The SuperCable:
Dual Delivery of Chemical and Electric Power

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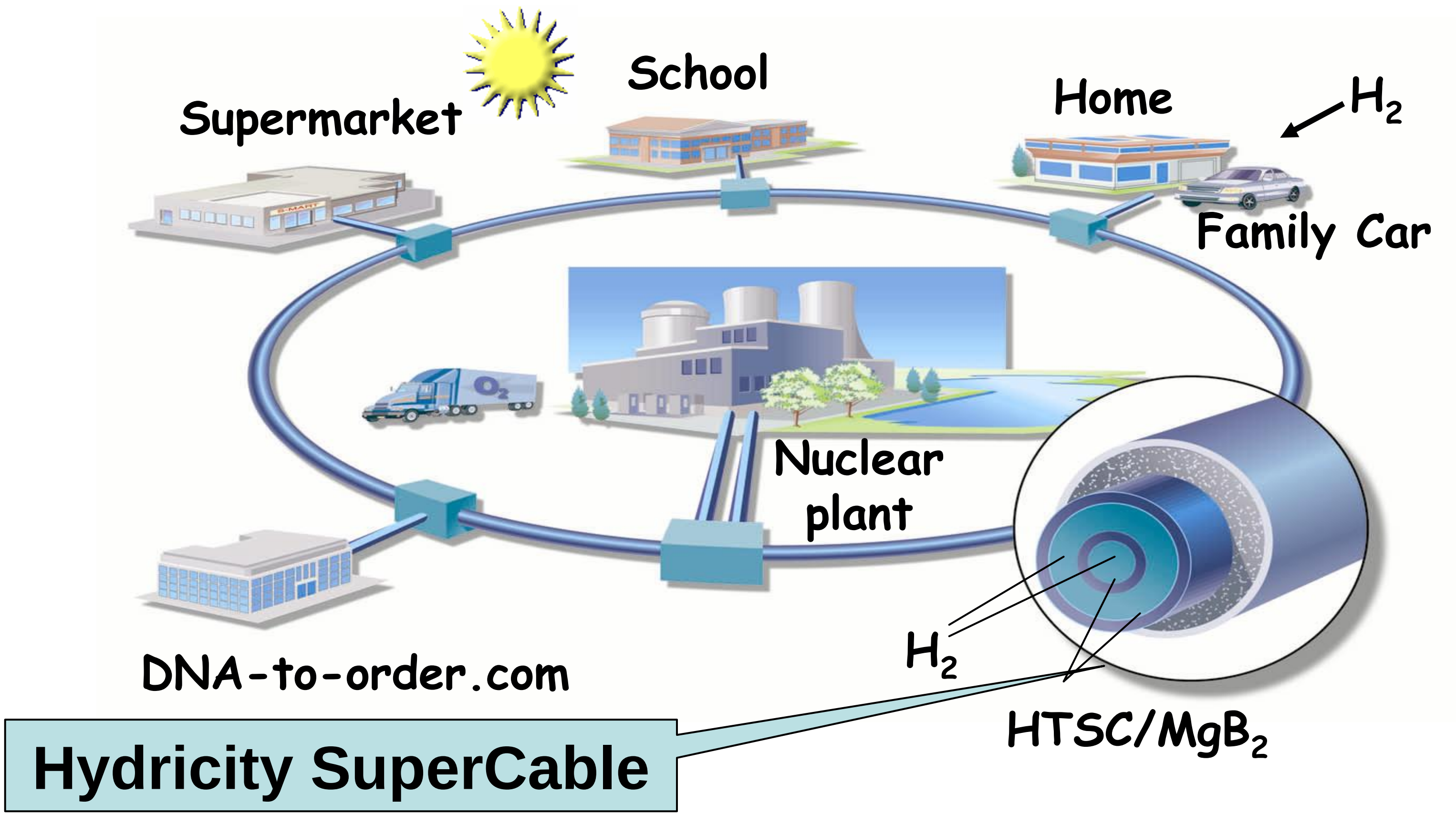
SuperCity



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

<u>Concept originally presented at the 2000 Peer Review</u>

SuperCities & SuperGrids

A Symbiosis of

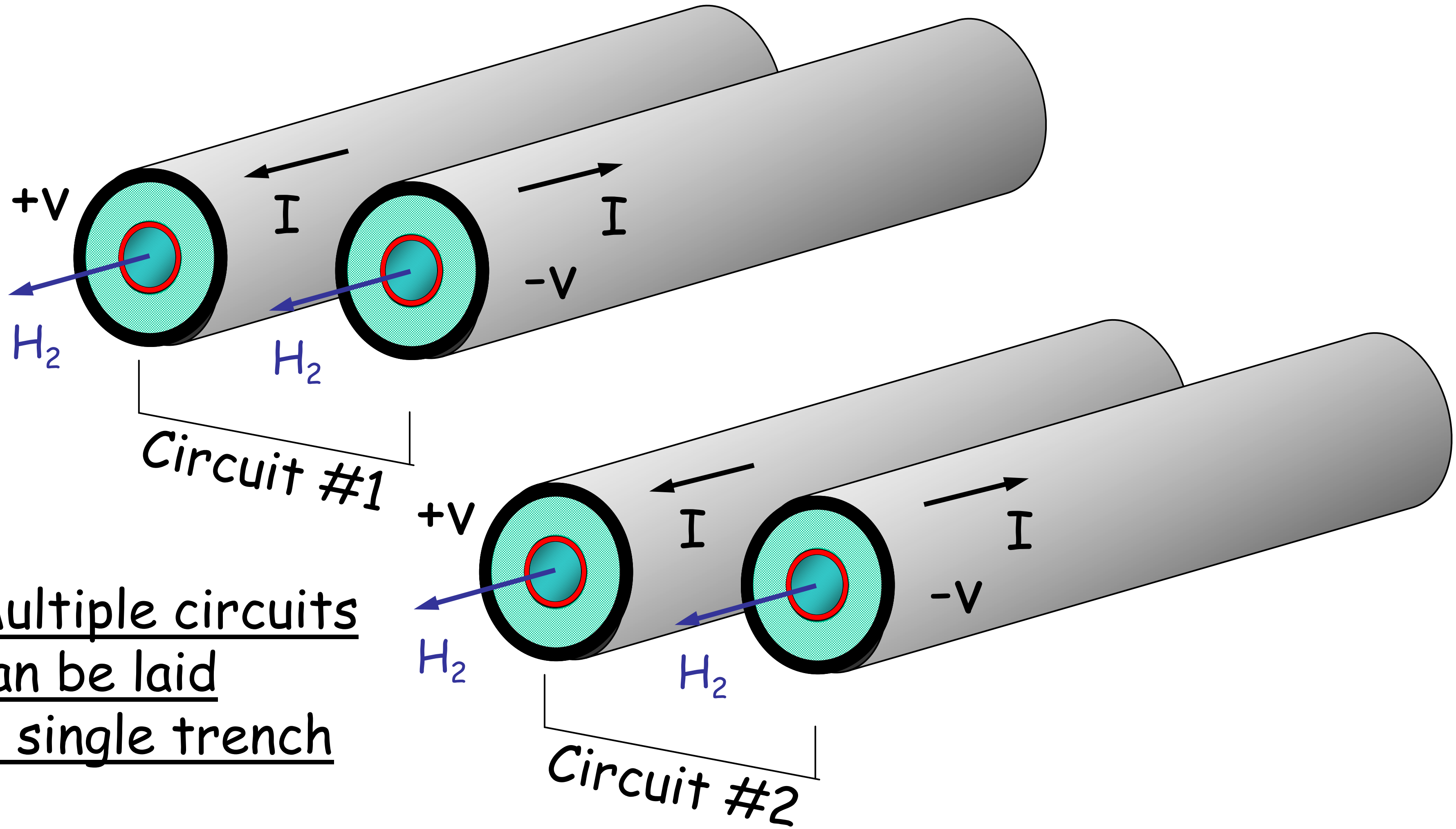
Nuclear/Hydrogen/Superconductivity

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

“Boundary Conditions”

- Givens
  - Energy Efficiency
  - Recyclables
- Off-the-Table: Eco-invasive Generation
  - Fossils
    - Carbon Sequestration
  - Baseline Renewables
    - “Farms” – Wind, Solar, Biomass
- On-the-Table
  - Nuclear (undergrounding)
  - Solar Roofs
  - Urban/Agro Biomass

"Hydricity" SuperCables

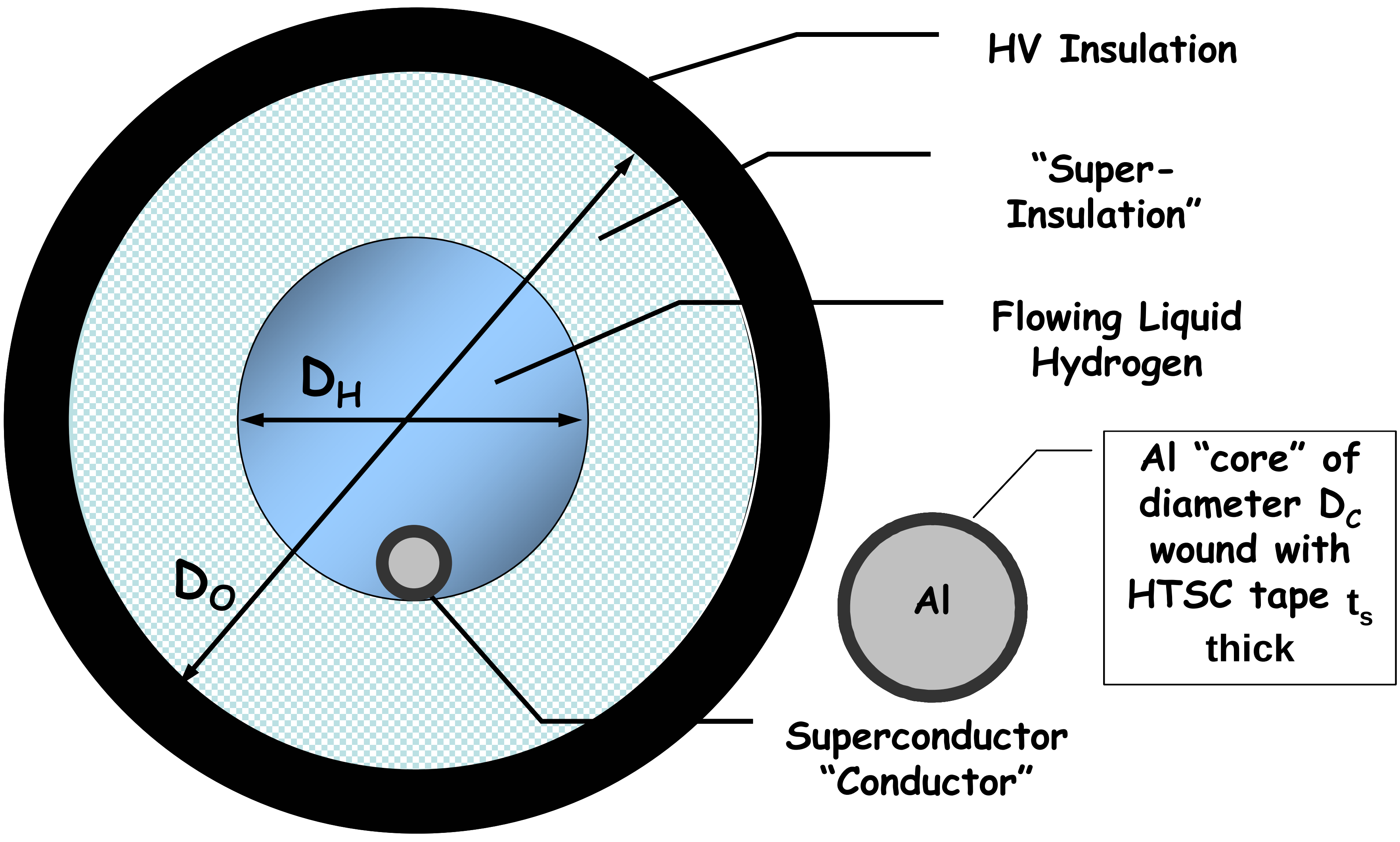


<u>Multiple circuits can be laid in single trench</u>

Why Mono-Axial and Not Coax?

- Simple Design – Cheaper
- Room temperature dielectric – no cryo – dielectrics – wide separation of pole to pole potential
- Simpler design and separate placement of “accessories” (joints & terminations)
- Allows for independent (& redundant) cooling and pumping stations.
- Easy to take one pole out for service and use earth return (at lower power)
- Probably easier to handle faults – parallel normal metal shunt on each pole.
- Better suited to large scale projects – opportunity for on-site “construction kits.”

SuperCable RTD Monopole



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

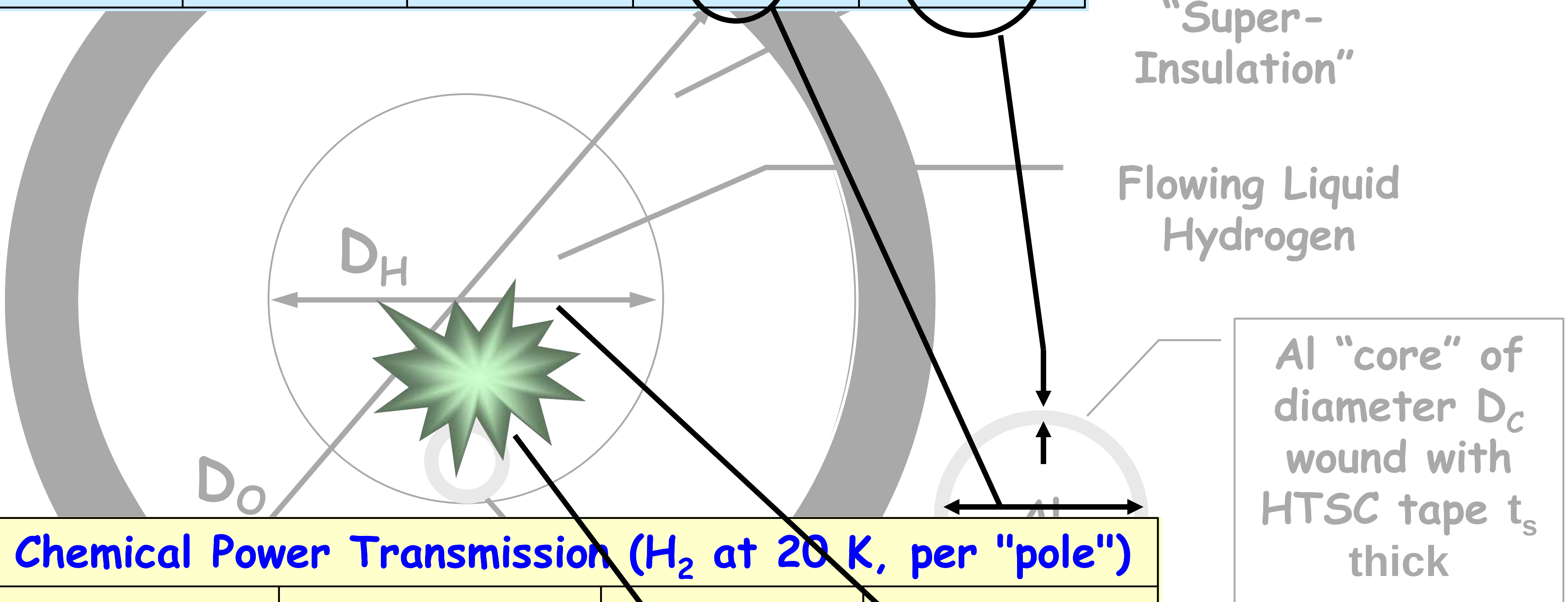
Hydrogen

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

Power Flows: 5 GW_e/10 GW_{th}

Electrical Power Transmission (+/- 25 kV)				
Power (MW_e)	Current (A)	HTS J_C (A/cm^2)	D_C (cm)	t_s (cm)
5,000	100,000	25,000	3.0	0.38



Chemical Power Transmission (H_2 at 20 K, per "pole")			
Power (MW_{th})	D_H-effective (cm)	H_2 Flow (m/s)	D_H-actual (cm)
5,000	40	4.76	45.3

Thermal Losses

Radiation 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

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

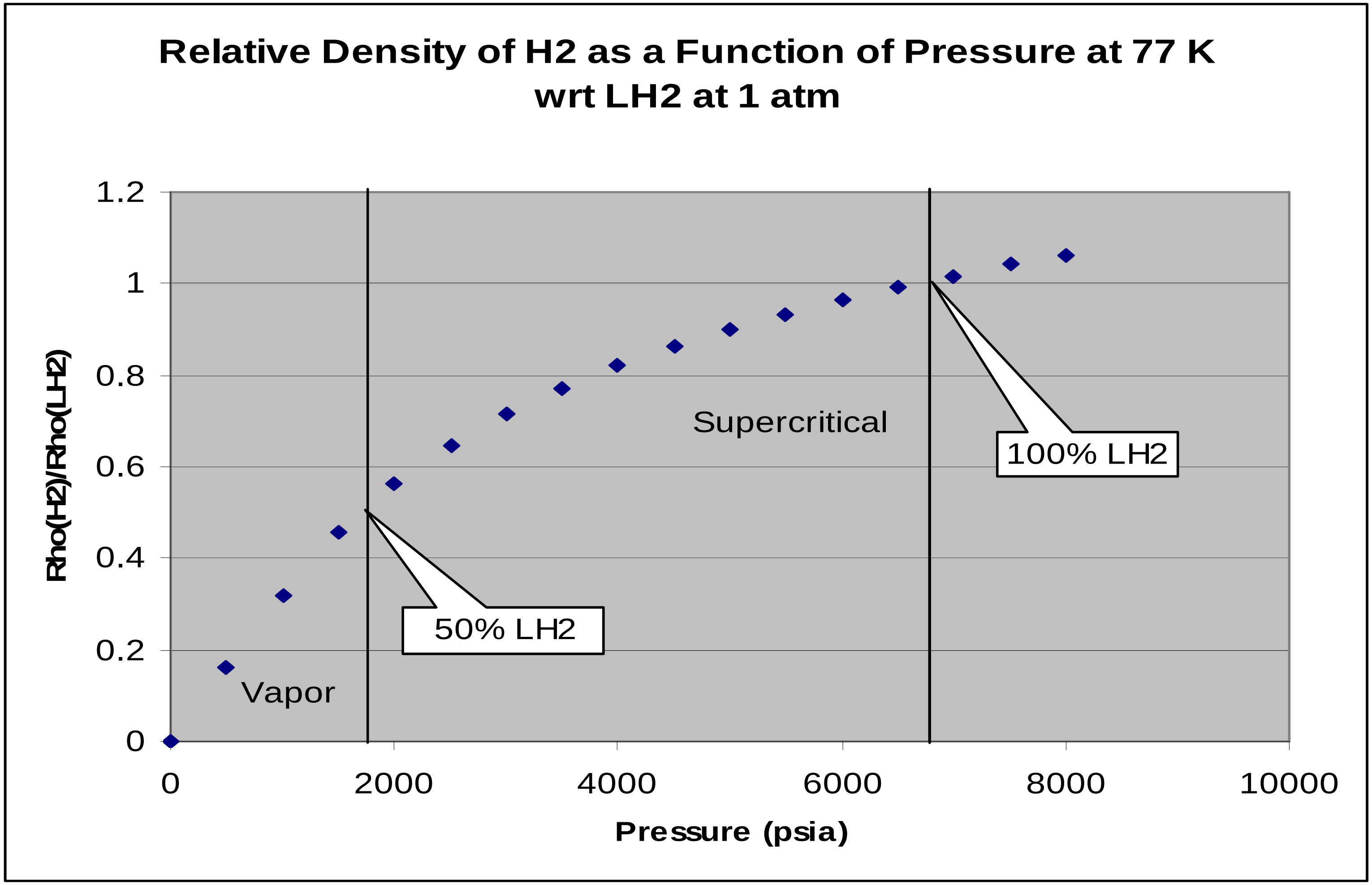
Heat Removal

$dT/dx = W_T/(\rho v C_P A)_{H2}$, 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, <u>0.2 K over a 10 km distance</u>

Hydrogen Energy Content



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

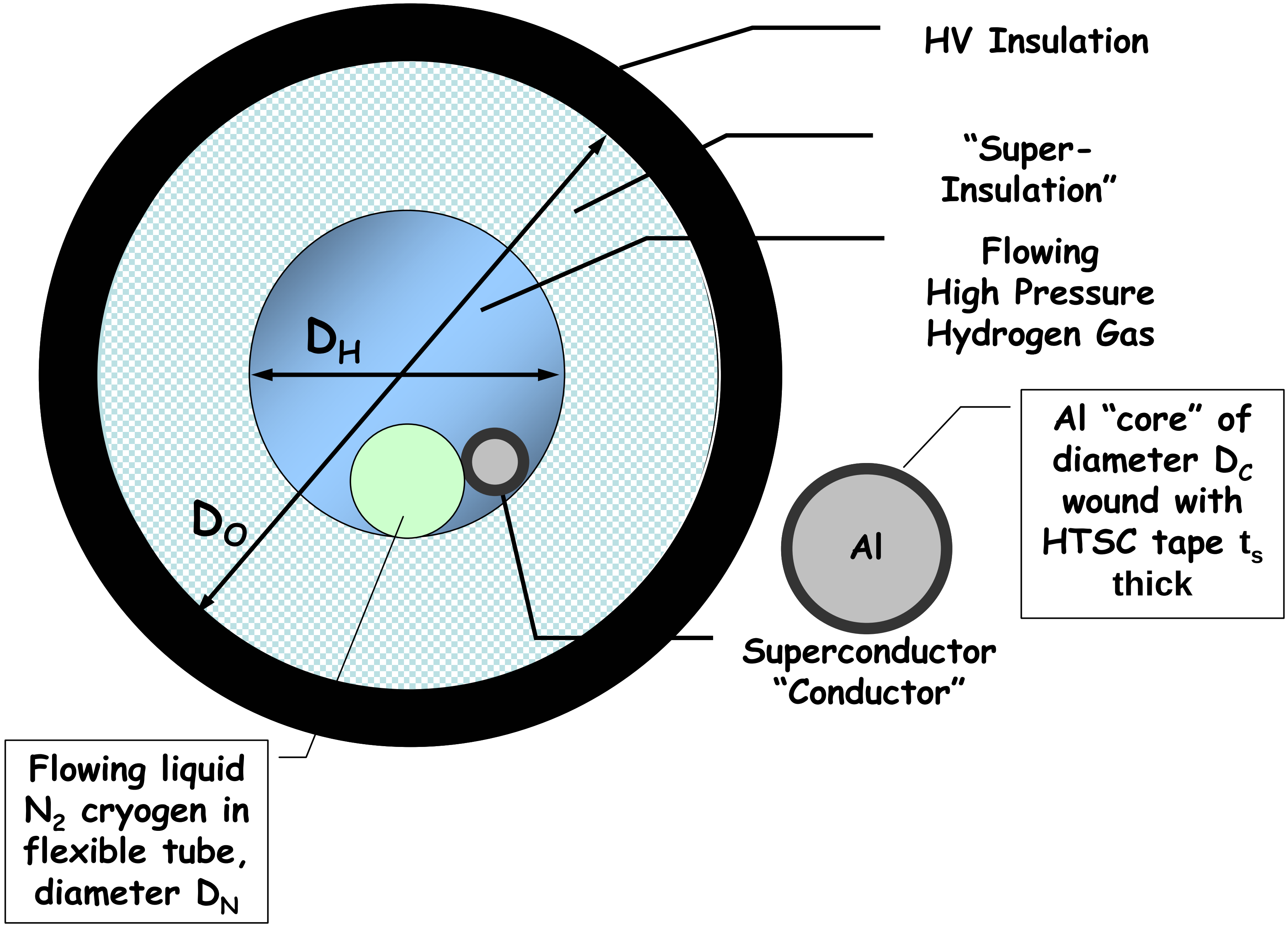
SuperCable H_2 Storage

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

"Hybrid" LN_2/GH_2 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/m^3	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

$$Re = \rho VD / \mu \approx \frac{\text{Inertial Forces}}{\text{Viscous Forces}}$$

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)

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

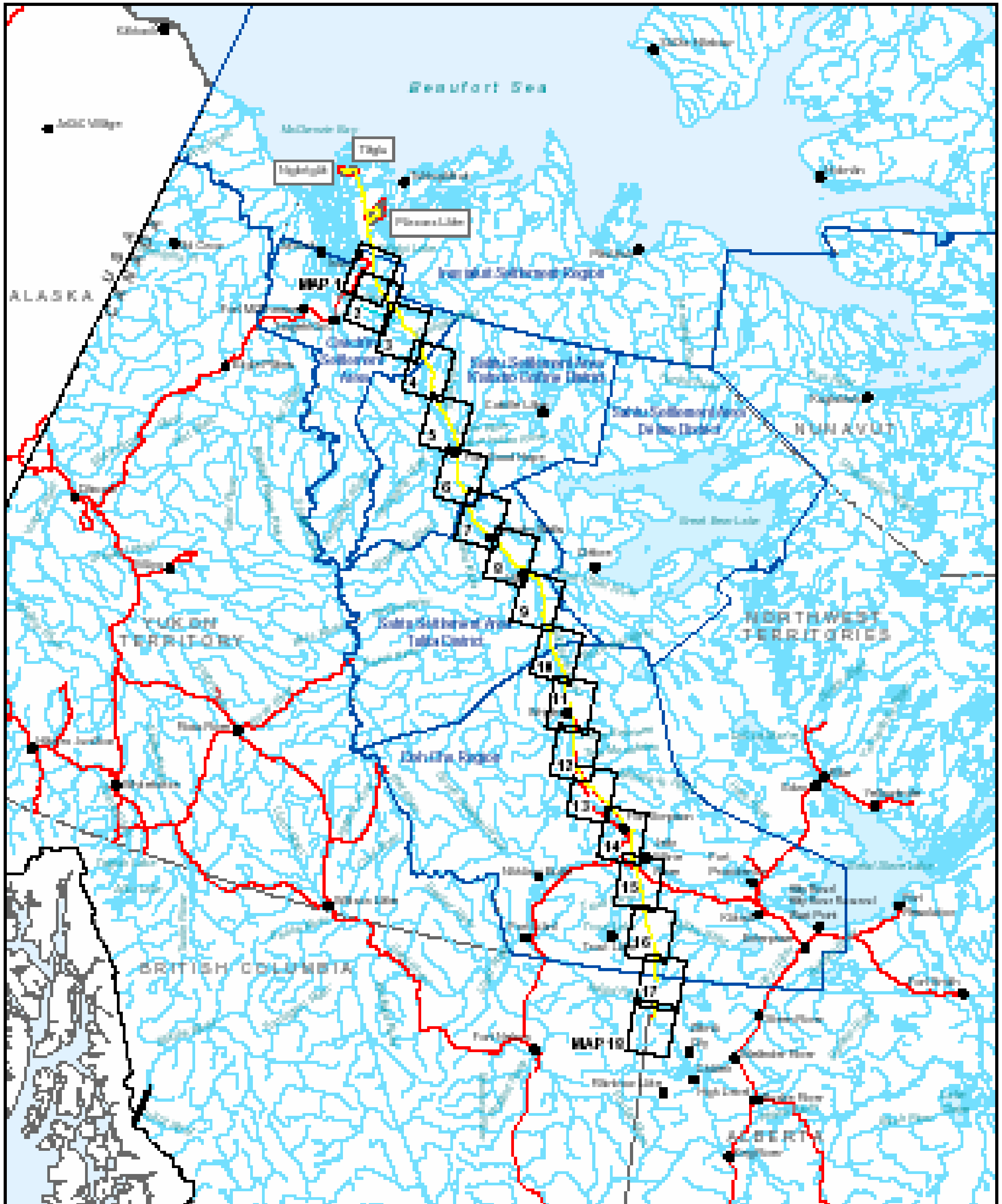
Where M **= mass flow per unit length**
P_{loss} **= pressure loss per unit length**
ρ **= fluid density**

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

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

SuperCables & Gas Pipelines

- Methane will be the “fossil fuel of choice” for the next 25 years and many long distance pipelines (such as the Mackenzie Valley Project) and LNG seaports will be built.
- 25 – 30% will be turned into electricity near the pipeline terminus.
- Alternatively, electricity can be generated at the wellhead or dock and it and methane co-transported on a LNG hybrid SuperCable to the end user.
- When the natural gas is depleted, HTGCR nuclear plants can be built at the well and dock sites to produce hydrogen and electricity and the delivery infrastructure will be already in place.

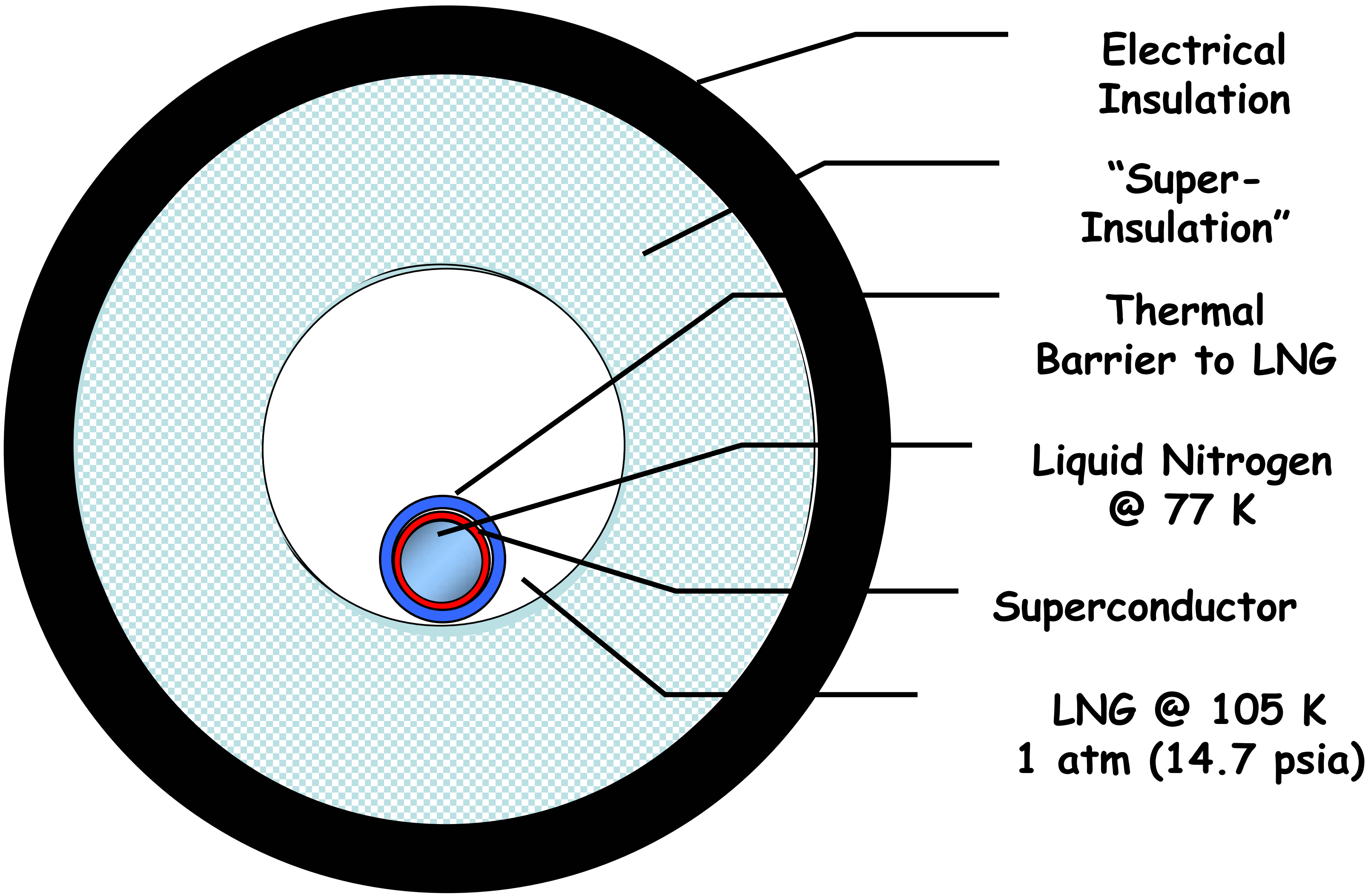


Mackenzie Valley Pipeline

1300 km

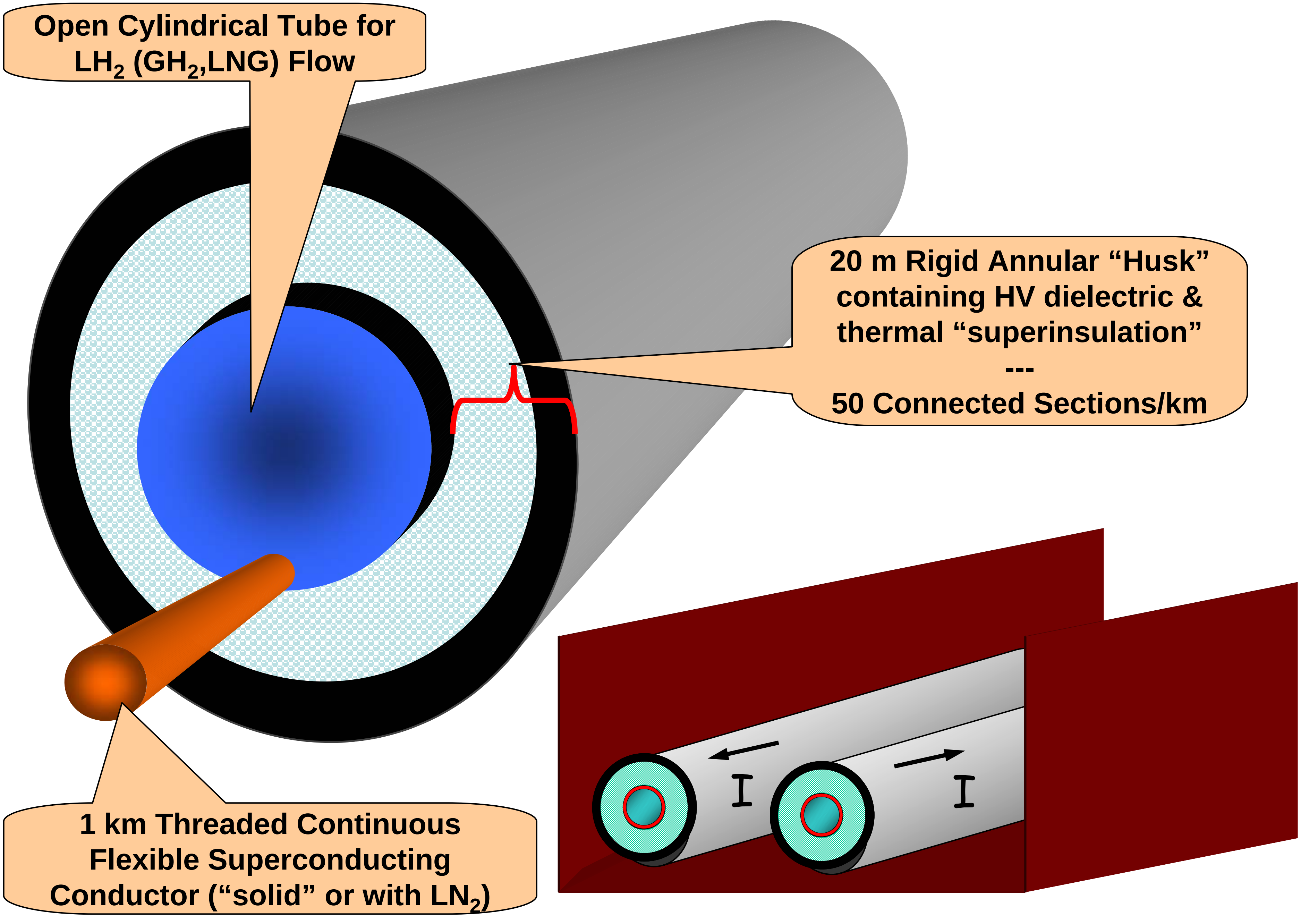
18 GW-thermal

LNG/LN_2 “Hybrid” SuperCable



Construction

- Housed in trenches/tunnels for safety/security
- 20 – m rigid pre-fabed “husks” for transport by truck/barge/copter to construction site – straight or with large radius of curvature
- Superinsulation volume of each husk under “permanent” vacuum
- Ends of husk contain thermal barrier to supress heat in-leak and bellows on inner cylinder for thermal expansion to enable jointing to neighbors.
- 1 km of pre-fabed HTSC conductor threaded from spool and loosely laid through 50 joined husks, then spliced – cooling and pumping stations every 5 km.



Open Cylindrical Tube for LH_2 (GH_2,LNG) Flow
20 m Rigid Annular “Husk” containing HV dielectric & thermal “superinsulation”
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50 Connected Sections/km
1 km Threaded Continuous Flexible Superconducting Conductor (“solid” or with LN_2)
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Inverter/Converter Station Design

- Low voltage, high current
  - Parallel IGBTs?
  - 16” wafers?
  - Cryo-bipolars?
  - Fault tolerant (inverter capable of dumping fault energy into ac grid)
- “Zero Ripple Factor”
  - Necessary to reduce ac losses
  - Cable distributed reactance may aid
- Power flow management thru voltage control
  - Maintain constant current
  - New design paradigm wrt to conventional hvdc

Additional Resources

- More information and background on the SuperCable and SuperGrid concepts can be found at
  - **http://www.w2agz.com/PMG%20SuperGrid%20Home.htm**
- A PDF copy of this poster can be downloaded from
  - http://www.w2agz.com/Documents/2005%20PR%20SuperCable%20Poster.pdf
- Portions of this poster will be amplified upon in two invited papers at the upcoming CEC – ICMC and PacRim 6 conferences
  - **"Cryo-Delivery Systems for the Co-Transmission of Chemical and Electrical Power," http://www.cec-icmc.org/techindiv.asp?PaperNumber=C1-I-01**
  - **"System, Construction and Integration Issues for Long Distance, High Capacity, Ceramic HTSC dc Cables," http://ocms.acers.org/abstract_action.asp?confid=32&sympid=422&sessid=3117 (click on Abstract List)**