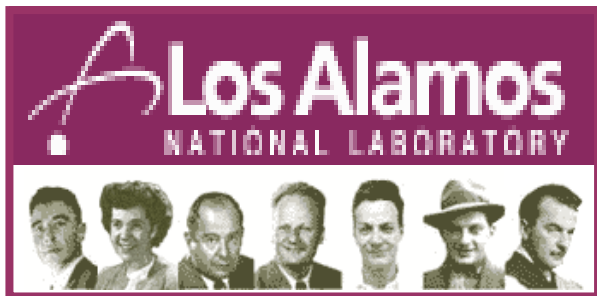


SuperCable: Combined Delivery and Storage of Electricity and Hydrogen

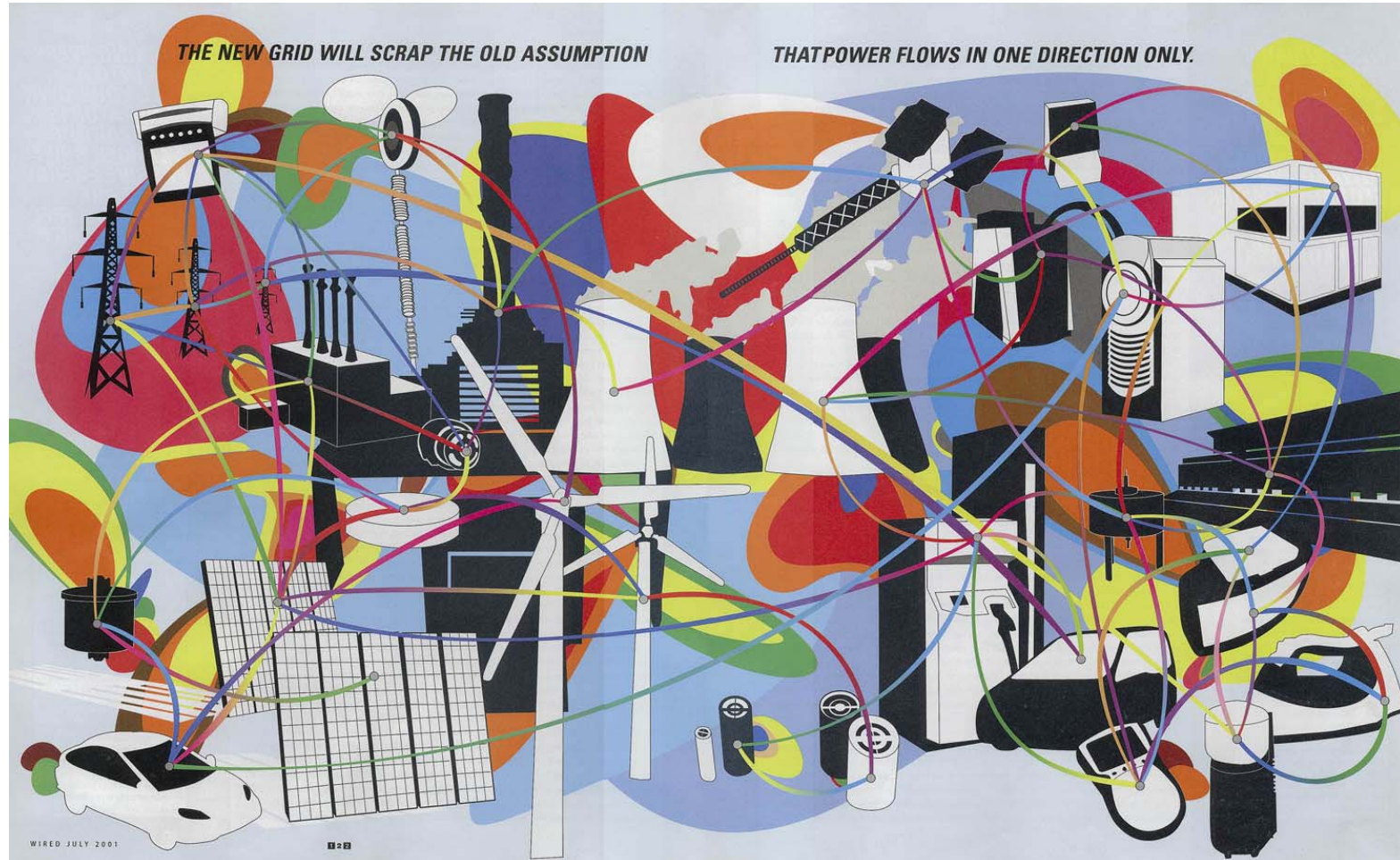
*P. M. Grant, (Electric Power Research Institute)
pgrant@epri.com*

<ftp://grant:marulo@ftp.epri.com/Nat%20Lab%20SuperGrid%20Proposal/>





"The Challenge"

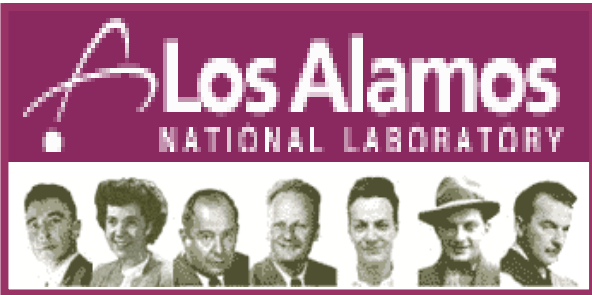


EPRI

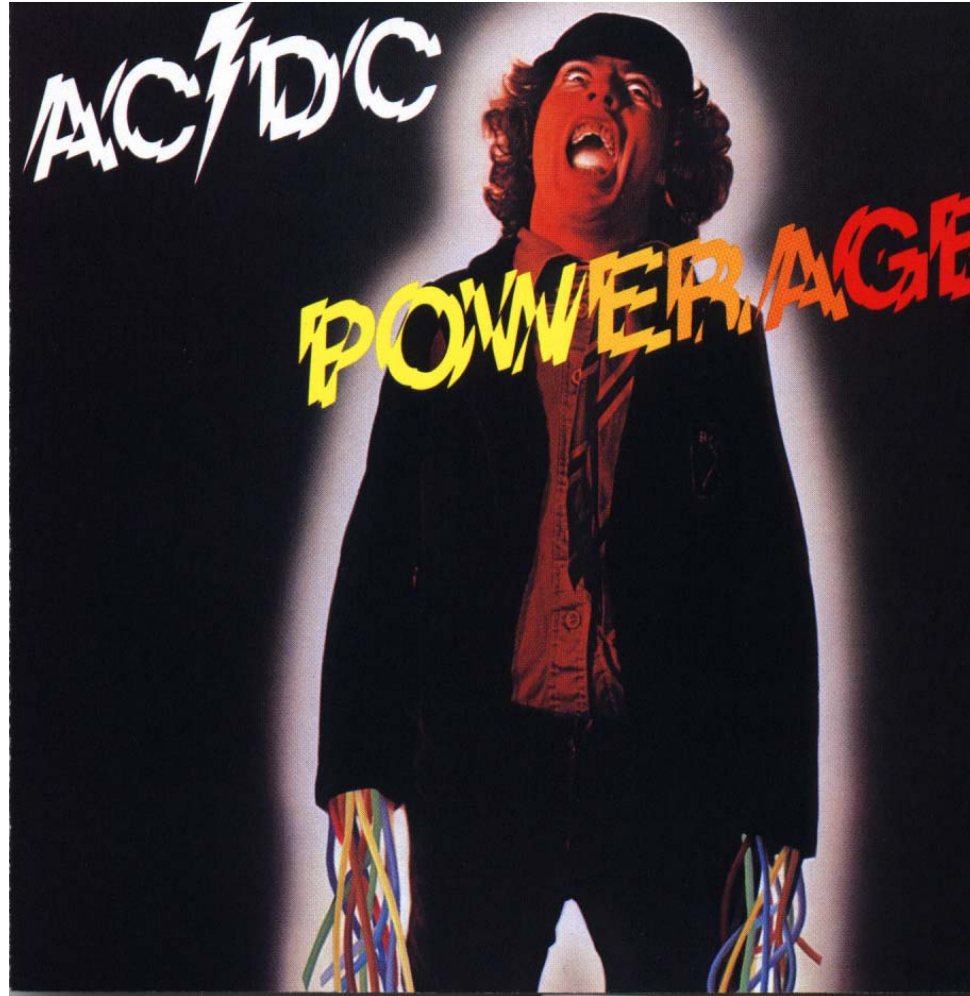
SuperCable: Combined Delivery and Storage of Electricity and Hydrogen

Wired Magazine, June 2001

Paul M. Grant



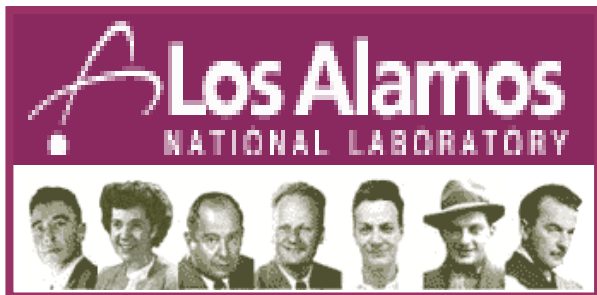
Californication!



EPRI

SuperCable: Combined Delivery and Storage of Electricity and Hydrogen

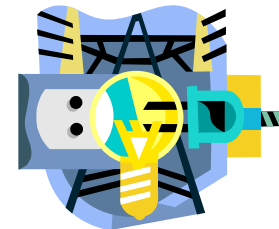
Paul M. Grant



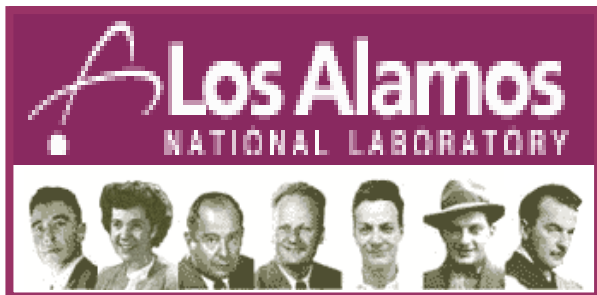
Architecture

Three Dimensions

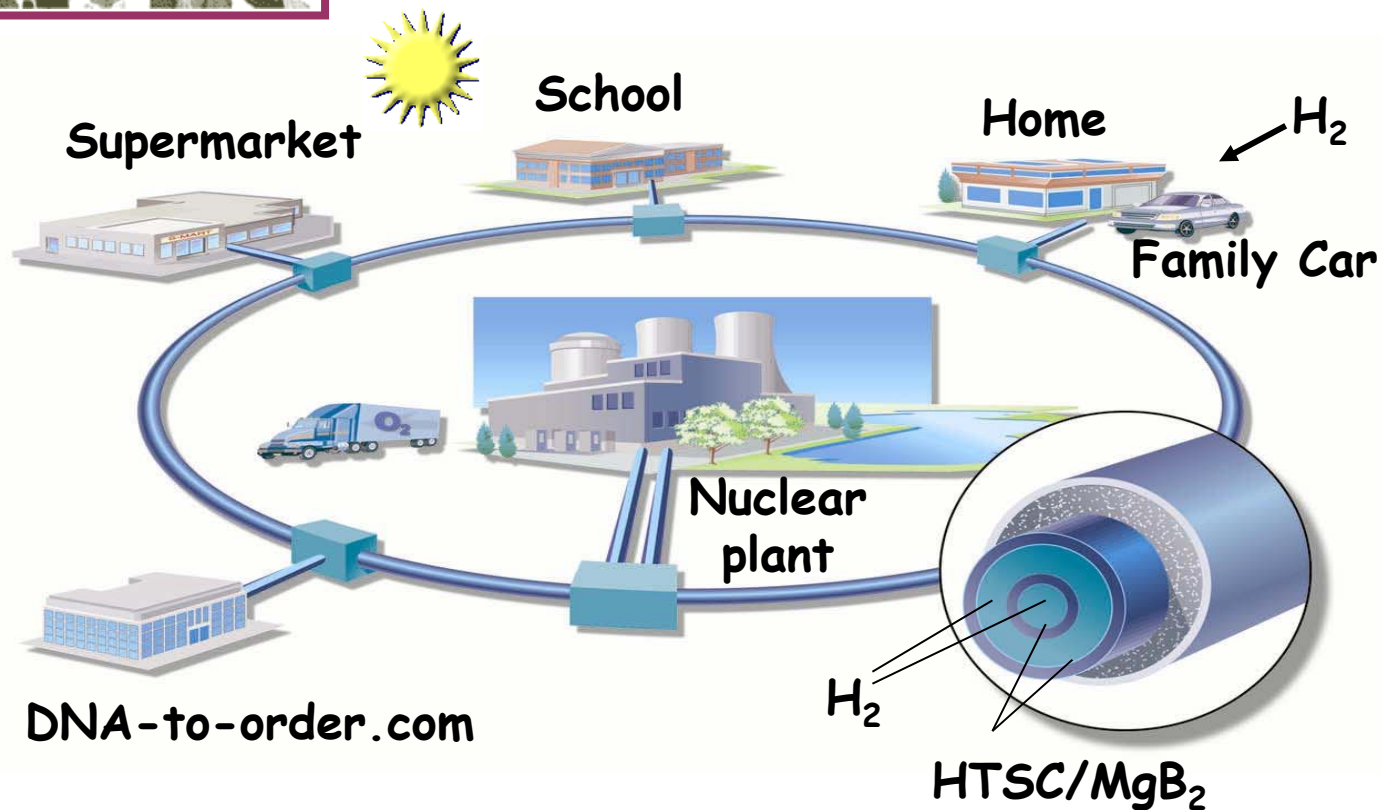
- **SuperGrid** – A superconducting, H₂-cooled interstate “backbone” connecting regions coast to coast.
- **RegionGrid** – Two grid operators (East and West) with upgraded high capacity lines to transmit power regionally.
- **CityGrid** – Local mini- and micro-grids with distributed intelligence, energy resources, and demand response



**Integrated systems architecture enables
NationalGrid operations across all dimensions.**



SuperCity



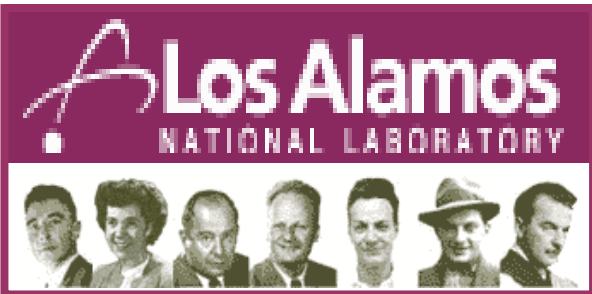
P.M. Grant, *The Industrial Physicist*, Feb/March Issue, 2002

<ftp://grant:marulo@ftp.epri.com/Nat%20Lab%20SuperGrid%20Proposal>

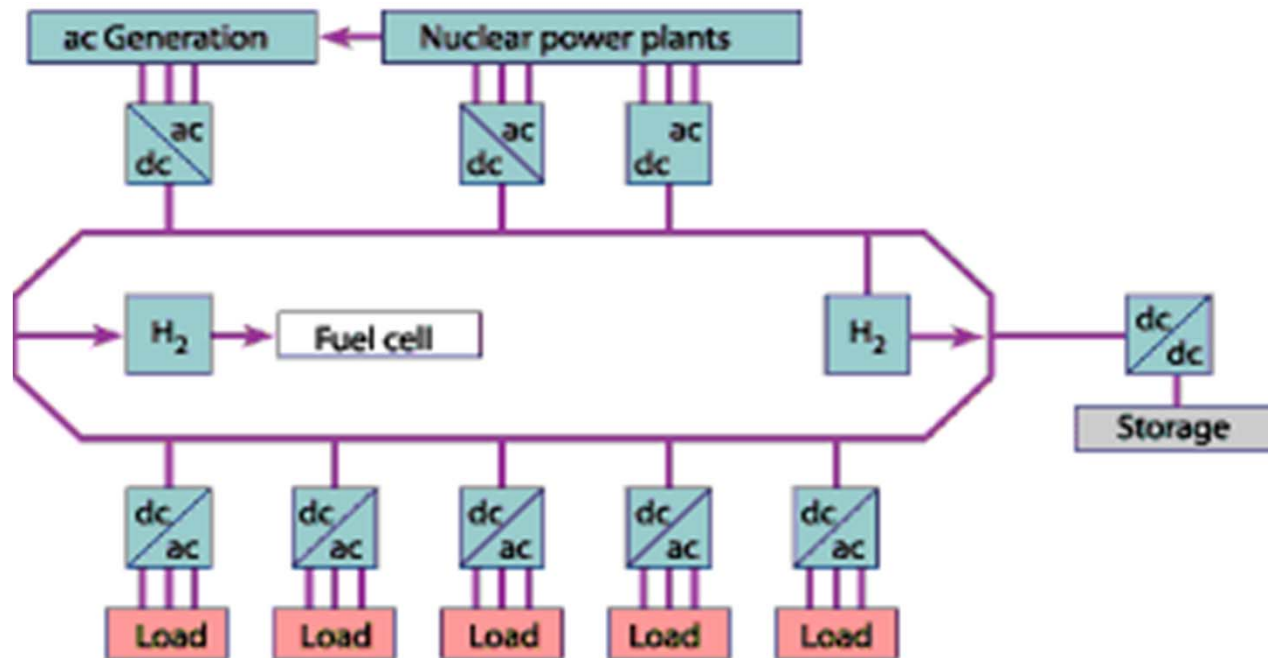


SuperCable: Combined Delivery and Storage of Electricity and Hydrogen

Paul M. Grant



SuperGrid



Continental SuperGrid

“Continental SuperGrid Workshop,” UIUC/Rockefeller U., Palo Alto, Nov. 2002

<ftp://grant:marulo@ftp.epri.com/Energy%20SuperGrid%20Workshop%20Proceedings/>

<http://www.epri.com/journal/details.asp?doctype=features&id=511>

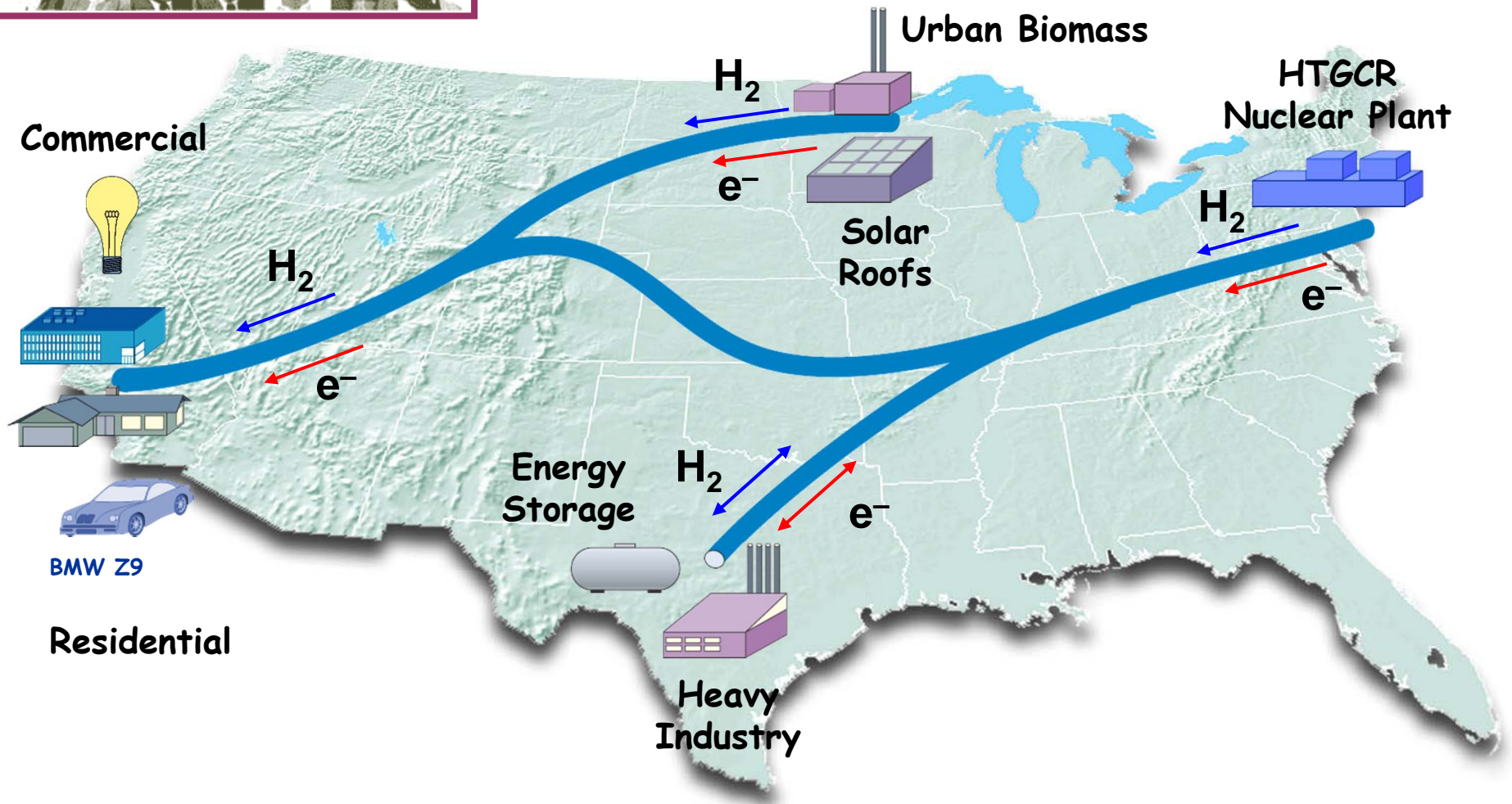


SuperCable: Combined Delivery and Storage of Electricity and Hydrogen

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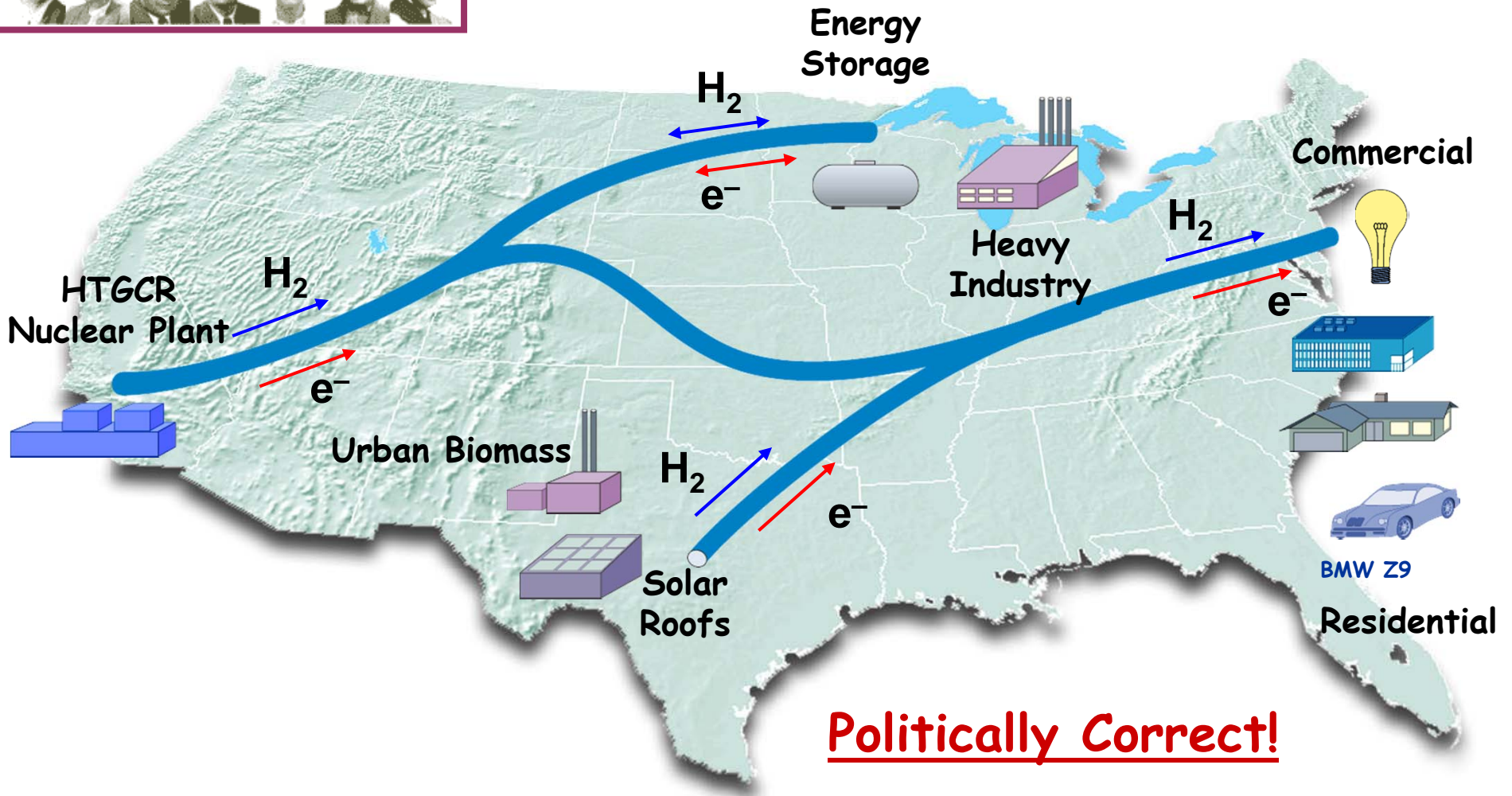


North American 21st Century Energy SuperGrid



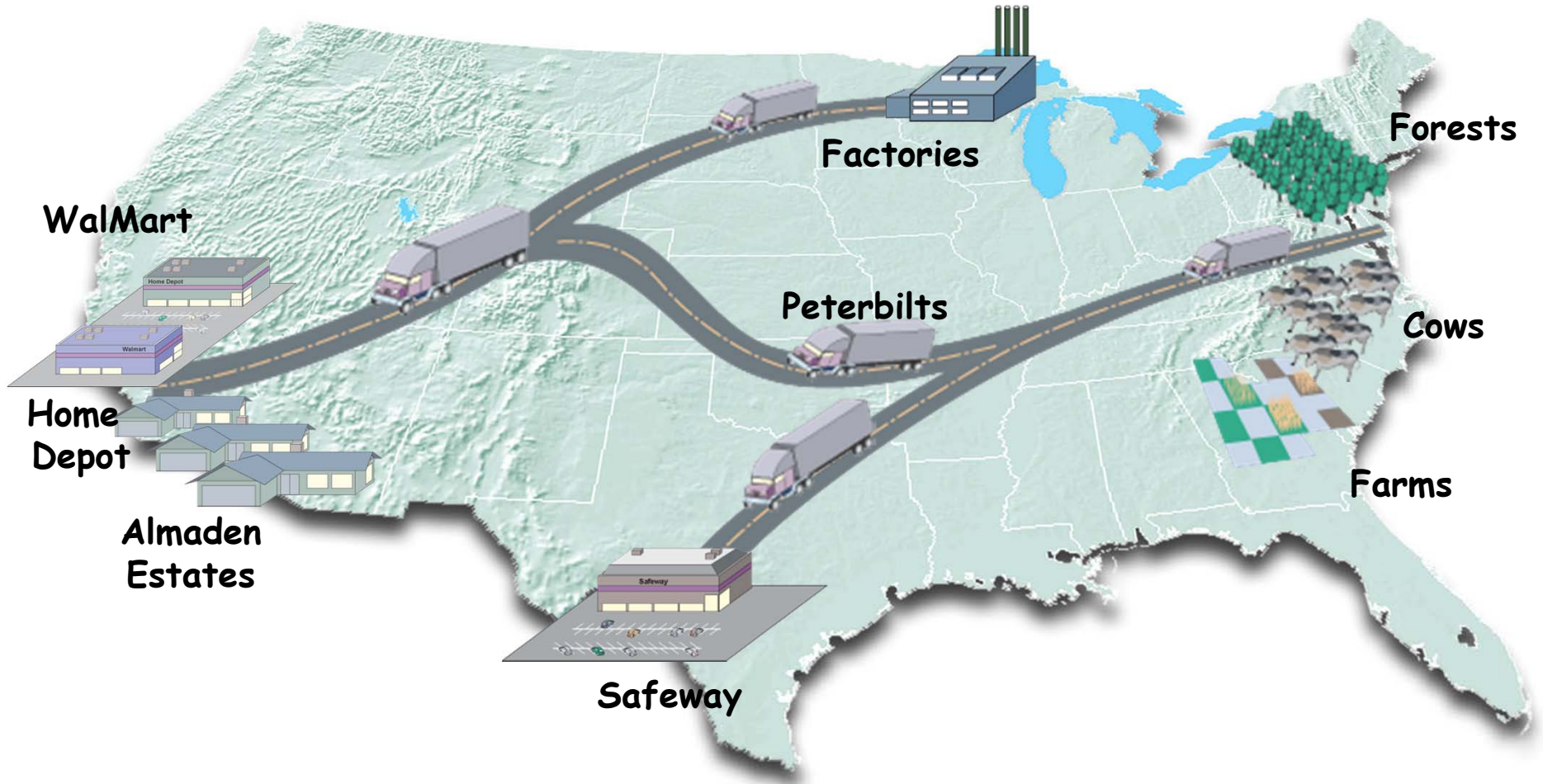


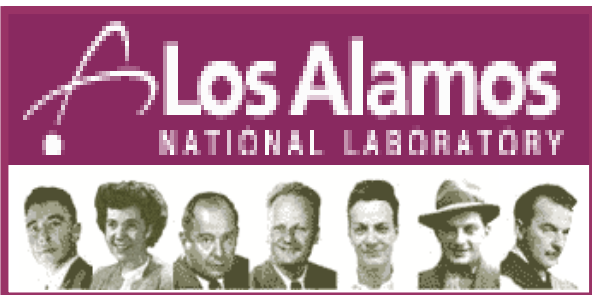
North American 21st Century Energy SuperGrid





Interstate 80 The 20th Century Diesel Grid





Garwin-Matisoo (IBM, 1967)

100 GW dc, 1000 km !

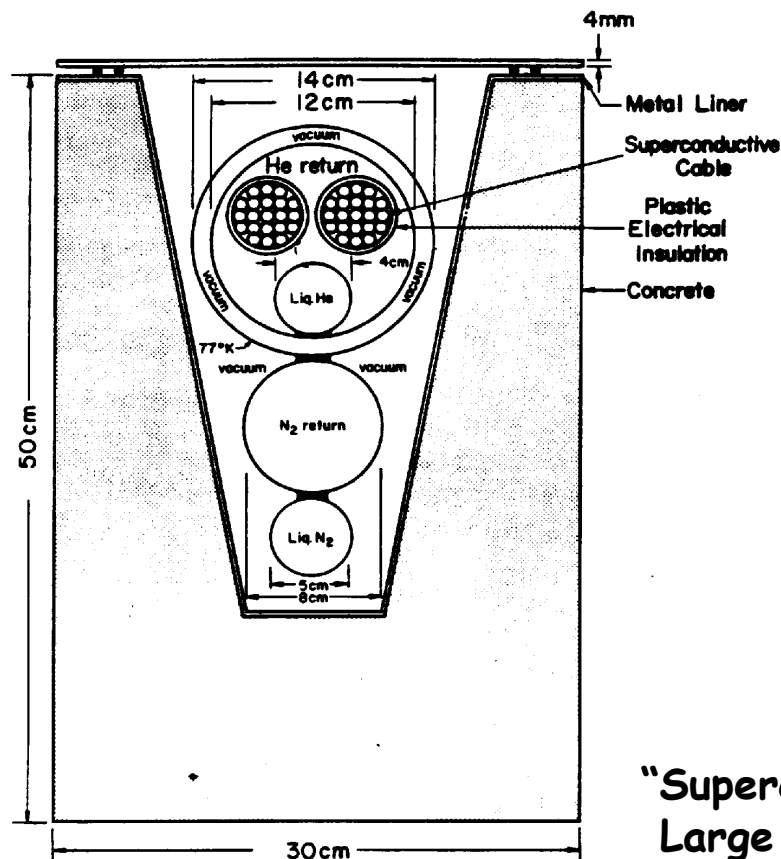


Fig. 1. Cross section of the 100-GW line.

- Nb_3Sn Wire
- $T_c = 18 \text{ K}$
- LHe liquid-vapor cooled
- LN_2 heat shield

"Superconducting Lines for the Transmission of Large Amounts of Electric Power over Great Distances,"
R. L. Garwin and J. Matisoo, Proc. IEEE 55, 538 (1967)



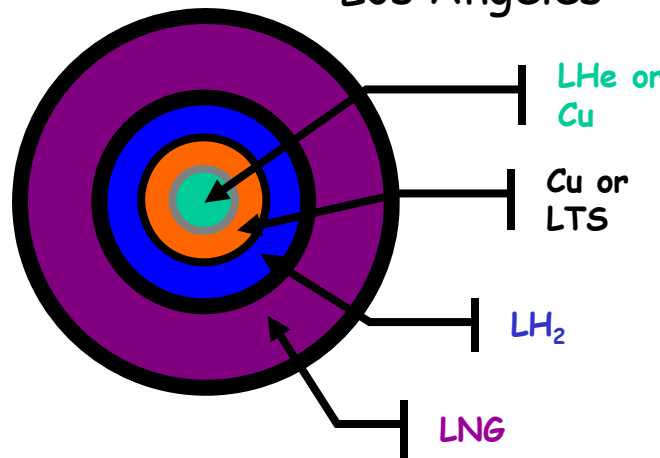
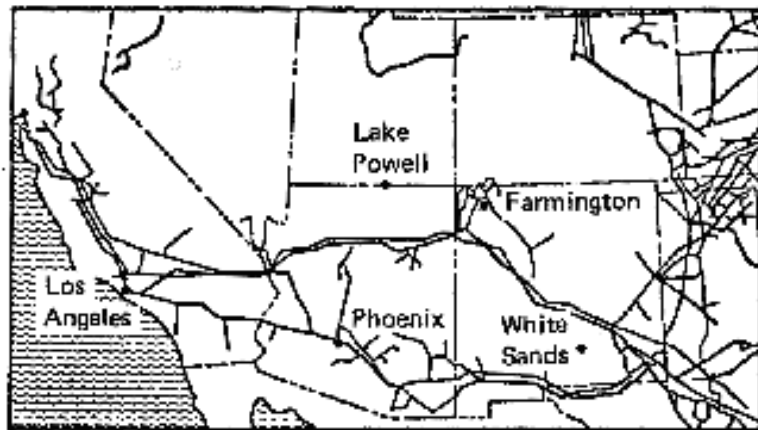
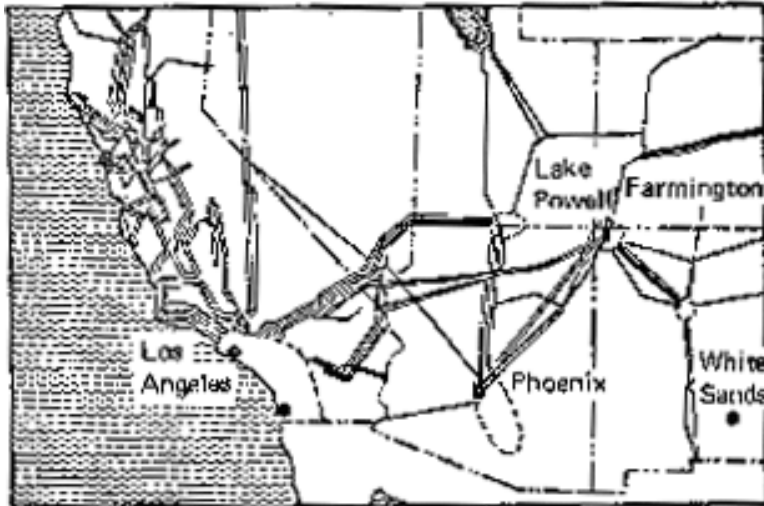
Electricity + Gas (LASL, 1972)

"Multiple Use of Cryogenic Fluid Transmission Lines."

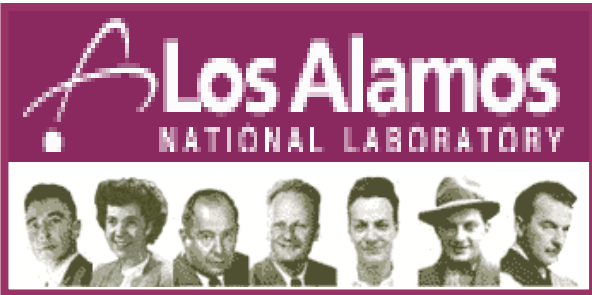
J.R. Bartlit, F.J. Edeskuty, & E.F. Hammel, ICEC 4, 1972.

NM Space Shuttle Center

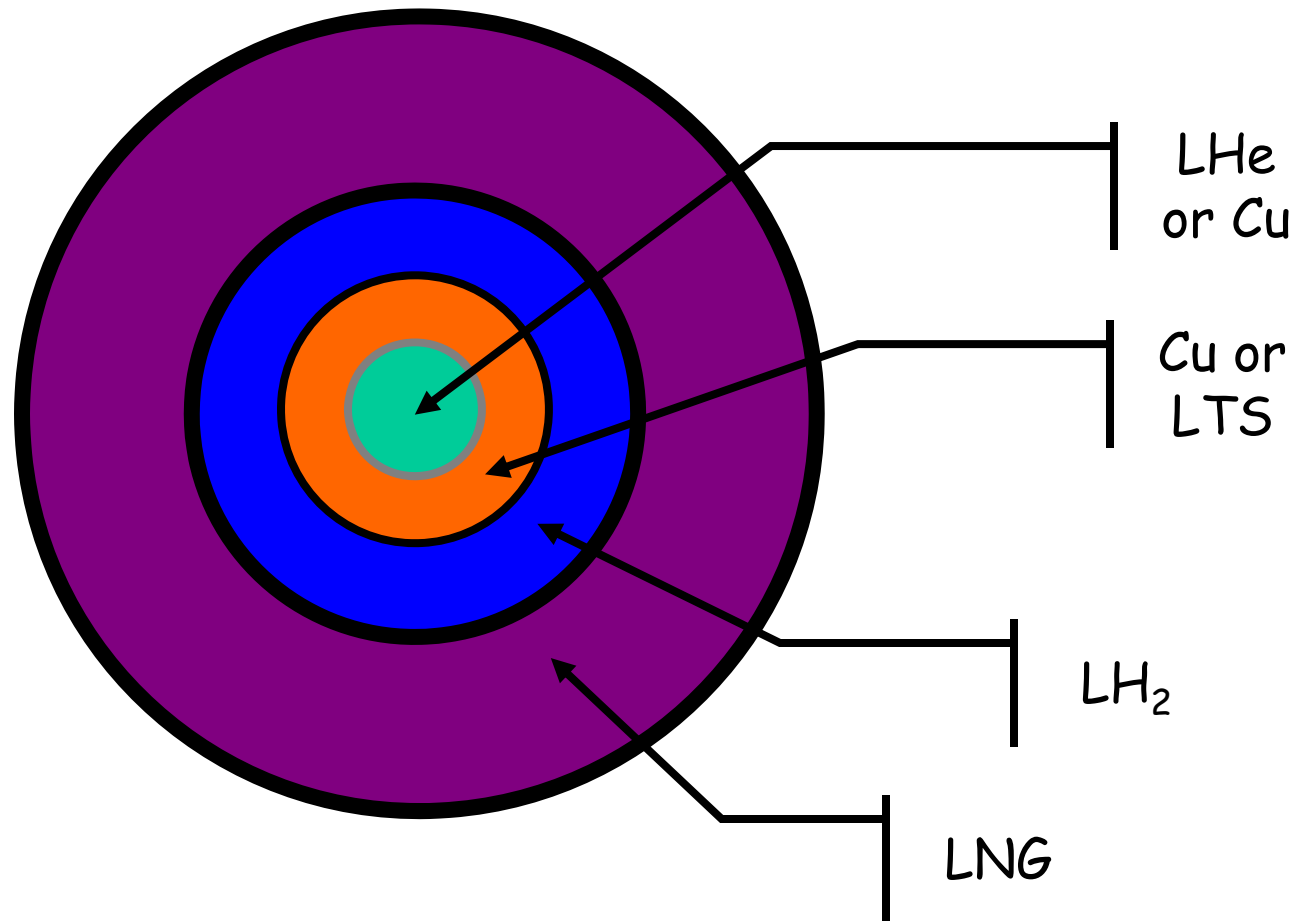
- Electricity
 - Four Corners
 - Lake Powell
- Natural Gas
 - Coal Gasification (NM)
- Hydrogen
 - Los Angeles

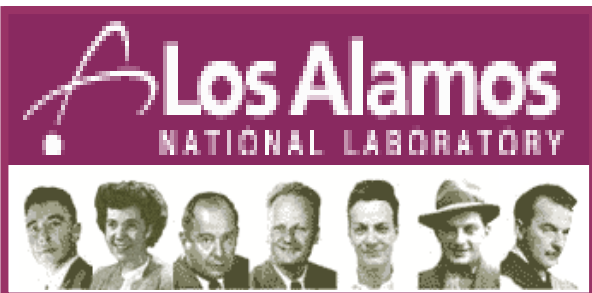


Cryogenic fluids served as heat shields for superconducting or cryoresistive conductor

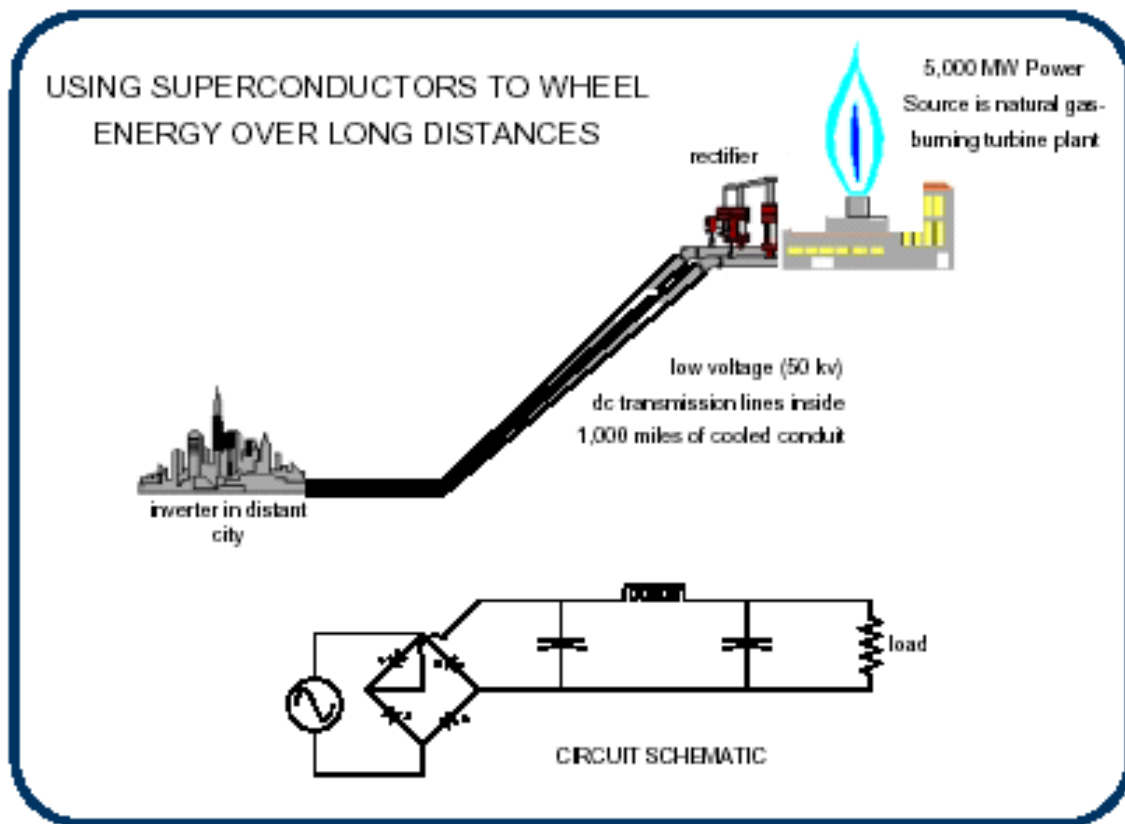


LASL Energy Delivery System





Electricity Pipe



Initial EPRI
study on long
distance (1000 km)
HTSC dc cable
cooled by liquid
nitrogen
-- 1997 --

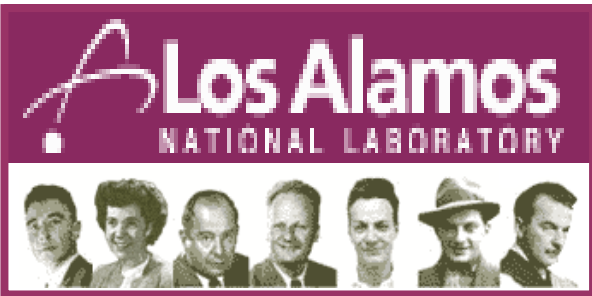
P.M. Grant, S. Schoenung, W. Hassenzahl, EPRI Report 8065-12, 1997

<ftp://grant:marulo@ftp.epri.com/Nat%20Lab%20SuperGrid%20Proposal>

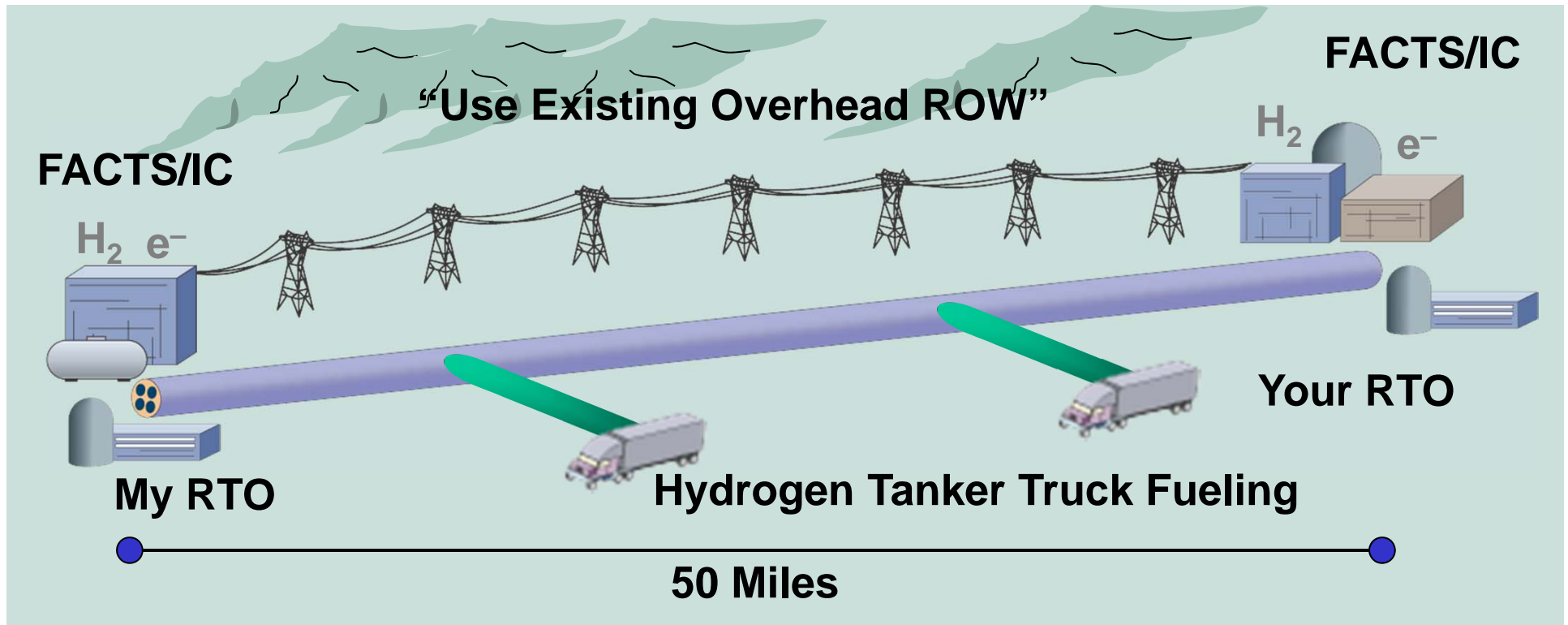
EPRI

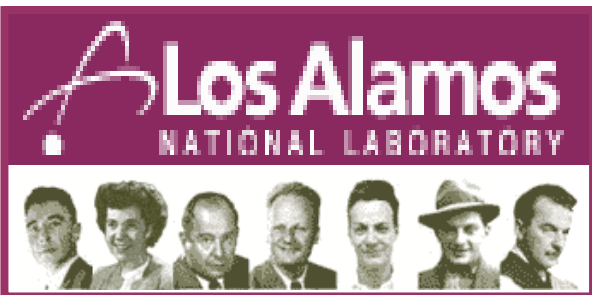
SuperCable: Combined Delivery and Storage of Electricity and Hydrogen

Paul M. Grant

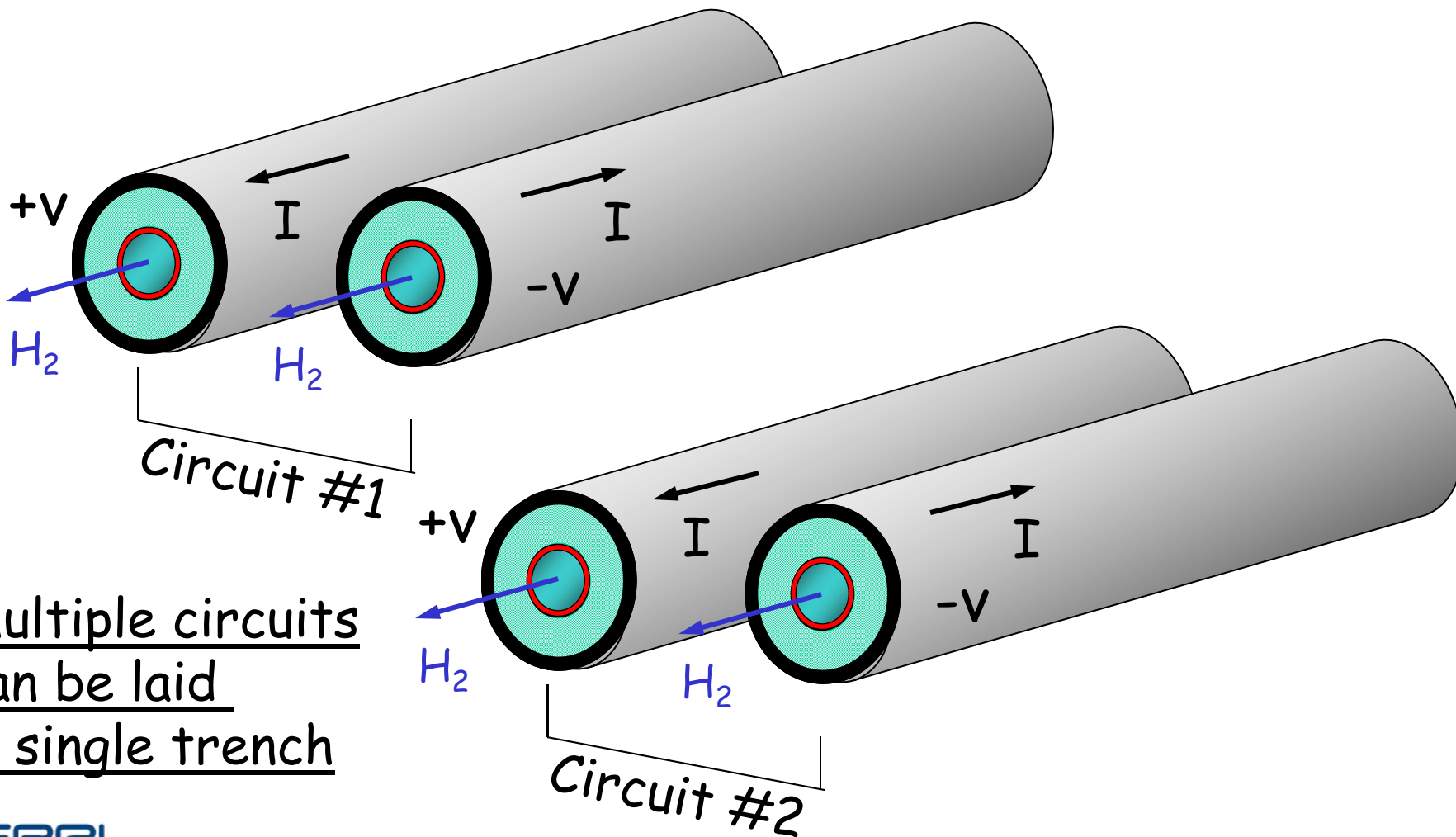


RegionGrid Interconnection





SuperCables

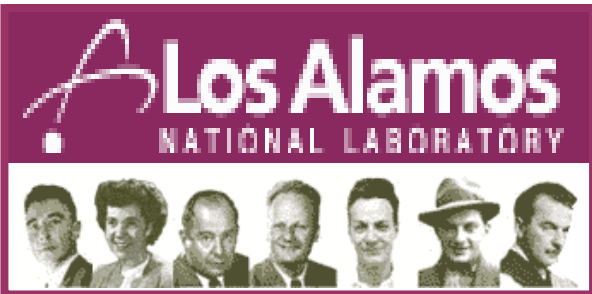


Multiple circuits
can be laid
in single trench

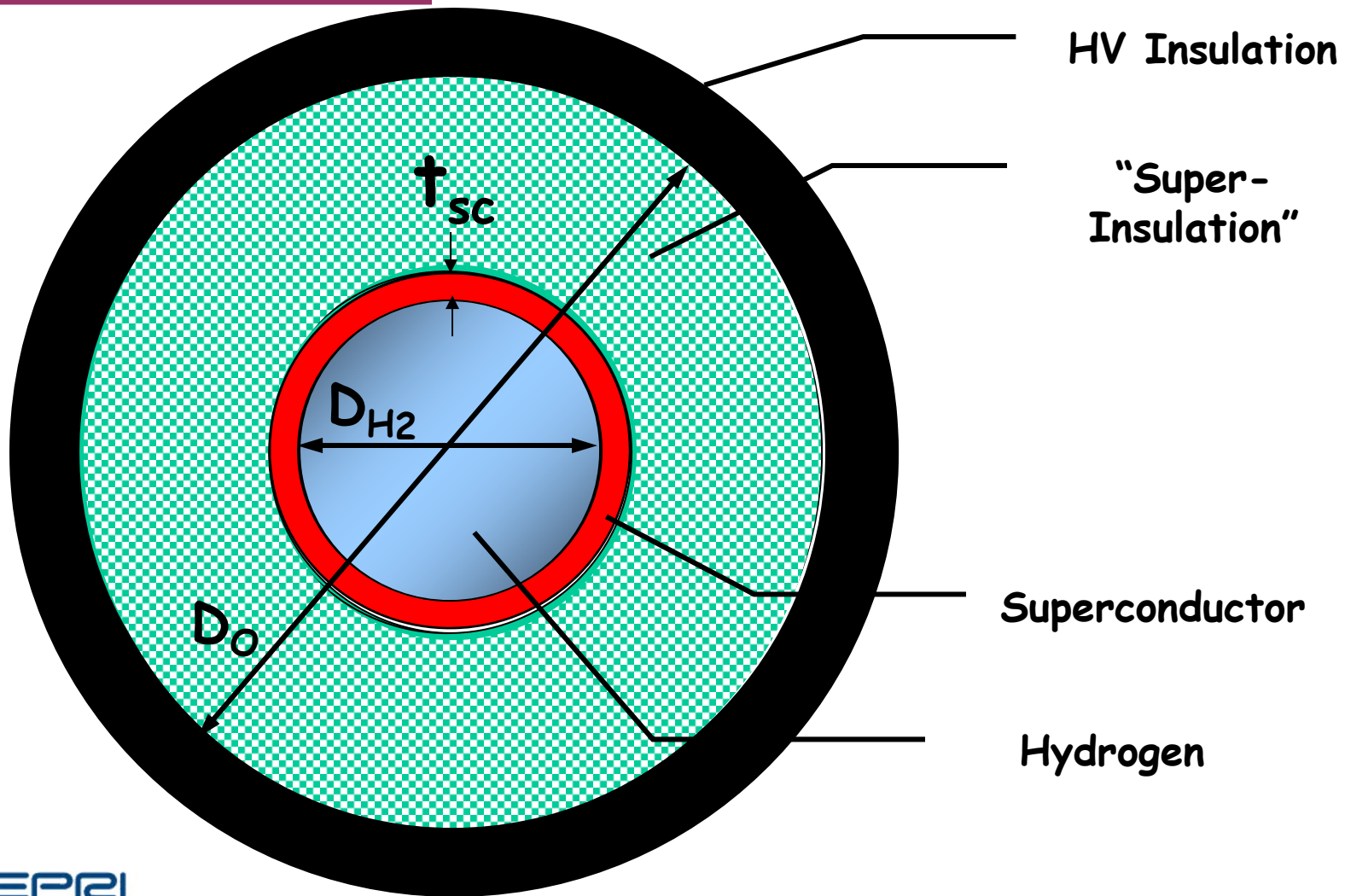
EPRI

SuperCable: Combined Delivery and Storage of Electricity and Hydrogen

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SuperCable





Power Flows

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

Electricity

P_{SC} = Electric power flow

V = Voltage to neutral (ground)

I = Supercurrent

A_{SC} = Cross-sectional area of superconducting annulus

$$P_{H_2} = 2(Q\rho vA)_{H_2}, \text{ where}$$

Hydrogen

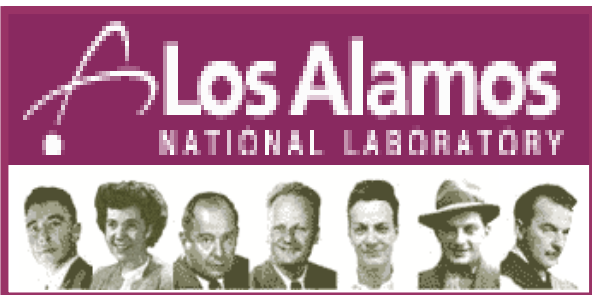
P_{H_2} = Chemical power flow

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



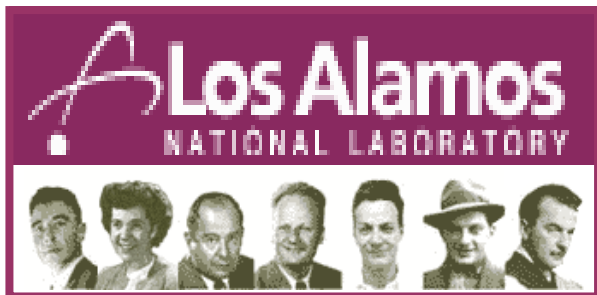
Electric & H₂ Power

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 (LH₂, 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



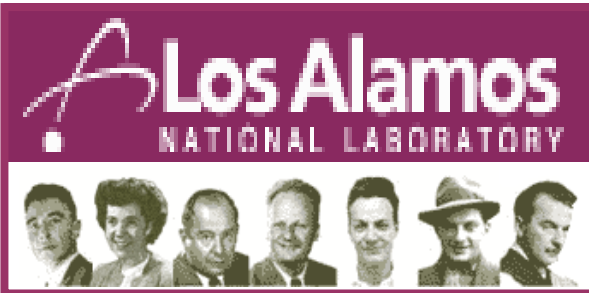
SuperCable H₂ Storage

<u><i>Some Storage Factoids</i></u>	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,

or

250 miles of SuperCable with an 8 inch inner diameter!



Thermal Losses

$$W_R = 0.5\epsilon\sigma (T_{amb}^4 - T_{SC}^4), \text{ where}$$

W_R = Power radiated in as watts/unit area

$$\sigma = 5.67 \times 10^{-12} \text{ W/cm}^2\text{K}^4$$

$$T_{amb} = 300 \text{ K}$$

$$T_{SC} = 20 \text{ K}$$

$\epsilon = 0.05$ per inner and outer tube surface

$$D_{SC} = 10 \text{ cm}$$

$$W_R = 3.6 \text{ W/m}$$

Radiation Losses

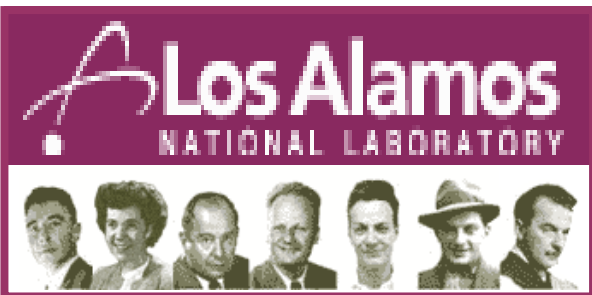
Superinsulation: $W_R^f = W_R/(n-1)$, where

n = number of layers

Target: $W_R^f = \underline{0.5 \text{ W/m}}$ requires ~10 layers

Other addenda (convection, conduction): $W_A = \underline{0.5 \text{ W/m}}$

$$W_T = W_R^f + W_A = \underline{1.0 \text{ W/m}}$$



Heat Removal

$$dT/dx = W_T / (\rho v C_p A)_{H_2}, \text{ where}$$

dT/dx = Temp rise along cable, K/m

W_T = Thermal in-leak per unit Length

ρ = H_2 Density

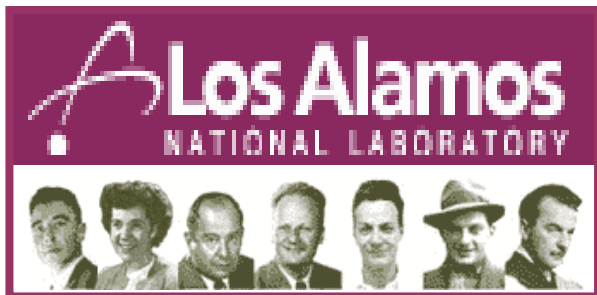
v = H_2 Flow Rate

C_p = H_2 Heat Capacity

A = Cross-sectional area of H_2 cryotube

Take $W_T = 1.0 \text{ W/m}$, then $dT/dx = 1.89 \times 10^{-5} \text{ K/m}$,

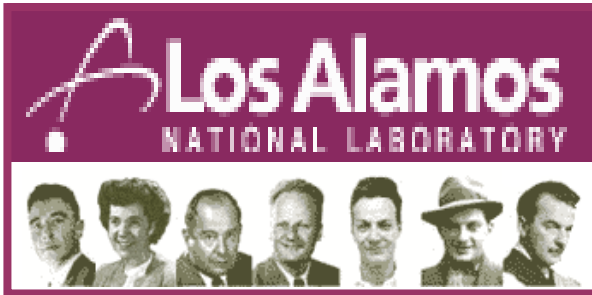
Or, 0.2 K over a 10 km distance



Remaining Issues

Current stabilization via voltage control

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



Remaining Issues

Power Electronic Discretetes

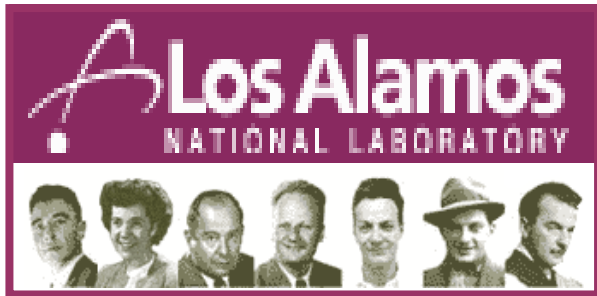
- GTOs vs IGBTs
- 12" wafer platforms
- Cryo-Bipolars
 - Minority carrier concentration
 - Doping profiles



Remaining Issues

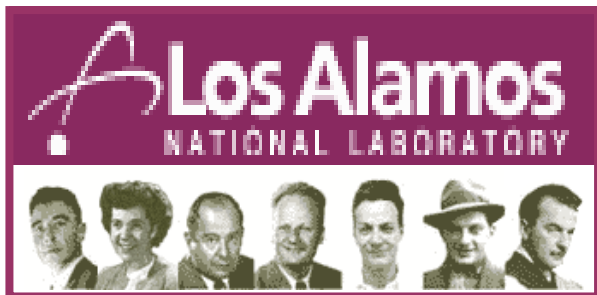
Hydrogen Issues

- Safety
- Generation (electrolysis)
- Cryocoolers
- Liquid vs Pressurized Gas
- Flow Rate
- Storage & Delivery



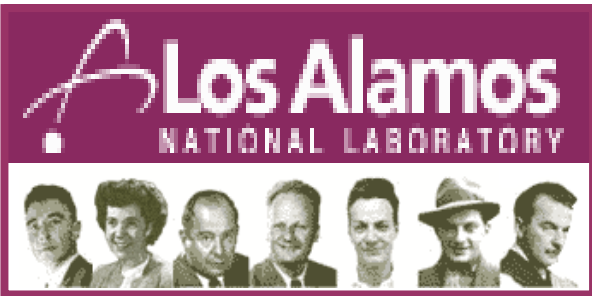
Remaining Issues

Design & Prototyping!

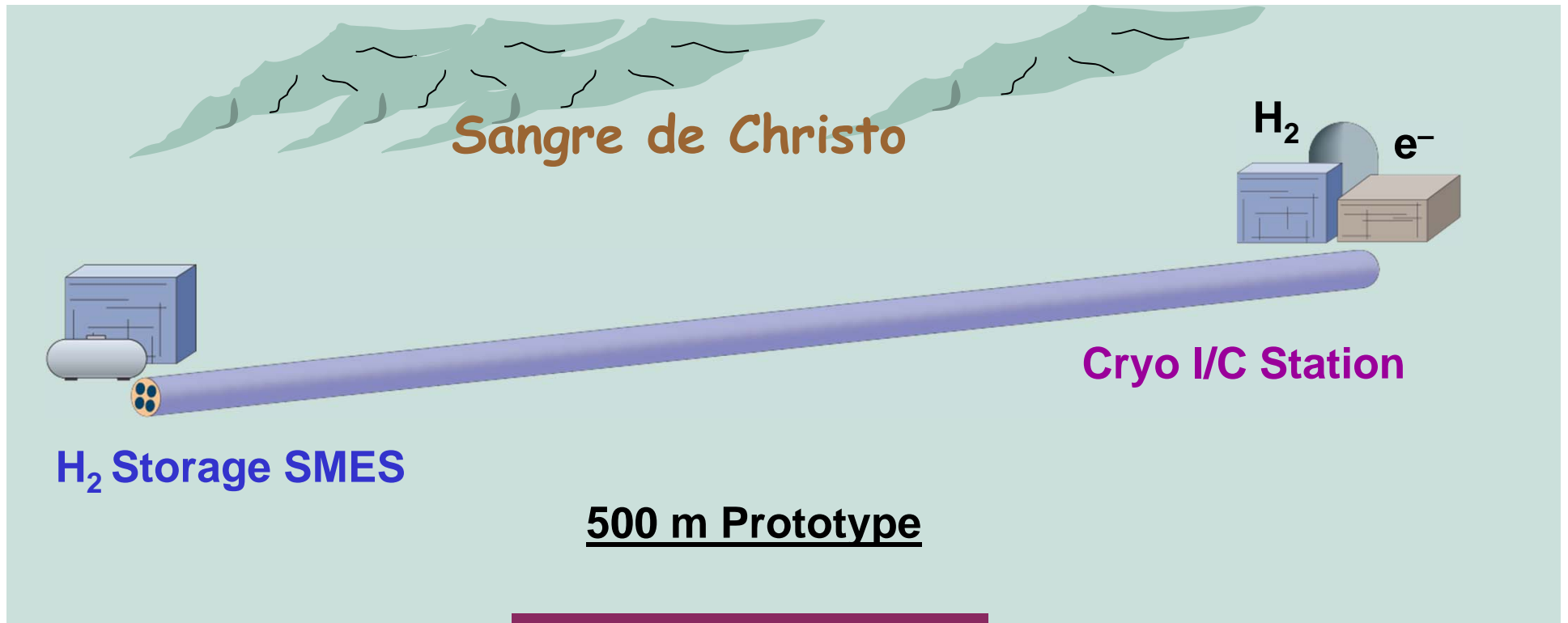


S.14 Opportunity

- S.14 - Senate Energy Omnibus Bill
 - FY04 \$15 M Authorization For OETD R&D
 - Section 927(e)(C):
 - *"Facilitate commercial transition toward direct current power transmission, storage, and use for high power systems utilizing high temperature superconductivity."*
- FY04 National Lab Study targeting prototype SuperCable by FY05-09 (\$20 M ?)



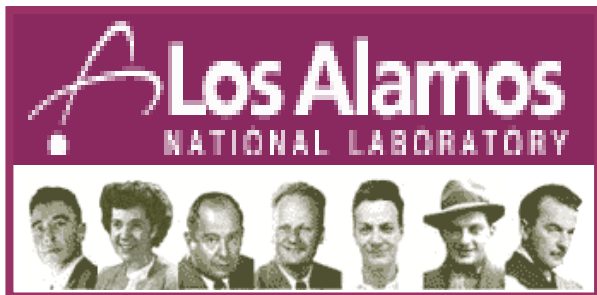
SuperCable Prototype Project



EPRI

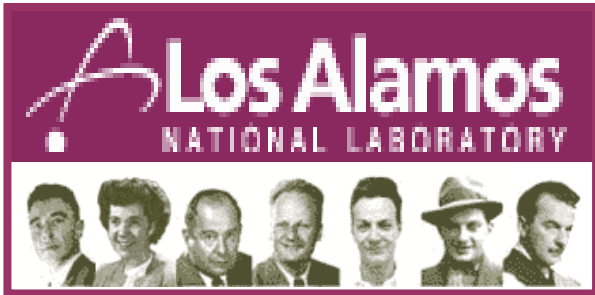
SuperCable: Combined Delivery and Storage of Electricity and Hydrogen

Paul M. Grant



Where there is no vision,
the people perish...

Proverbs 29:18



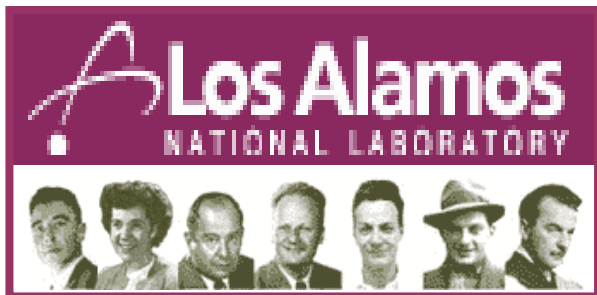
"You can't always get
what you want..."



EPRI

SuperCable: Combined Delivery and Storage of Electricity and Hydrogen

Paul M. Grant



"...you get what you need!"



EPRI

SuperCable: Combined Delivery and Storage of Electricity and Hydrogen

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