SuperCities and SuperGrids:

A Vision of Long-term Sustainable and Climate-Compatible Energy

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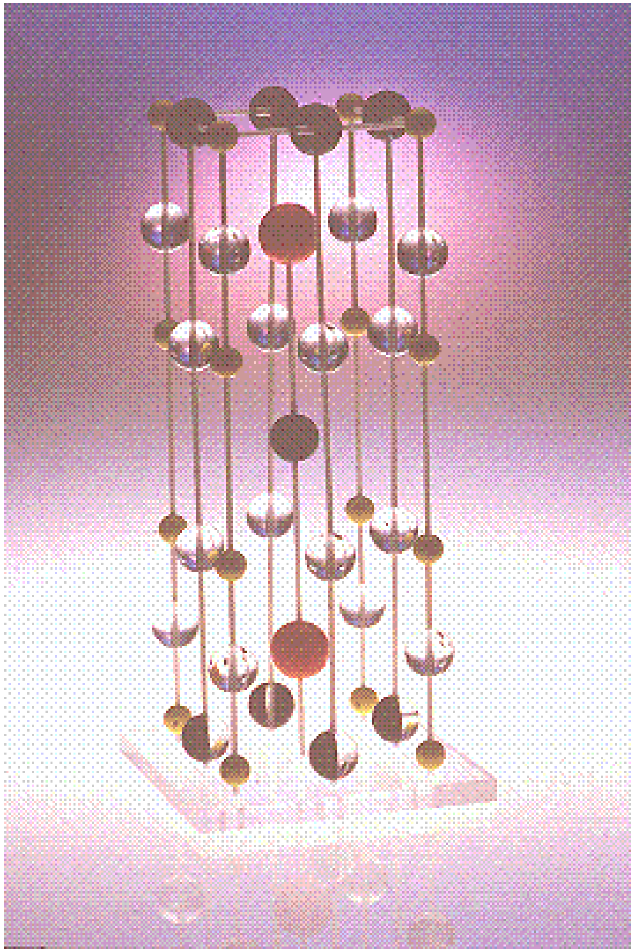
IBM Almaden Research Center
21 January 2005

1953

Project Sage – IBM/MIT

35 Years Later…

March 3, 1987: "123" Structure at ARC



Acknowledgements

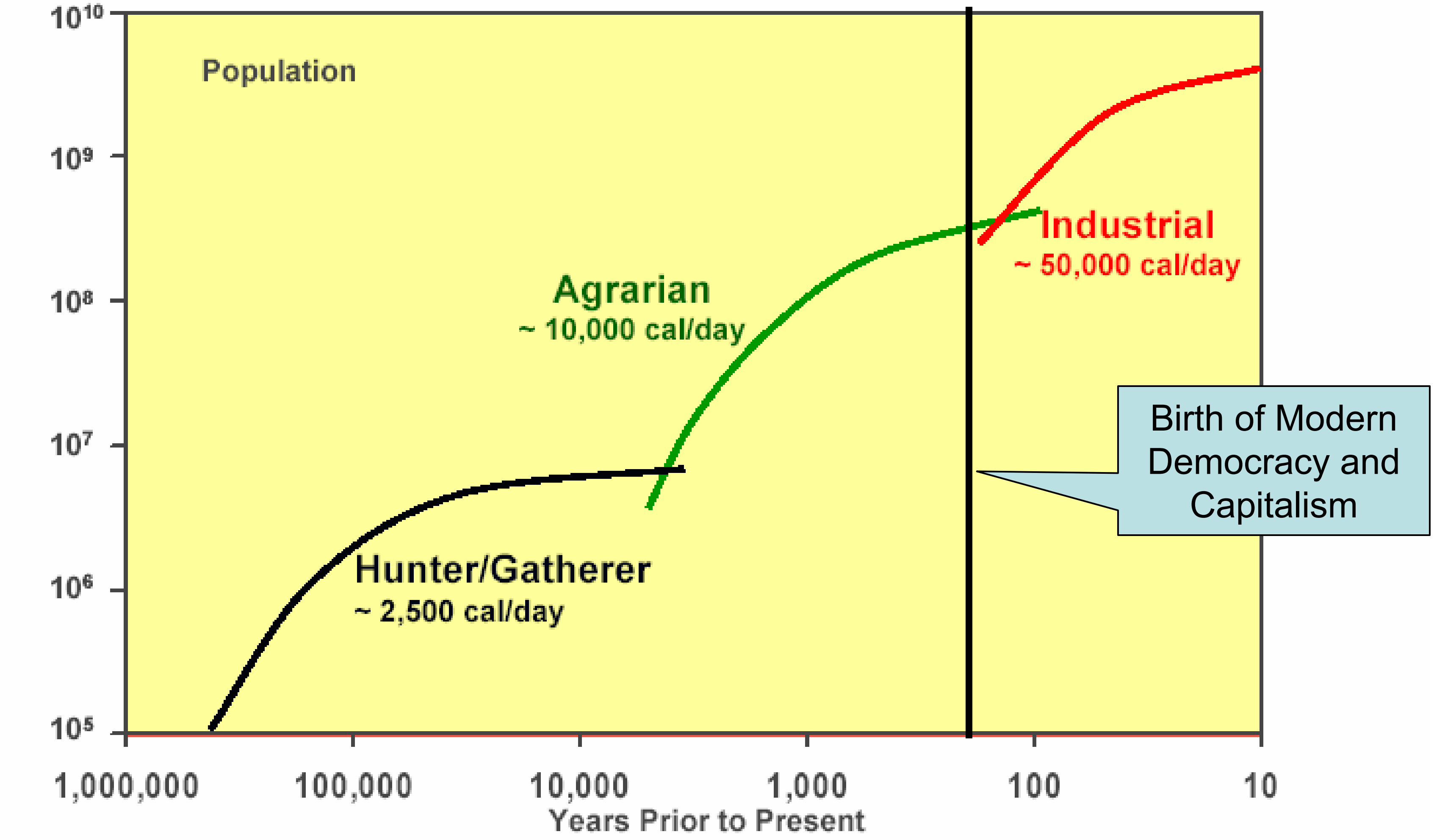
- Jesse Ausubel, PHE-RU
- Kurt Yeager, EPRI
- Arnulf Grubler, Yale
- Jim Daley, DOE
- Shirabe Akita, CRIEPI
- Zheng-He Han, Tsinghua U.
- Chauncey Starr, EPRI

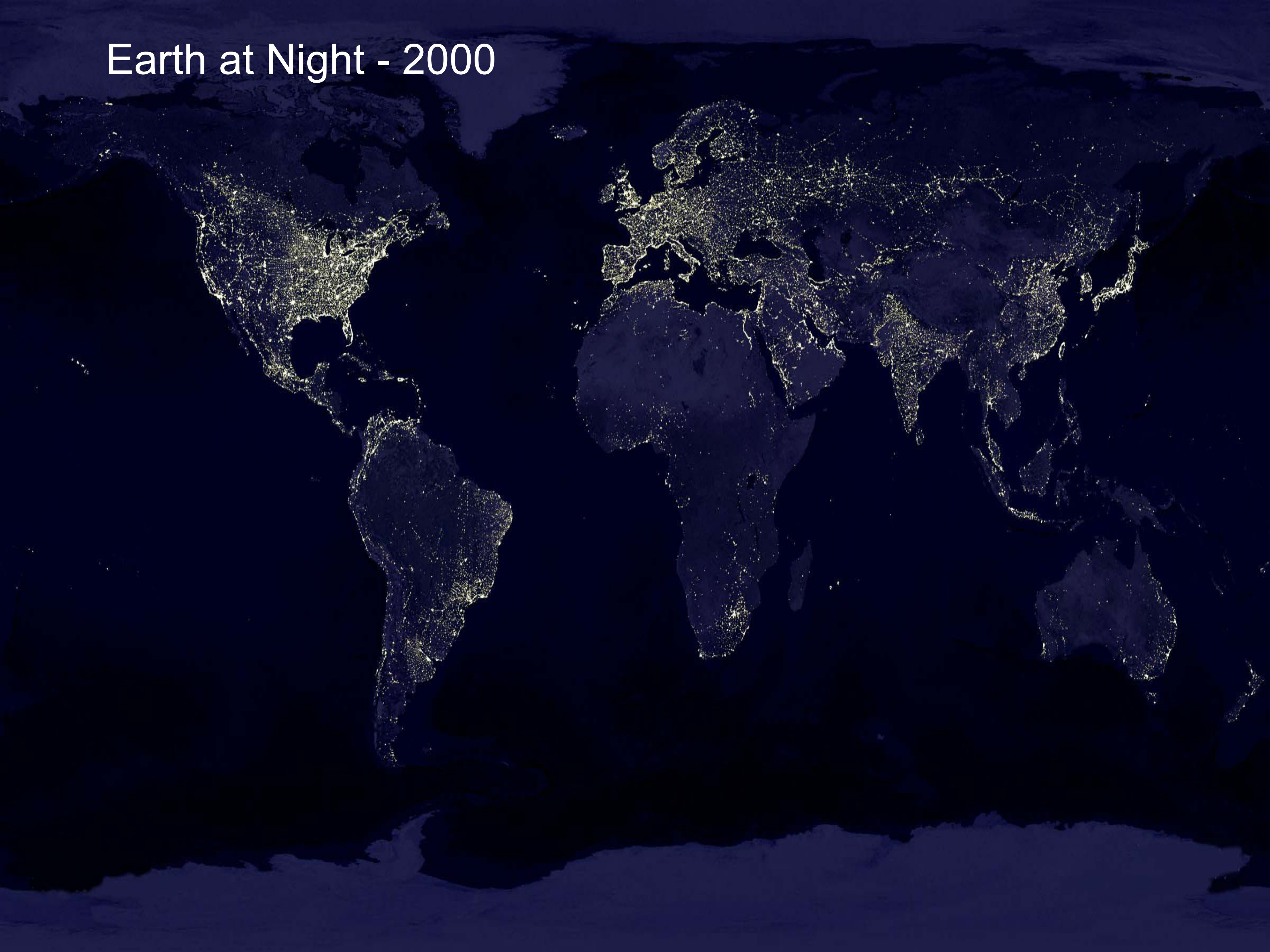
Chauncey Starr

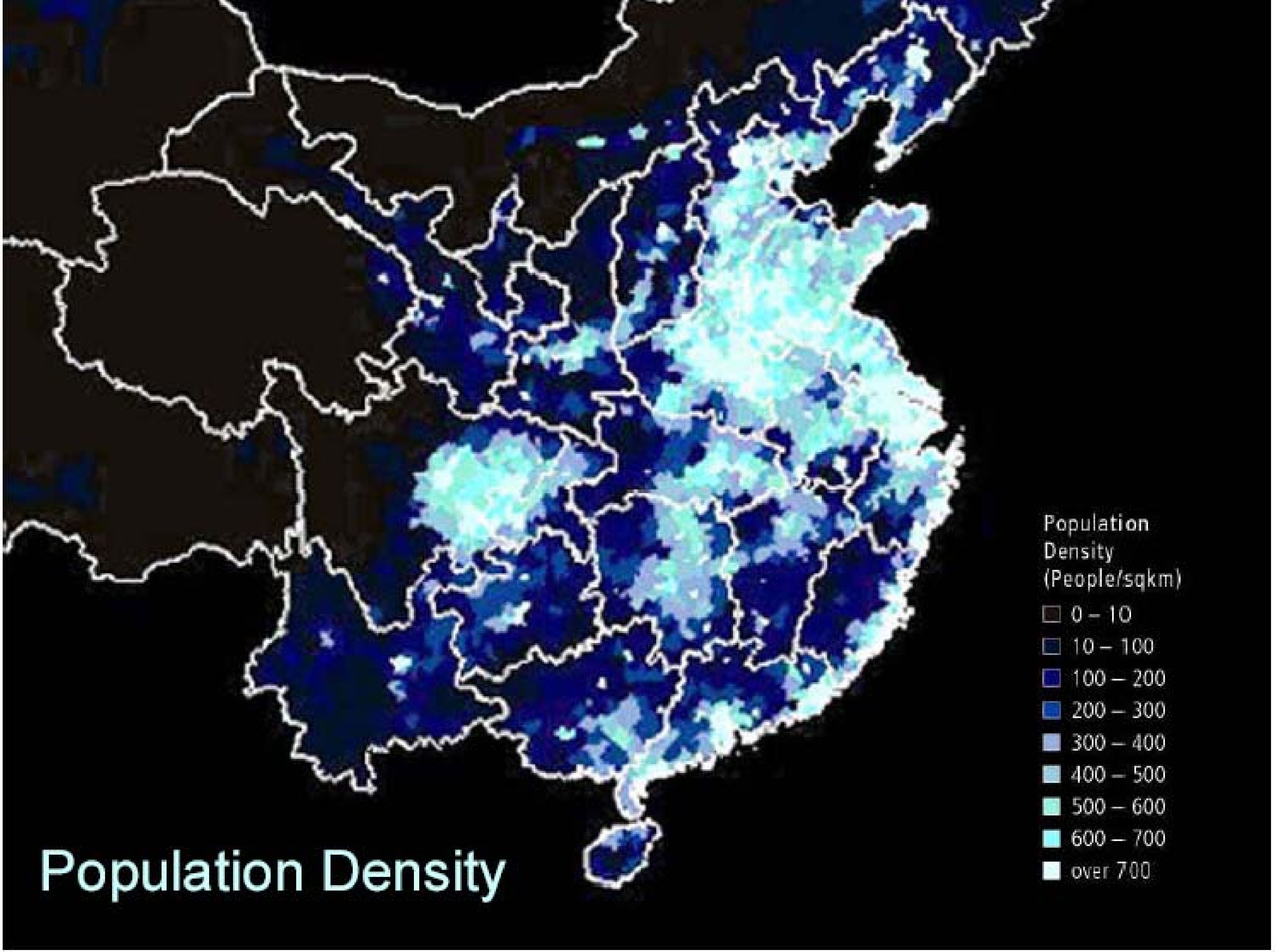
"If scientists and engineers think they can build something, they will invariably do it…

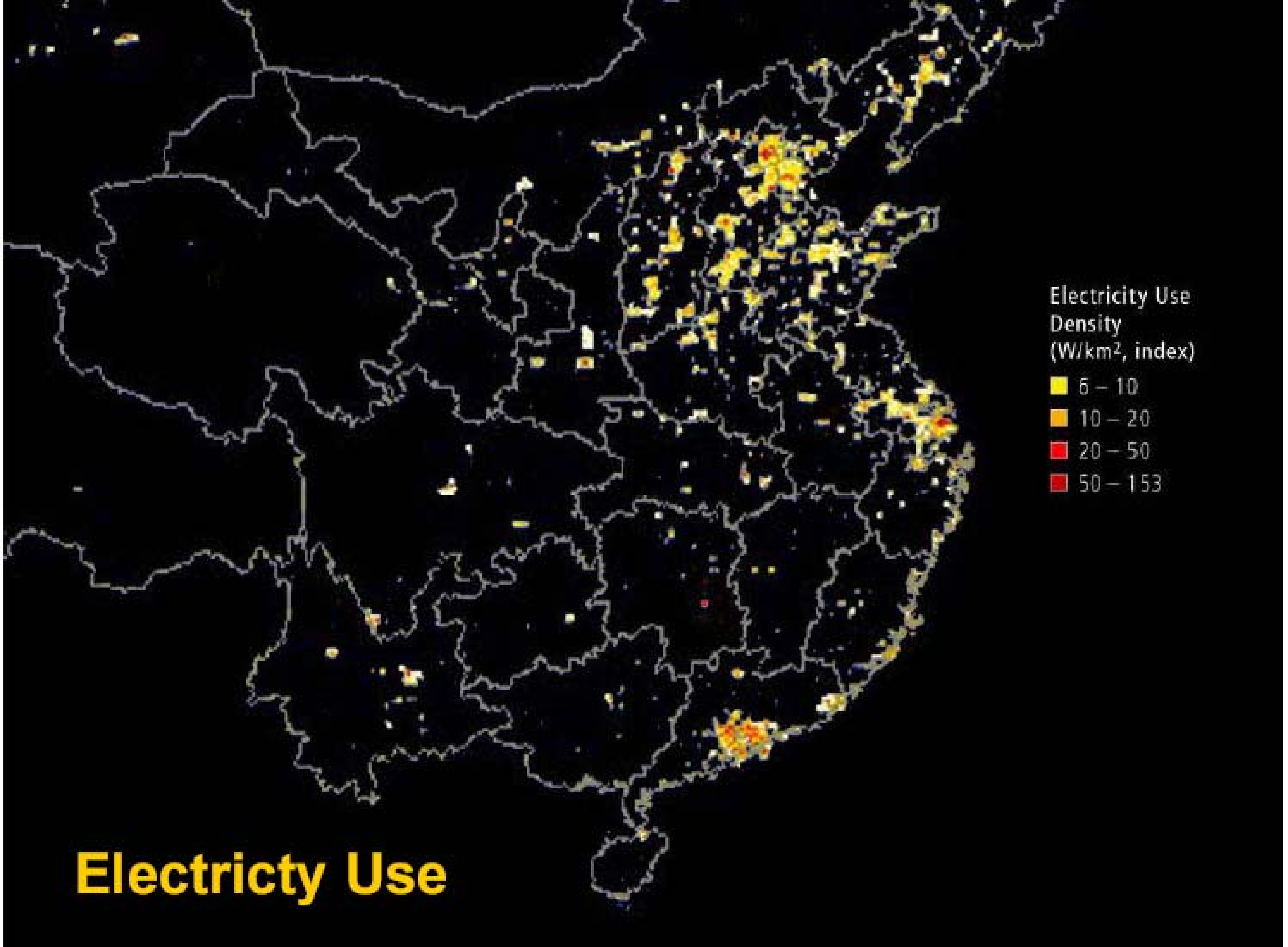
without much thought to the consequences!"

Cycles of Demography and Per Capita Energy Intensity

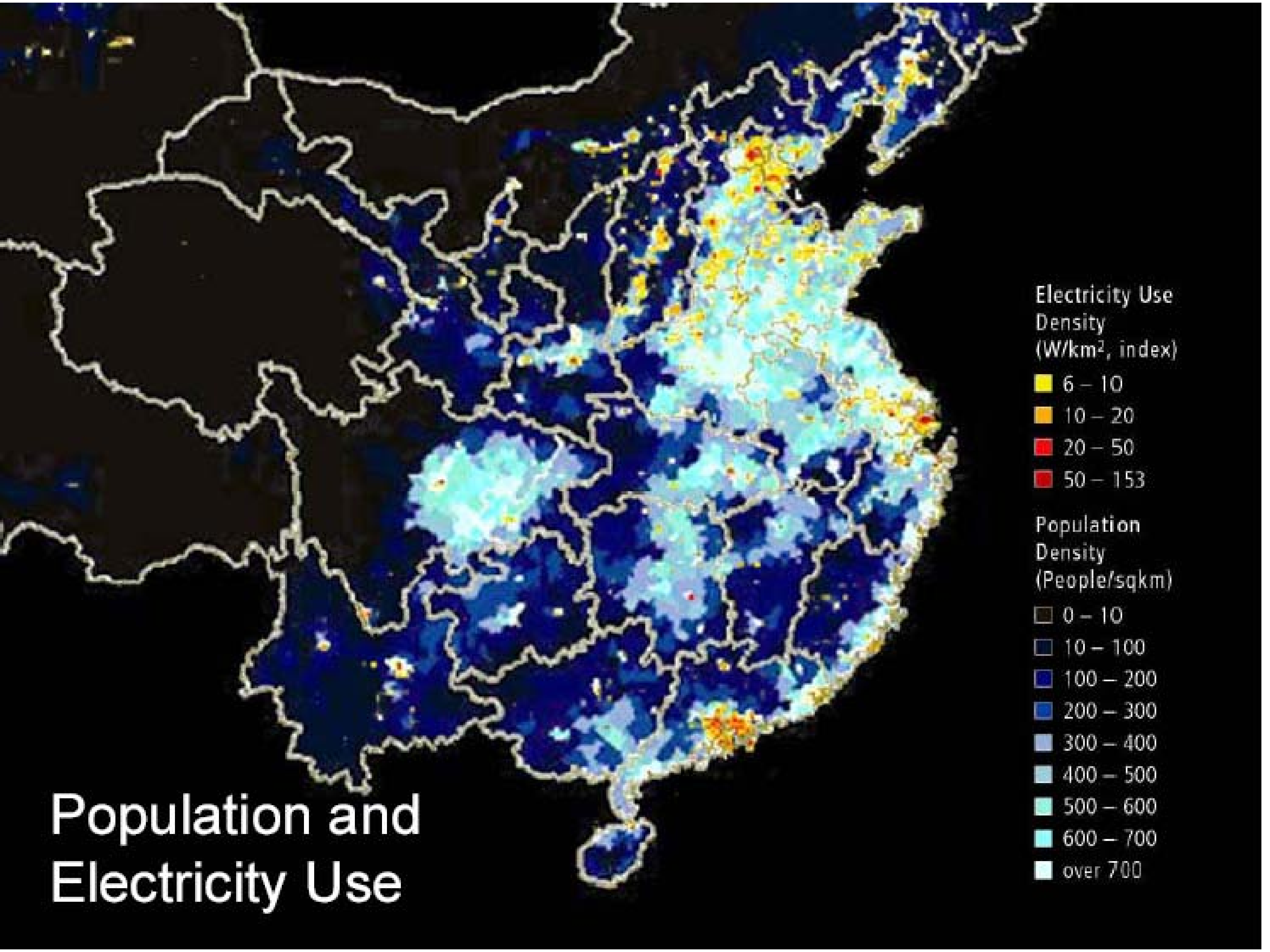



Earth at Night - 2000


Population Density (People/sqkm)
0 – 10
10 – 100
100 – 200
200 – 300
300 – 400
400 – 500
500 – 600
600 – 700
over 700
Population Density



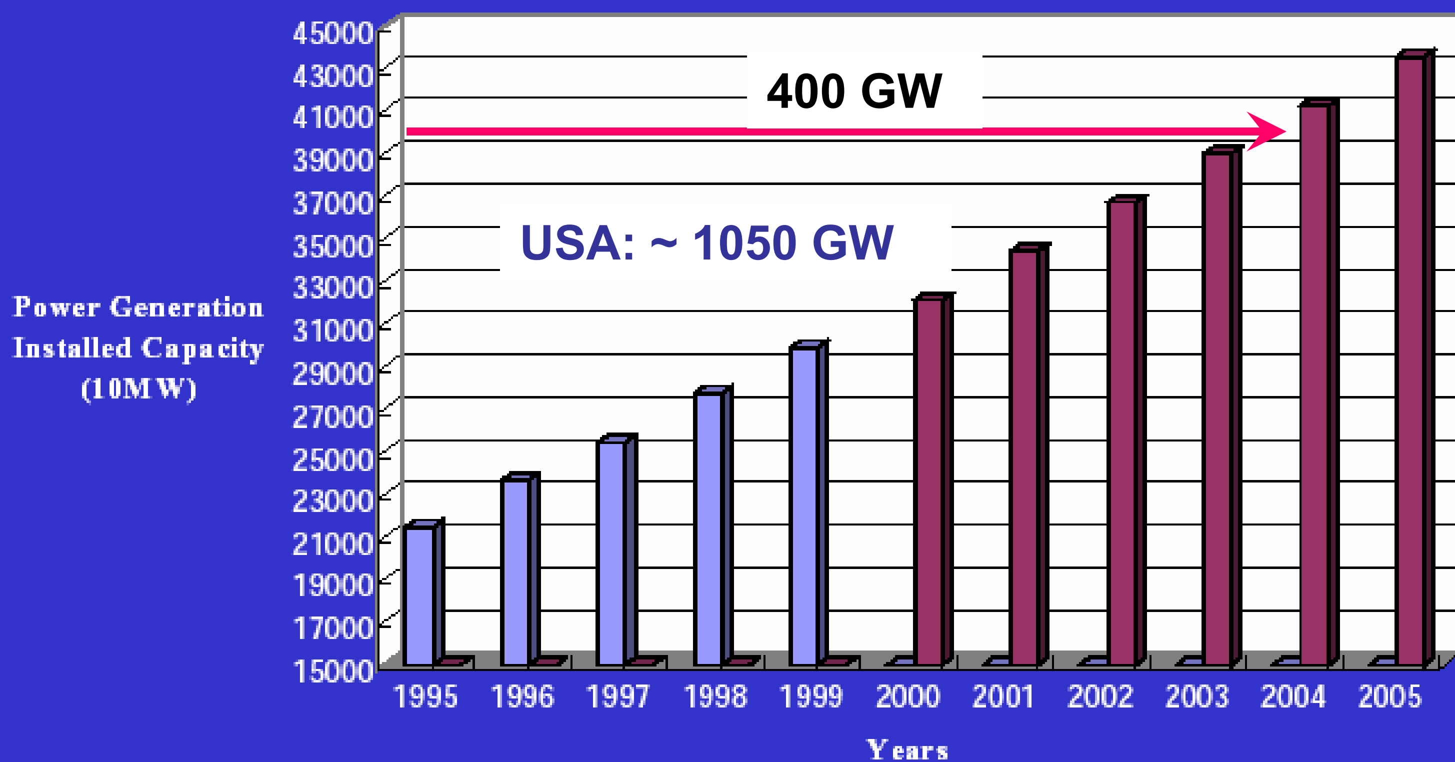
Electricty Use


Population and
Electricity Use
Electricity Use
Density
(W/km², index)
6 – 10
10 – 20
20 – 50
50 – 153
Population
Density
(People/sqkm)
0 – 10
10 – 100
100 – 200
200 – 300
300 – 400
400 – 500
500 – 600
600 – 700
over 700

China – Installed Generation Capacity

7%/year increasing (now > 380 GW)

根据预测，2010年将达到6.5亿千瓦左右，2020年达到9.5亿千瓦左右。



电荒，2004年中国仲夏夜之恶梦

Electrical power shortage (30GW), the midsummer nightmare of 2004 .

2月全国发电量1581.77亿千瓦时（日均发电量54.54亿千瓦时），比上年同期增长31.36%。

全国发电装机容量已达３．８５亿千瓦，在建电力项目１．３亿千瓦。

Capacity 385GW,

Shortage 30GW,

线损率 line losses 7% (Three Gorges Project: 18 GW)

130GW under construction

It is said that 2006 could be better

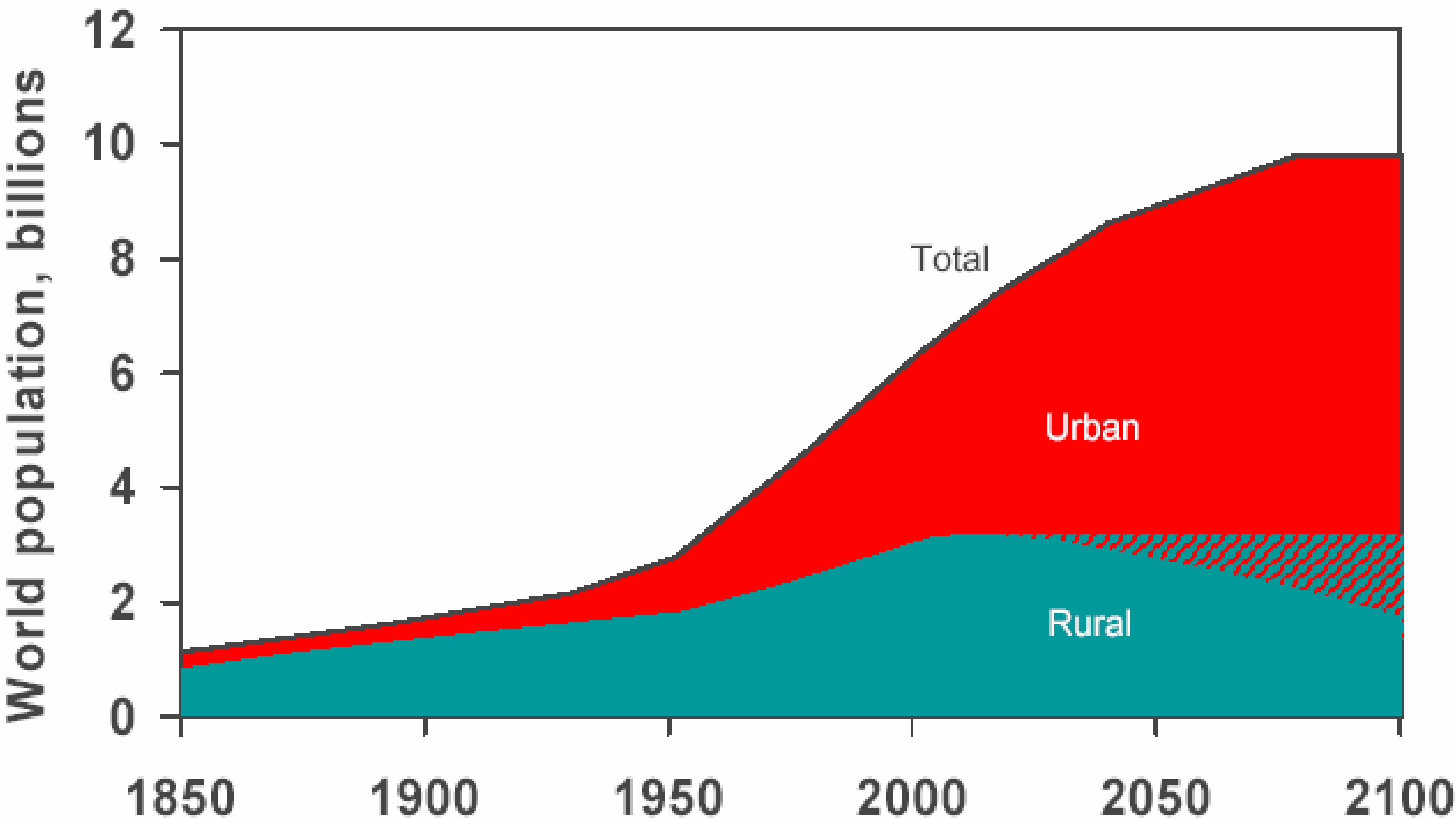
Could be worse

China "Factoid"

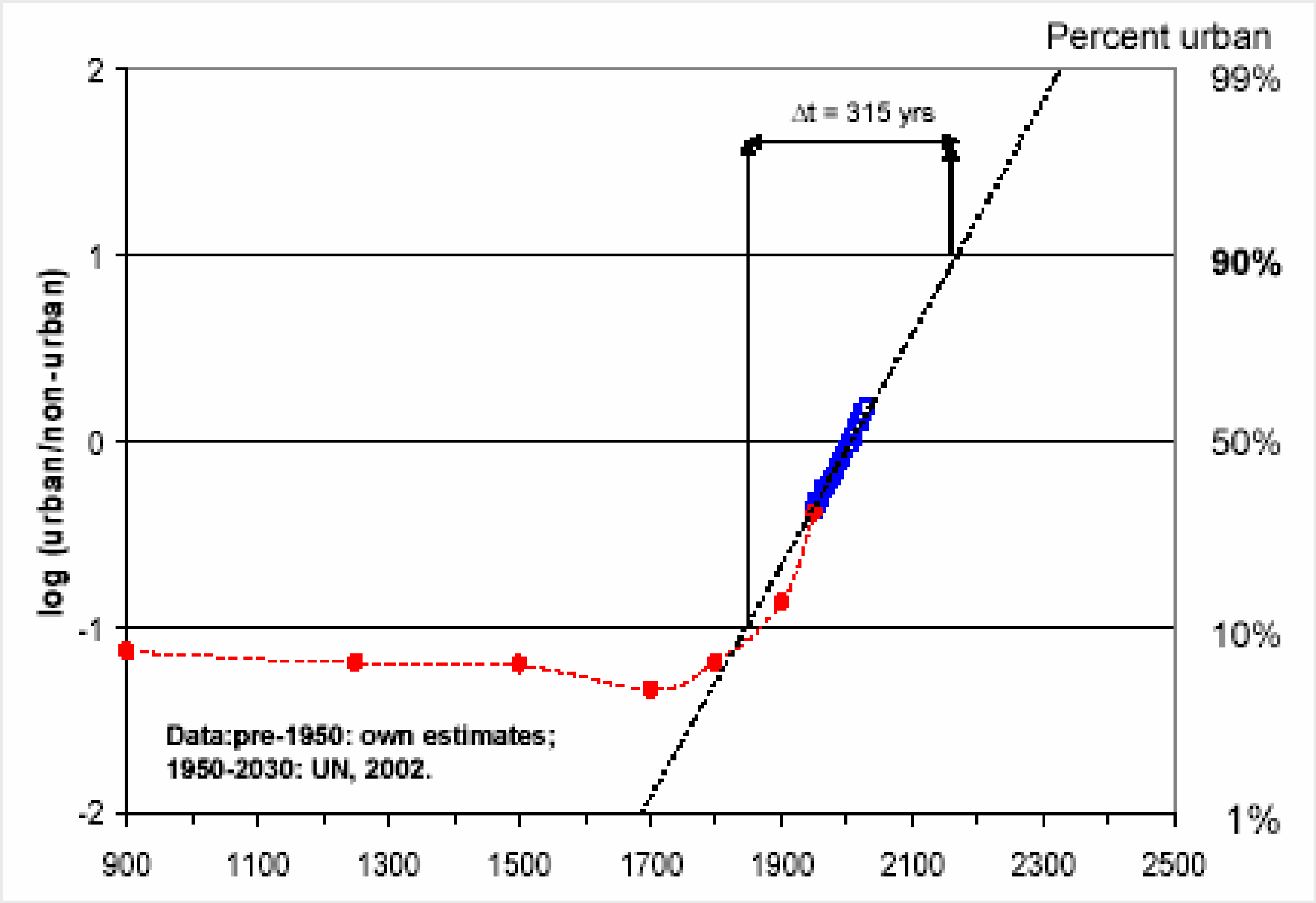
- Current Population: 1.3 Billion Souls
- All want to live like Americans
- Chinese Family Priorities:
  - (1) TV, (2) Washer, (3) Fridge…
  - Next an Air Conditioner (200 USD, 1 kW)
- Assume an average family size of three, then…

An extra 500 GW of generation capacity must be added just to keep them cool!

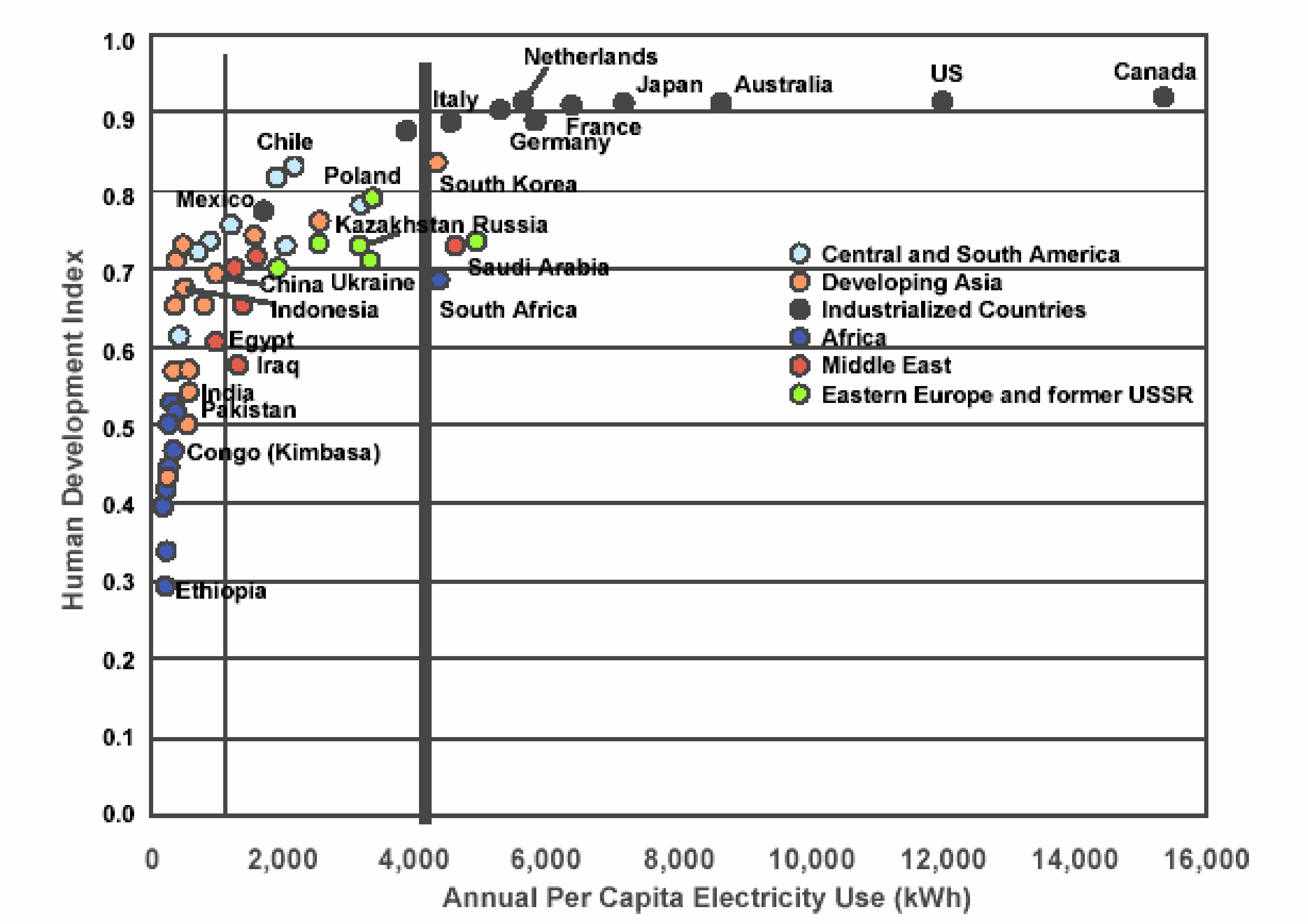
World Population: 1850 – 2100 Urban/Rural



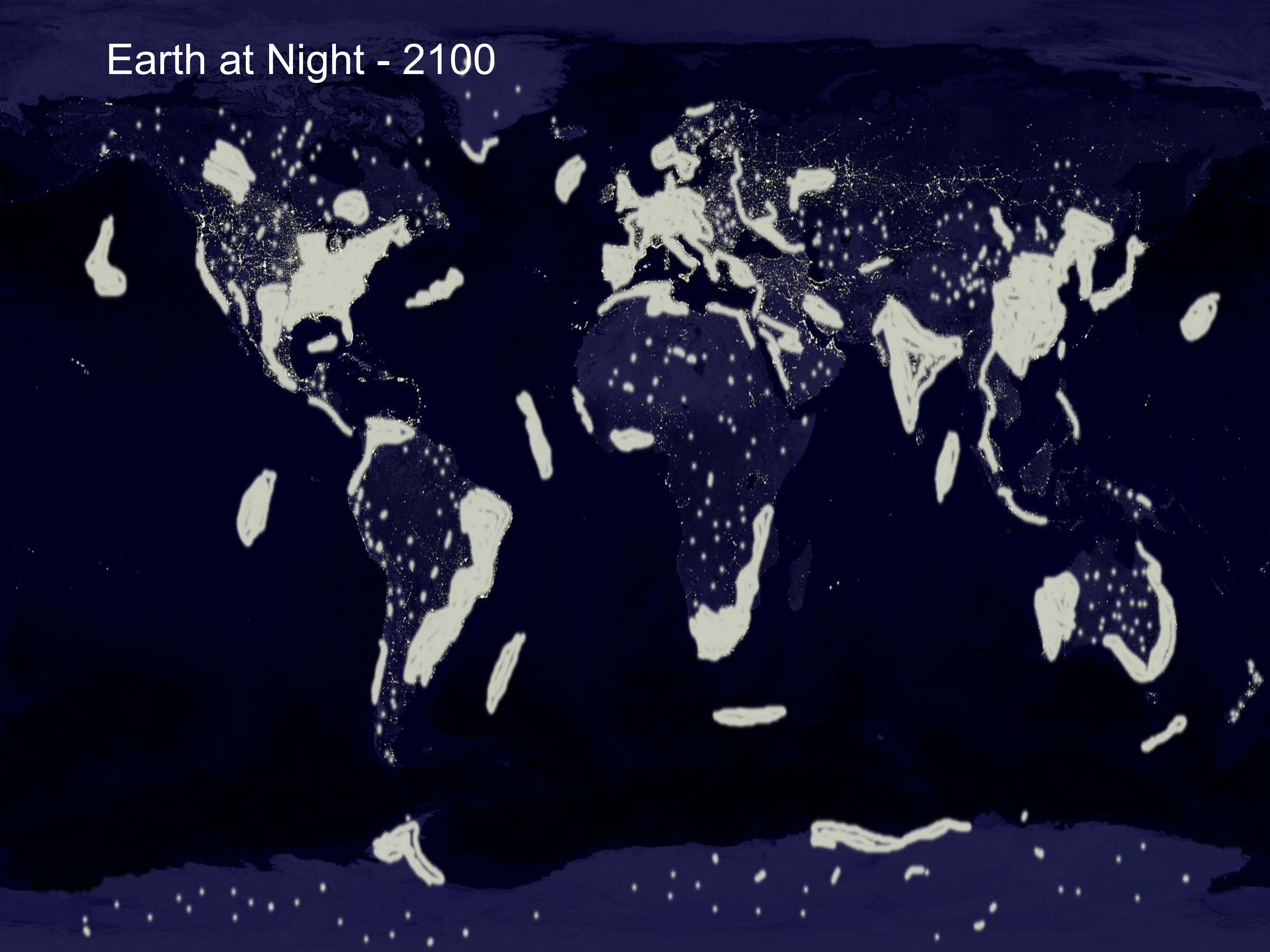
Future Urban Population Growth



HDI vs Electricity Consumption



Earth at Night - 2100



US Energy Consumption (2001)

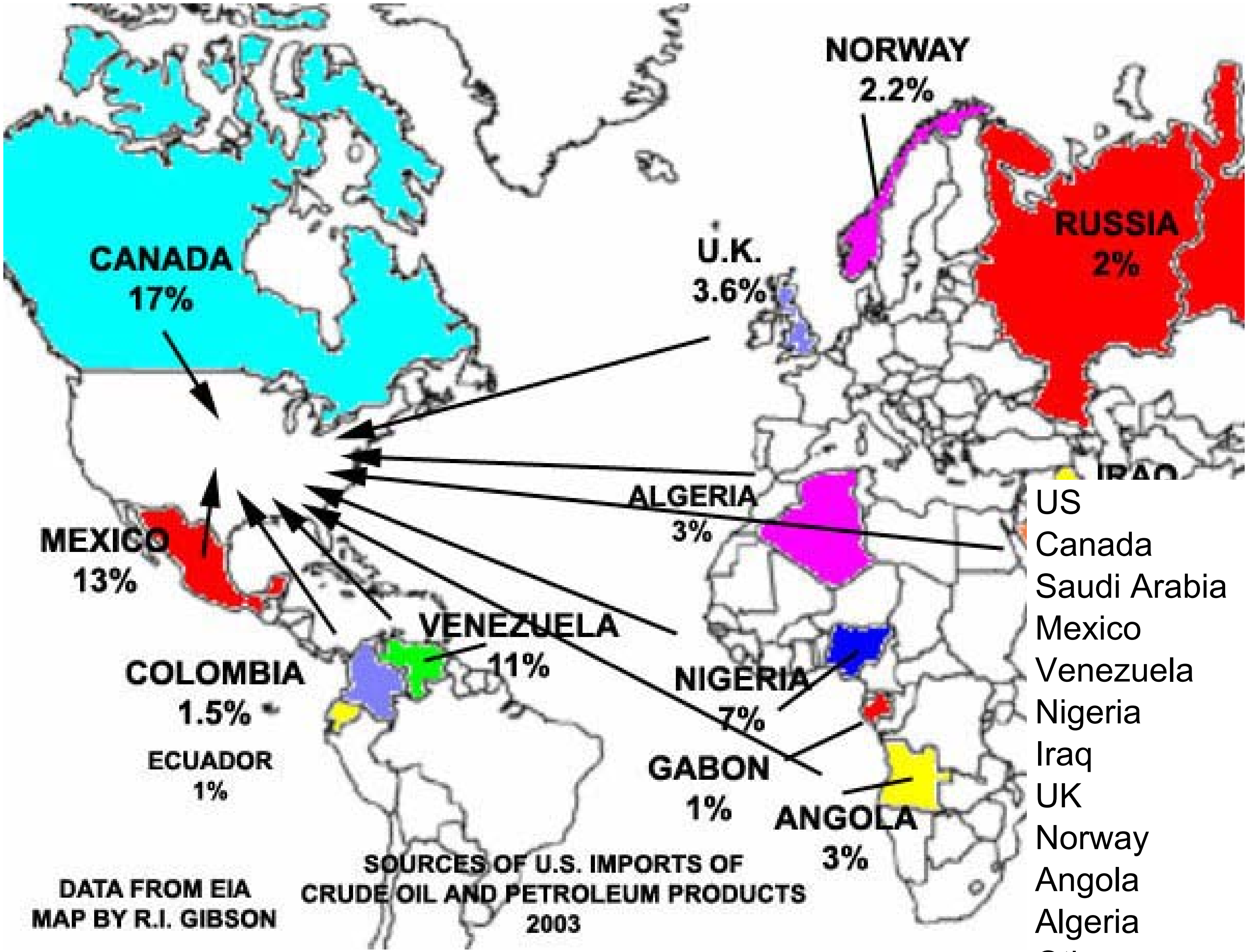
Energy Source	**Percentage of total**
Petroleum	42%
Coal	24%
Natural Gas	20%
Nuclear	8%
Hydro power	2%
Solar, Wind, etc.	2%

China-USA Electricity Statistics (2001)

Source (CIA & EIA)

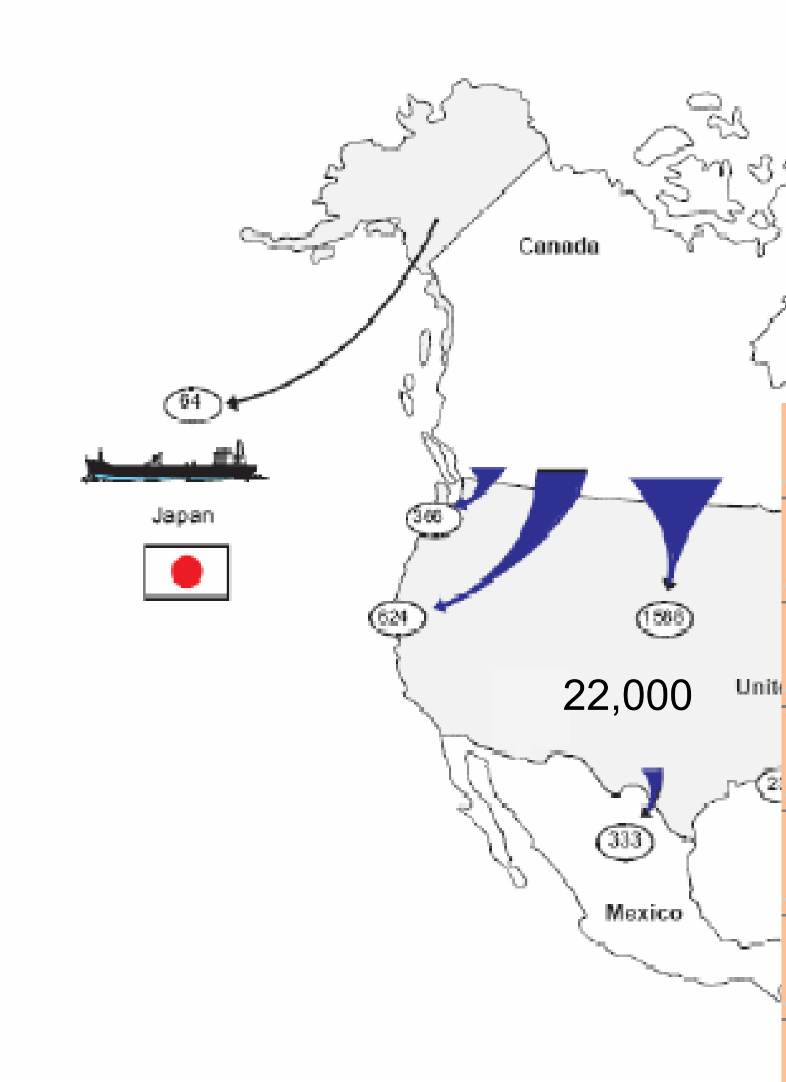
Production Source (%)	China	USA (NA)
Fossil	80.2	71.4 (15% NG)
Hydro	18.5	5.6
Other	0.1	2.3
Nuclear	1.2	20.0
Annual Producton (TkWh)	1.42	3.72

US Oil Imports (2003)



US	39%
Canada	13%
Saudi Arabia	10%
Mexico	10%
Venezuela	9%
Nigeria	4%
Iraq	4%
UK	3%
Norway	3%
Angola	2%
Algeria	2%
Other	2%

US Natural Gas Imports (BCF, 2003)



Country	Reserve estimate
World	4,980 trillion cubic feet
1. Russia	1,748 trillion cubic feet
2. USA	1,475 trillion cubic feet
3. Iran	742 trillion cubic feet
4. Qatar	245 trillion cubic feet
5. Abu Dhabi	188 trillion cubic feet

China-USA Recoverable Coal Reserves (2002)

	Million Short Tons	Years Left*
China	126,215	273
USA (NA)	280,464	309

- One Short Ton = 6150 kWh

  Efficiency Conversion – 40%




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!

“Boundary Conditions”

- Sustainable and efficient use of energy resources
- Carbon-free
- Non eco-invasive
- Uses available technology

What Does “Non-Eco-Invasive” Mean?

- Least use of land area, ruling out
  - Wind farms
  - Solar (except for roofs)
  - Biomass cultivation
- Least by-product disposal volume, ruling out
  - CO_2 sequestration
  - Once-through fuel cycles
- Minimal visual pollution, ruling out
  - Wind farms, either onshore or offshore
  - Overhead transmission lines
- Underground as much as possible
  - Nuclear plants
  - The SuperCable

The Solution

r

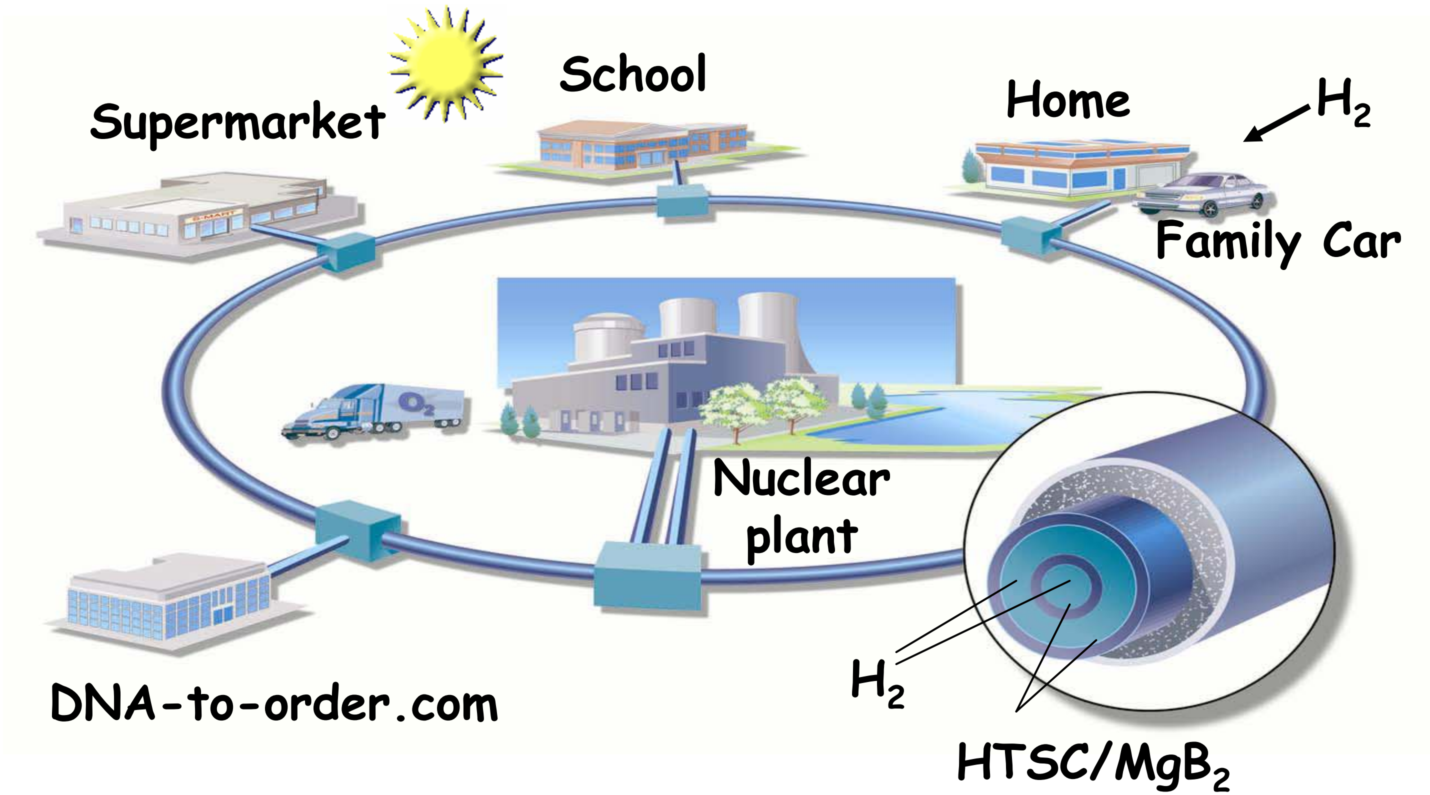
Teratechnology for an Exajoule World

A Symbiosis of

Nuclear/Hydrogen/Superconductivity

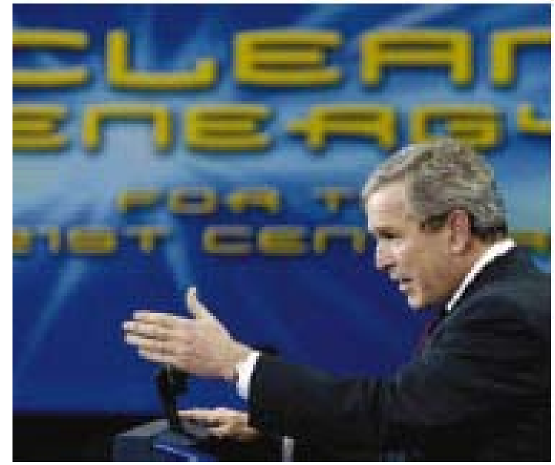
to Supply Carbon-free, Non-Intrusive Green Energy for all Inhabitants of Planet Earth

SuperCity



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

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)

Hydrogen for US Surface Transportation

The "25% 80-80-80 400 GW" Scenario

http://www.w2agz.com

Hydrogen per Day	
Tonnes	Shuttles
230,000	2,225

Water per	
Tonnes	Mete
2,055,383	

Heavy Water ?

Hydrogen for US Surface Transportation

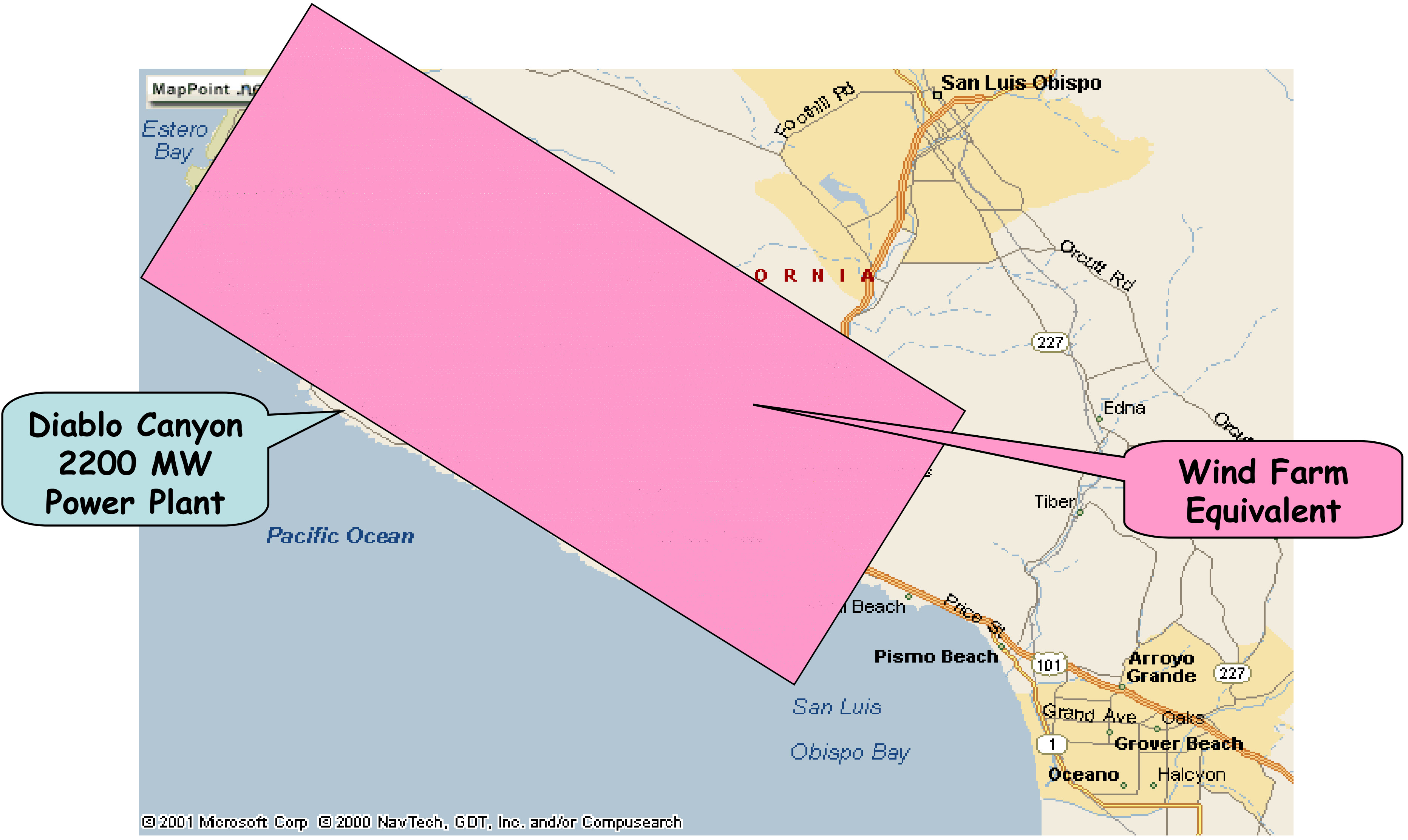
The "25% 80-80-80 400 GW" Scenario
http://www.w2agz.com

Renewable Land Area Requirements		
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

Diablo Canyon

Diablo Canyon

California Coast Power



Kashiwazaki Kariwa: 8000 MW

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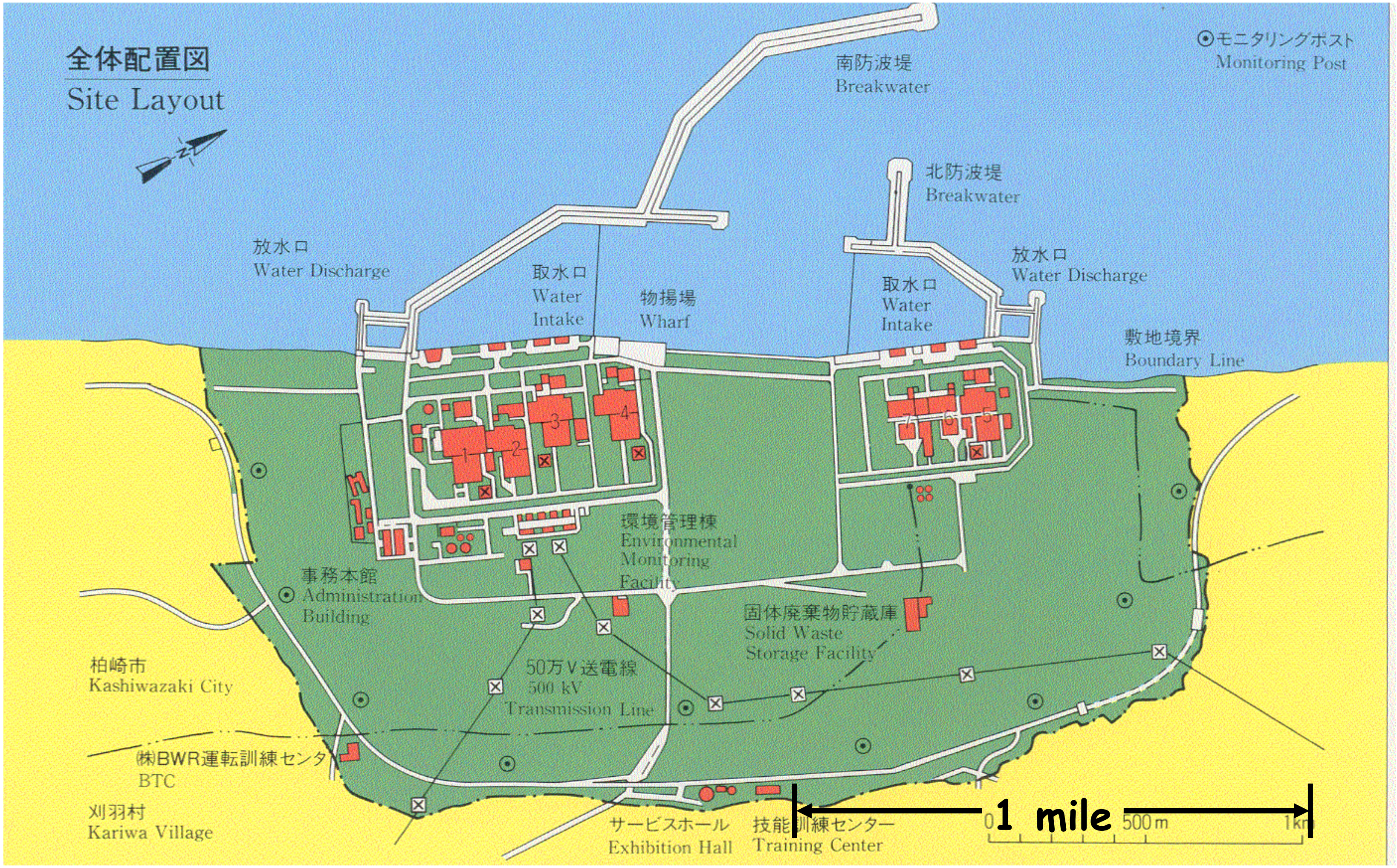
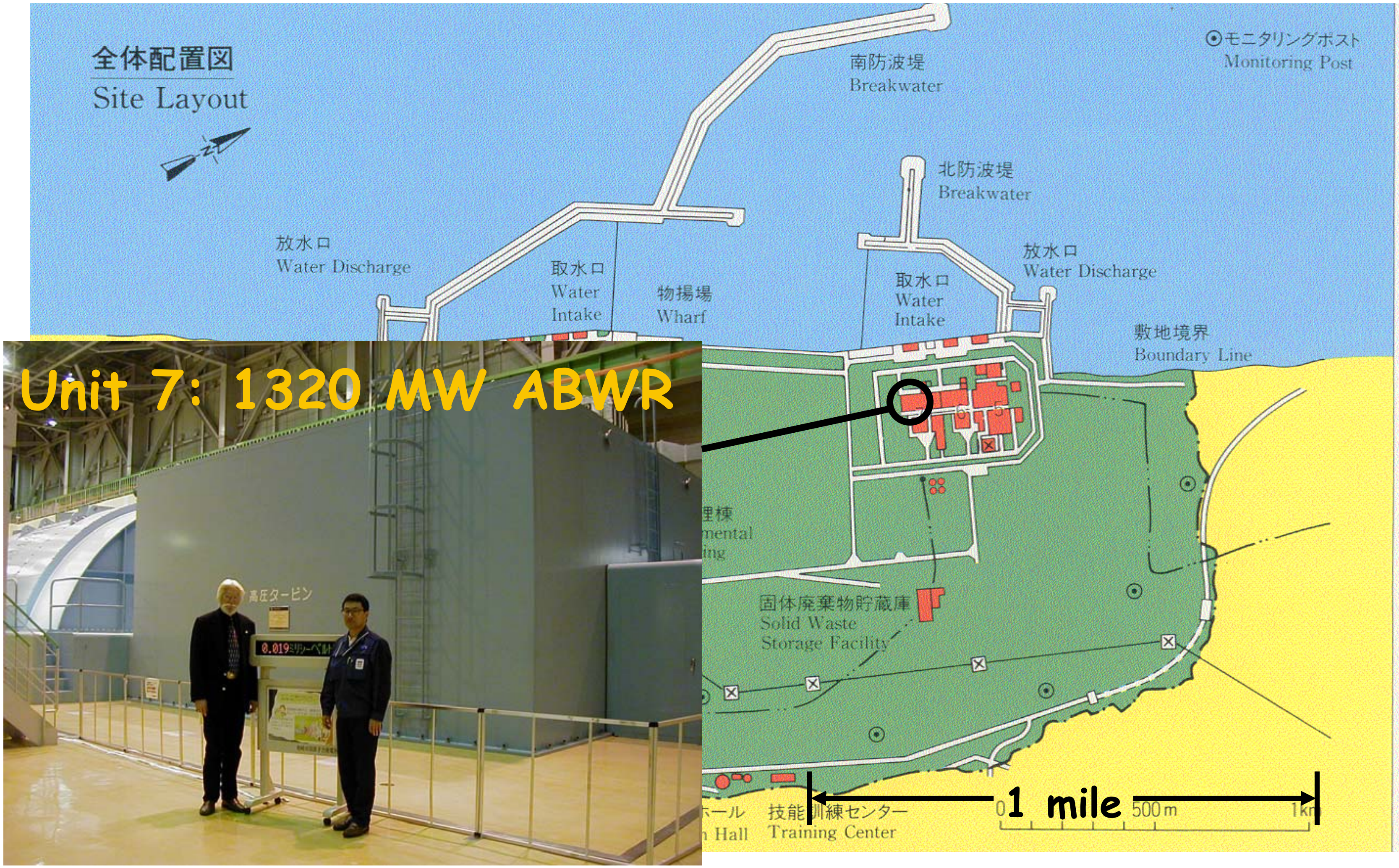
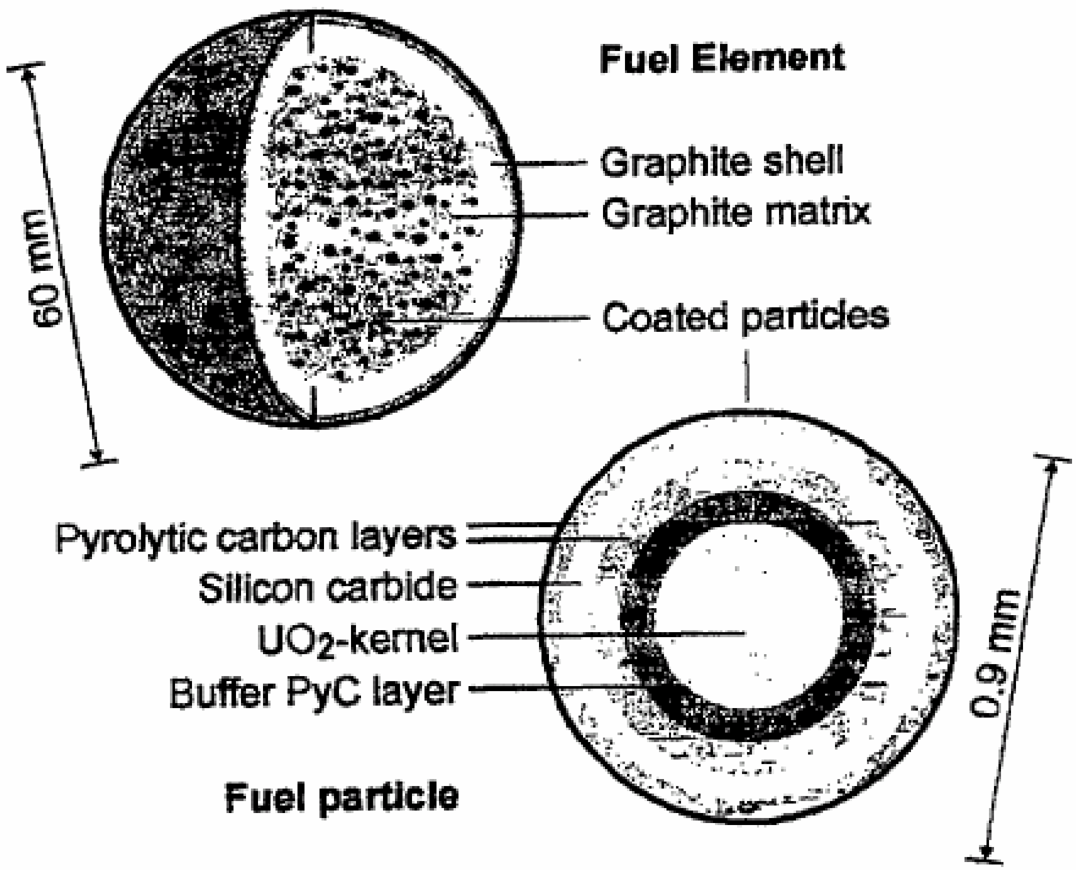


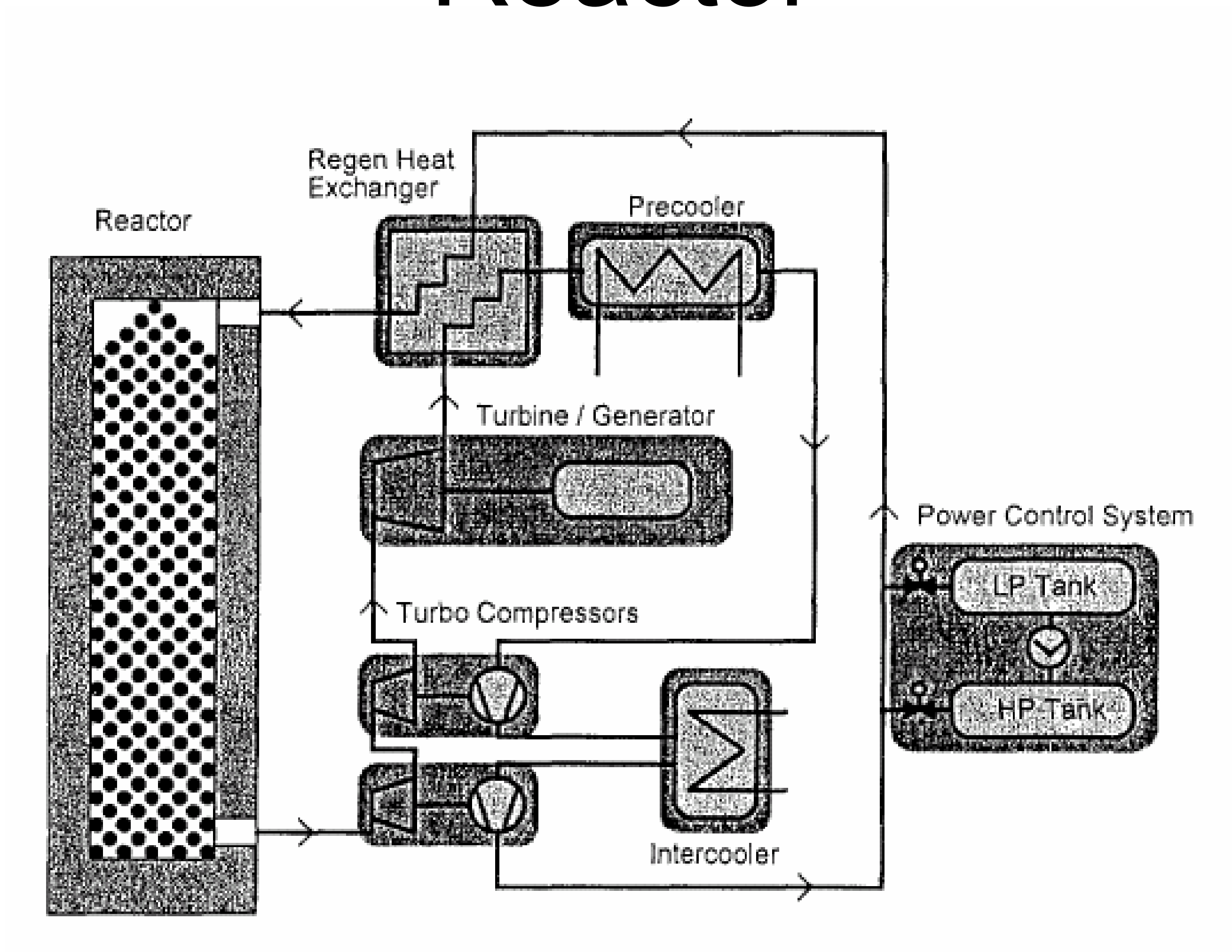
Kashiwazaki Kariwa: 8000 MW



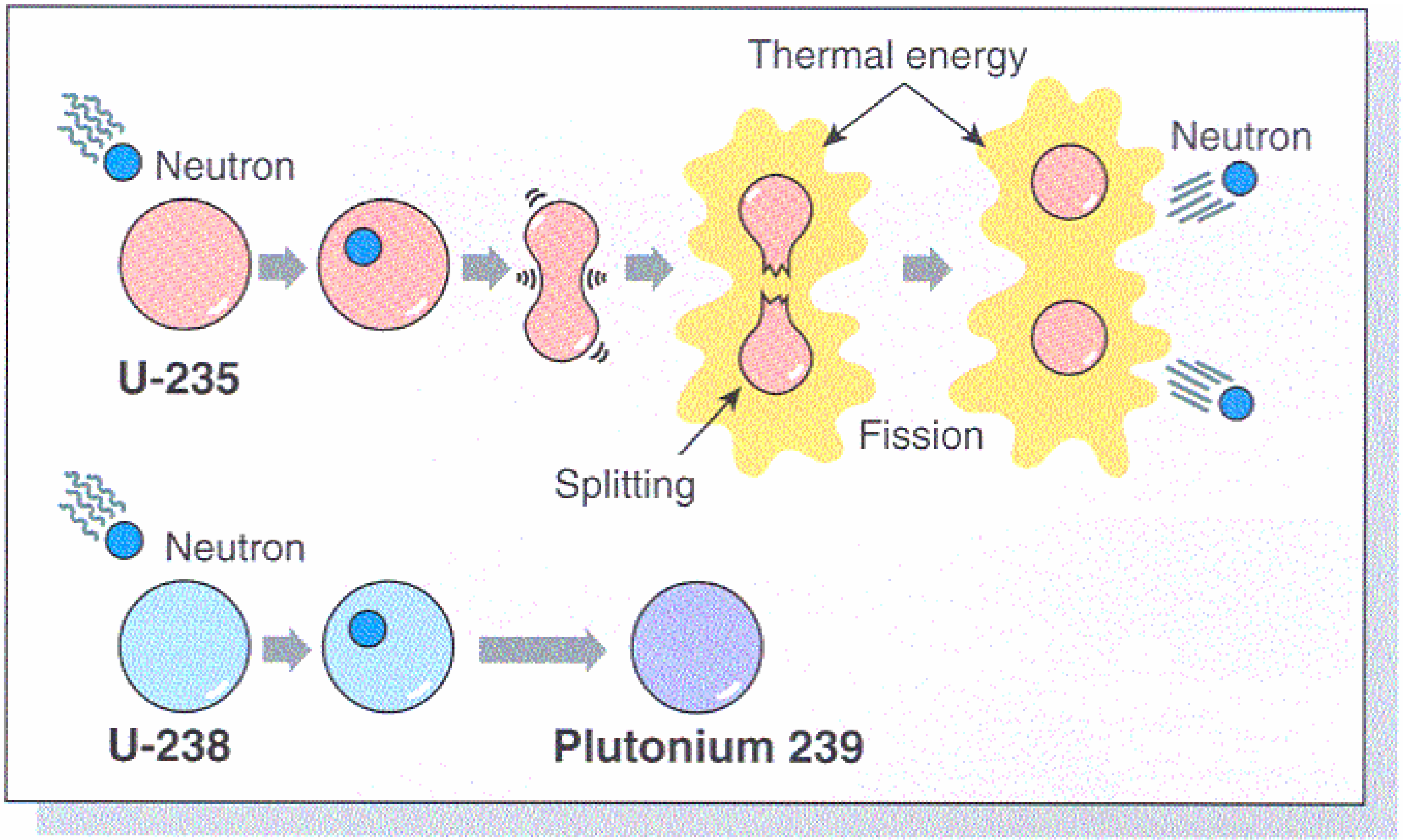
Particle/Pebble Nuclear Fuel



High Temperature Gas Cooled Reactor



Reprocessing “Spent” Fuel



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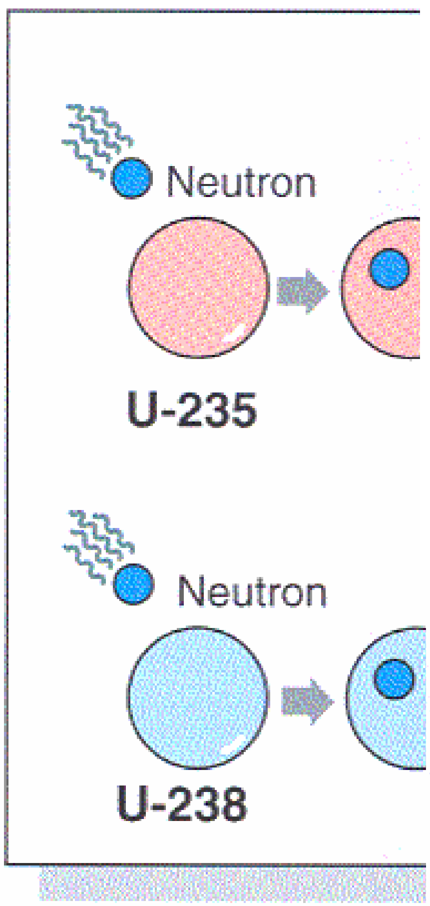
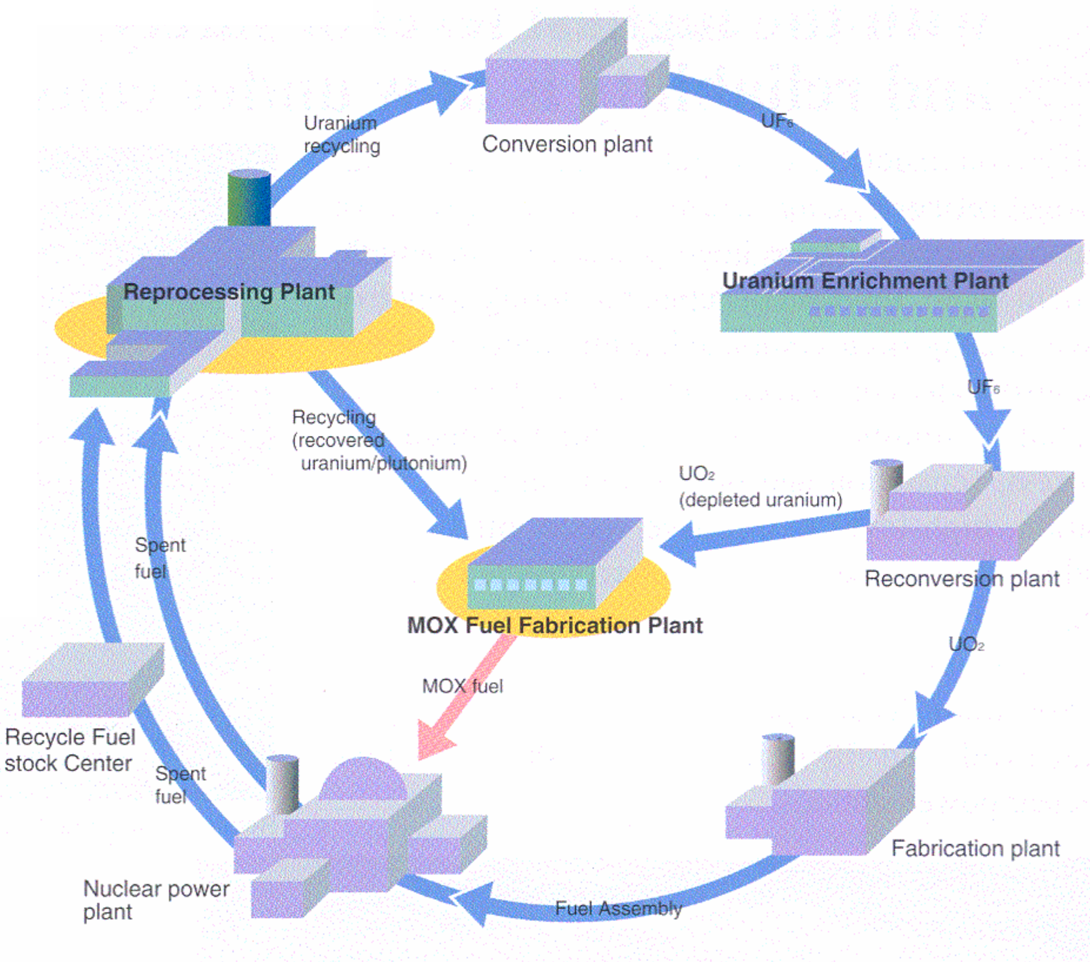
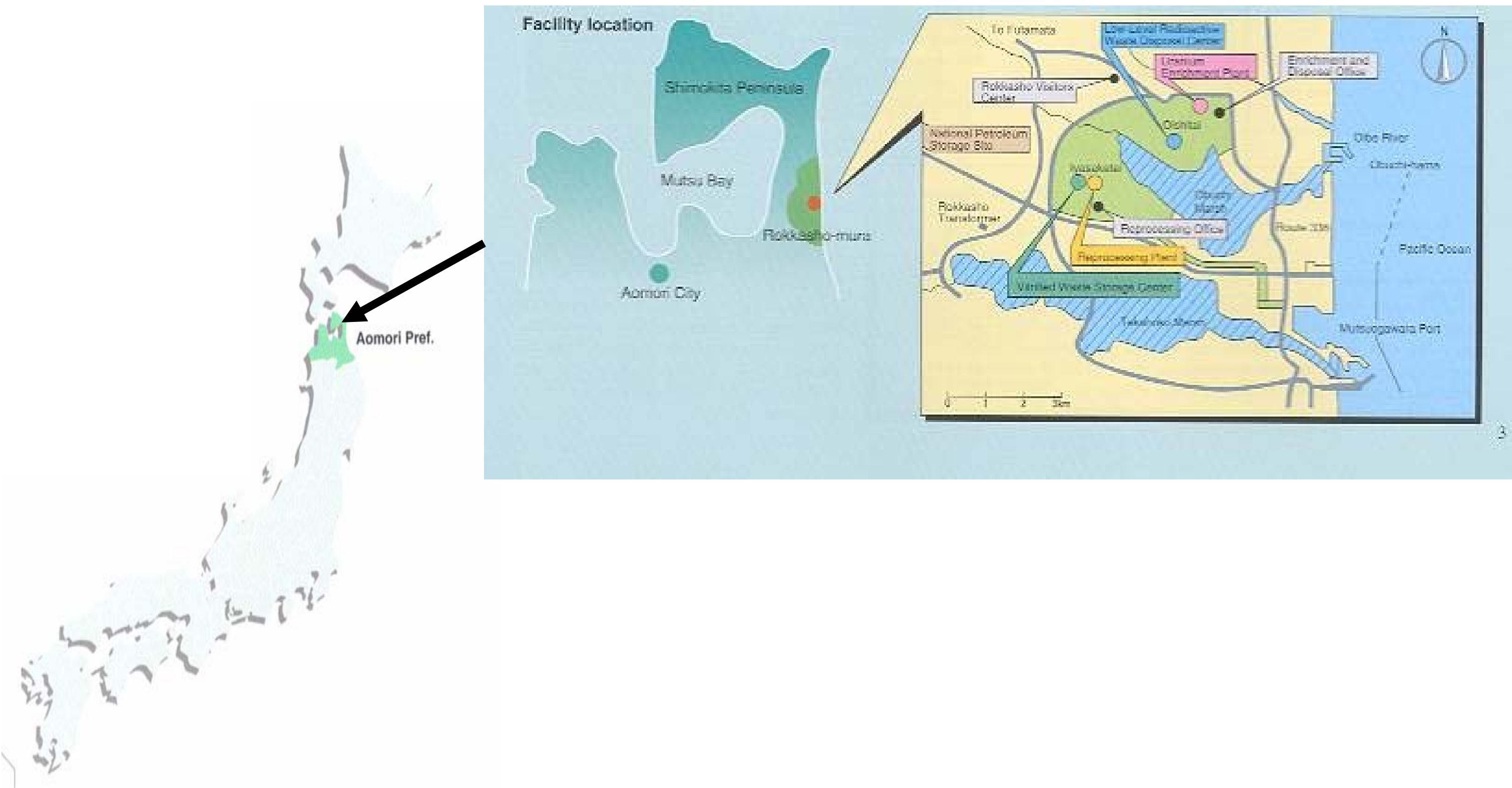




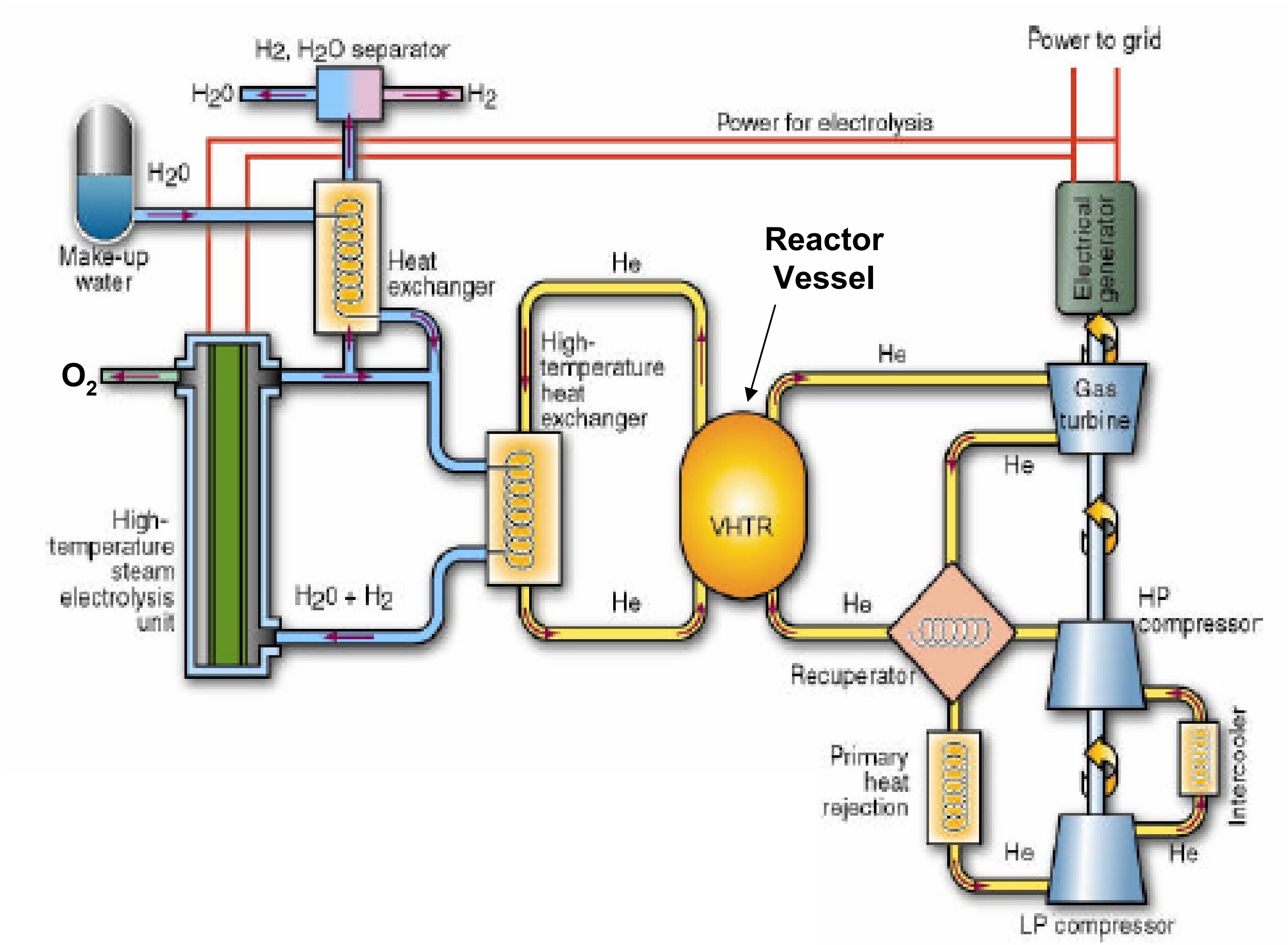
JNFL Rokkasho Reprocessing Plant



JNFL Rokkasho Reprocessing Plant

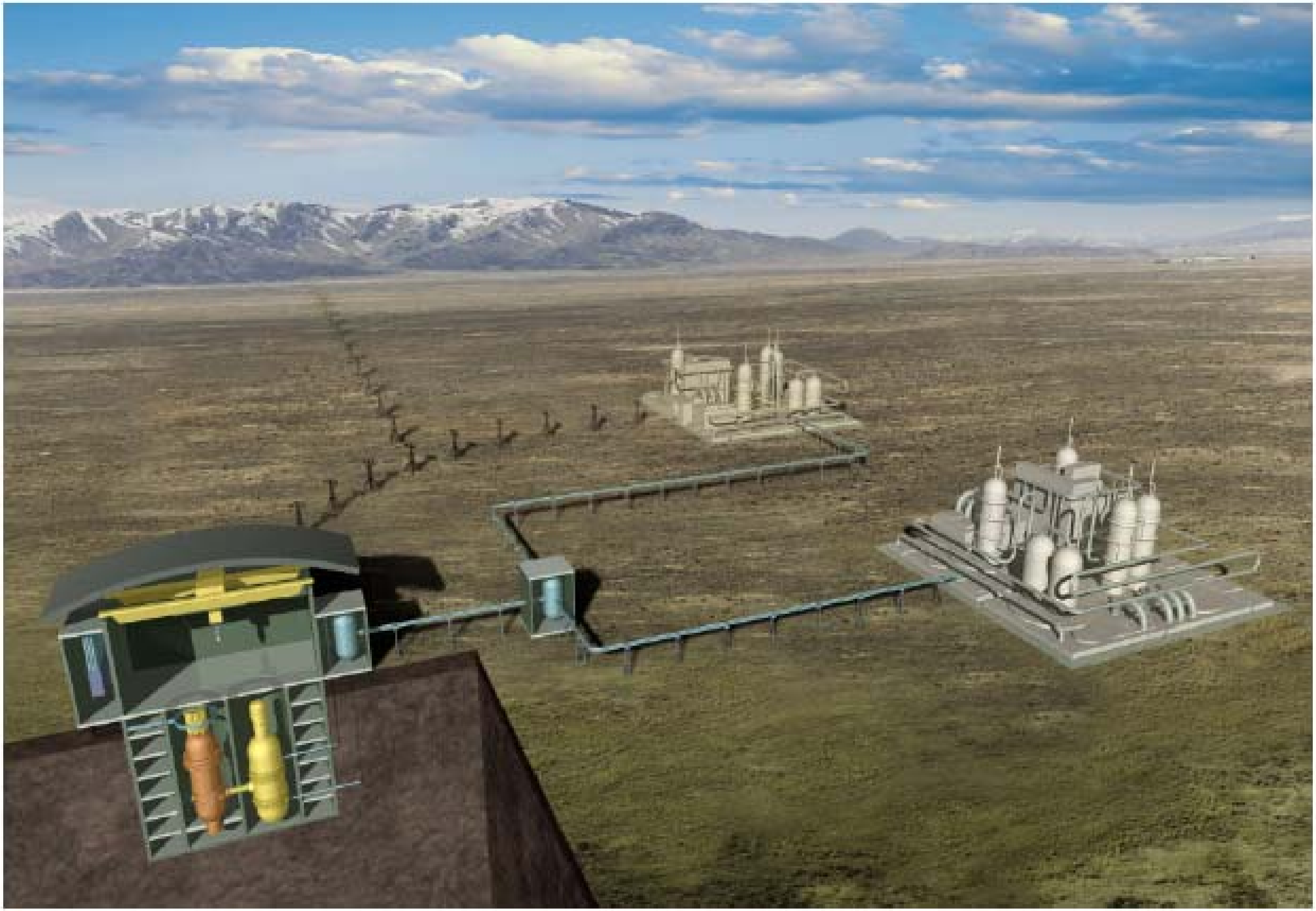
- $20 B, 5 Year Project
- 800 mt U/yr
- 1 mt U -> 50 kg HLW

Co-Production of Hydrogen and Electricity



Source: INEL & General Atomics

Nuclear “Hydricity” Production Farm



Source: General Atomics

1967: SC Cable Proposed!

538 PROCEEDINGS OF THE IEEE, VOL. 55, NO. 4, APRIL 1967

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

R. L. GARWIN AND J. MATISOO

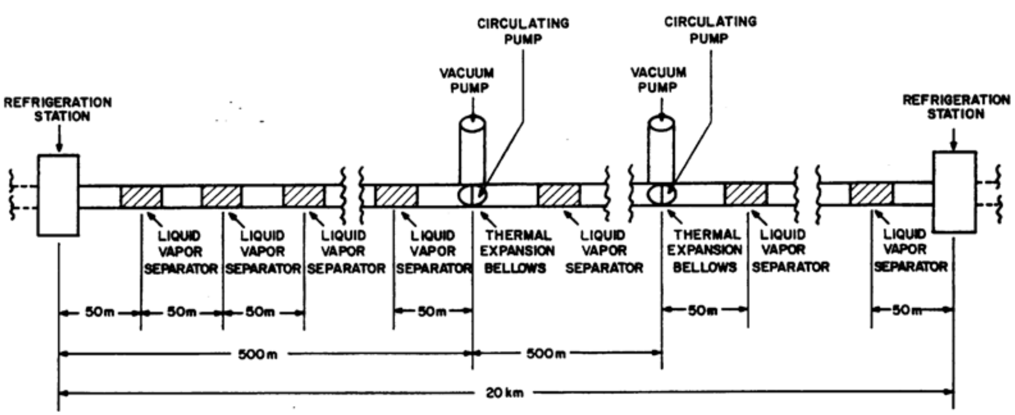


Fig. 2. A 20-km module of the 1000-km, 100-GW line.

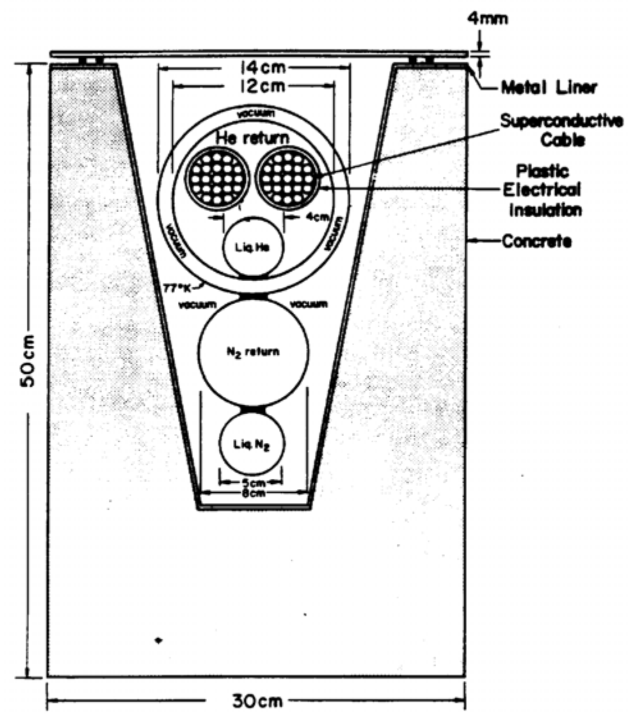
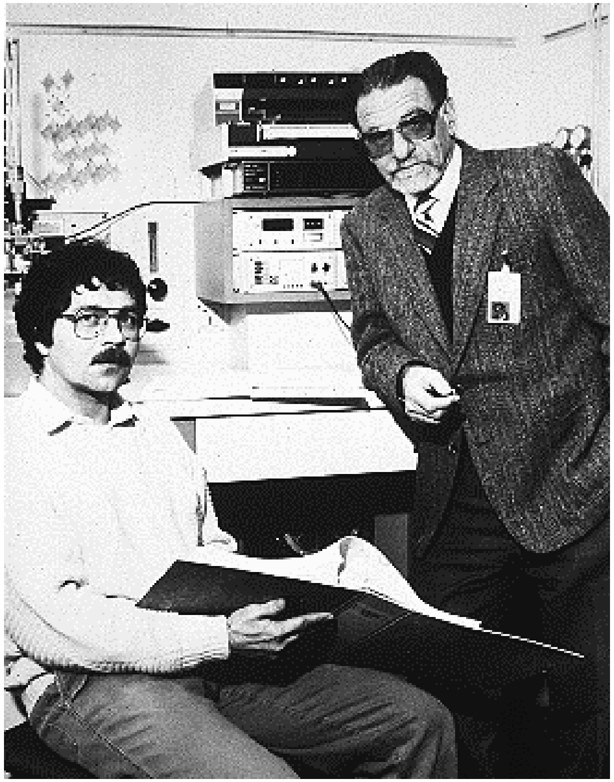


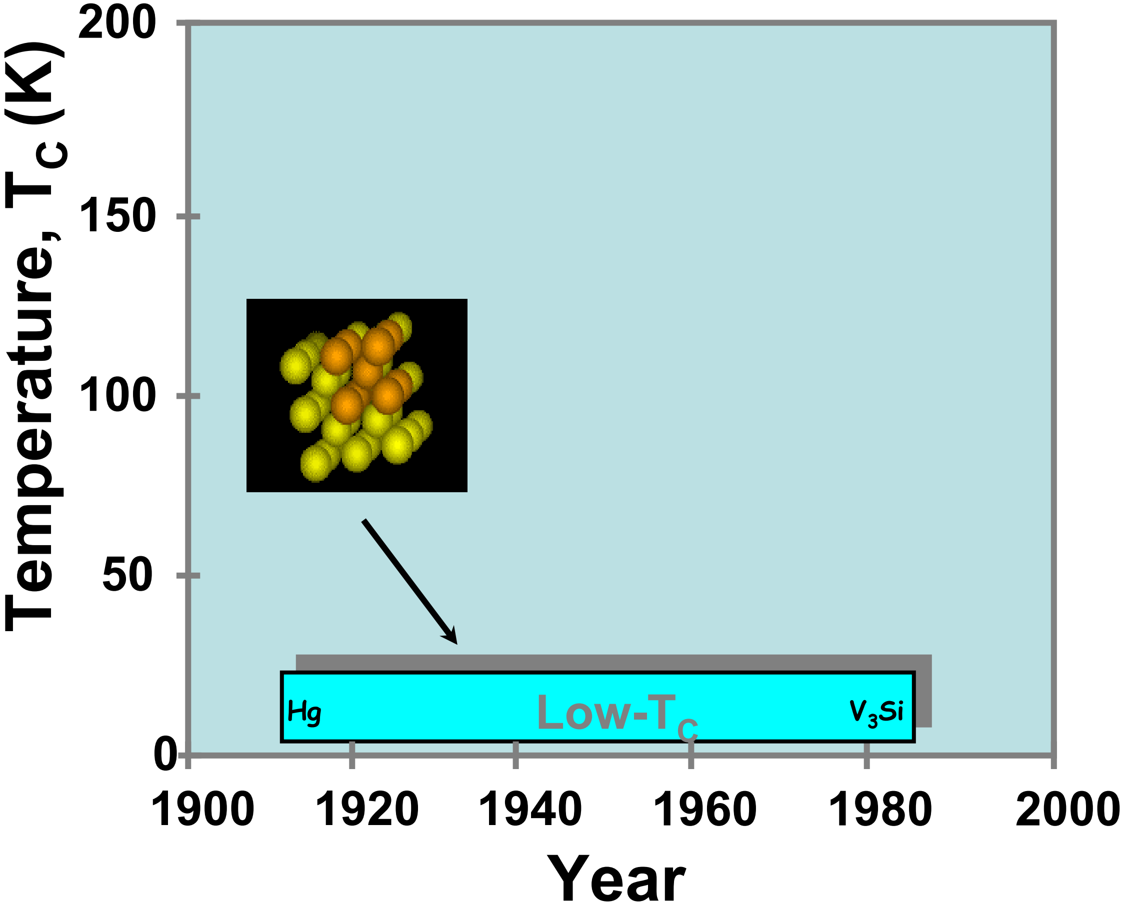
Fig. 1. Cross section of the 100-GW line.

100 GW dc, 1000 km !

1986: A Big Surprise!



Bednorz and Mueller
IBM Zuerich, 1986



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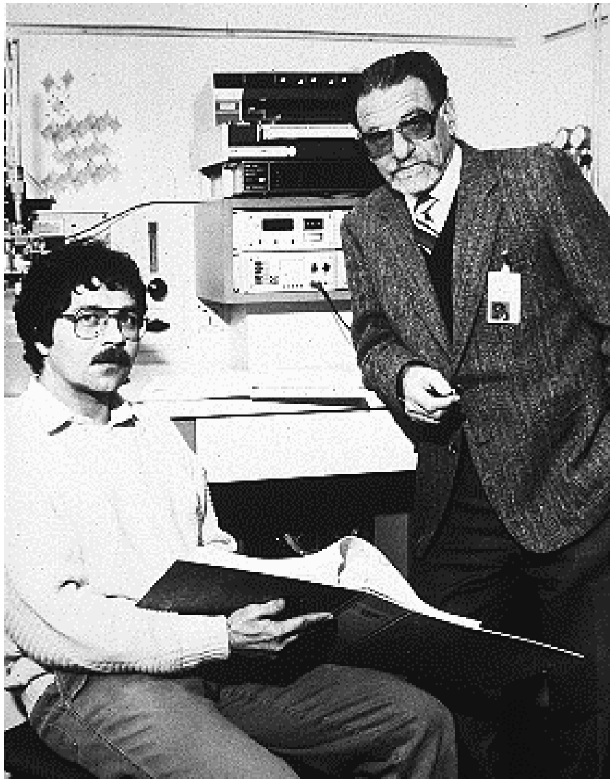

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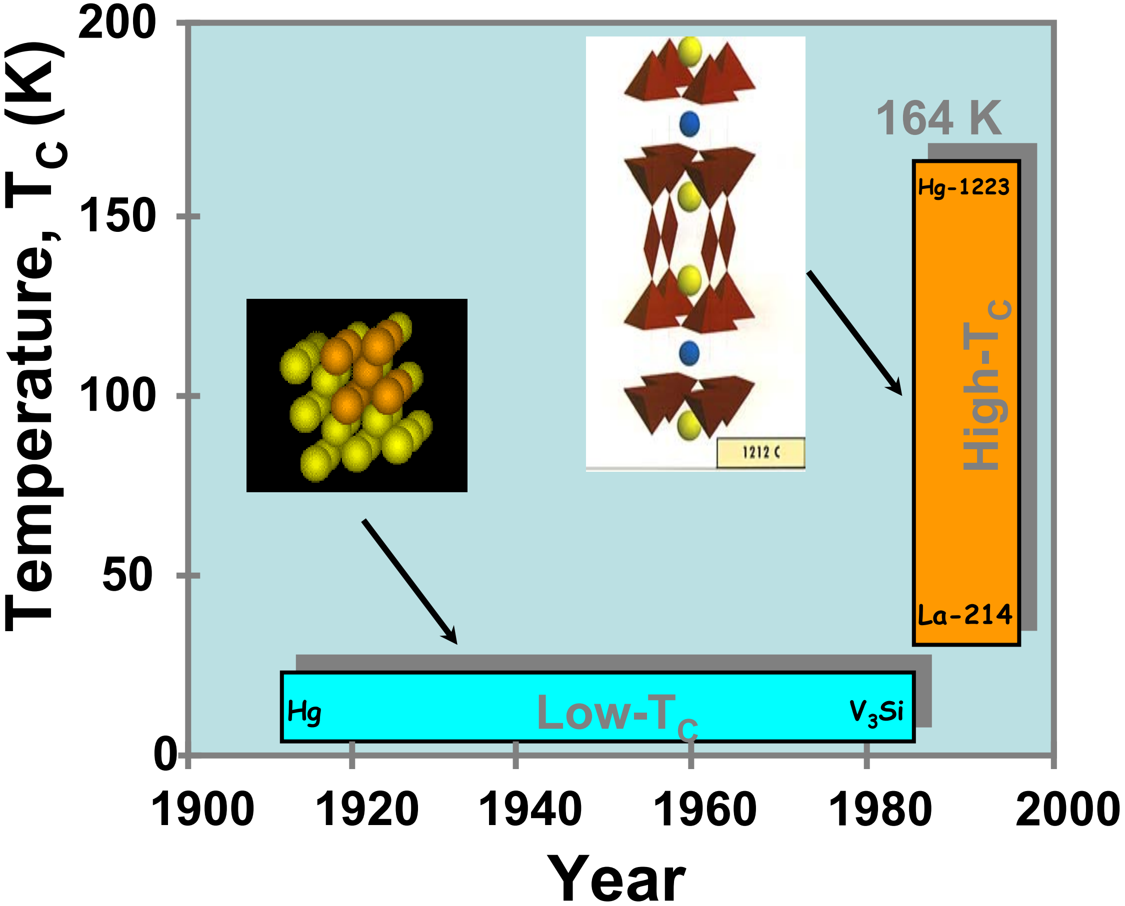

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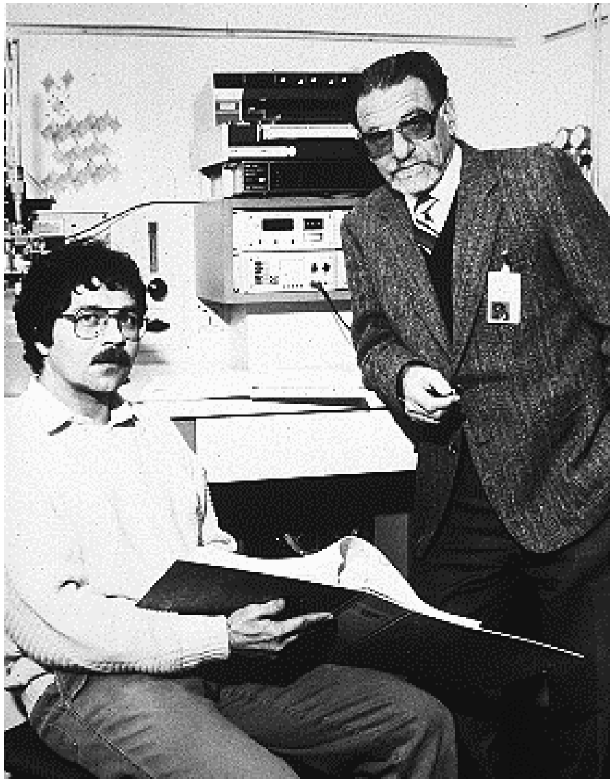

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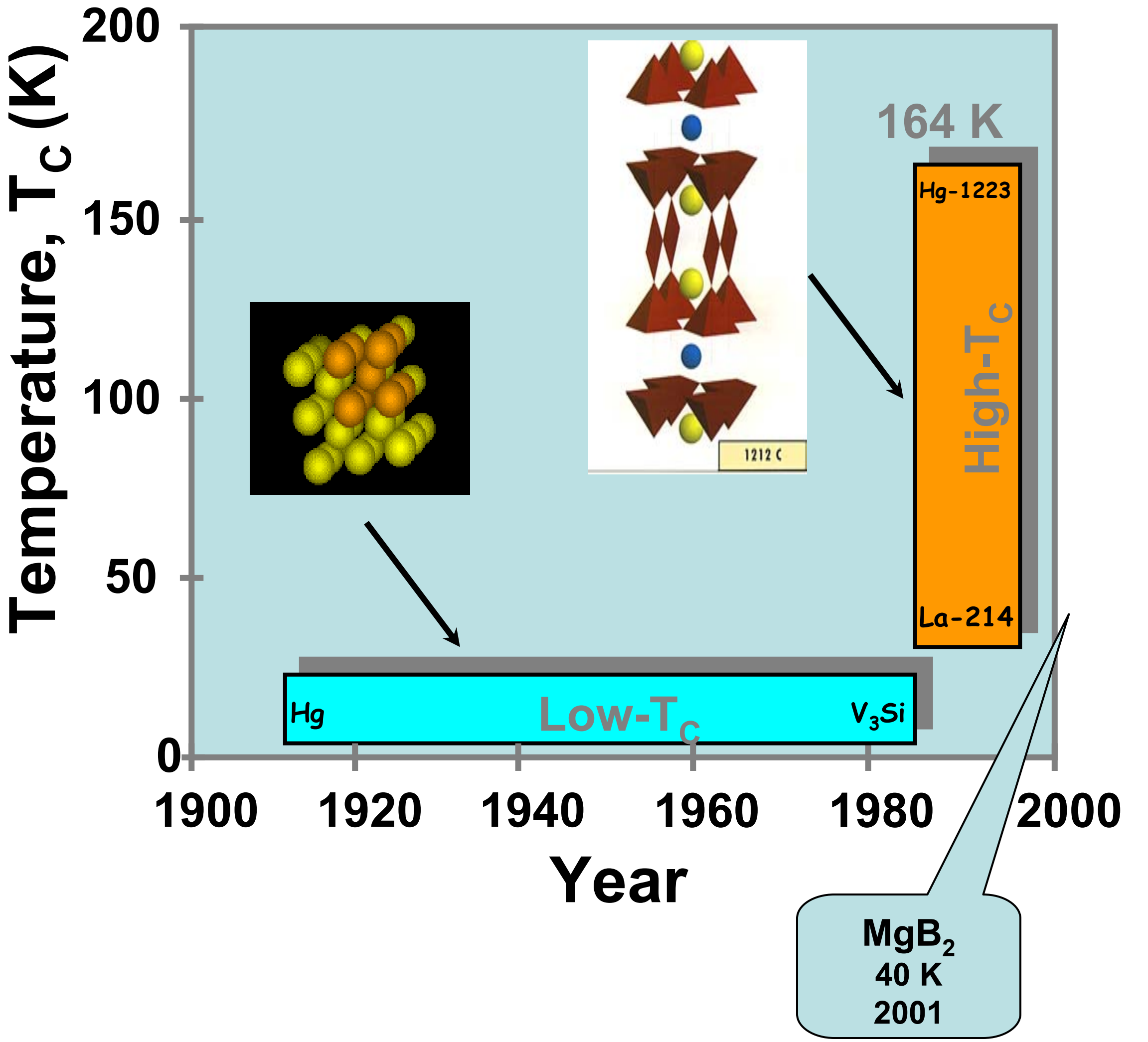


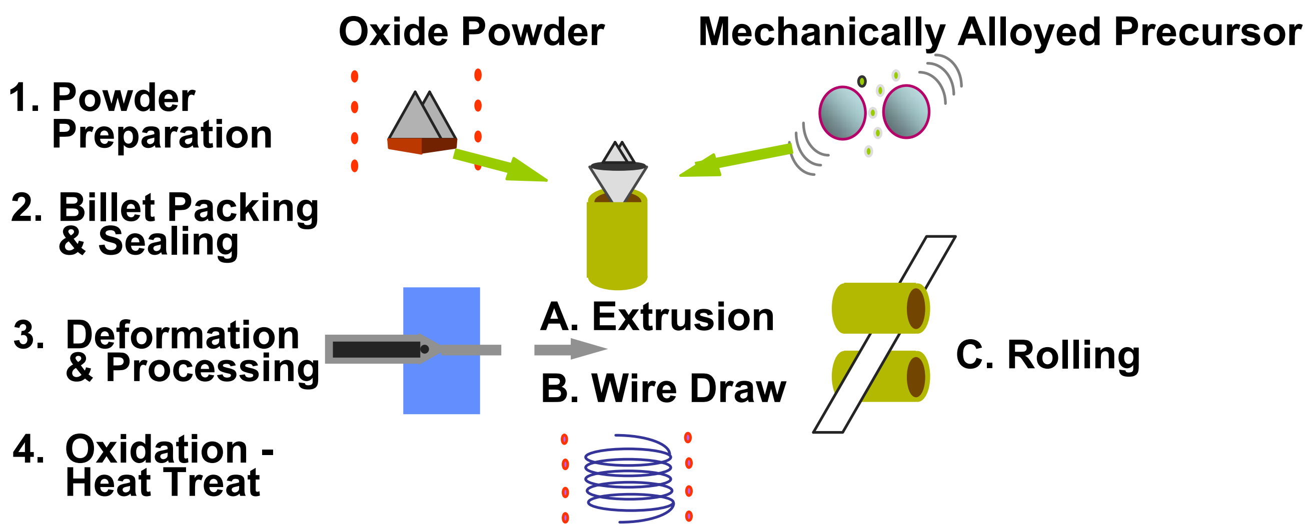
1987: “The Prize!”

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

HTSC Wire Can Be Made!



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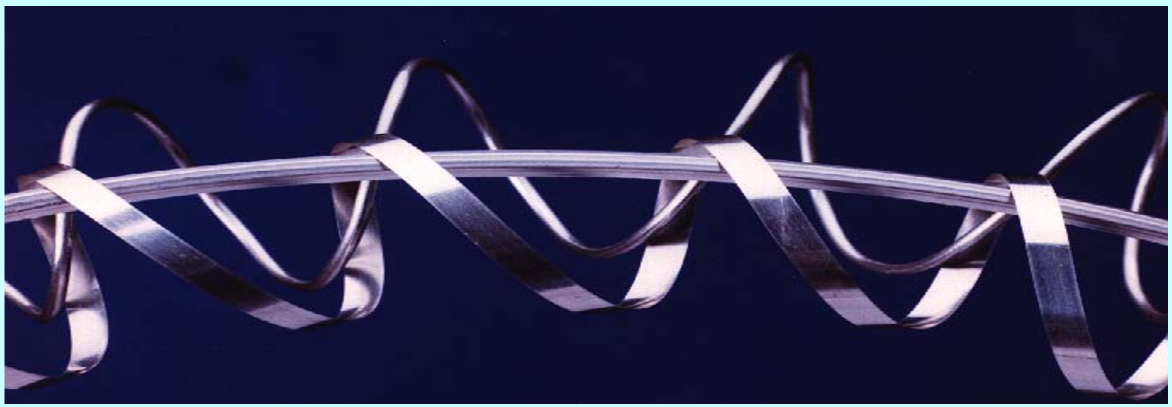
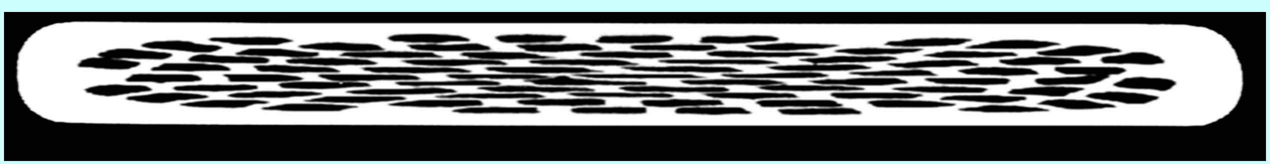


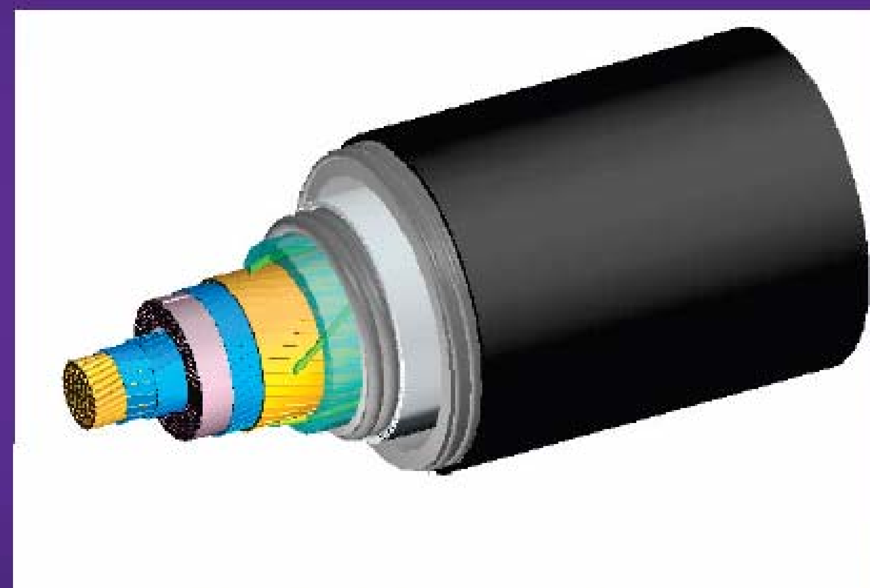
But it's 70% silver!



"Long Island"

LONG ISLAND TEAM* PLANS TO BUILD AND DEMONSTRATE 3 COAXIAL PHASES

- 3 phase AC
- each phase coaxial
- 2.4 kA
- 69 kA
  during 15 cycle fault
- 138 kV
- 600 MW
- 610 meter
- Bi-2223
- 1 splice
- each phase has Cu shunt to increase Z during fault
- conventional cooling and pulse tube



AMSC design promises very low (& variable) impedance

* AMSC, Nexans, Air Liquide, Long Island Power Authority (LIPA)

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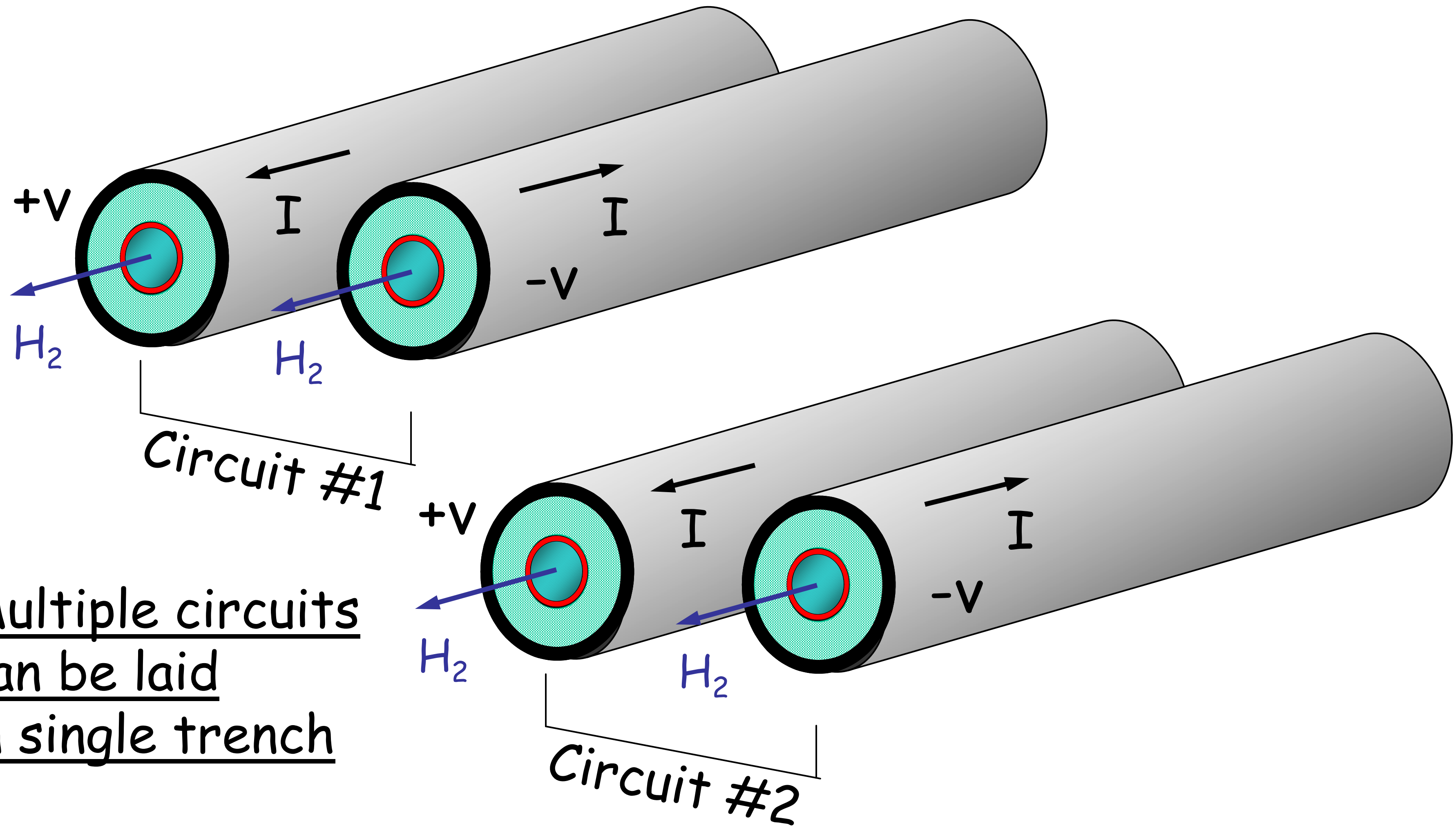
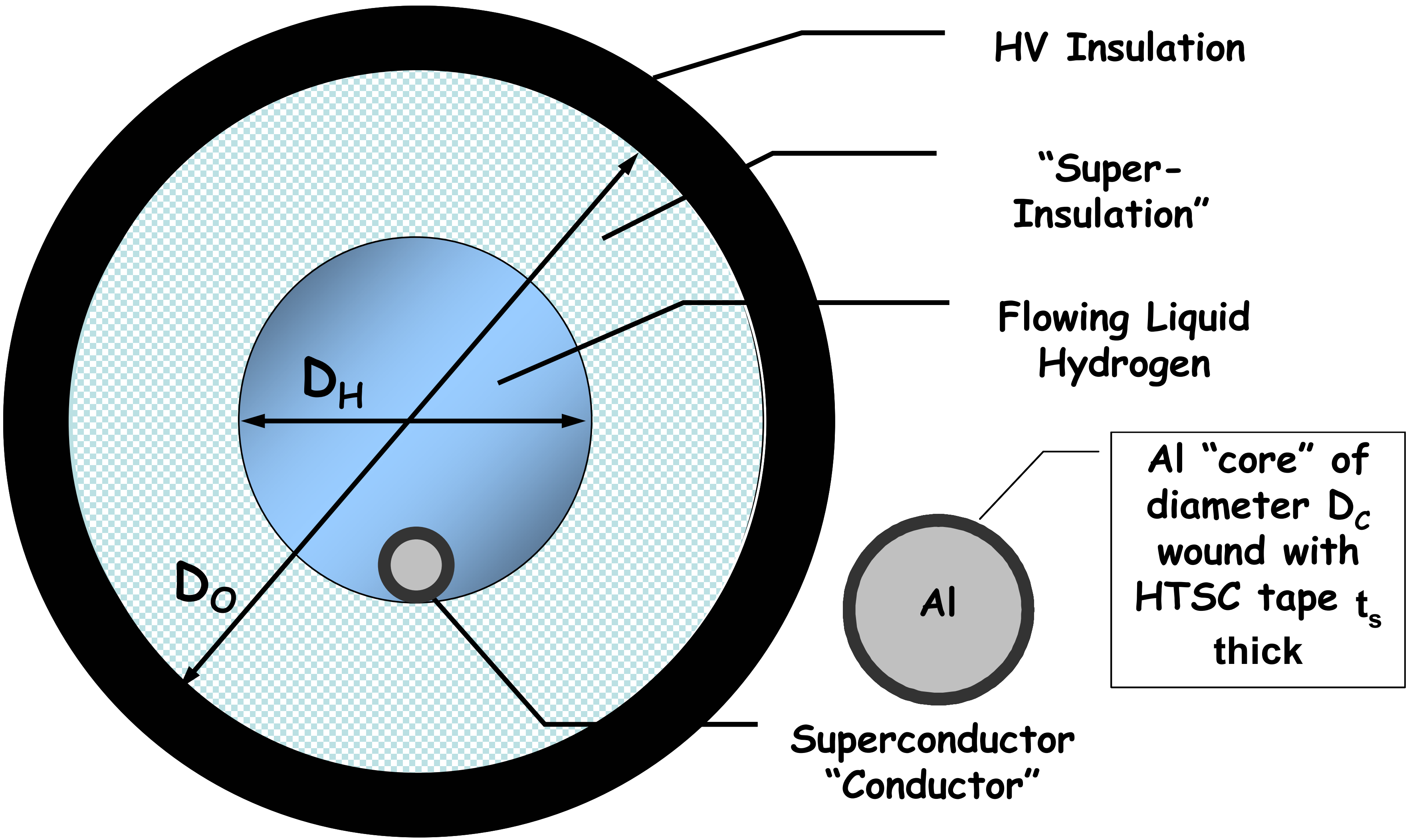
“Hydricity” SuperCables



Multiple circuits
can be laid
in single trench

SuperCable



HV Insulation
"Super-Insulation"
Flowing Liquid Hydrogen
D_H
D_O
Al
Al "core" of diameter D_C wound with HTSC tape t_s thick
Superconductor "Conductor"

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

Radiation Losses

$W_R = 0.5\varepsilon\sigma\,(T^4_{amb} - T^4_{SC})$, where

W_R = Power radiated in as watts/unit area
$\sigma = 5.67\times10^{-12}\ W/cm^2K^4$
T_{amb} = 300 K
T_{SC} = 20 K
ε = 0.05 per inner and outer tube surface
D_H = 45.3 cm

W_R = 16.3 W/m

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

n = number of layers = 10

Net Heat In-Leak Due to Radiation = 1.8 W/m

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

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

Fluid	Re	ε(mm)	D_H (cm)	v (m/s)	ΔP (atm/10 km)	Power Loss (W/m)
H (20K)	2.08×10^6	0.015	45.3	4.76	2.0	3.2

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

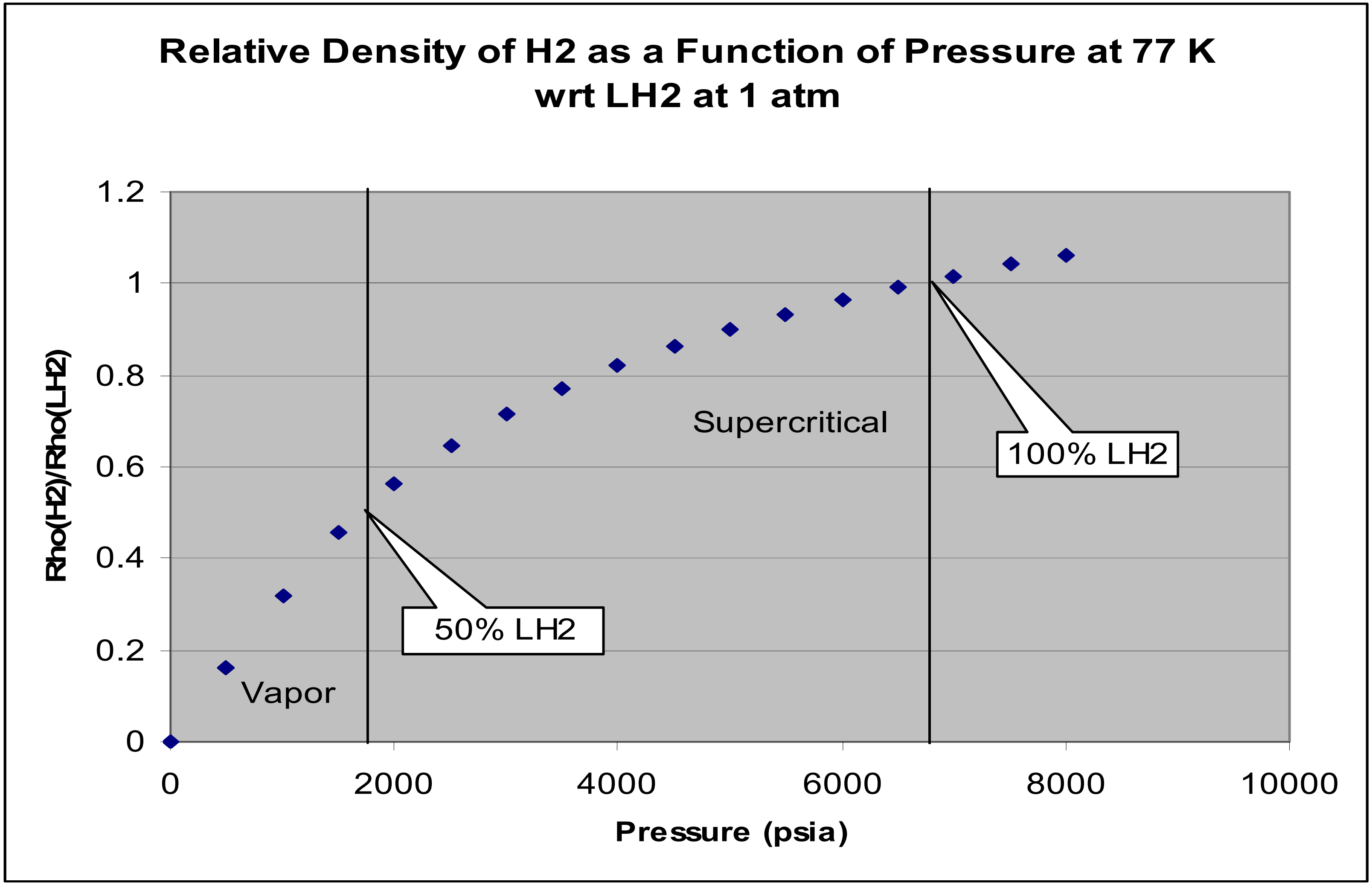
SuperCable Losses (W/M)					K/10km
Radiative	**Friction**	**ac Losses**	**Conductive**	**Total**	**dT/dx**
1.8	3.2	1	1	7	10^{-2}

SuperCable H_2 Storage

Some Storage Factoids	**Power (GW)**	**Storage (hrs)**	**Energy (GWh)**
TVA Raccoon Mountain	1.6	20	32
Scaled ETM SMES	1	8	8

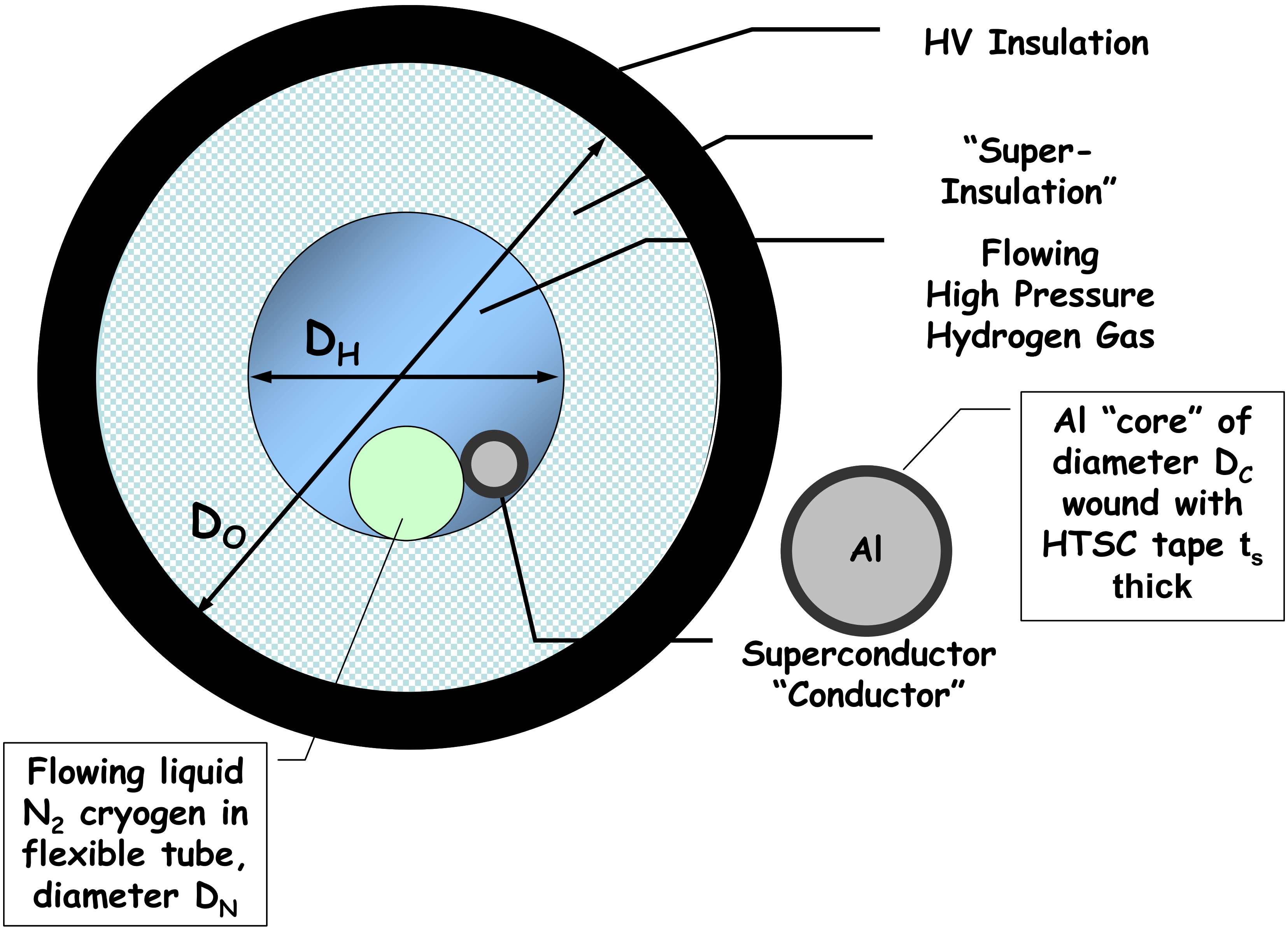
One Raccoon Mountain = 13,800 cubic meters of LH2

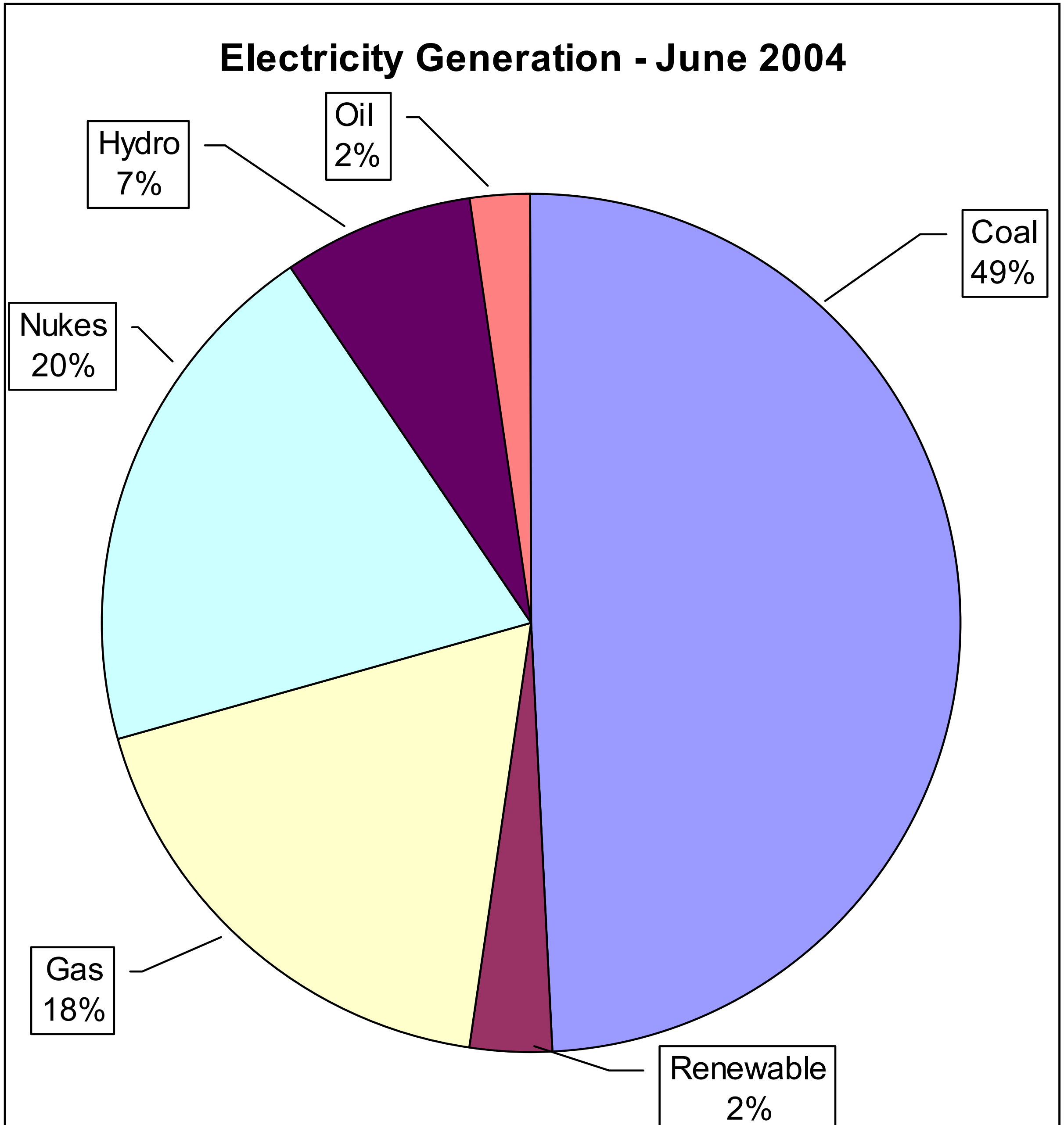
LH_2 in 45 cm diameter, 20 km bipolar SuperCable
= Raccoon Mountain

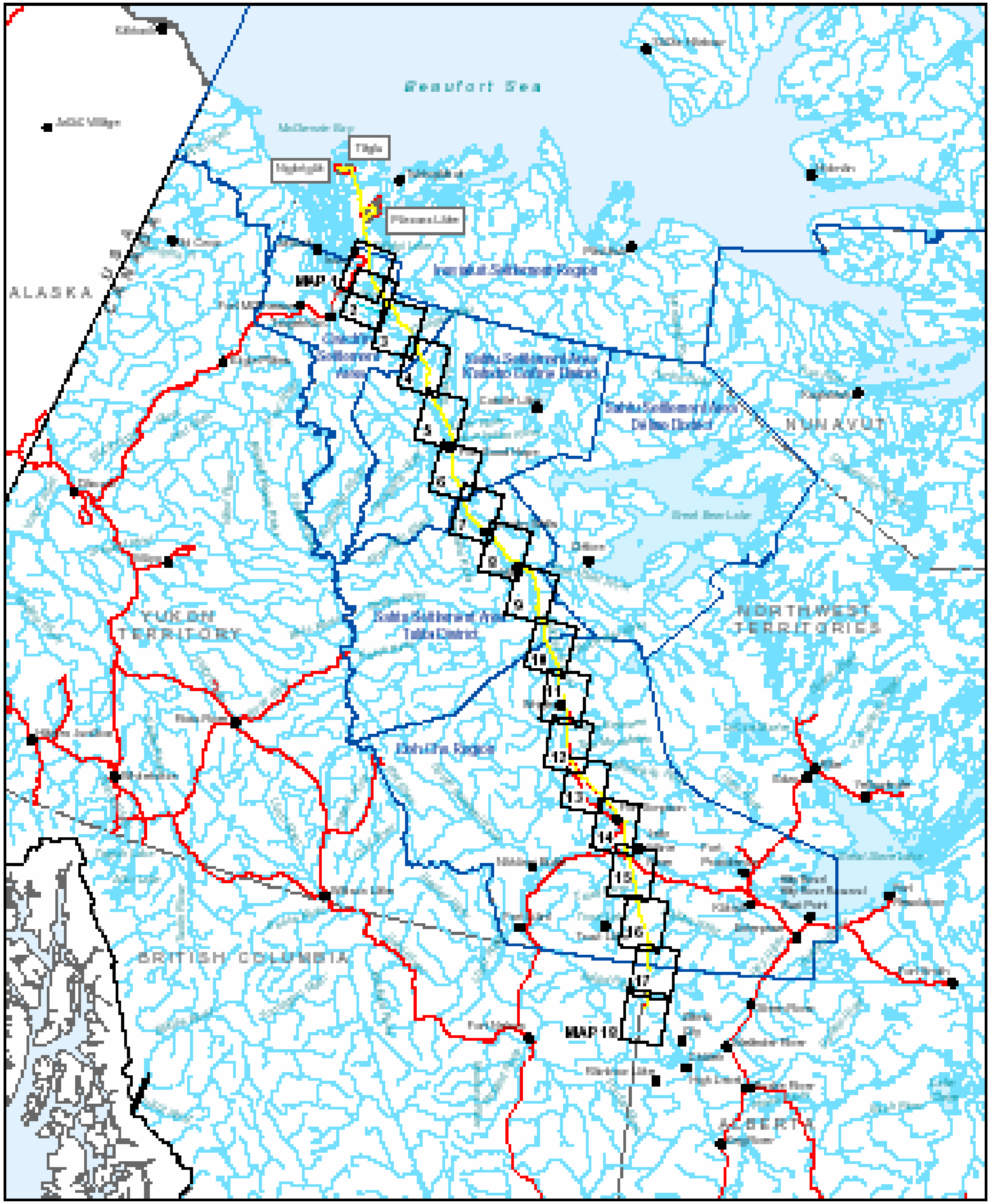


H_2 Gas at 77 K and 1850 psia has 50% of the energy content of liquid H_2 and 100% at 6800 psia

"Hybrid" SuperCable




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

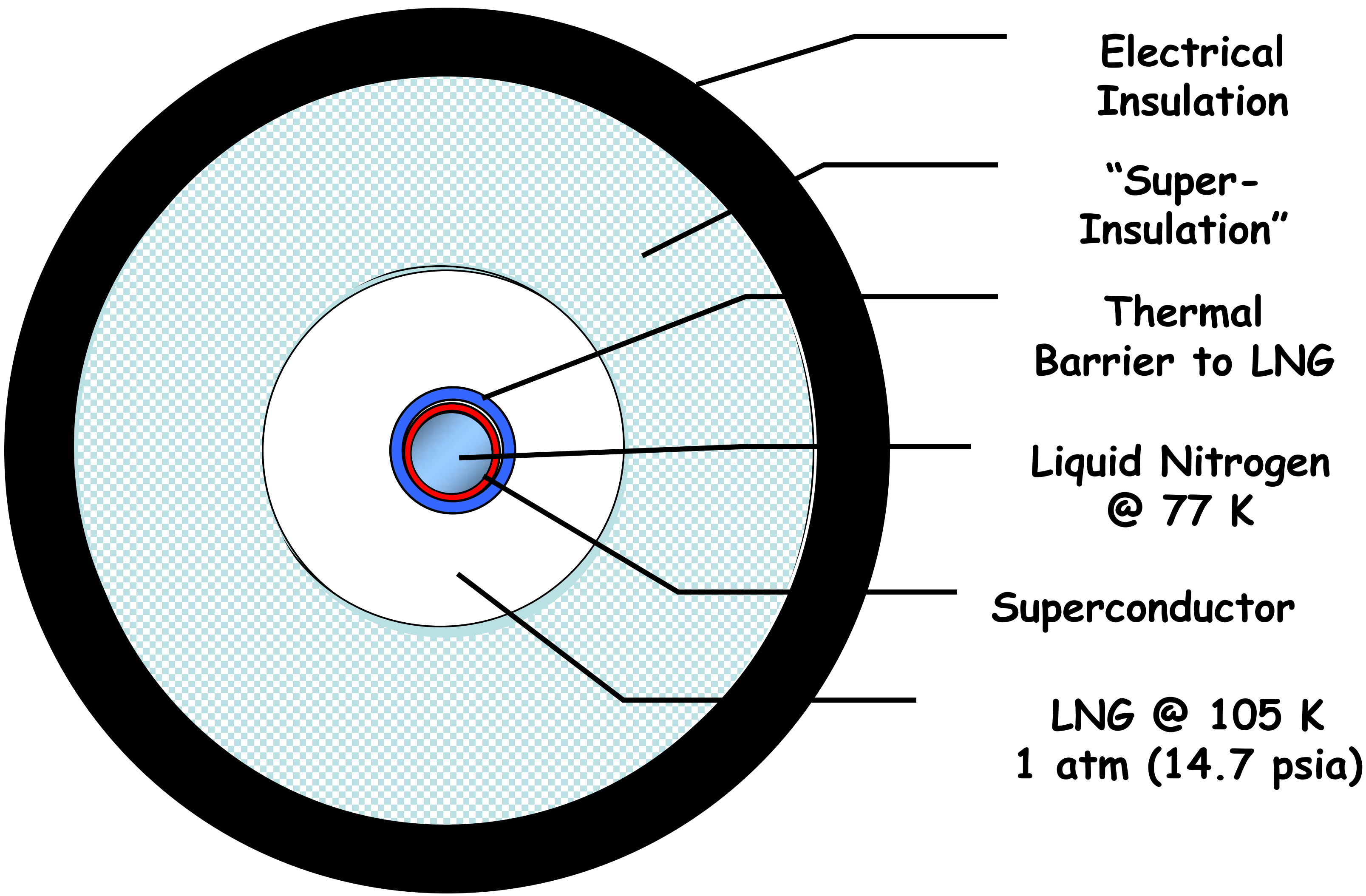


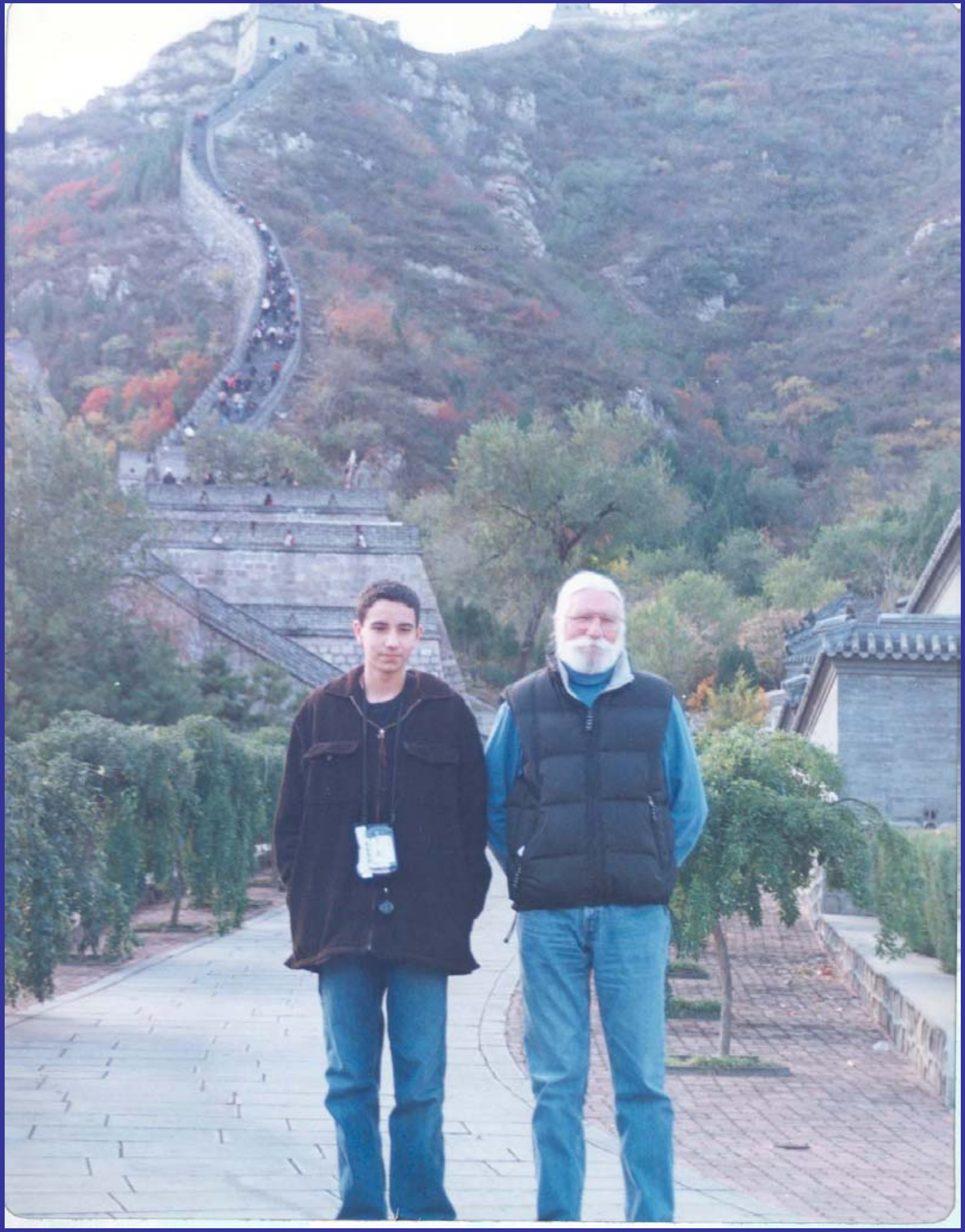
Mackenzie Valley Pipeline

1300 km

18 GW-thermal

LNG SuperCable





Questions and/or Comments?

Slings and Arrows Welcomed!