The SuperCable:
Dual Delivery of Chemical and Electric Power

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Panel on Future Power Delivery Options for Long-Term Energy Sustainability
Panel-13.1, Wednesday, 13 October 2004, 2:00 PM

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

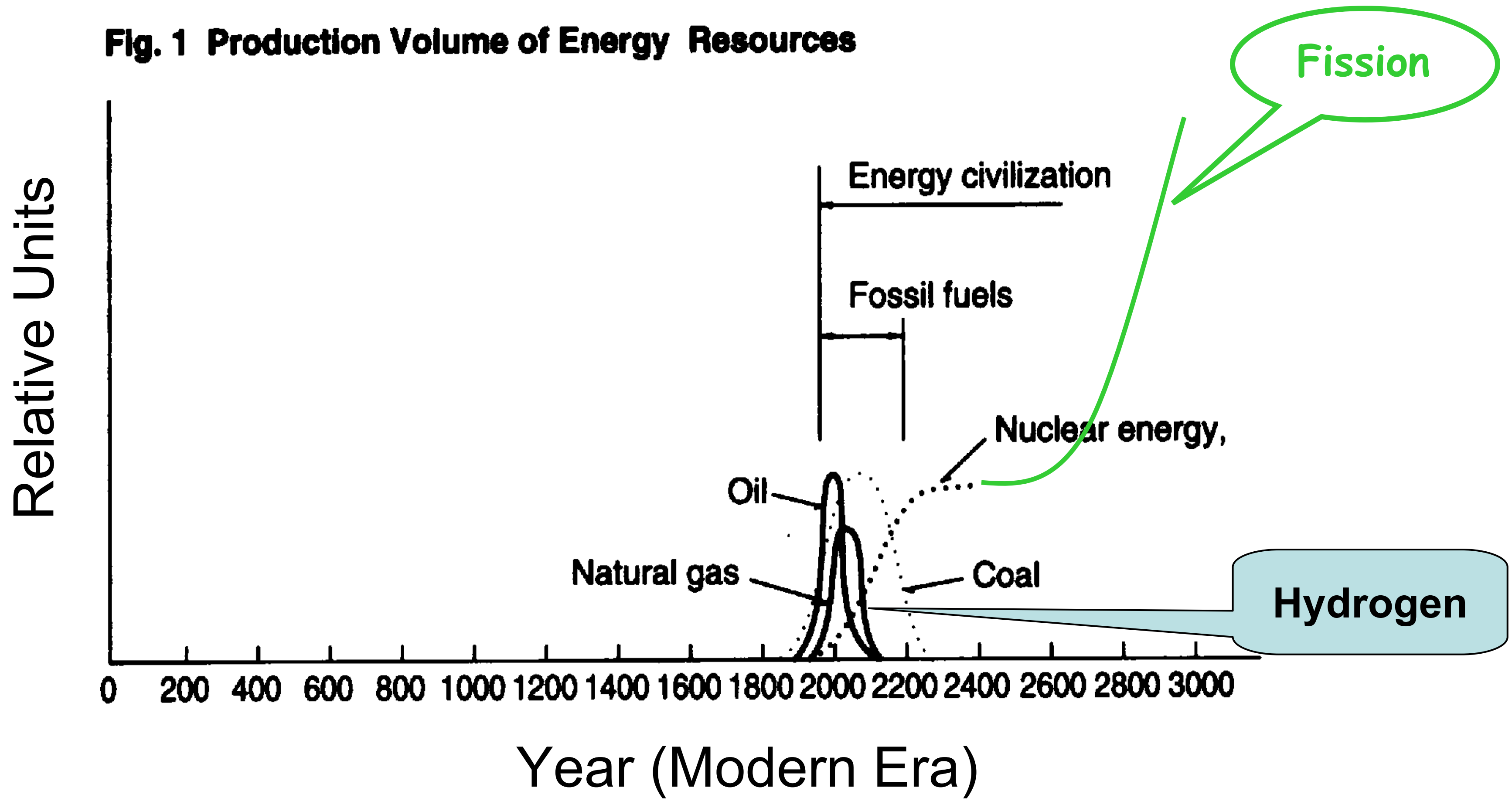
Technologies supplying Carbon-free, Non-Intrusive Energy for all Inhabitants of Planet Earth

Reading Assignment

1. **Garwin and Matisoo, 1967 (100 GW on Nb_3Sn)**
2. **Bartlit, Edeskuty and Hammel, 1972 (LH_2, LNG and 1 GW on LTSC)**
3. **Haney and Hammond, 1977 (Slush LH_2 and Nb_3Ge)**
4. **Schoenung, Hassenzahl and Grant, 1997 (5 GW on HTSC, 1000 km)**
5. **Grant, 2002 (SuperCity, Nukes+LH_2+HTSC)**
6. **Proceedings, SuperGrid Workshop, 2002**

These articles, and much more, can be found at www.w2agz.com, sub-pages SuperGrid/Bibliography

Past & Future Energy Supply

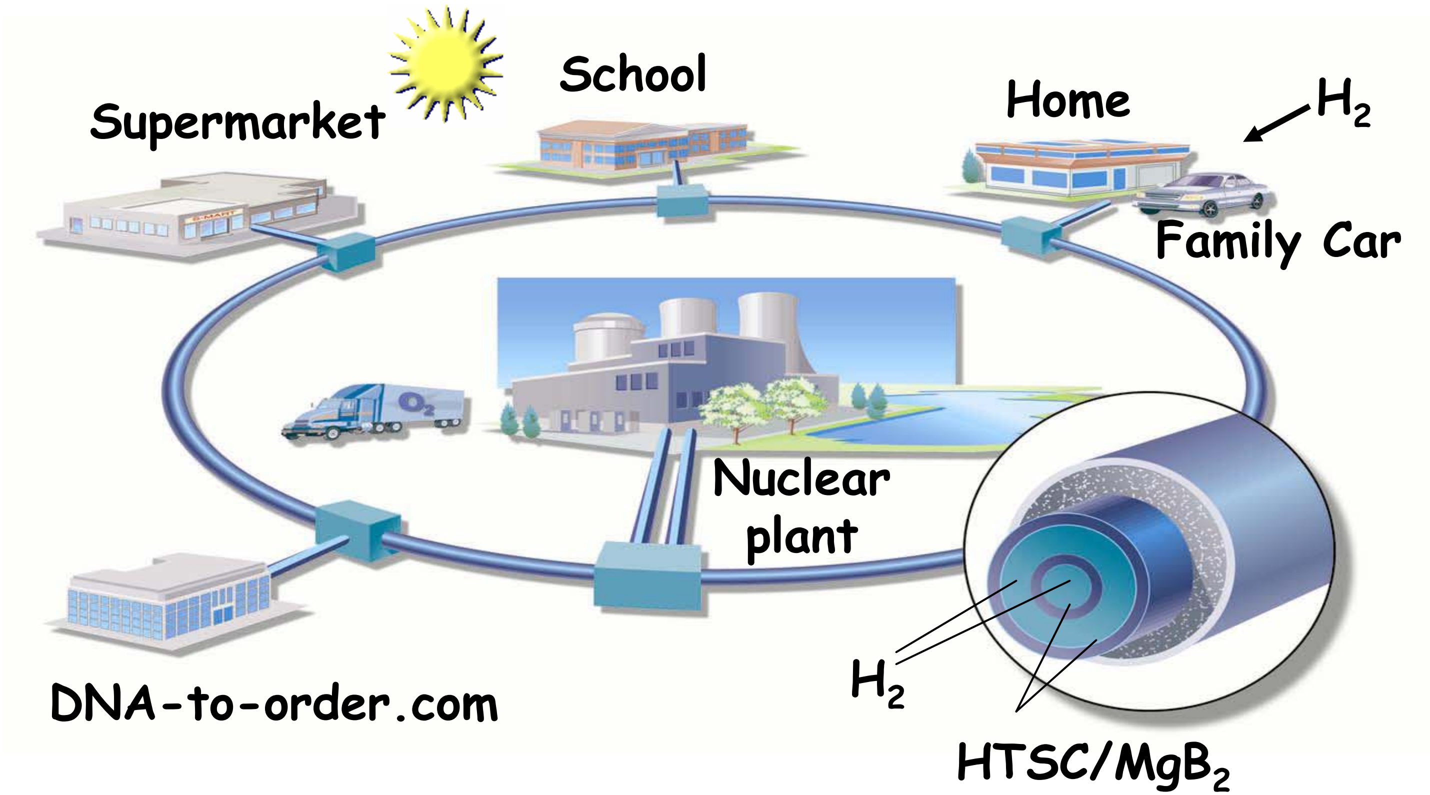


The Hydrogen Economy

- 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)

SuperCity

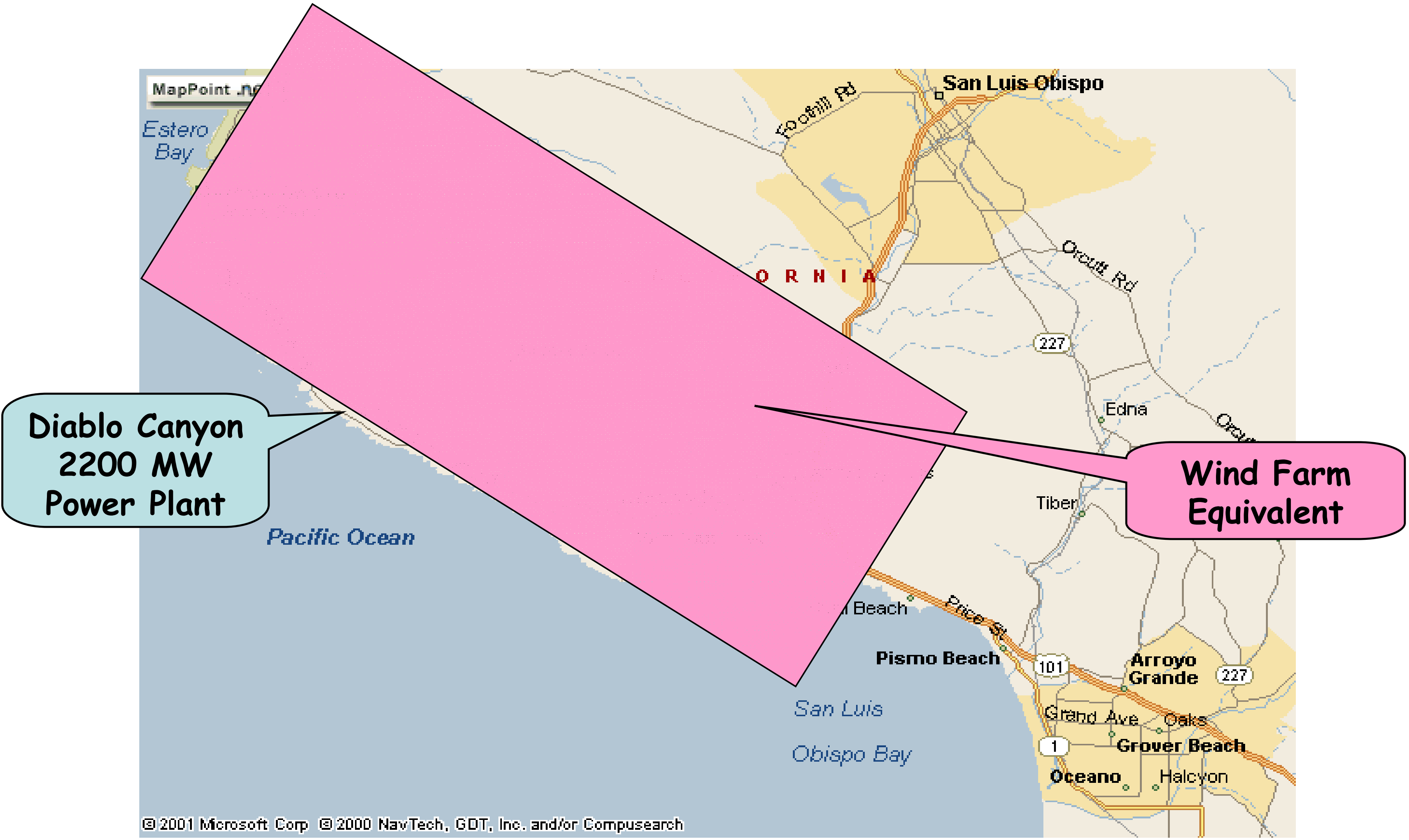


P.M. Grant, The Industrial Physicist, Feb/March Issue, 2002

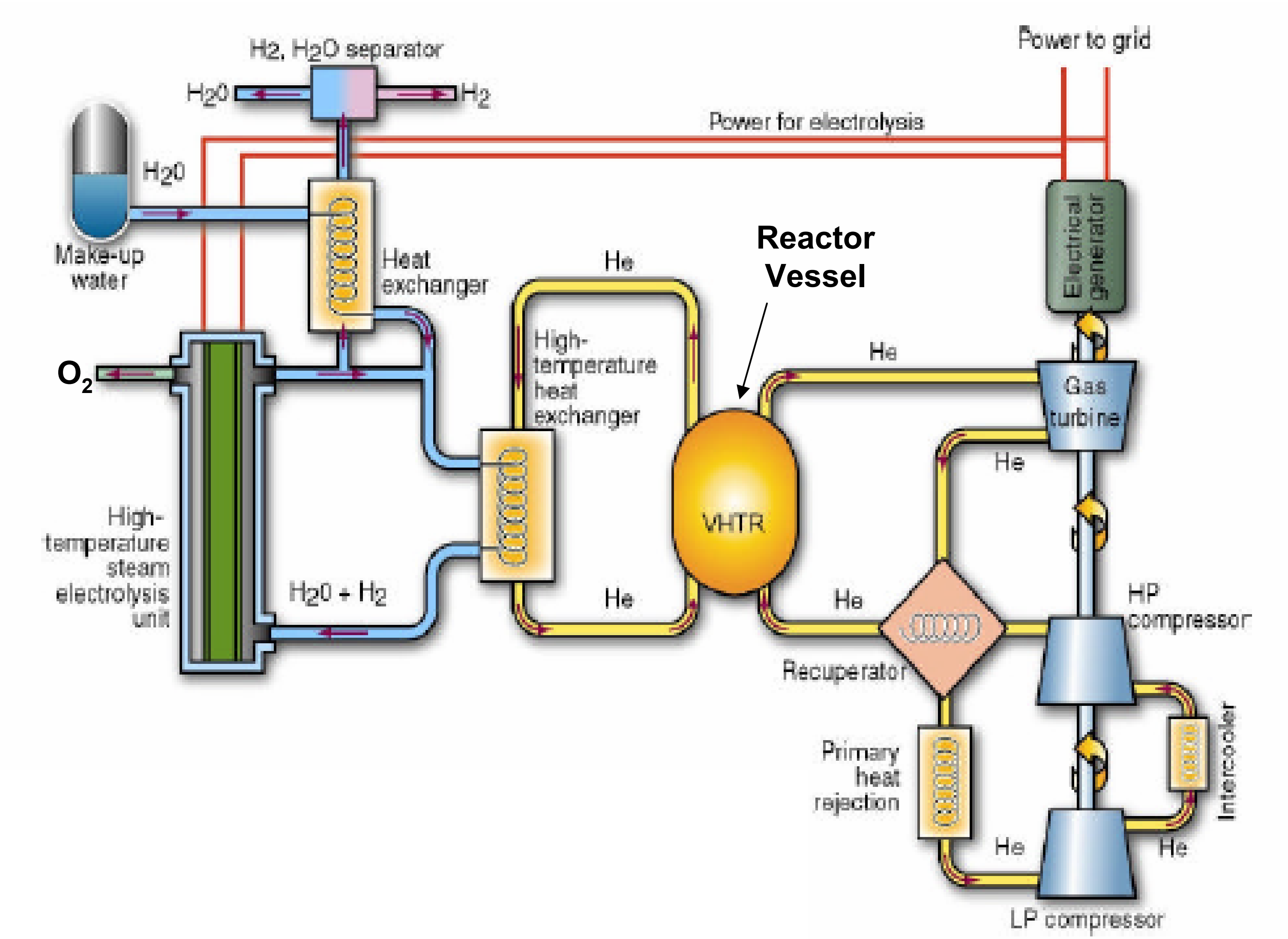
Diablo Canyon

Diablo Canyon Windmill Farm

California Coast Power

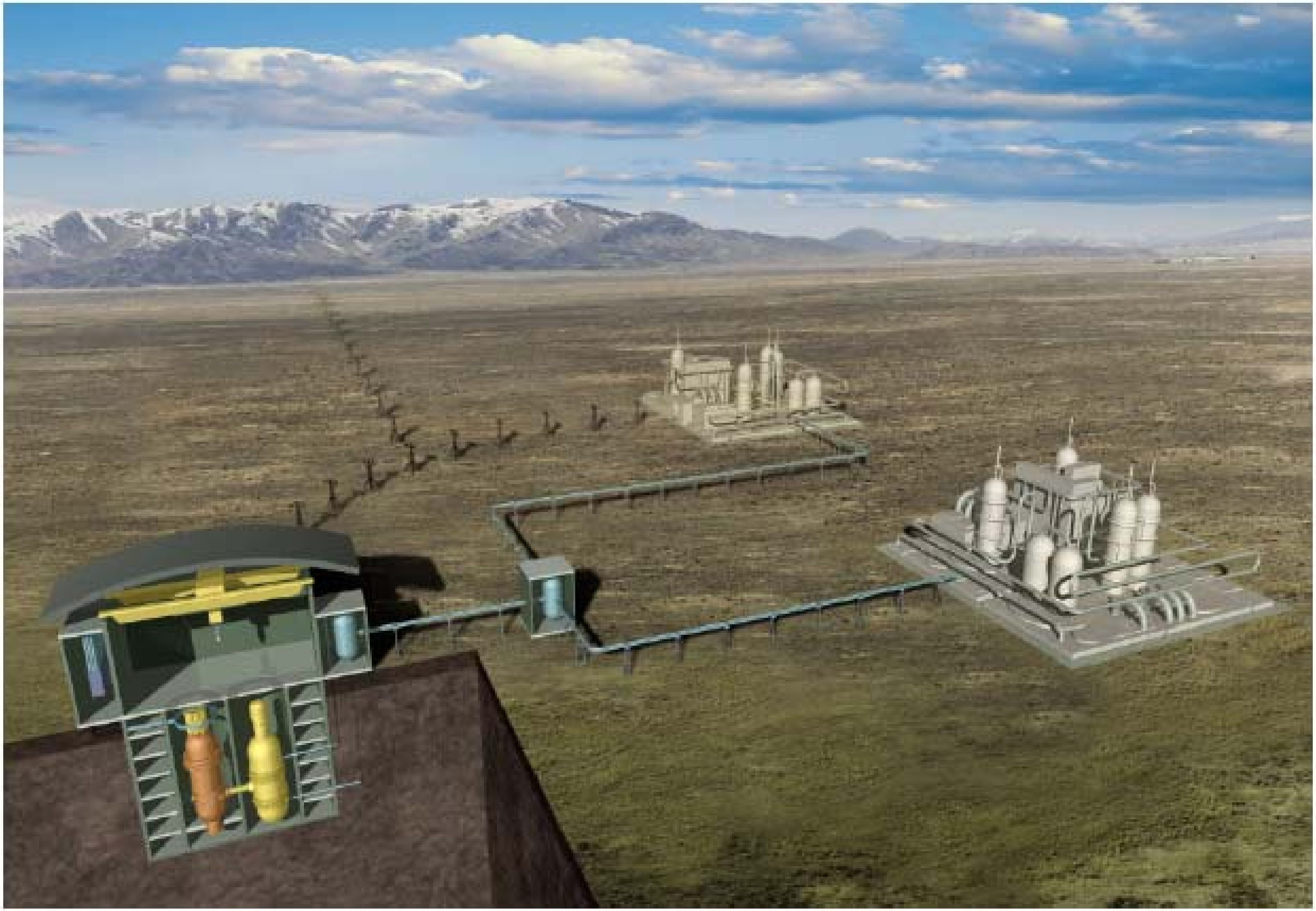


Co-Production of Hydrogen and Electricity



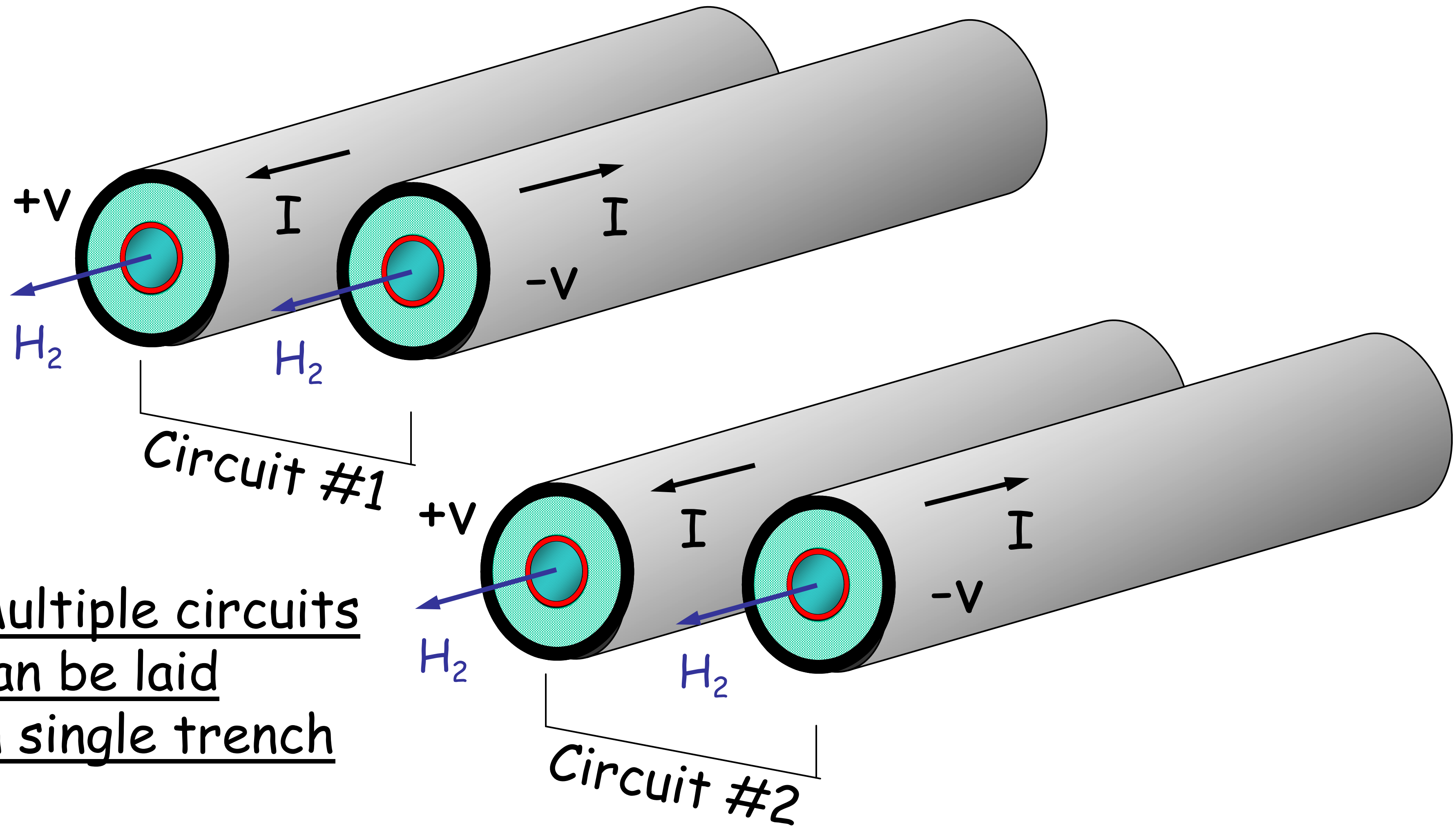
Source: INEL & General Atomics

Nuclear “Hydricity” Production Farm



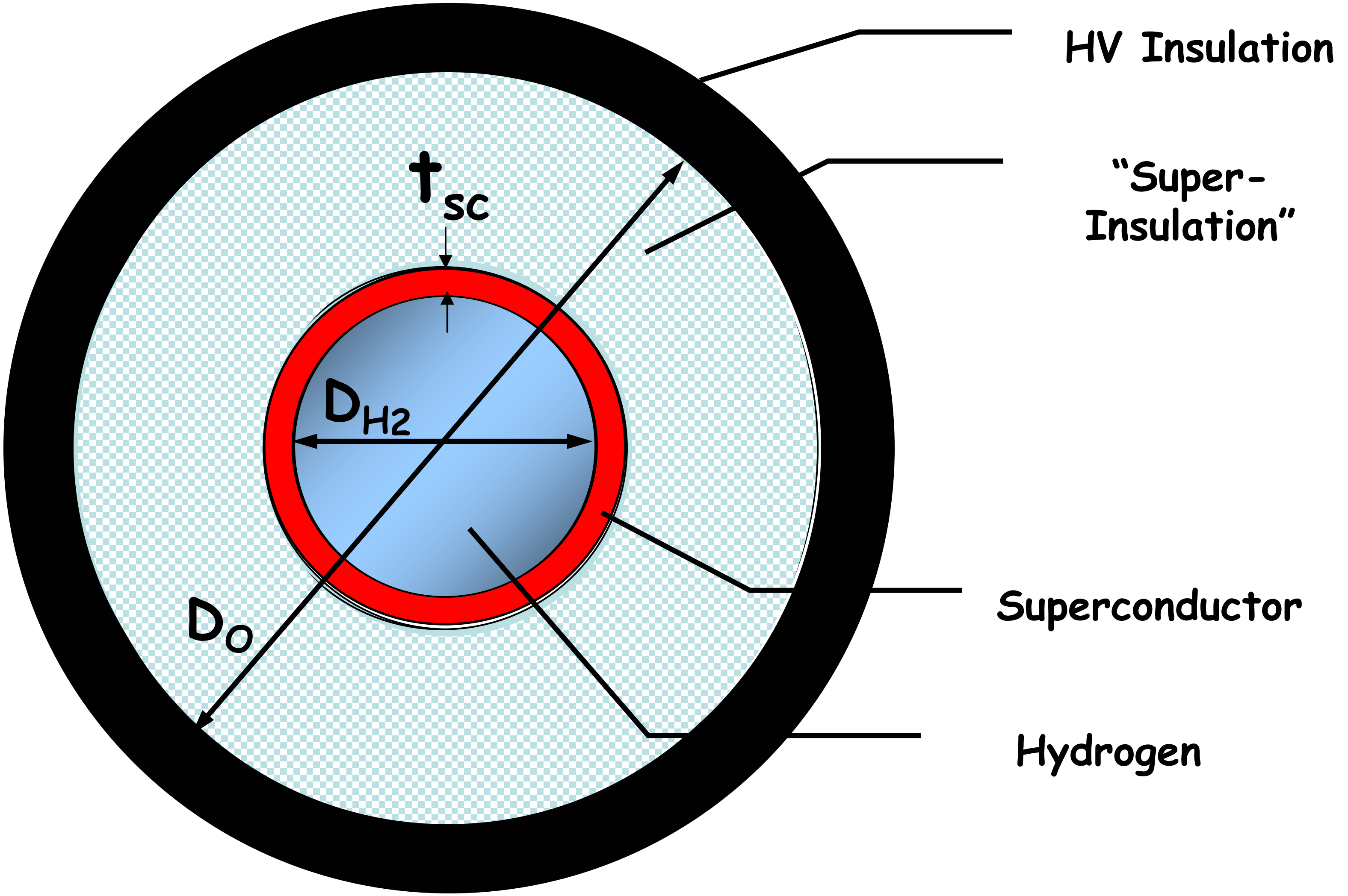
Source: General Atomics

"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

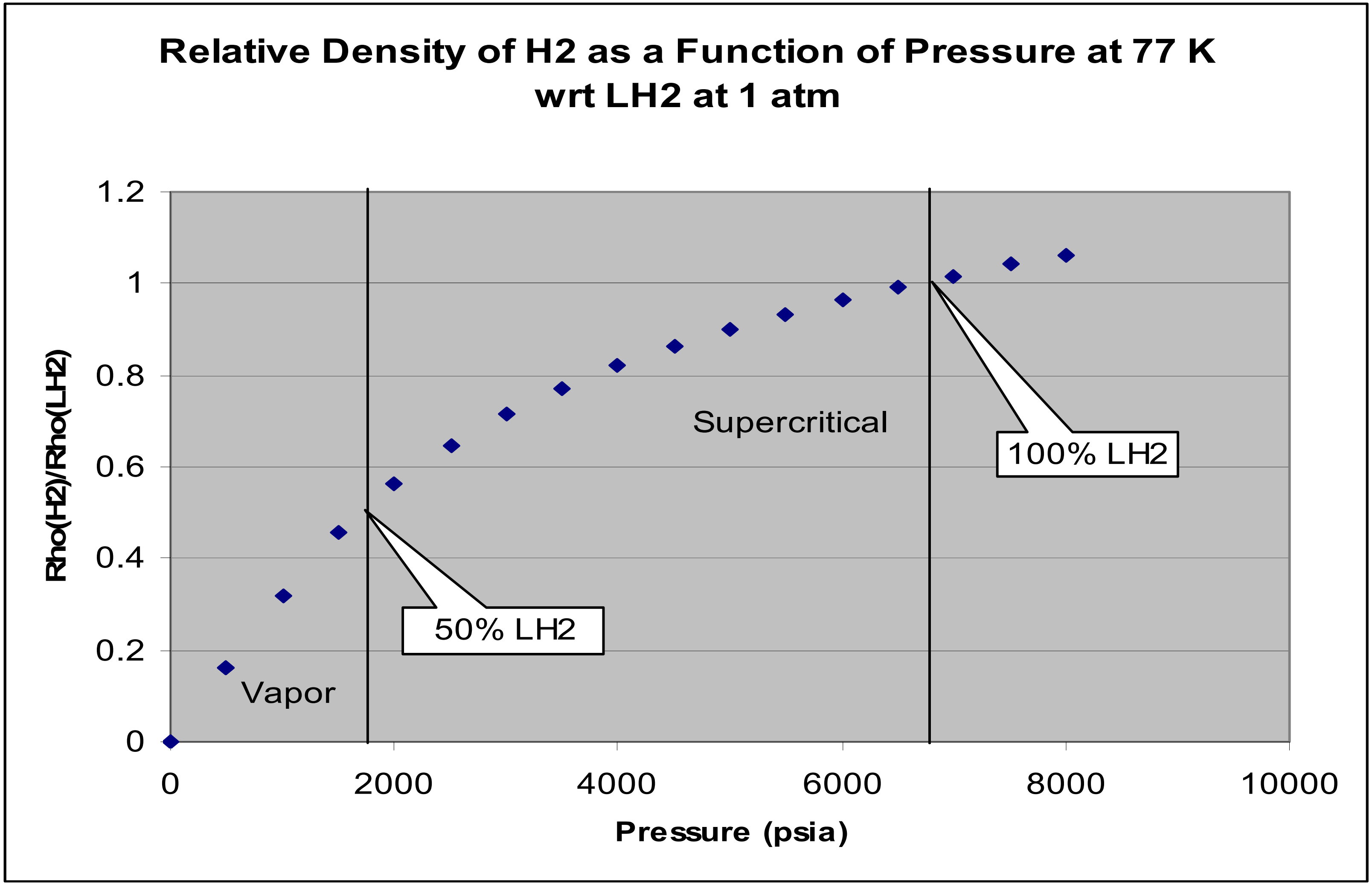
Take $W_T = 1.0$ W/m, then $dT/dx = 1.89\times10^{-5}$ K/m,
Or, 0.2 K over a 10 km distance

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

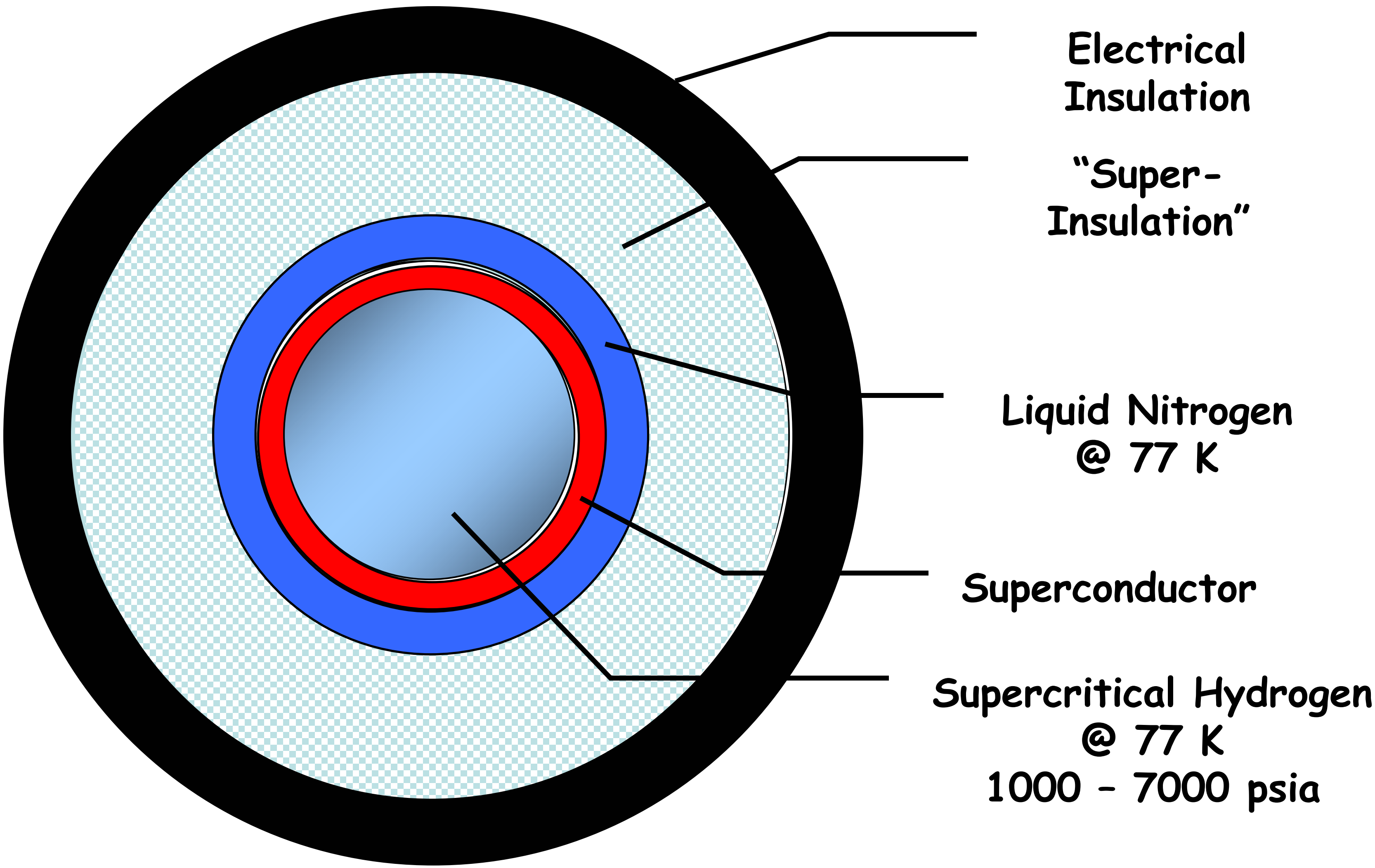
One Raccoon Mountain = 13,800 cubic meters of LH2

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



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

H_2 - Gas SuperCable



Fluid Properties Comparison of Liquid to Gaseous Hydrogen Transporting 500 MW_t in a 10-cm Diameter Pipe

T °**K**	**P** **psia**	ρ **kg/m³**	μ **μPa×s**	μ^2/ρ **ndyne**	**V** **m/s**	**Re** **10^6**
20	14.7	70.8	13.6	261	4	2.08
77	1850	35.4	5.6	87	8	5.06

$$\mathrm{Re} = \rho V D / \mu \approx \frac{\text{Inertial Forces}}{\text{Viscous Forces}}$$

Thus, it takes only 0.5 dynes "push" on an object with the above Reynolds Numbers on the gas to overcome viscous forces exerted by the given fluid

Fluid Friction Losses

$p_{loss} = \lambda\, (l / d_h)\, (\rho\, v^2 / 2)$

where

p_{loss} = pressure loss (Pa, N/m^2)

λ = friction coefficient

l = length of duct or pipe (m)

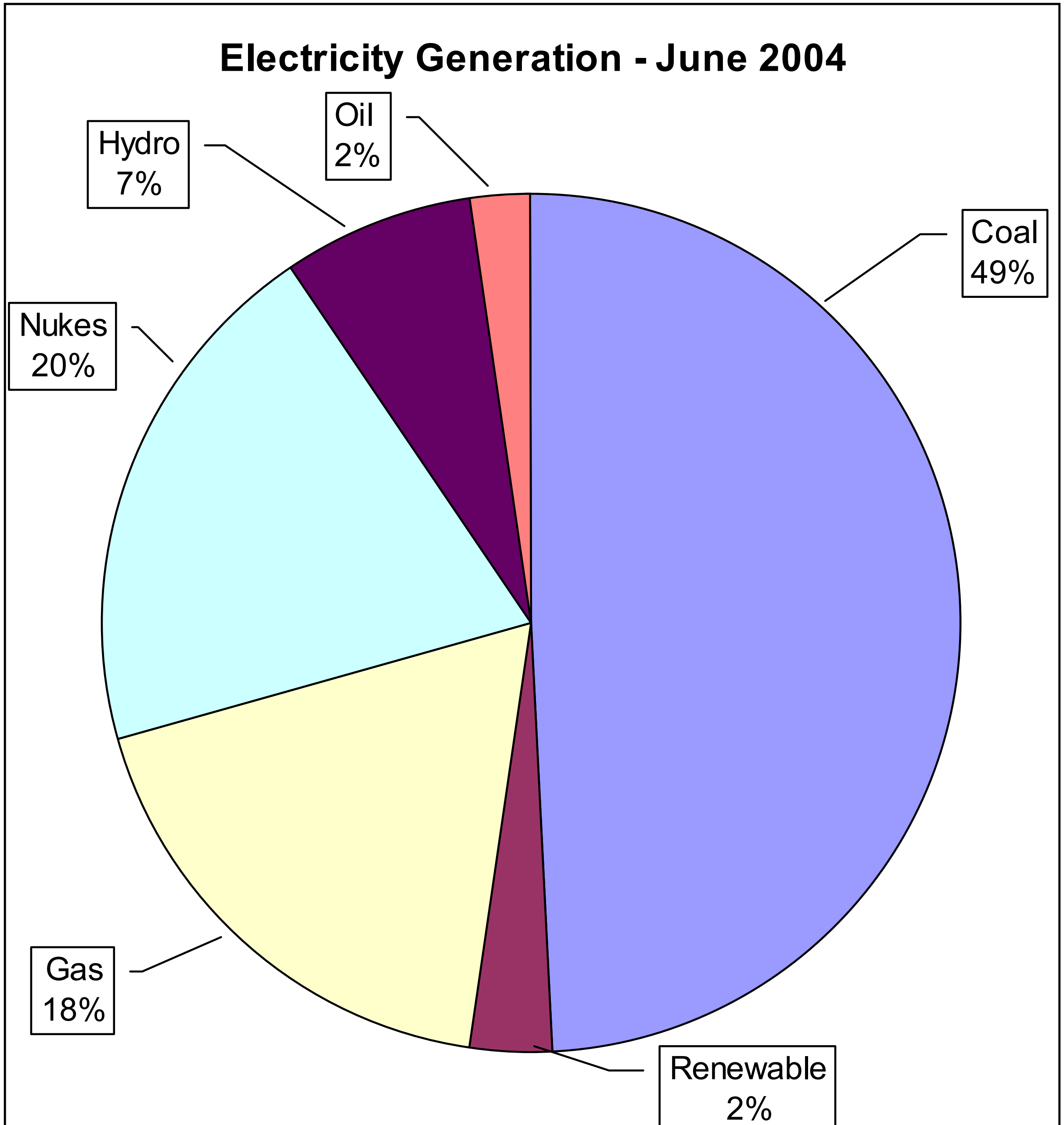
d_h = hydraulic diameter (m)

$$W_{loss} = M\, P_{loss} / \rho,$$

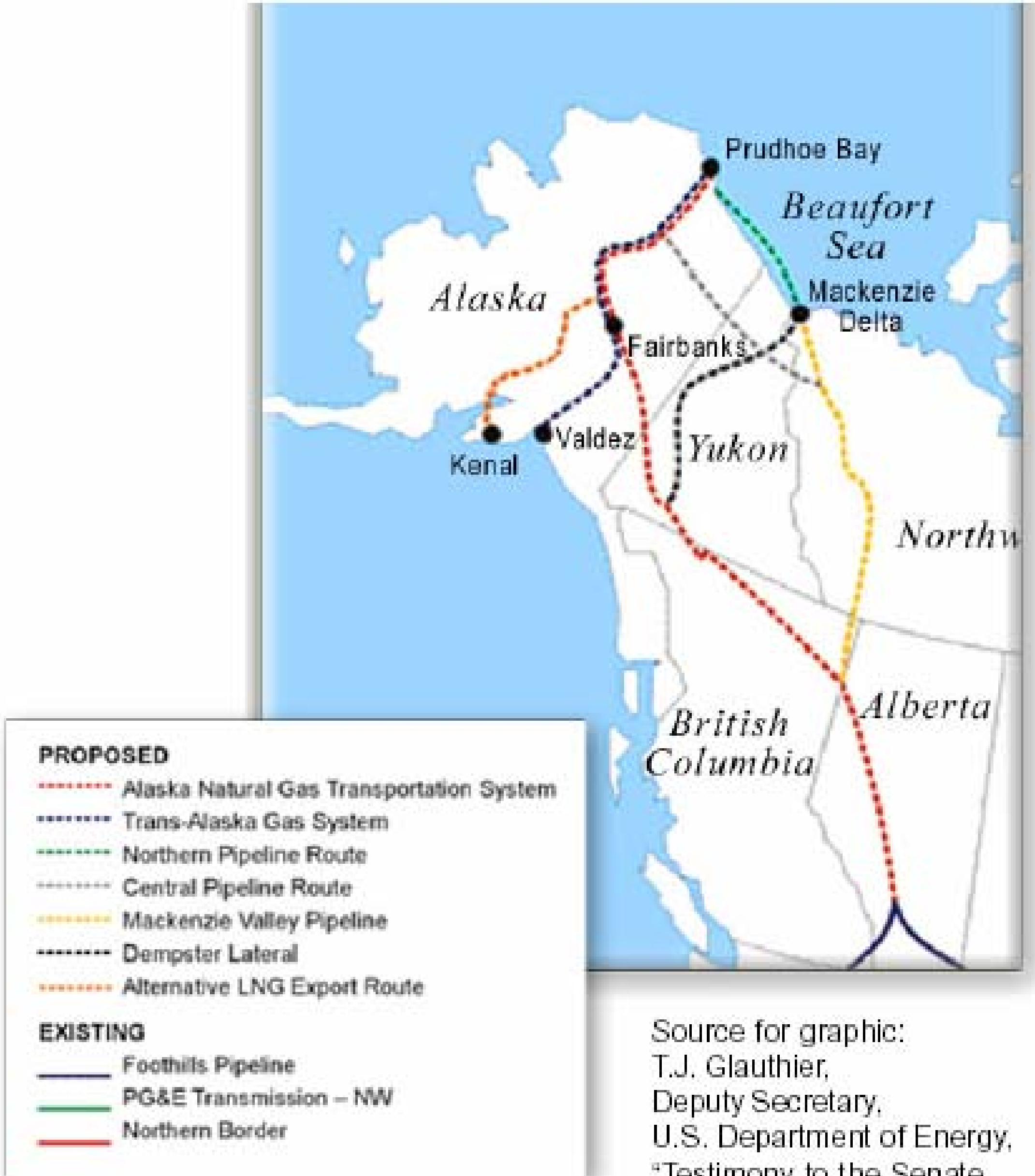
Where M **= mass flow per unit length**
P_{loss} **= pressure loss per unit length**
ρ **= fluid density**

$$1 / \lambda^{1/2} = -2{,}0 \log_{10} [\, (2{,}51 / (Re\, \lambda^{1/2})) + (\varepsilon / d_h) / 3{,}72\,]$$

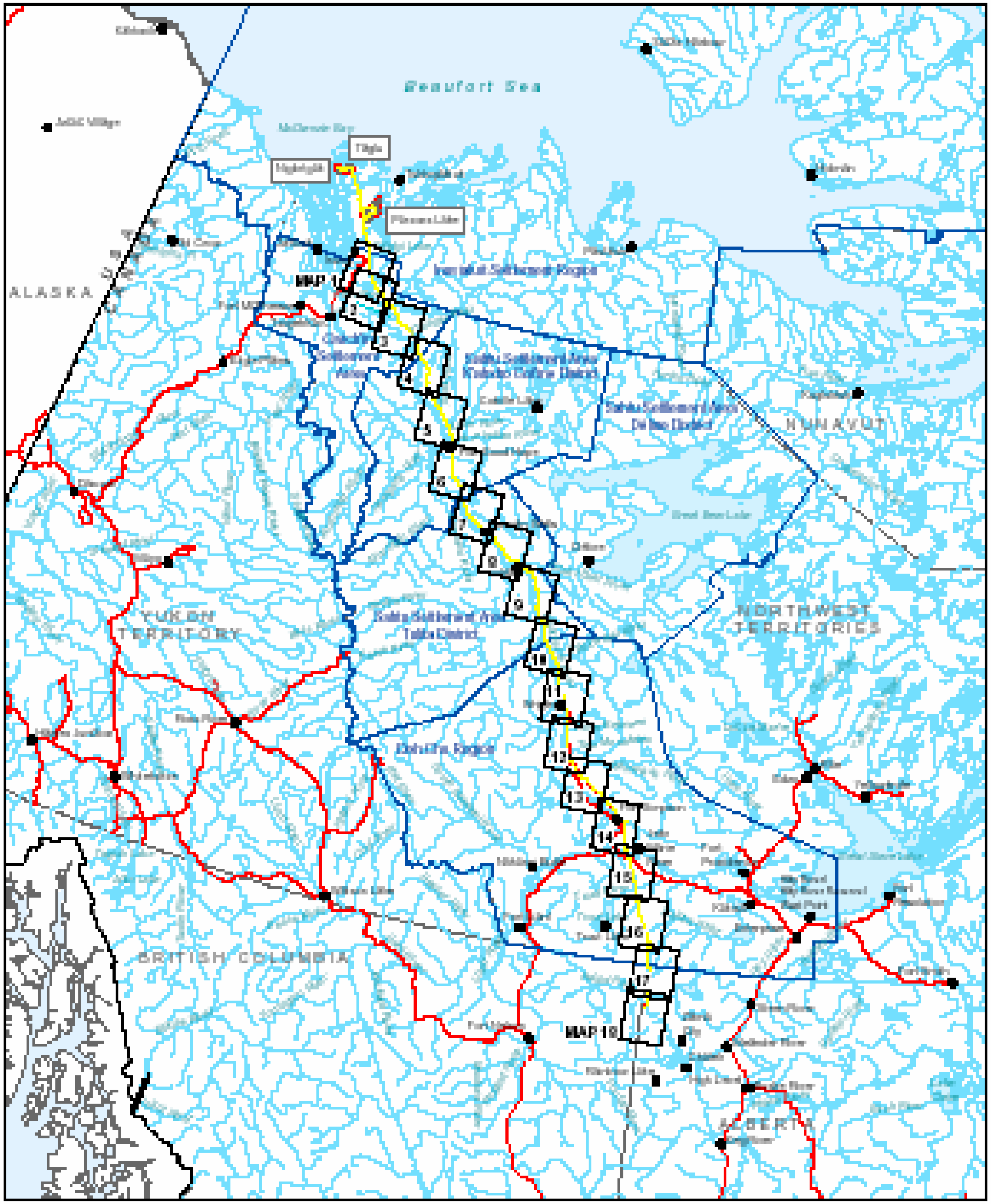
ε = 0.015 mm (stainless steel)	
	W_{loss} (W/m)
22 K	0.72
77 K	1.30


Electricity Generation - June 2004
Oil 2%
Hydro 7%
Coal 49%
Nukes 20%
Gas 18%
Renewable 2%

Al-Can Gas Pipeline Proposals



Source for graphic:
T.J. Glauthier,
Deputy Secretary,
U.S. Department of Energy,
"Testimony to the Senate Committee on Energy and Natural Resources"
(September 14, 2000).

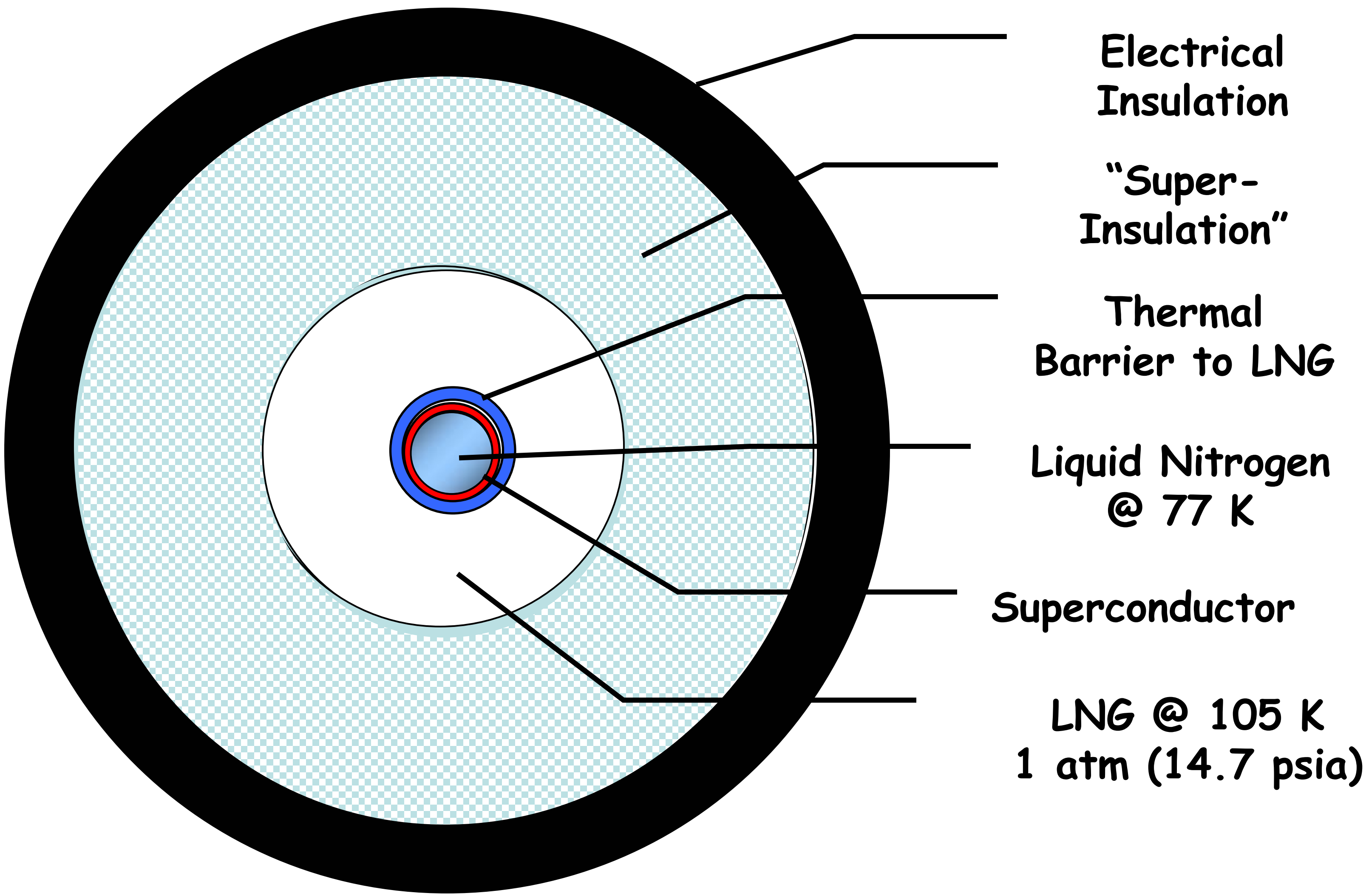


Mackenzie Valley Pipeline

1300 km

18 GW-thermal

LNG SuperCable



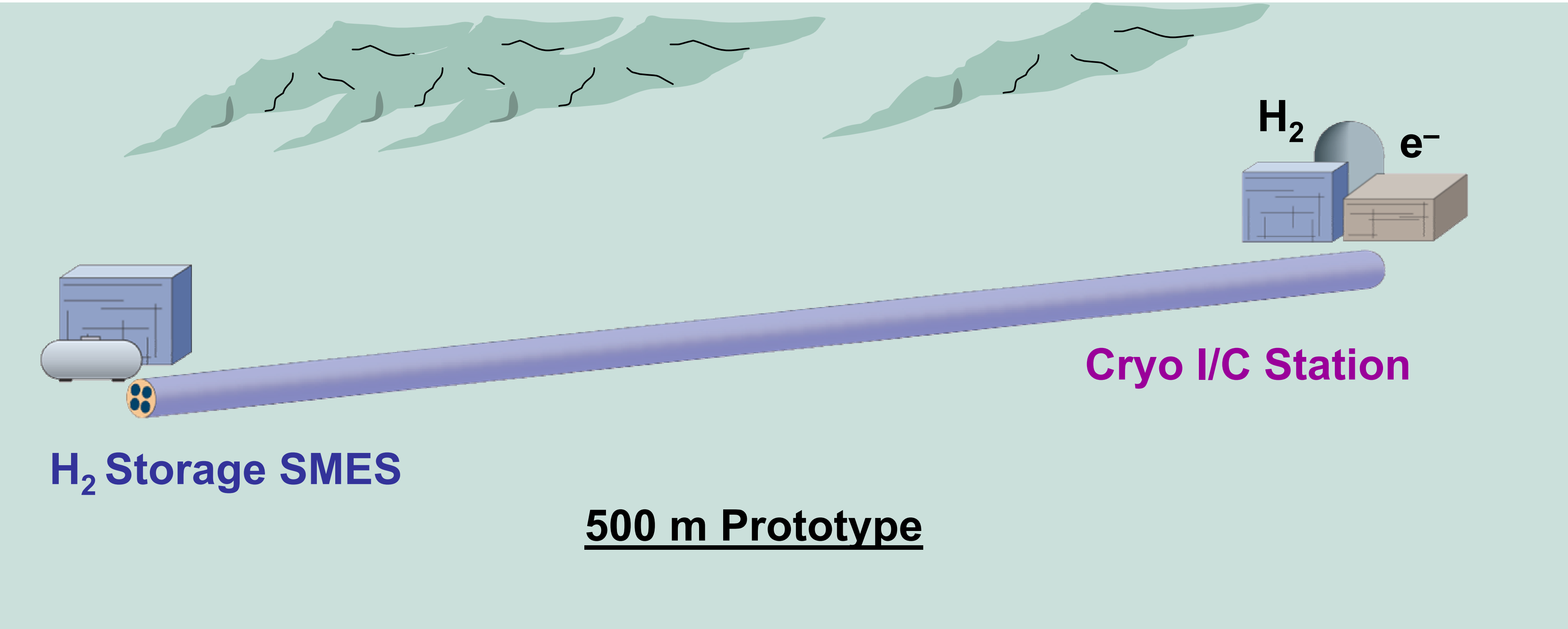
Electrical Issues

- Voltage – current tradeoffs
- AC interface (phases)
- Ripple suppression
- Charge/Discharge cycles (Faults!)
- Power Electronics
  - GTOs vs IGBTs
  - 12” wafer platforms
  - Cryo-Bipolars

Construction Issues

- Pipe Lengths & Diameters (Transportation)
- Coax vs RTD
- Rigid vs Flexible?
- On-Site Manufacturing
  - Conductor winding (3-4 pipe lengths)
  - Vacuum: permanently sealed or actively pumped?
- Joints
  - Superconducting
  - Welds
  - Thermal Expansion (bellows)

SuperCable Prototype Project



"Appropriate National Laboratory"
2005-09