Superconductivity
SuperCables
SuperGrid

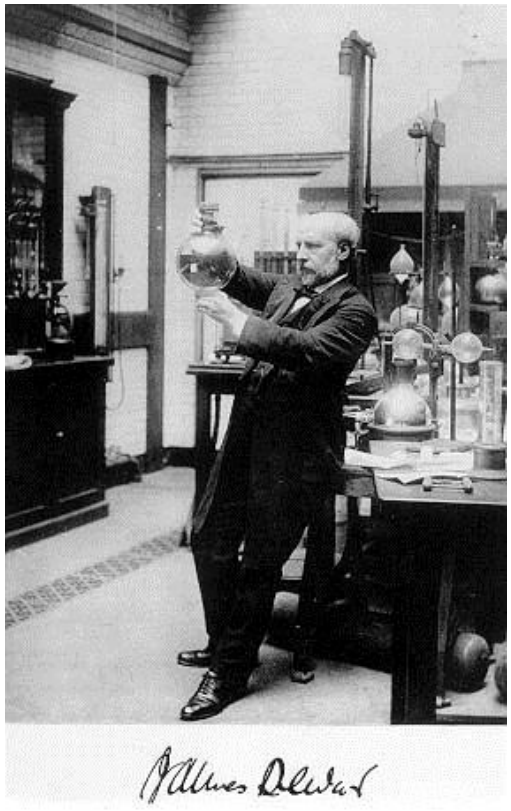
SuperStuff!

Sloan Foundation Seminar
630 Fifth Avenue
New York City, 28 July 2003

Paul M. Grant
Science Fellow
pgrant@epri.com
Electric Power Research Institute
Palo Alto, California USA

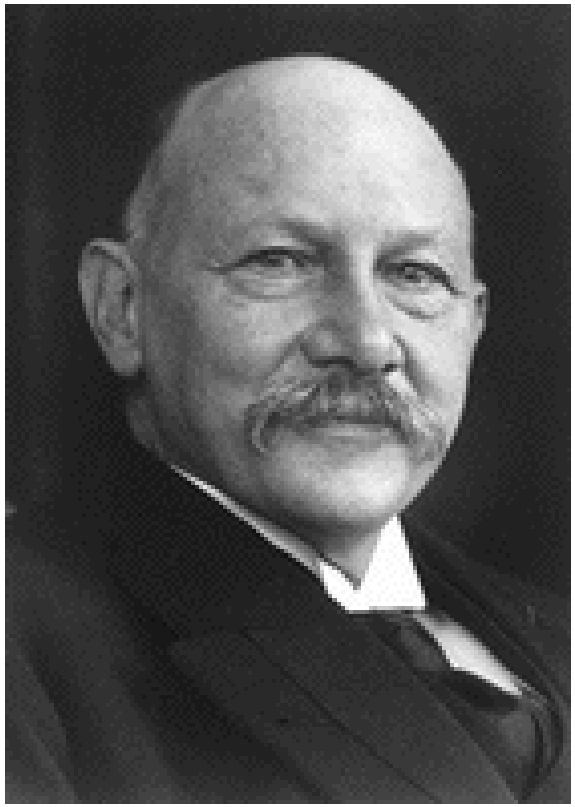
EPRI

Fathers of Cryogenics



Dewar

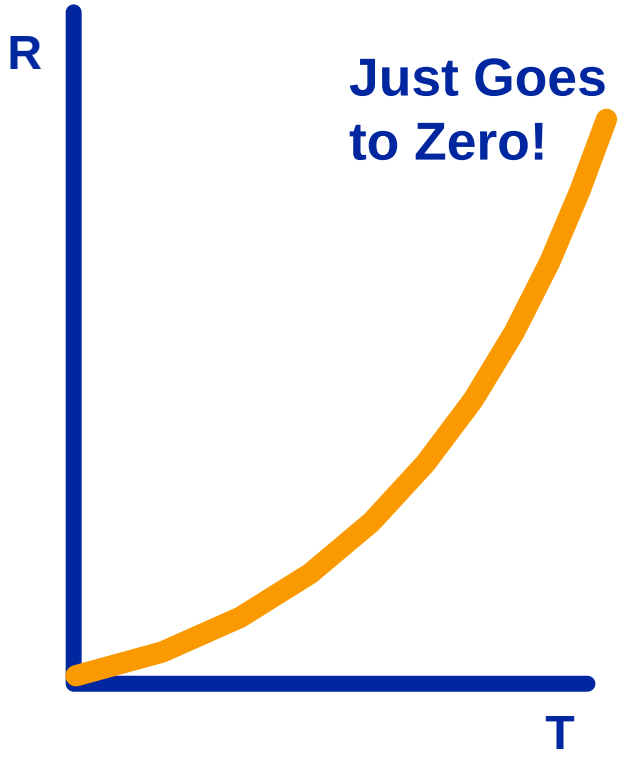
CH_4	112 K
O	90
N_2	77
Ne	27
H_2	20
He	4.2

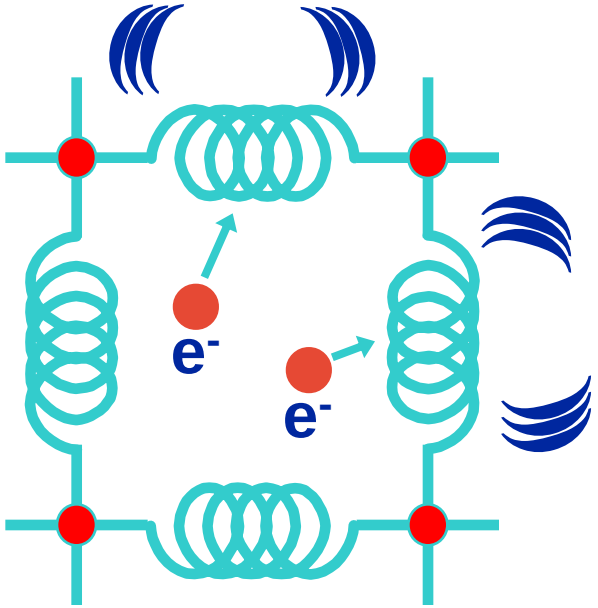


Kammerlingh-Onnes

Models of Electrical Conductivity

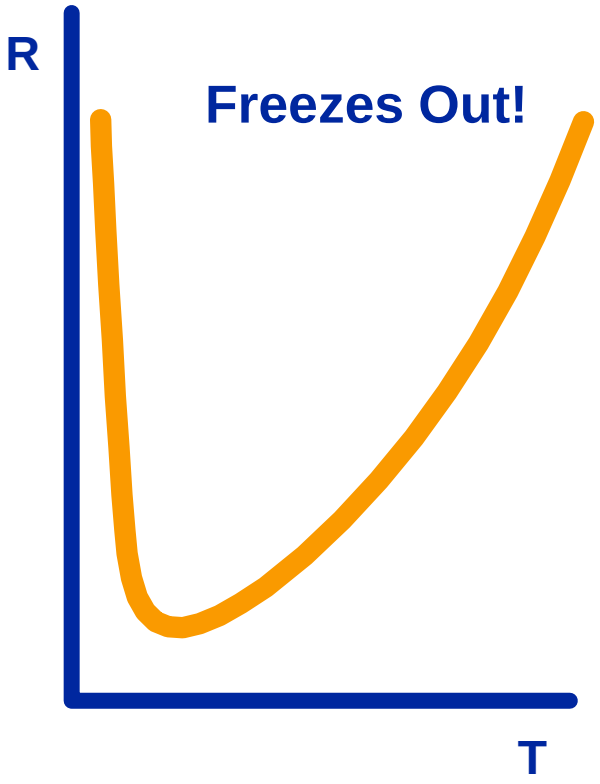
One Idea:

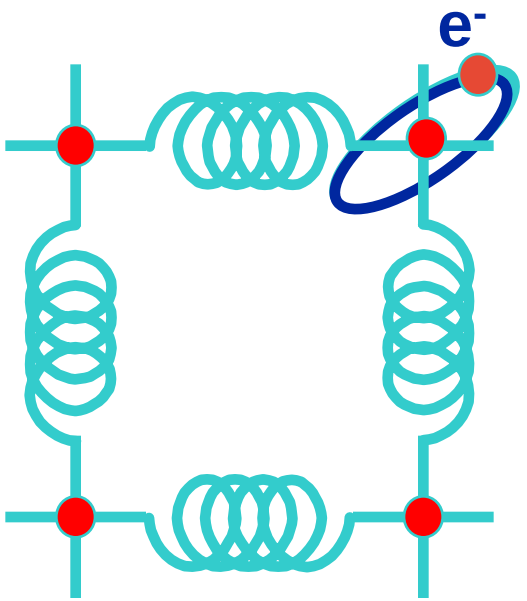




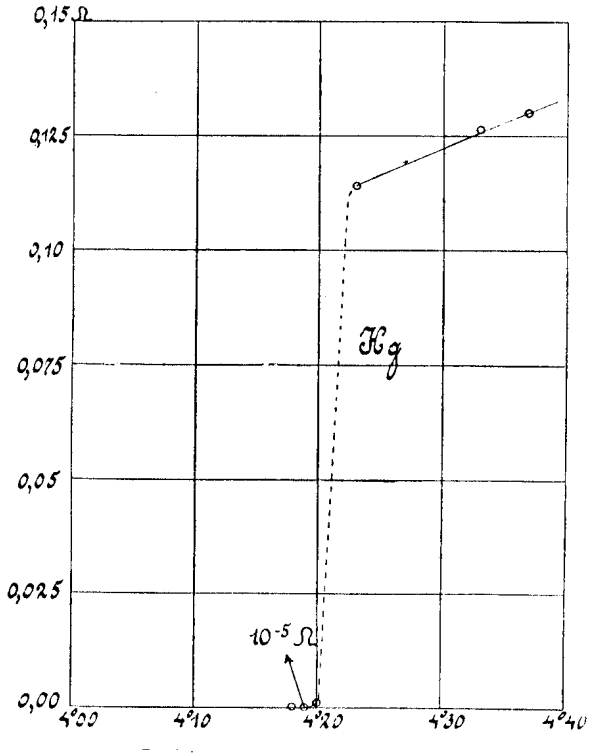
Models of Electrical Conductivity

The Most Popular:





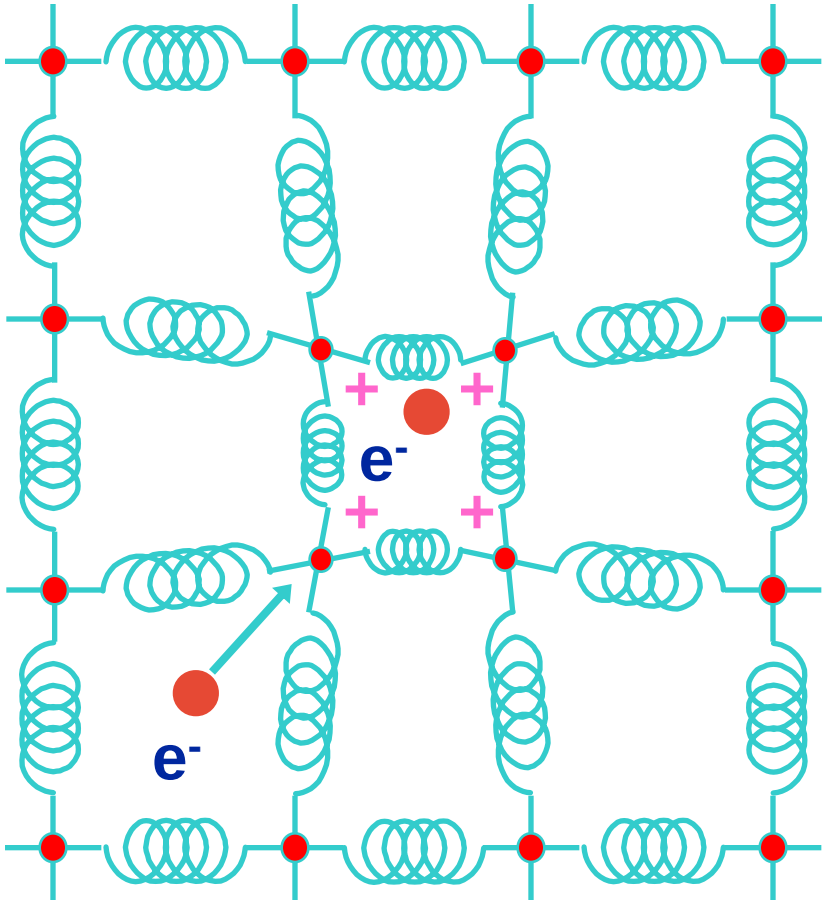
1911: A Big Surprise!



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)

Physics of Superconductivity



Electrons Pair Off!

BCS Equation

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

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

$$\lambda = 0.28,$$

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

1967: SC Cable Proposed!

Superconducting Lines for the Transmission of Large Amounts of Electrical Power over Great Distances

R. L. GARWIN AND J. MATISOO

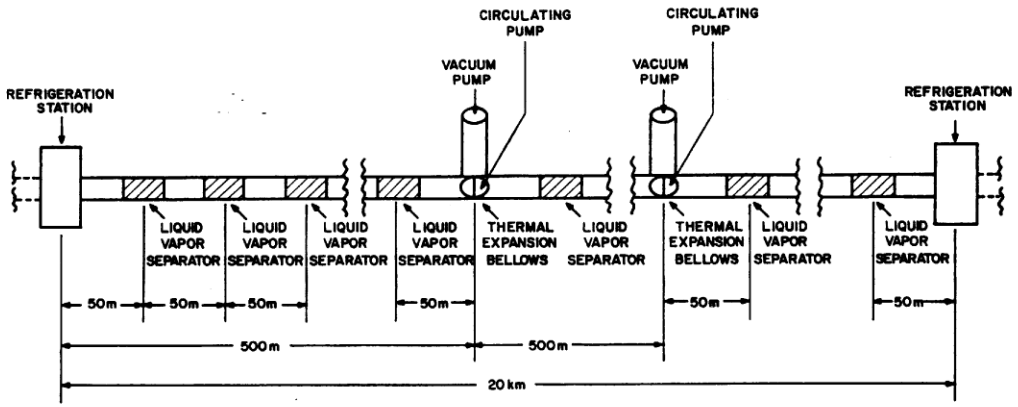


Fig. 2. A 20-km module of the 1000-km, 100-GW line.

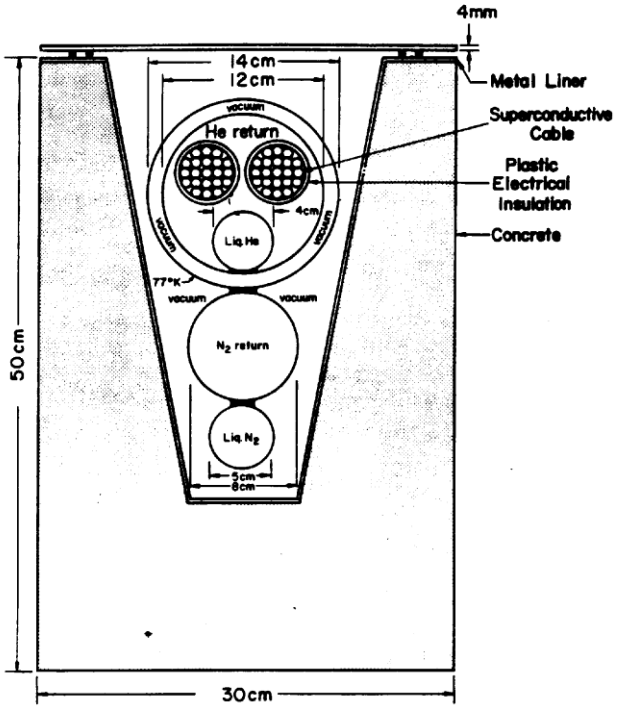
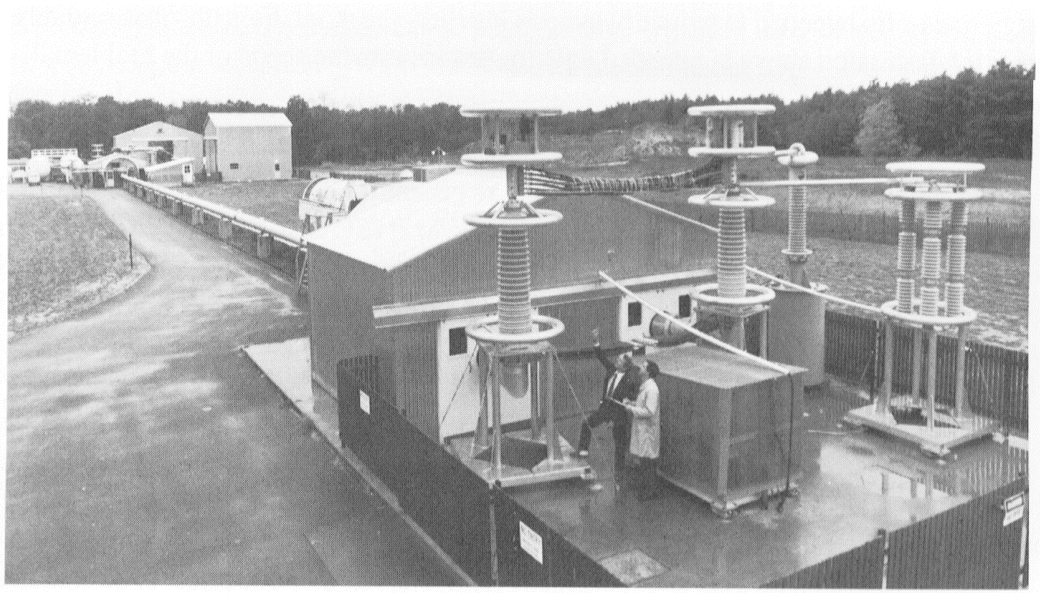


Fig. 1. Cross section of the 100-GW line.

100 GW dc, 1000 km !

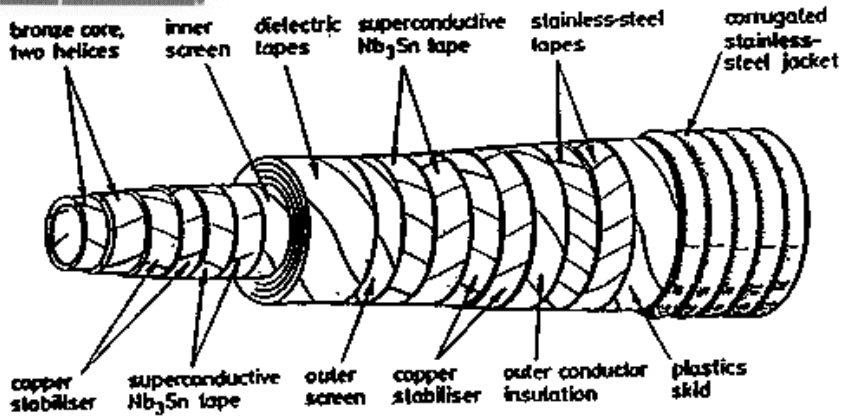
Brookhaven LTS ac Cable 1975-86



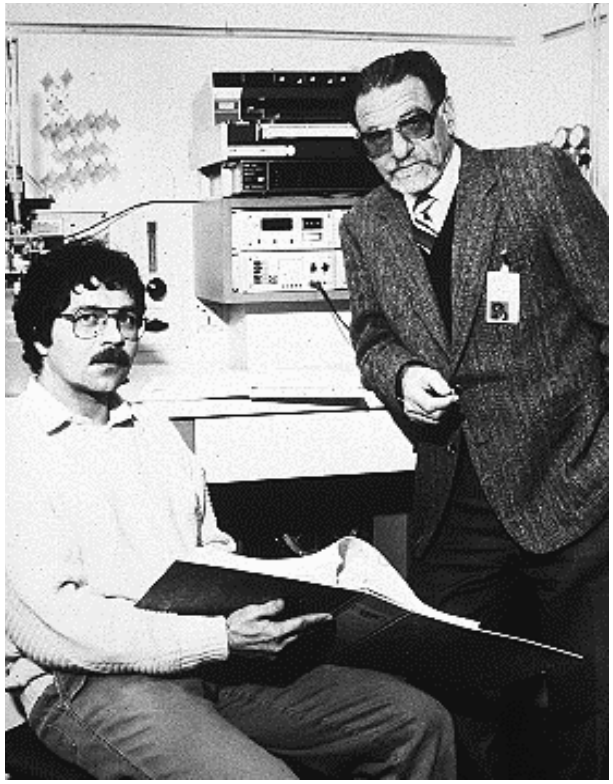
- Technical Success
- Economics Unclear

135 kV, 1000 MVA, 3ϕ, 115 m

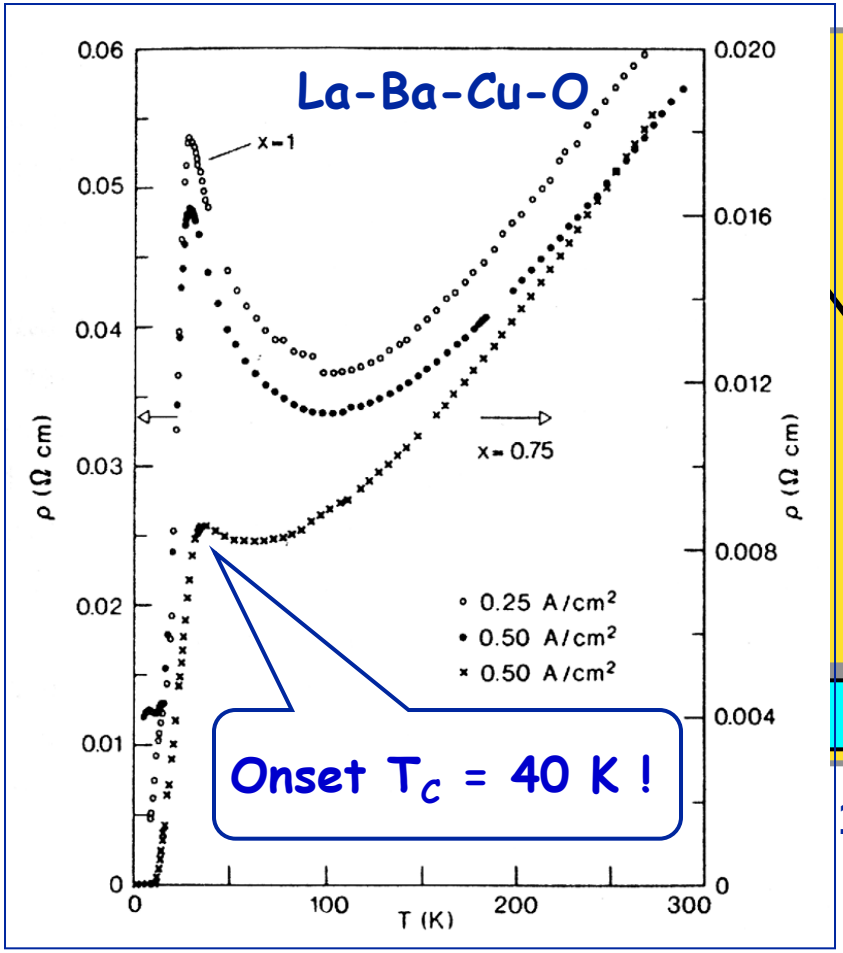
Nb_3Sn, 7-9 K

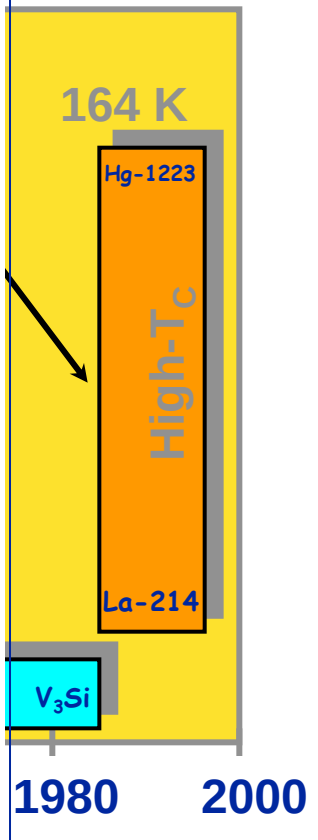


1986: Another Big Surprise!



Bednorz and Mueller
IBM Zuerich, 1986





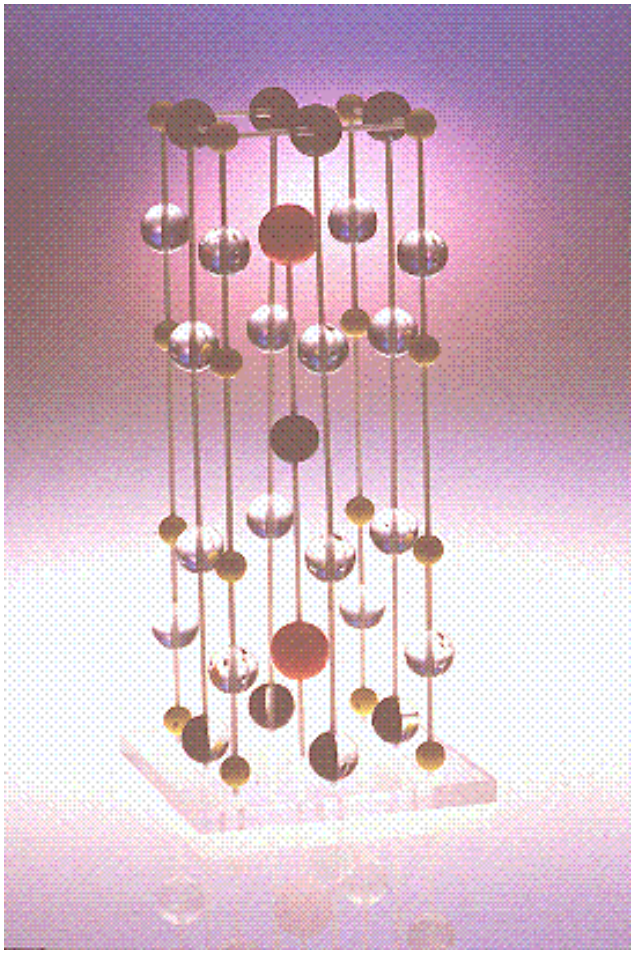
1987: "The Prize!"

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

March 3, 1987: "123" Structure
IBM Almaden Research Center



Woodstock of Physics NYC, 1987

Physicists' Night Out!

commentary

Woodstock of physics revisited

Ten years have passed since the now famous American Physical Society meeting that heard the first breathless accounts of high-temperature superconductivity. Now, in calmer times, practical applications are emerging.

Paul M. Grant

Snap quiz: who can tell me the winner of the 1987 Super Bowl? Not most physicists, I suspect, for whom it was certainly eclipsed by two events of far greater consequence that shared the early months of that year. One, the discovery of Supernova 1987A, perhaps portended the other: the announcement of superconductivity above liquid-nitrogen temperature on planet Earth — a dream fulfilled for many condensed-matter physicists like myself, whose careers had orbited around this elusive star.

The successful sighting[1] fell to W. K. Wu and C. W. (Paul) Chu and their teams of students and postdocs at the Universities of Alabama and Houston, following only five months after the publication in autumn 1986 by Georg Bednorz and Alex Müller[2] at IBM Zürich of their discovery of superconductivity in a previously unexplored class of compounds, the layered copper-oxide perovskites.

The 'inside' story of the hectic interval between the first week in January 1987 — when an announcement of the confirmation of Bednorz and Müller's discovery first brought 'high-temperature superconductivity' to wide public attention — and the week of the American Physical Society's March meeting, remains to be told. Suffice it to say that this period, and the last three months of 1986, were replete with incredulity, credulity, excitement, secrecy and a sense of immediacy in competition with one's peers, all of which resulted in, frankly, a substantial amount of intrigue and suspicion. All who participated surely came to understand, if they had not done so before, that physics is not only a science but, perhaps more significantly, an intensely human pursuit — something they do not teach you in graduate school.

Rising stars: Müller and Chu with Shoji Tanaka (right), whose Tokyo laboratory provided one of the first confirmations of Bednorz and Müller's discovery.

The programme of the March meeting, held each year in a different US city, is 'cast in concrete' early the preceding December; thereafter, an absolute policy of no alterations prevails. By the deadline of 5 December 1986, for the 1987 meeting at the Hilton hotel in New York City, only one abstract had been accepted on the new materials: "Specific heat of Ba–La–Cu–O superconductors" by Rick Greene and his collaborators at IBM Yorktown. But the explosion of results that appeared in the new year prompted the meeting's organizers to take an unprecedented step. Brian Maple of the University of California, San Diego, was asked to put together a special post-deadline evening session devoted entirely to the discovery.

All those wishing to report results would be granted five minutes each, in order of the arrival of their request to take part — and did the requests rain in, reaching a downpour in the two weeks before the meeting, as confirmations of the Wu–Chu measurements were made. All in all, 51 presentations were to be given throughout the evening and early morning of Wednesday and Thursday, 18 and 19 March. That memorable and riotous session was to become our "Woodstock of physics", so named in honour of the village only 50 miles north where, in an obscure farmer's muddy field in 1969, the rock concert occurred that defined a generation of youth the world over.

Fever pitch: the room filled to overflowing with physicists eager for news of superconductivity.

Opening act

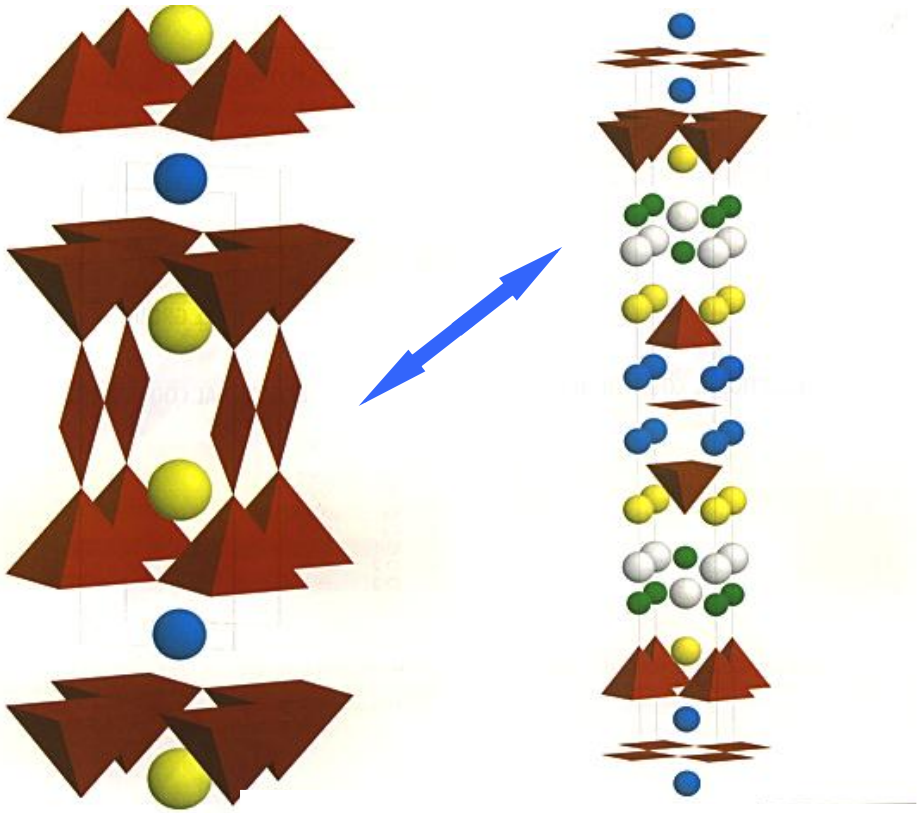
A few personal observations and anecdotes may help to convey the colour of that week in midtown Manhattan. Excitement was running high even before Wednesday night. On Monday, the opening day, the press were already beginning to catch some of us to be interviewed. That noon my colleague Ed Engler and I went to lunch at a nearby Brew 'n' Burger and found Alex Müller sitting by himself in a corner booth, attempting to escape the turmoil at the Hilton. At the time he was not yet widely recognizable to those attending the meeting or to the press — a situation that would soon change.

"The Great Communicator"

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.

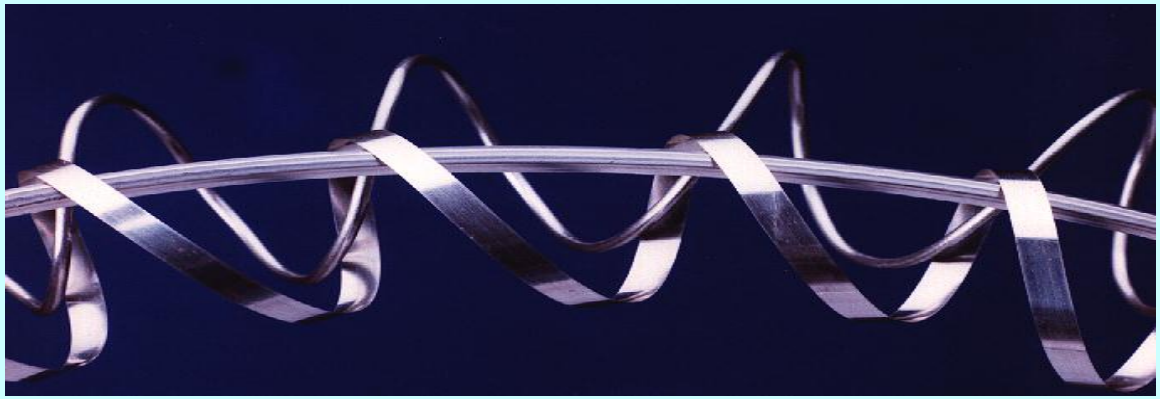
HTS Layered Perovskites

Y-123 Bi-2223

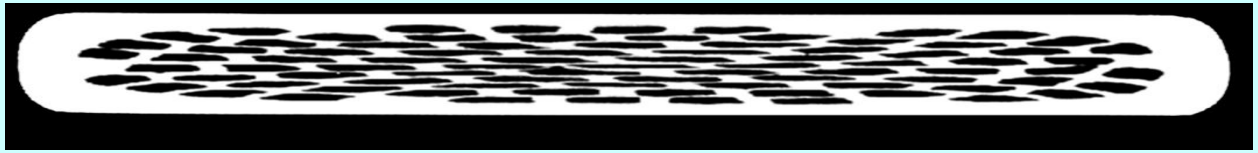


HTSC Wire Can Be Made!

"The Miracle of 1989"

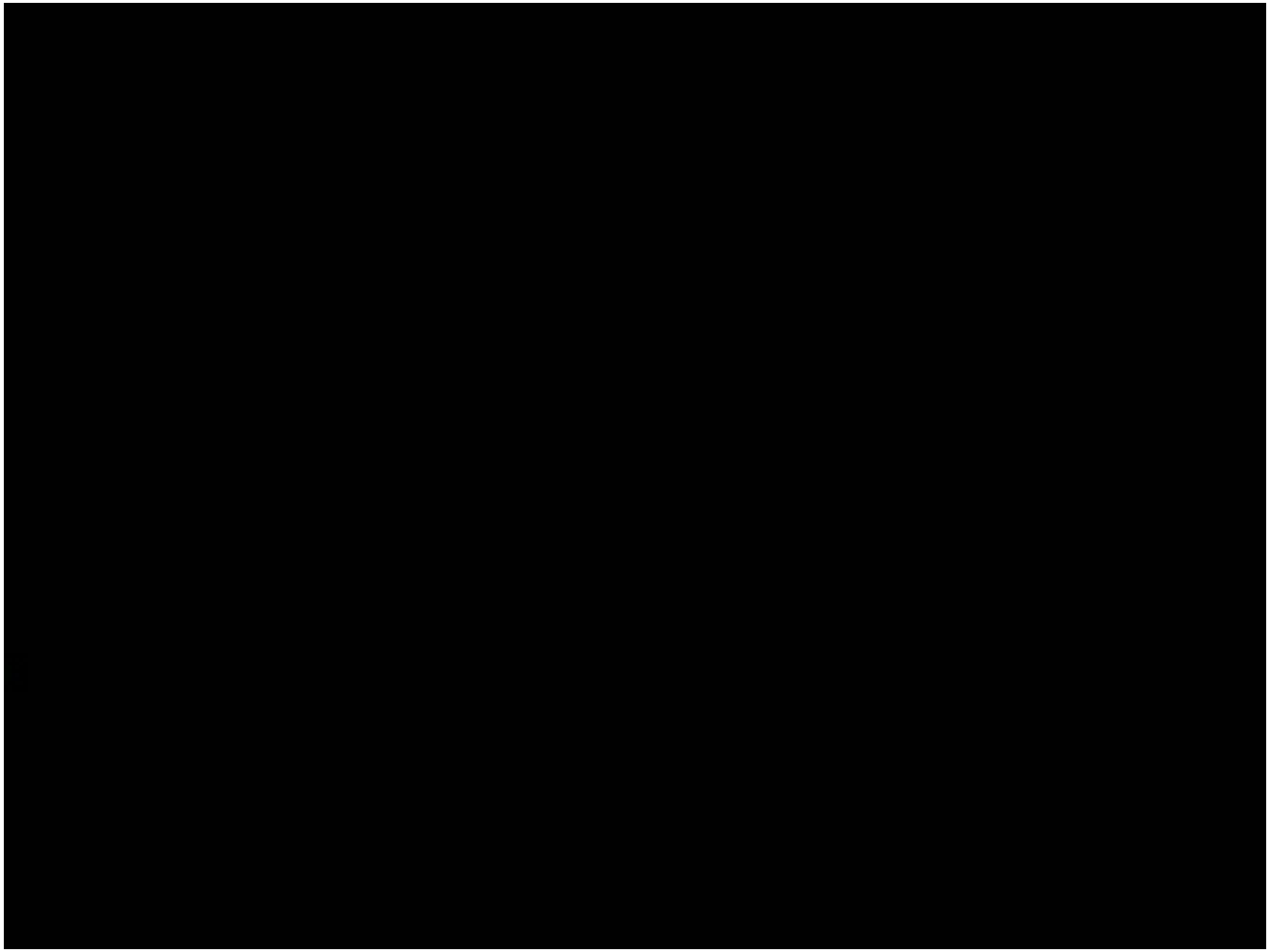


But it's 70% silver!



Finished Cable

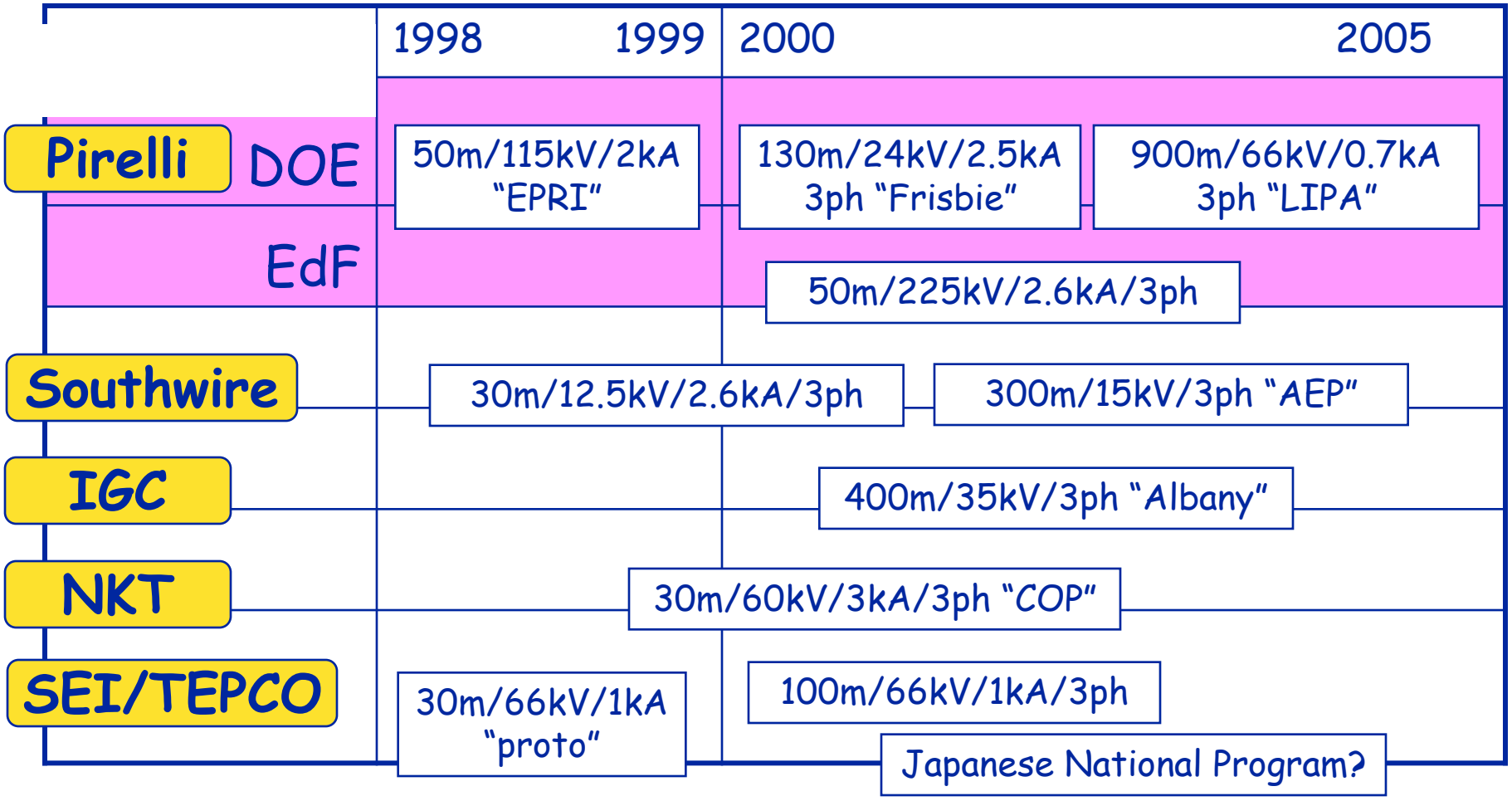
Men at Work



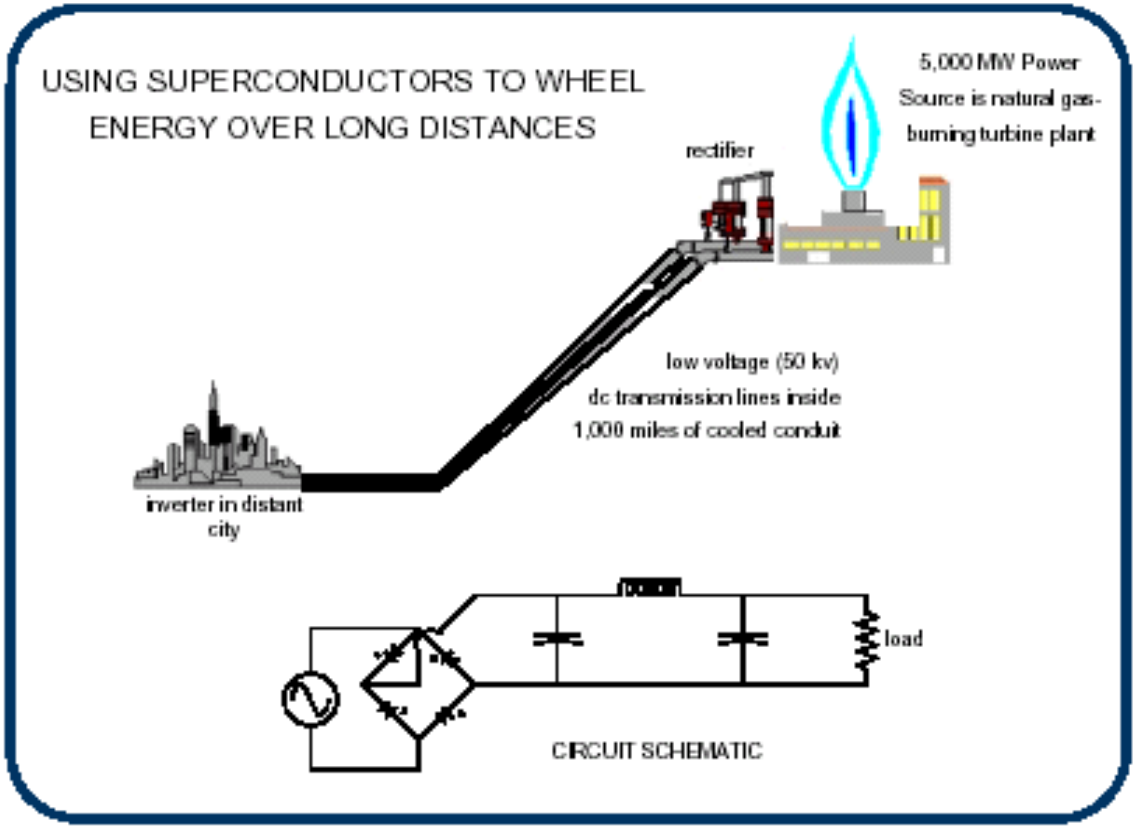
Men at Work, II

Men at Work, III

HTSC Cable Projects Worldwide



Electricity Pipe

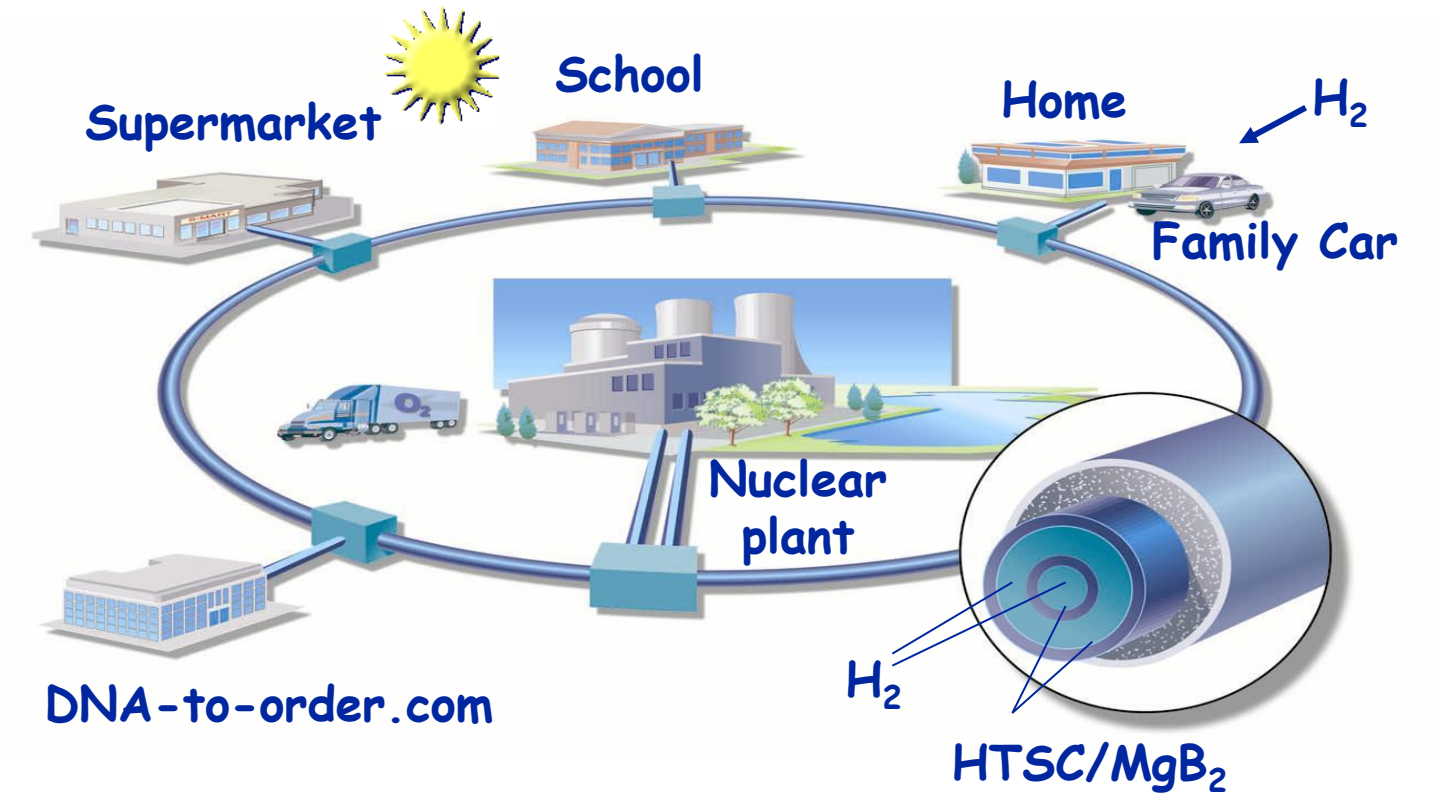


Initial EPRI study on long distance (1000 km) HTSC dc cable cooled by liquid nitrogen

-- 1997 --

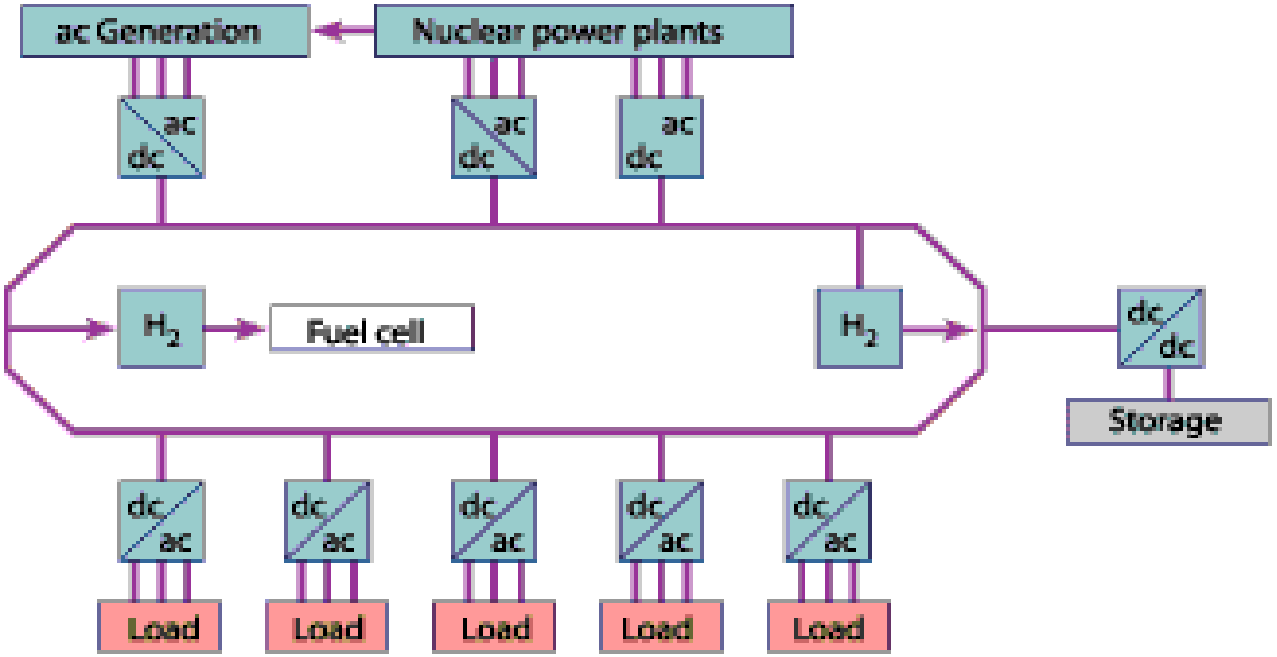
P.M. Grant, S. Schoenung, W. Hassenzahl, EPRI Report 8065-12, 1997

SuperCity



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

SuperGrid



Continental SuperGrid

C. S. Starr, "Continential SuperGrid," Nuclear News, Spring Issue, 2002

Distribution

10 MW Community Substation

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dc XFMR

H_2 Fuel Cell

H_2 Storage

End Use

Streetside Service

---

100 A @ +/- 25 Vdc

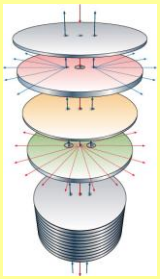
H_2 @ 200 K, 100 psi

PLC @ 5 MHz

H_2 Heat Exchanger for AC

H_2 for Heat/Hot H_2O

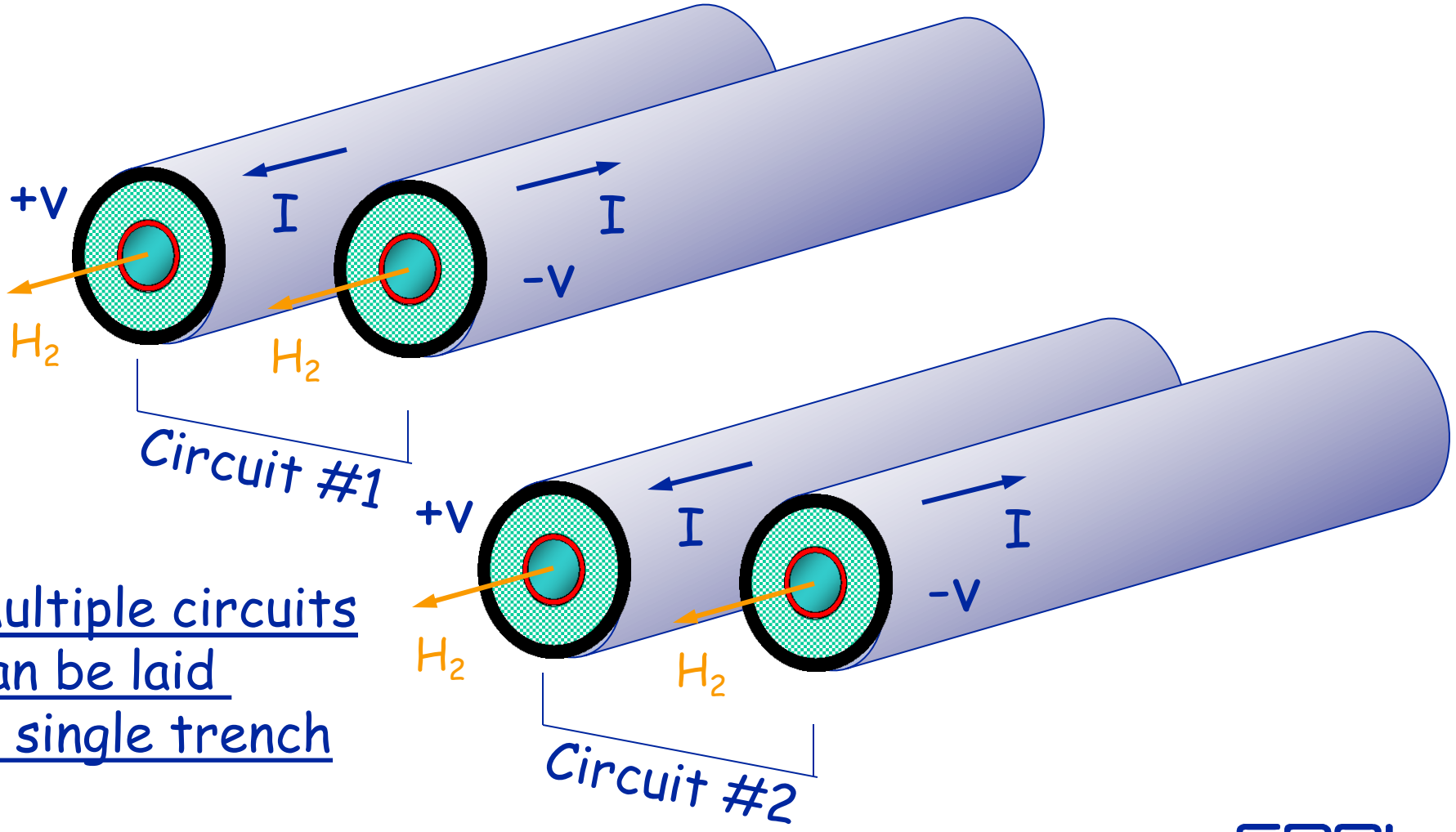
Household Fuel Cell



Inv/Conv for Electricity

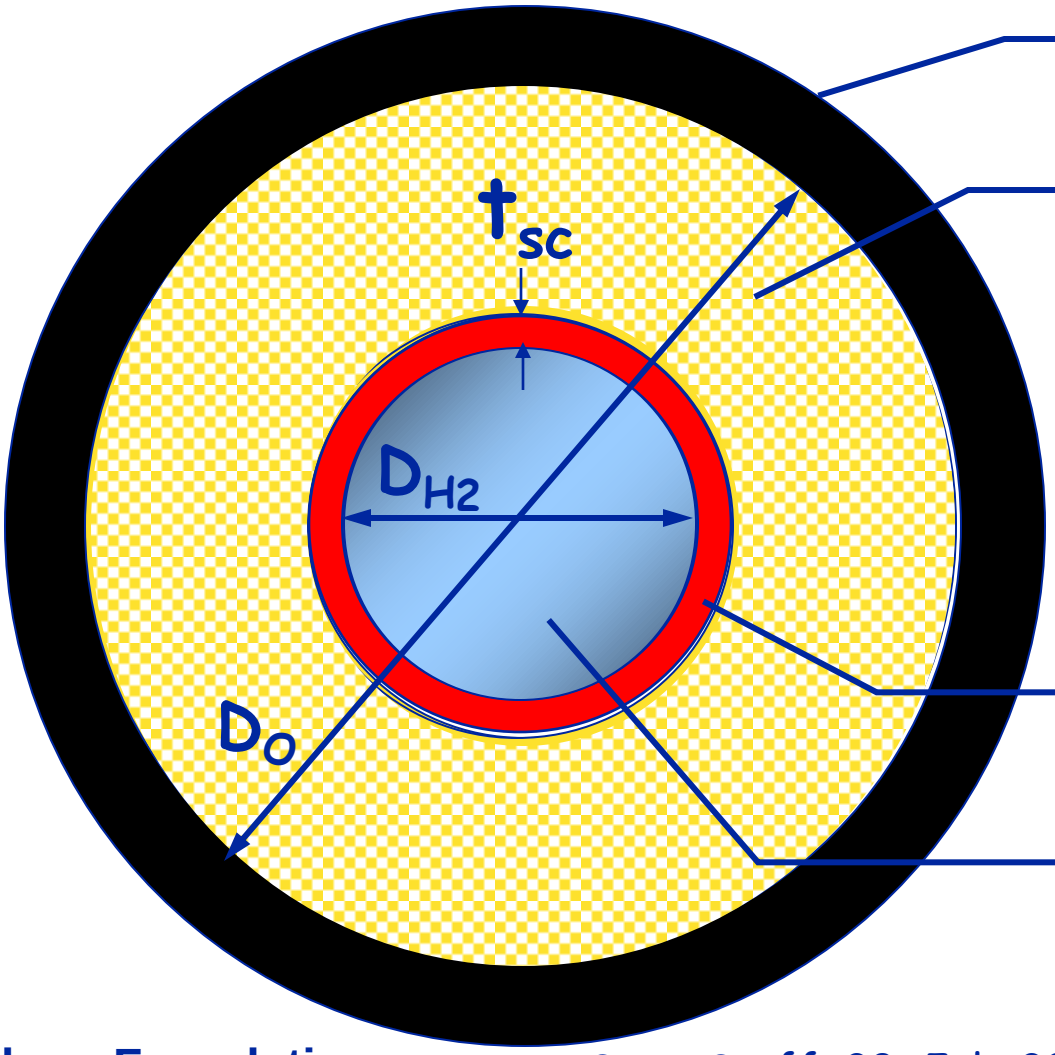
H_2 Storage for Auto

SuperCables



Multiple circuits can be laid in single trench

LH_2 SuperCable



HV Insulation

"Super-Insulation"

Superconductor

Hydrogen

Electric & H_2 Power

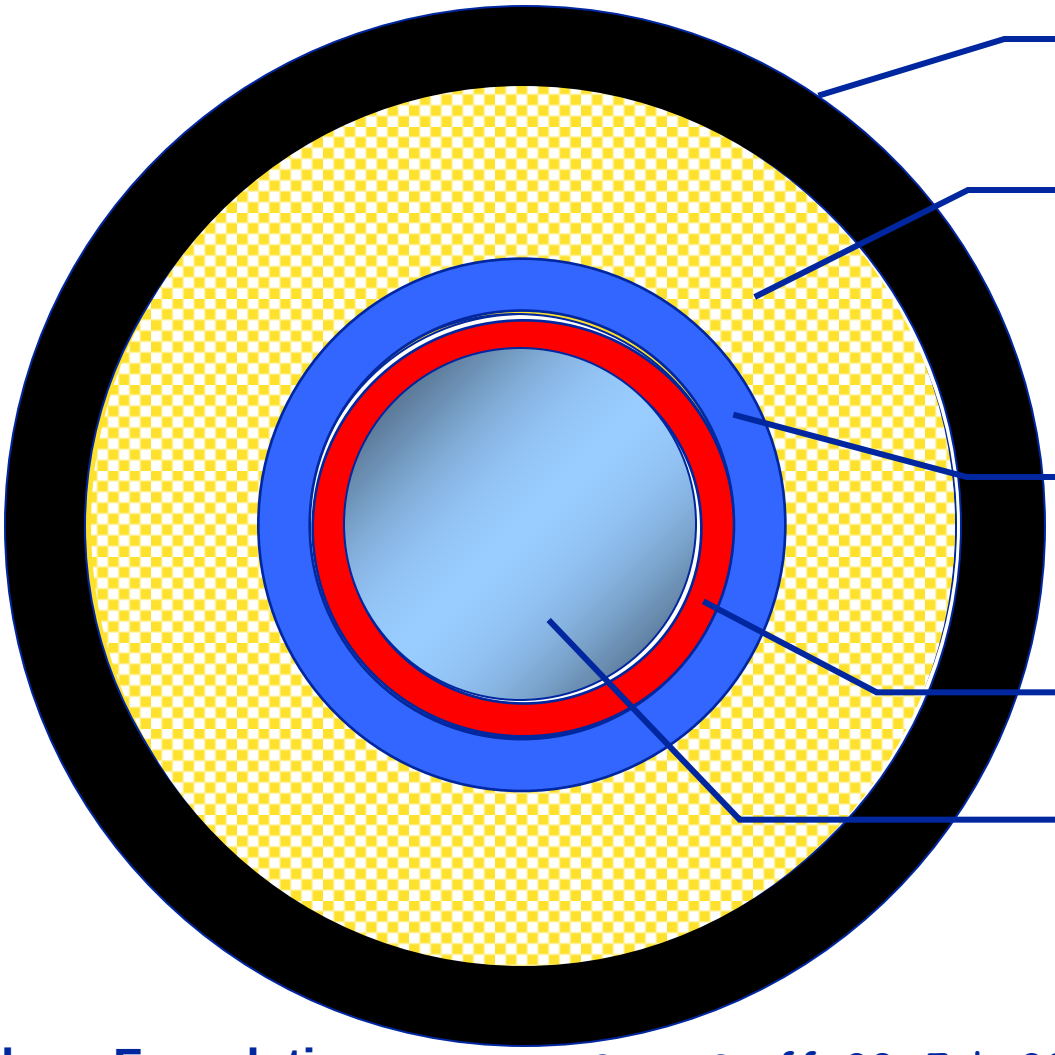
Electricity

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

H_2 - Gas SuperCable



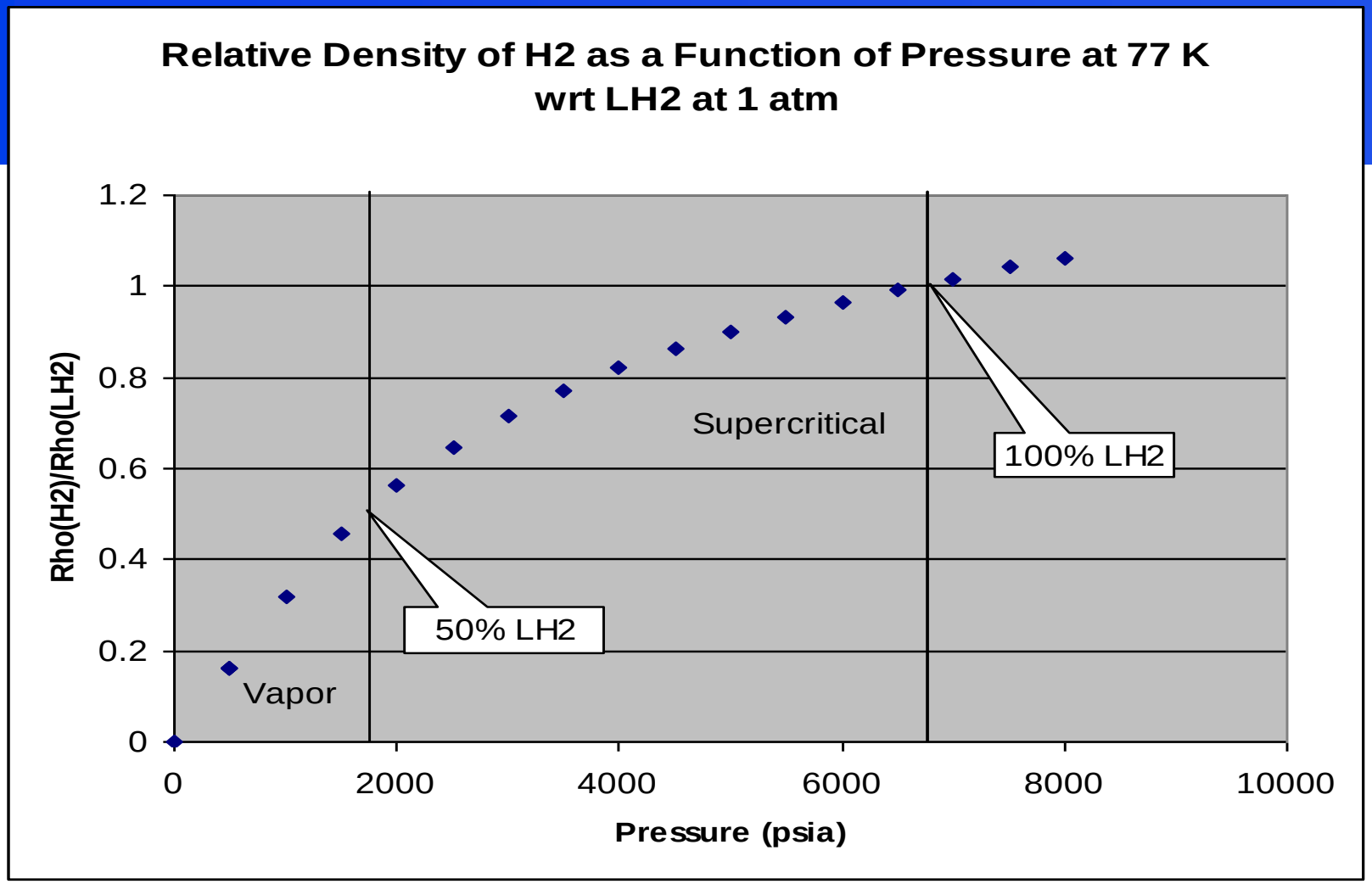
Electrical Insulation

"Super-Insulation"

Liquid Nitrogen @ 77 K

Superconductor

Supercritical Hydrogen @ 77 K 2000 – 7000 psia



H_2 Gas at 77 K and 1850 psia has 50% of the energy content of liquid H_2 and 100% at 6800 psia

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

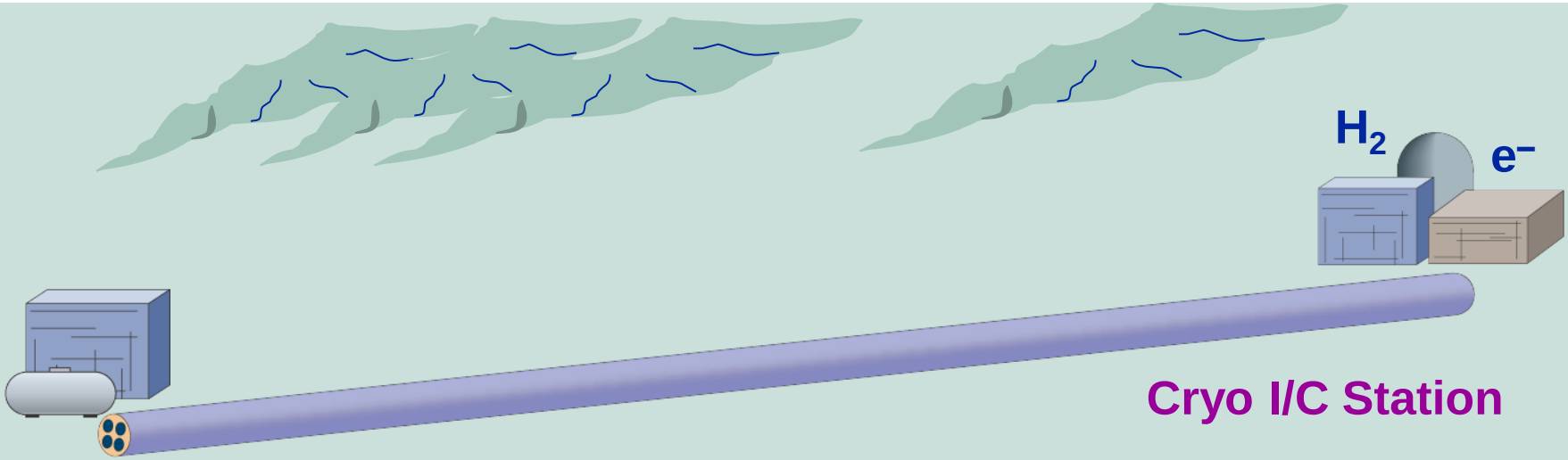
One Raccoon Mountain = 13,800 cubic meters of LH2

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

Issues & Challenges

- Policy
- Power Electronics
- Superconductivity & Cryosupport
- How to Begin?

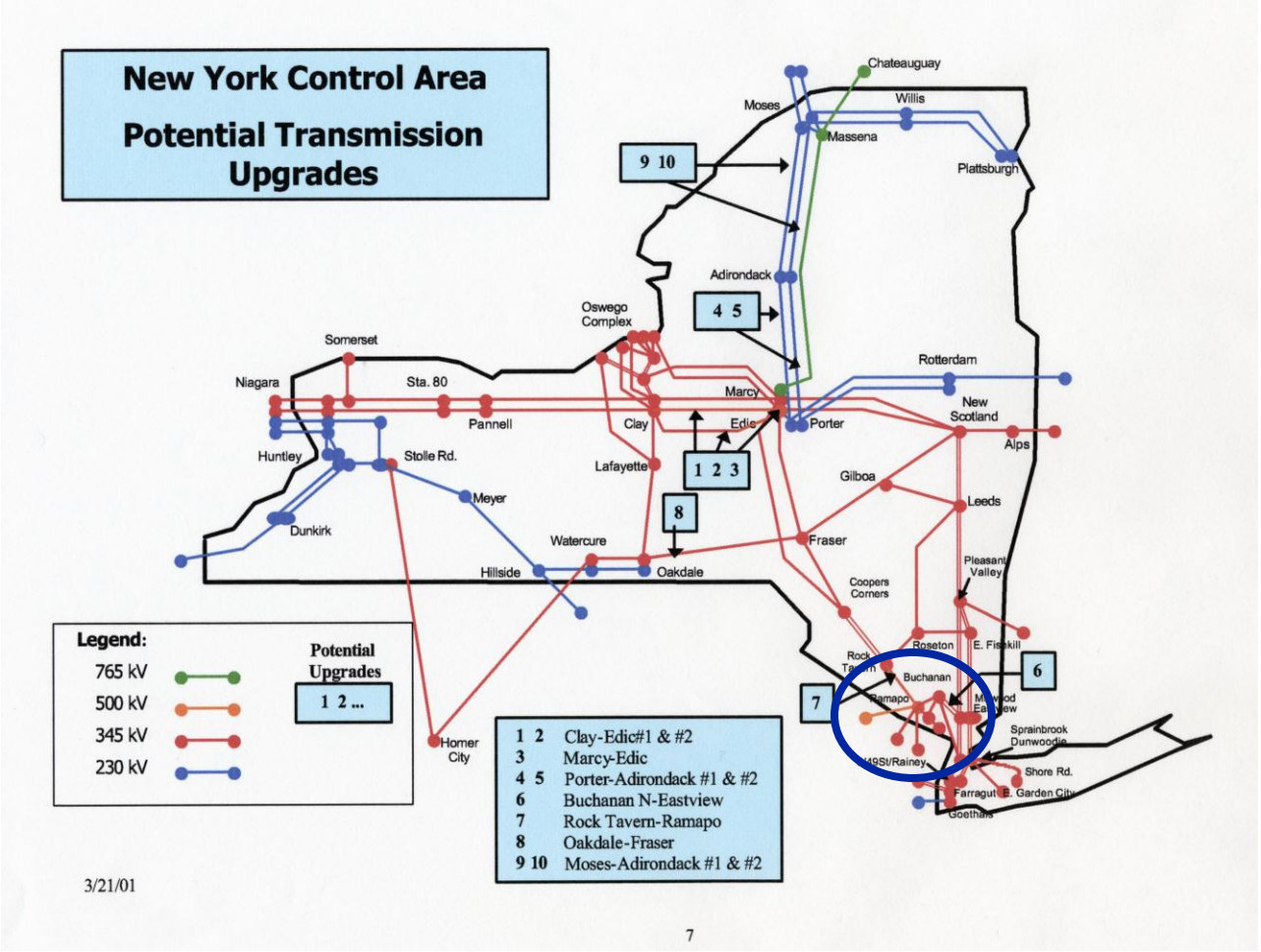
SuperCable Prototype Project



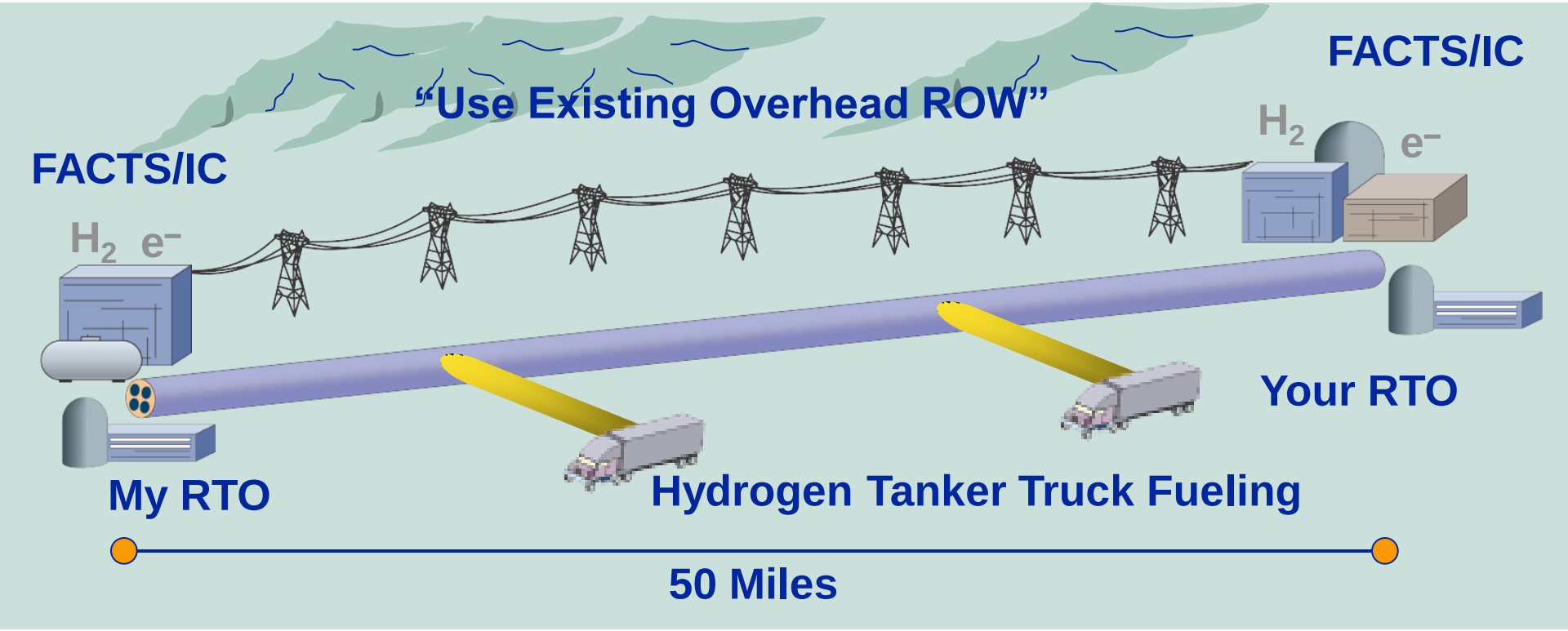
500 m Prototype

"Appropriate National Laboratory"
2005-09

Regional System Interconnections



RegionGrid Interconnection



“…an admirable work of science and patriotism.”

"Too often we fail to recognize and pay tribute to the

Marquis de Lafayette
…on first seeing the Erie Canal

creative spirit."

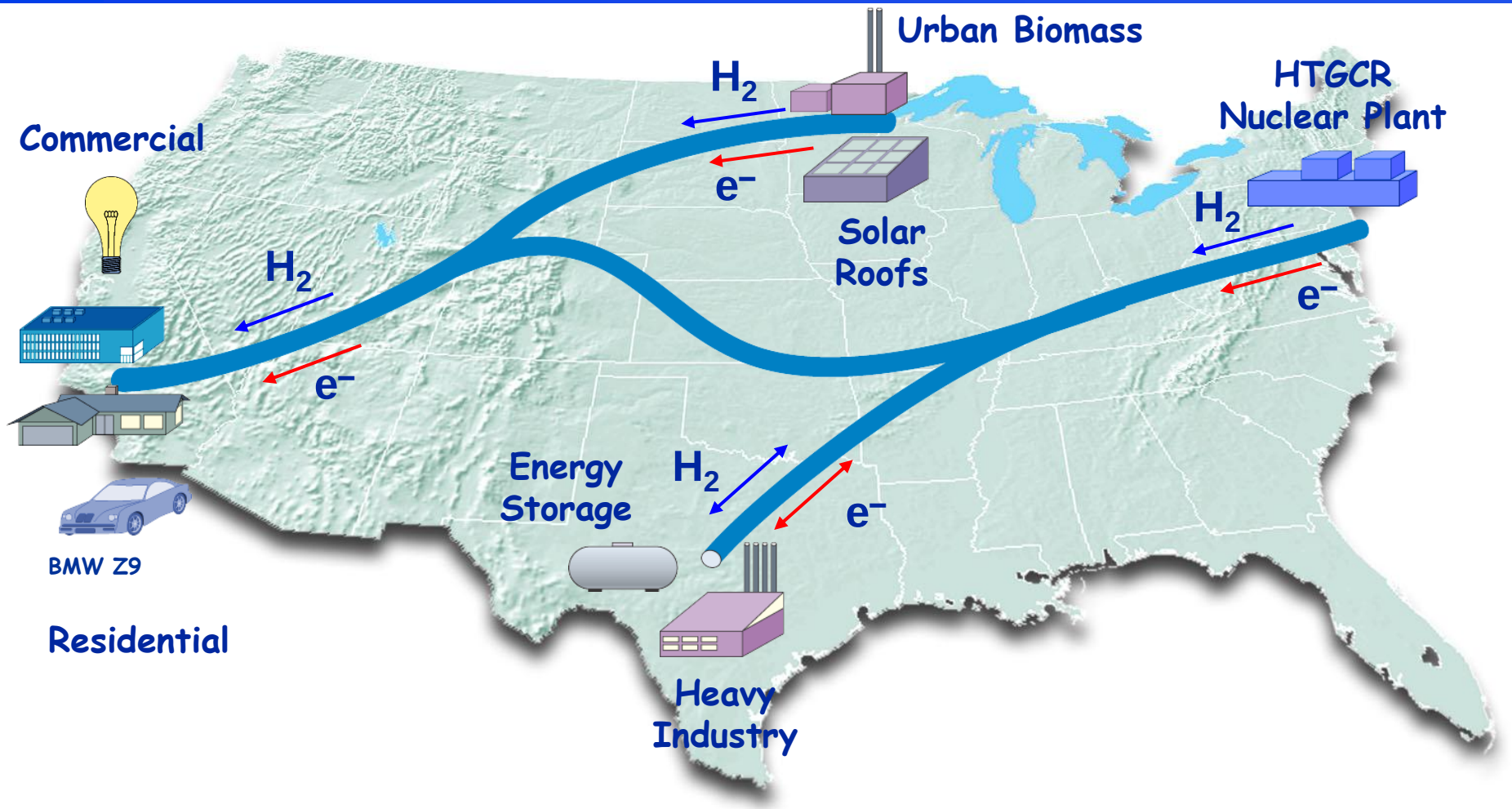
—Alfred P. Sloan, Jr.

Where there is no vision, the people perish…

Proverbs 29:18

A Vision Realized…

North American 21st Century Energy SuperGrid



Where there is no vision, the people perish…

Proverbs 29:18

"You can't always get what you want…"

"…you get what you need!"

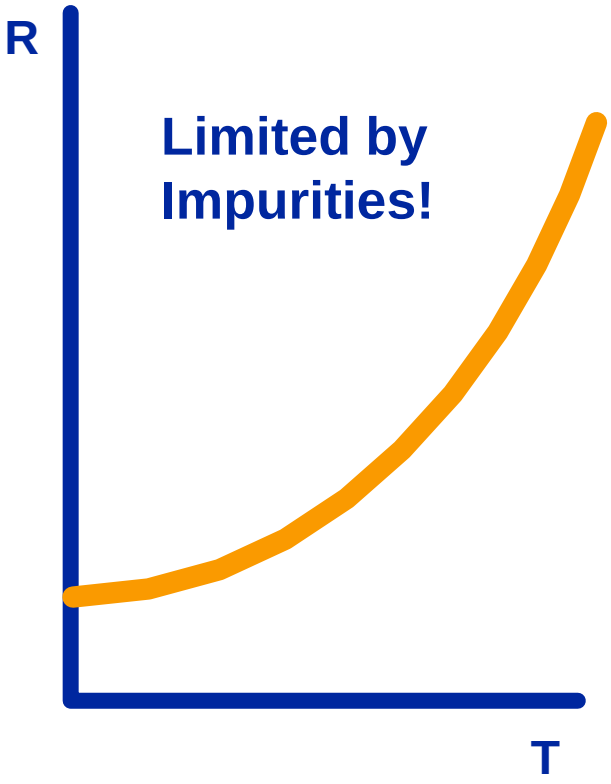
Prologue: The Two Energy Lemmas

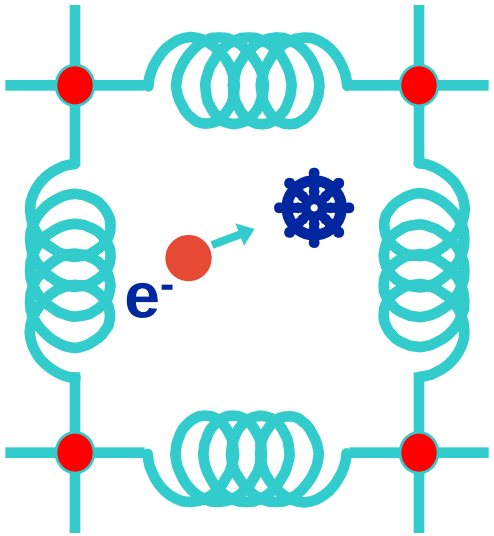
I. Any discussion of the application of energy technology must involve, from the very start, an explicit social and political scenario

II. The unique aspect of energy as a life-sustaining necessity separates it from the jurisdiction of many of the usual "laws" of economics

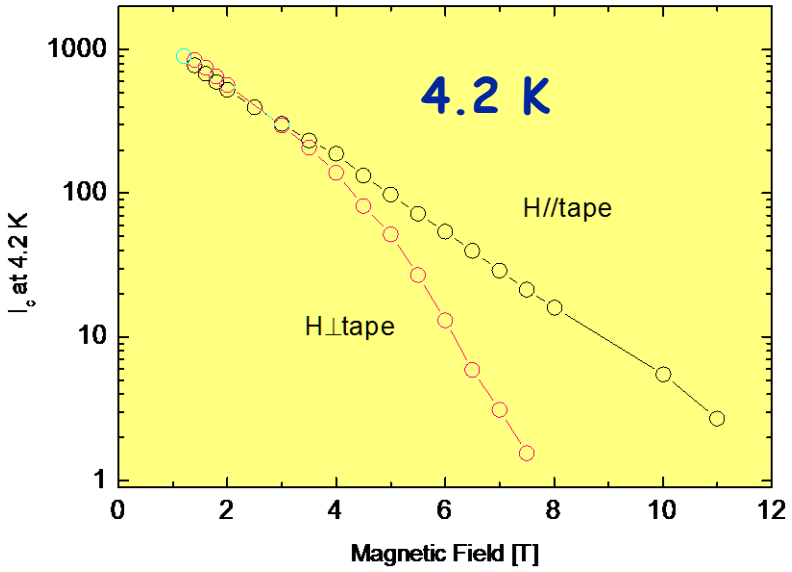
Models of Electrical Conductivity

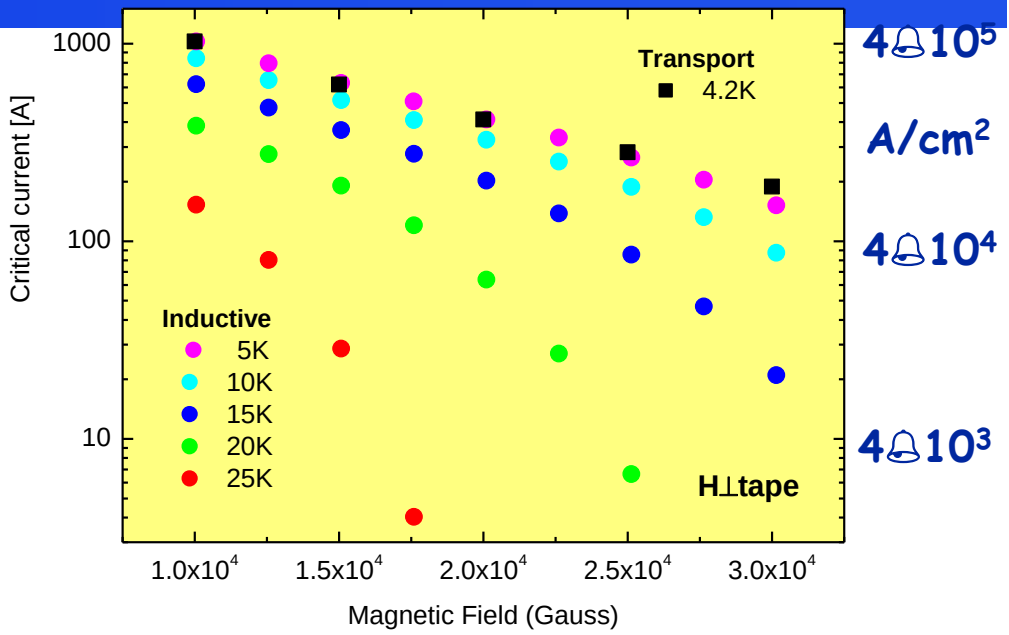
Reality:

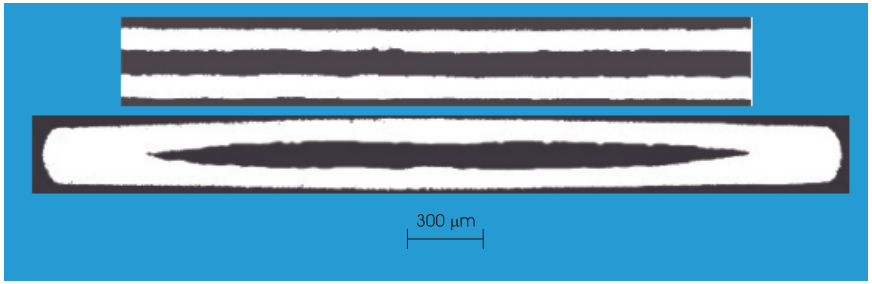




INFM-Genova
Ni-Sheathed MgB_2 Tape







Ex-Situ Sintered

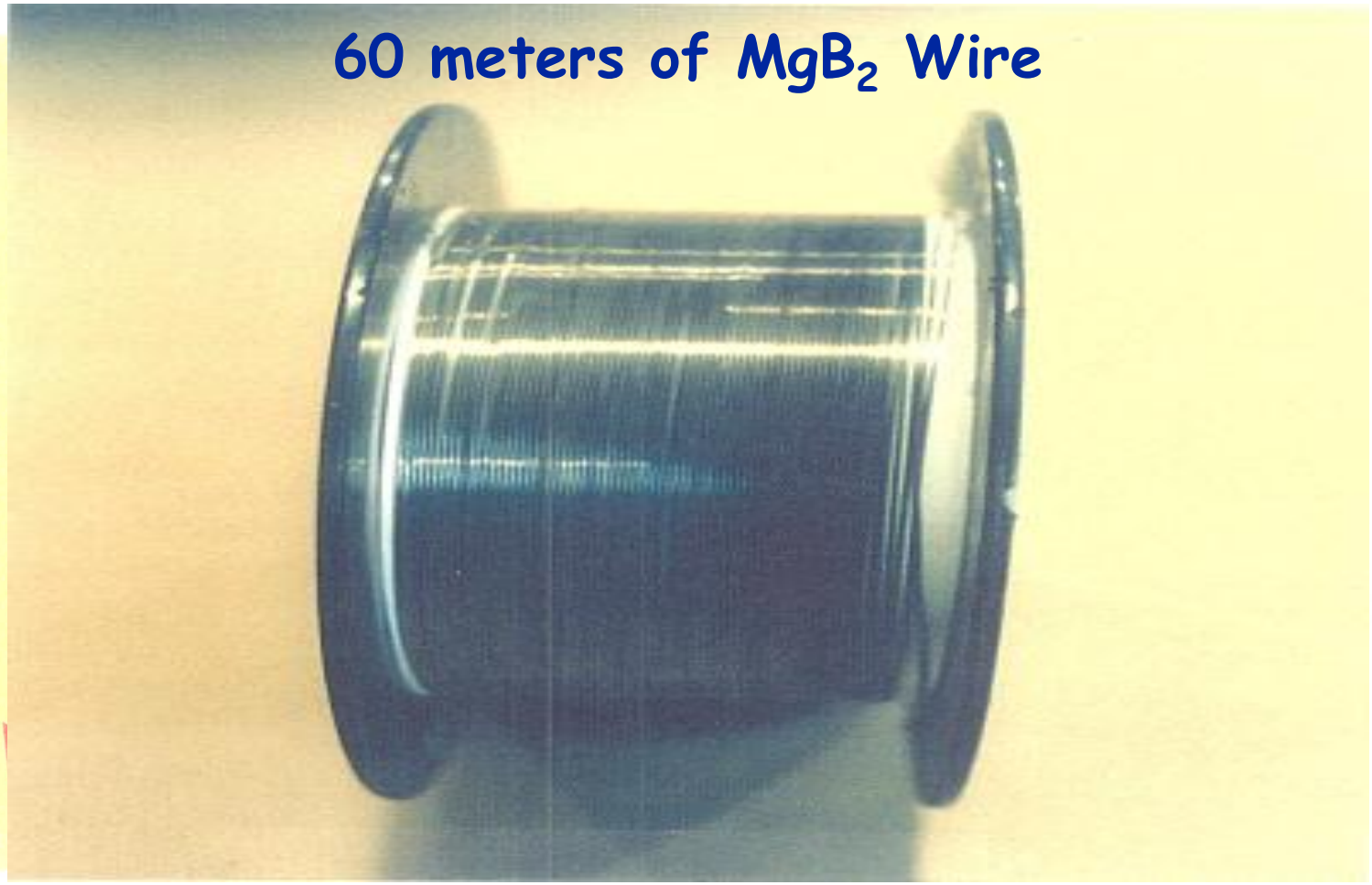
Tape dimensions: 3.5 mm x 0.35 mm

Filling factor 20% $A_{sc} = 2.5 \times 10^{-3}$ cm^2

Treated at 900°C for 2 hours in Ar

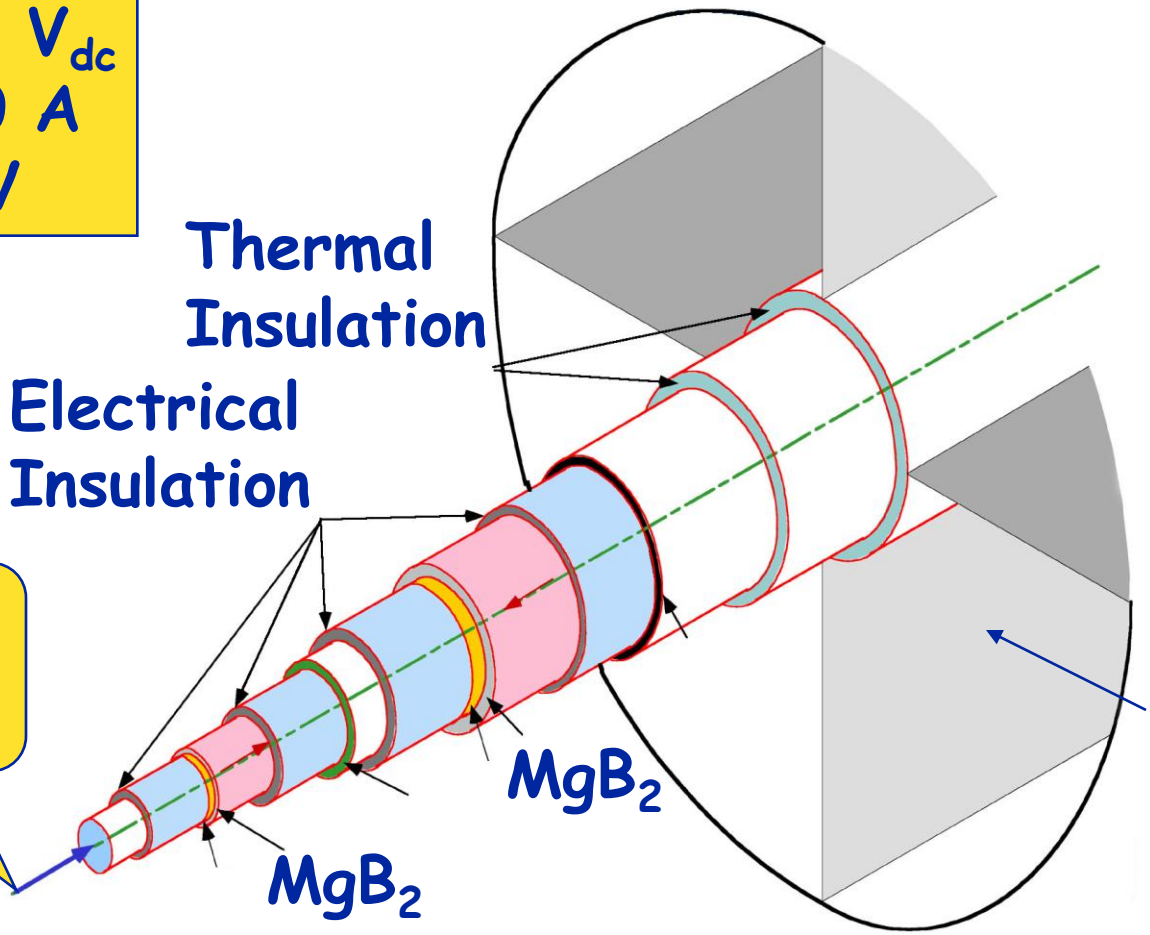
INFM-Genova, G. Grasso, A. Malagoli, V. Braccini, S. Roncallo, and A.S. Siri, Italy

Cheap MgB_2 Wire Here Now!

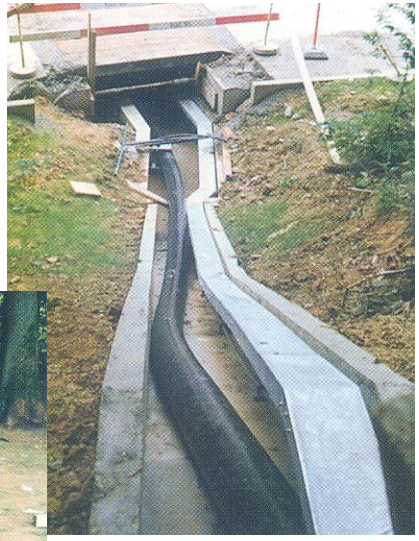


"The Energy Pipeline"

± 50,000 V_{dc}
100,000 A
10 GW



Small Scale Demonstration



Nexans LH_2 Transfer Line

Energy Intensity Factoids

Grant Household Power Requirements

Watts	Avg	Peak
Elect	2000	4000
Therm	4000	8000

Does not include 3 automobiles!

Peak Power for 250,000 GHE's

Electrical: 1000 MW

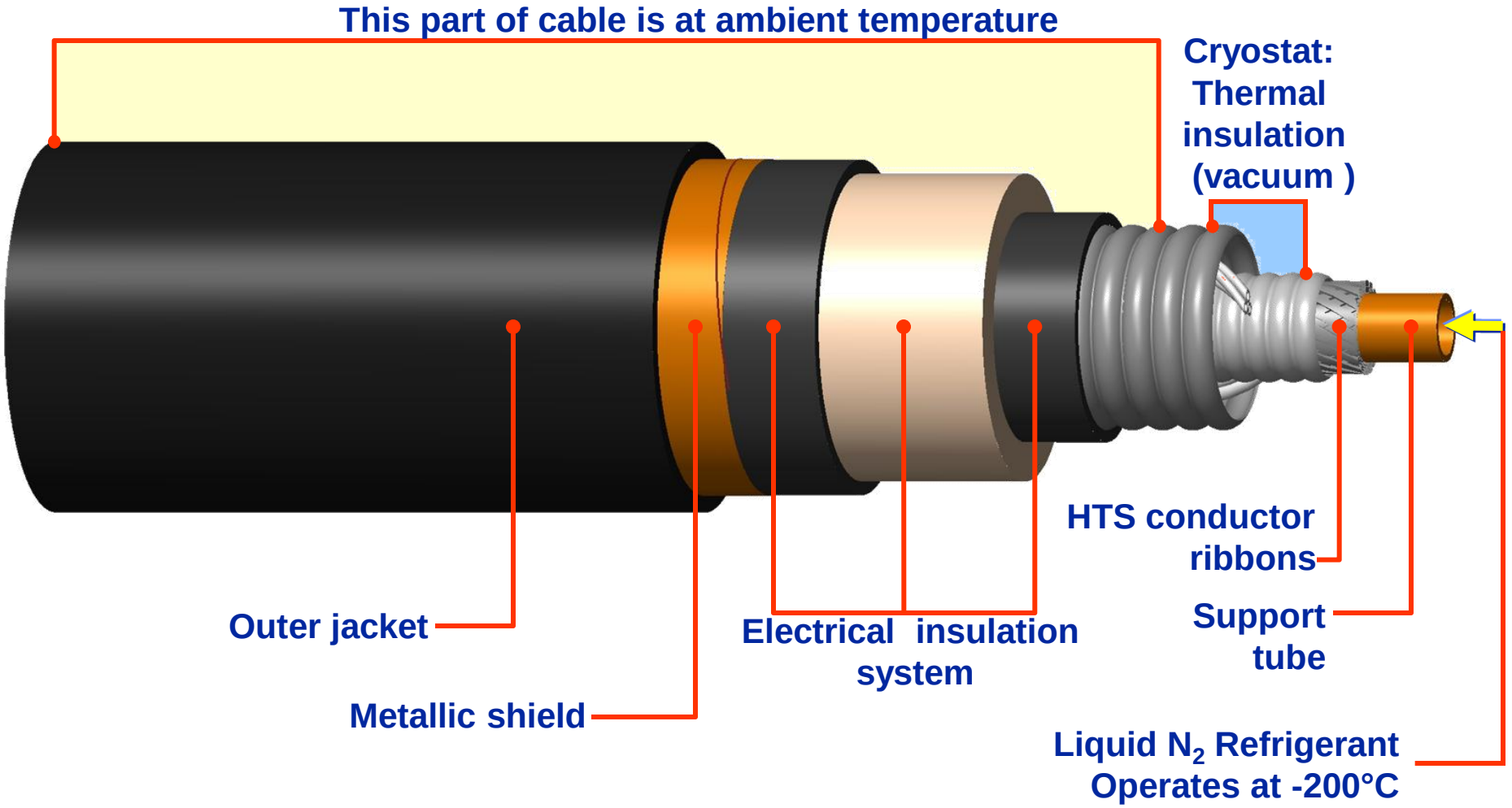
Thermal: 2000 MW

Hydrogen Factoids

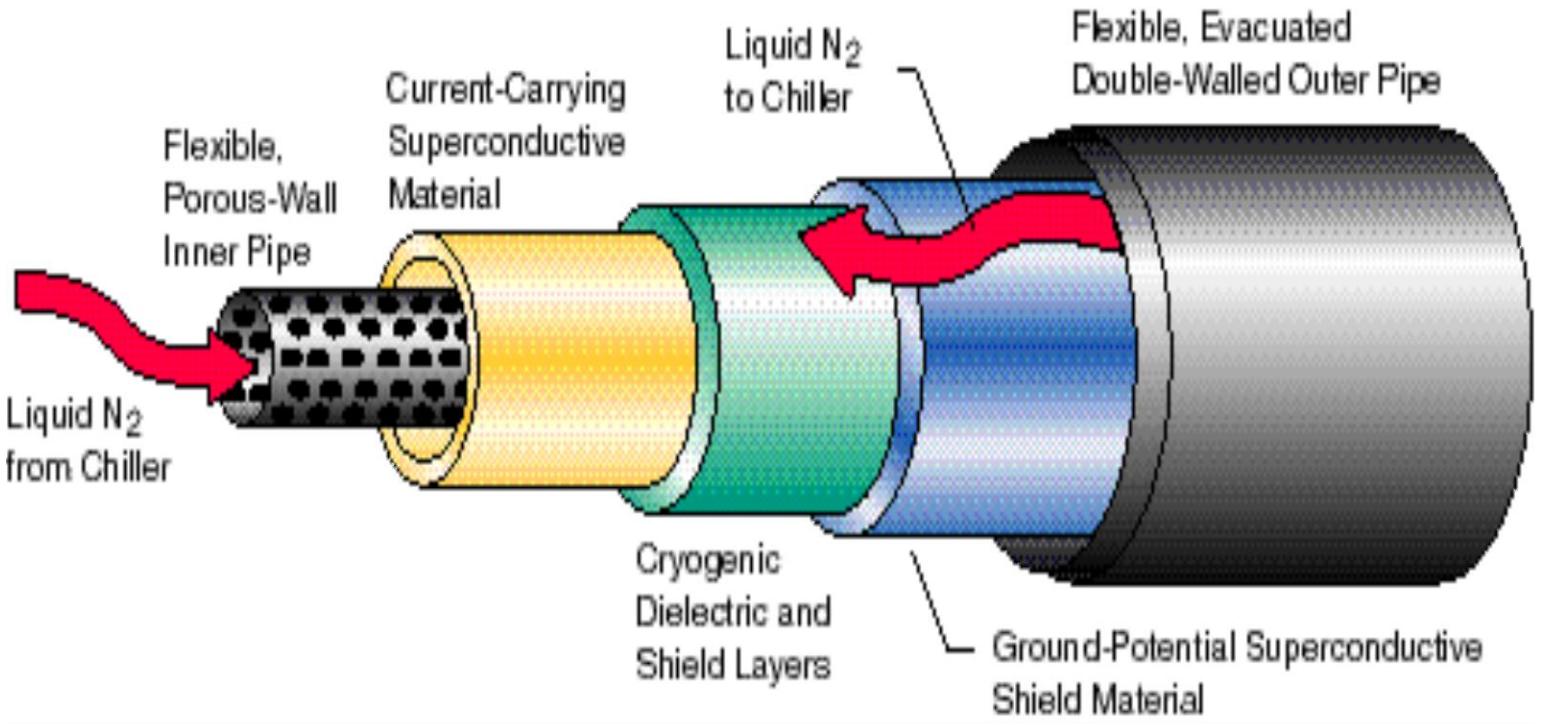
- 0.025 $/kWh Electricity -> 0.22 $/kWh Hydrogen
- Hydrogen flowing @ 1 m/s -> 0.6 MW/cm^2
- Delivering 2000 MW Hydrogen -> 67 cm dia pipe

  Electricity via superconductivity is essentially free!
- To power all cars in the US with hydrogen would require expropriating all present electric power generated in the US
- German studies show water emissions from powering all cars with hydrogen could cause changes in microclimate.

WTD Cable Breakaway



Cold Dielectric Cable



HTS Cables: They're Here!

12,400 Volts

1,250 Amps

3 Phase

Southwire Cable Plant
Carrolton, Ga.

Issues (Superconductivity)

- Wire Cost & Performance
  - *Gen I (BSCCO/Ag)* — *50 $/kA×m*
  - *Gen II (Y123 CC)* — *10*
  - *MgB_2* — *2*
  - *NBTi* — *0.90*
- Length
  - *Gen I (BSCCO/Ag)* — *> 1000 m*
  - *Gen II (Y123 CC)* — *10*
  - *MgB_2* — *> 100*
  - *NBTi* — *> 1000*
- Joints & Splices
  - *HTSC* — *TBD*

Issues (Cryogenic & Vacuum)

- Cryoplants: Cost & Performance
  - *Liquid or Gas?*
  - *ECE = 0.20 T_{cold} /(T_{sink} - T_{cold})*
  - *Cryo-unit Cost ~ $5/W Rating*
- Vacuum
  - *Continuously pumped, periodic or sealed?*
  - *Distance between ports*
  - *Gettering materials*

Issues (Cable Design/Power Control)

- Cable
  - *Parallel vs. Coaxial*
  - *Flexible vs. Rigid*
- Power
  - *Balance between Voltage & Current*
  - *dc vs. ac*
  - *ac Losses (ripple factor)*

T_c vs. Year: 1911 - 1999