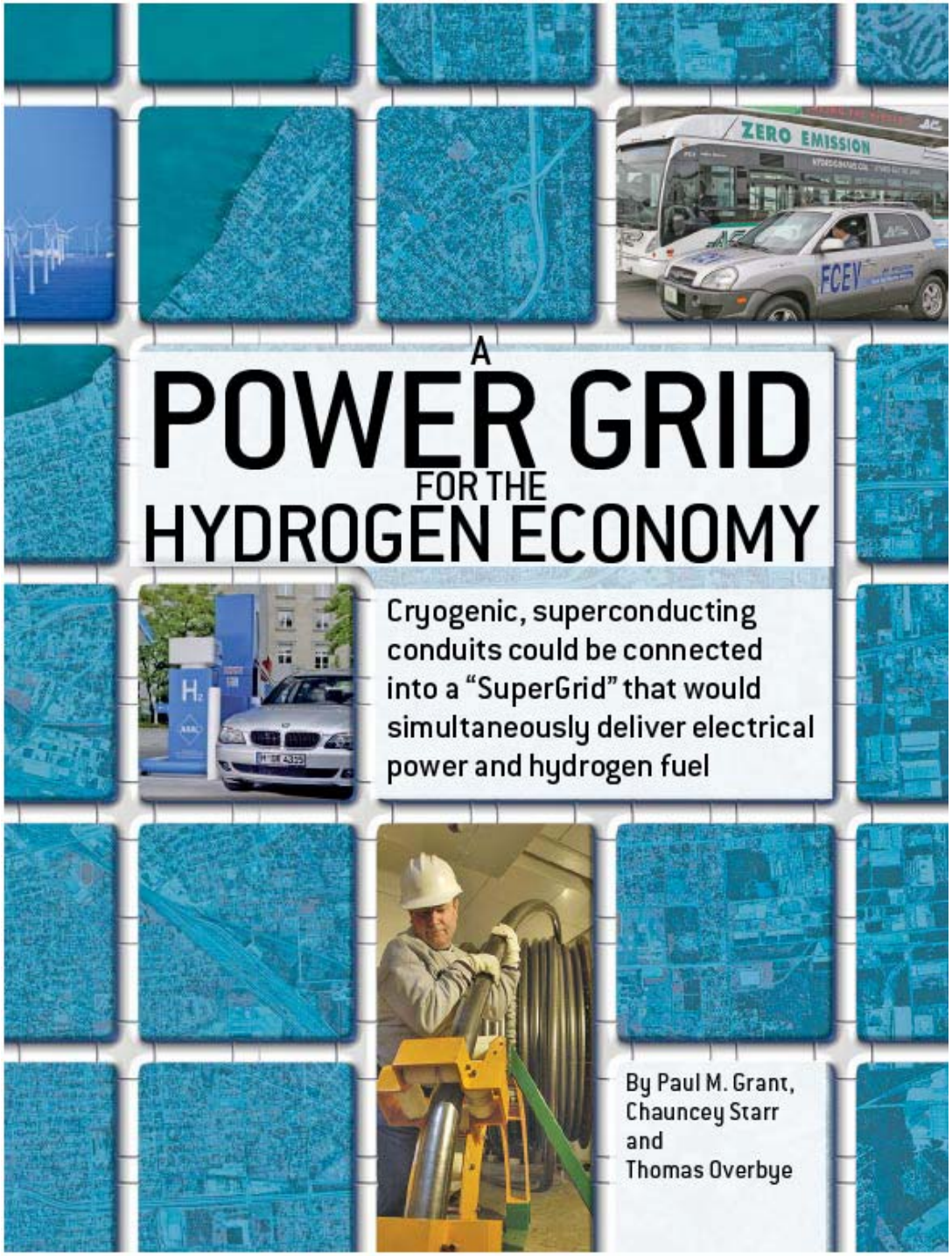

On the afternoon of August 14, 2003, electricity failed to arrive in New York City, plunging the 10 million inhabitants of the Big Apple—along with 40 million other people throughout the northeastern U.S. and Ontario—into a tense night of darkness.

Published in

SCIENTIFIC AMERICAN

July, 2006

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The Energy SuperGrid

Where there is no vision,
the people perish…

Proverbs 29:18 (1000 BCE)

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