

# SuperCities and SuperGrids

A Vision for Long-term Sustainable and  
Environmentally Compatible Energy  
Independence for North America

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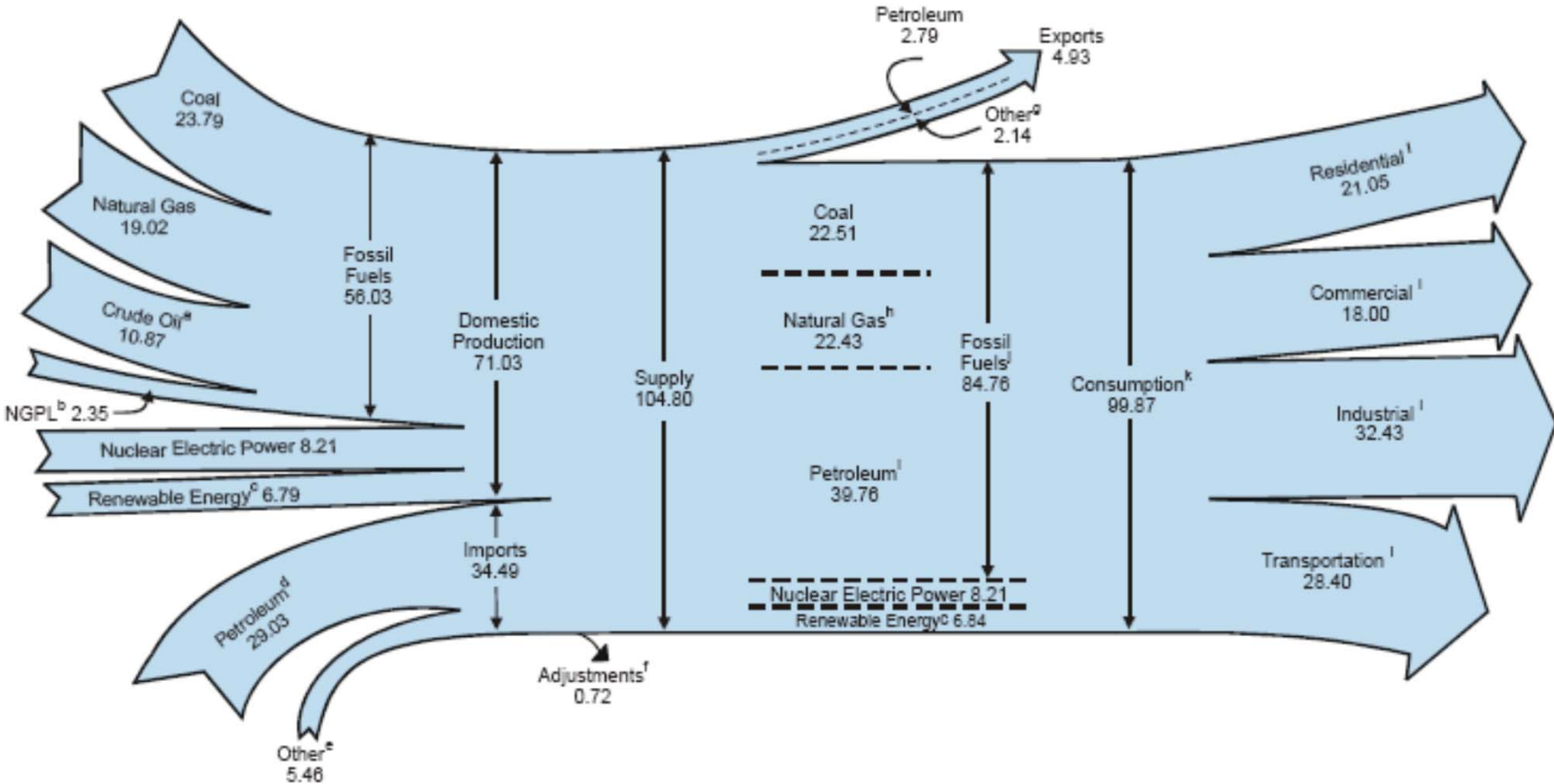
<http://www.w2agz.com/ucdpc08.htm>

Aging IBM Pensioner

# Cold Fusion After 20 Years



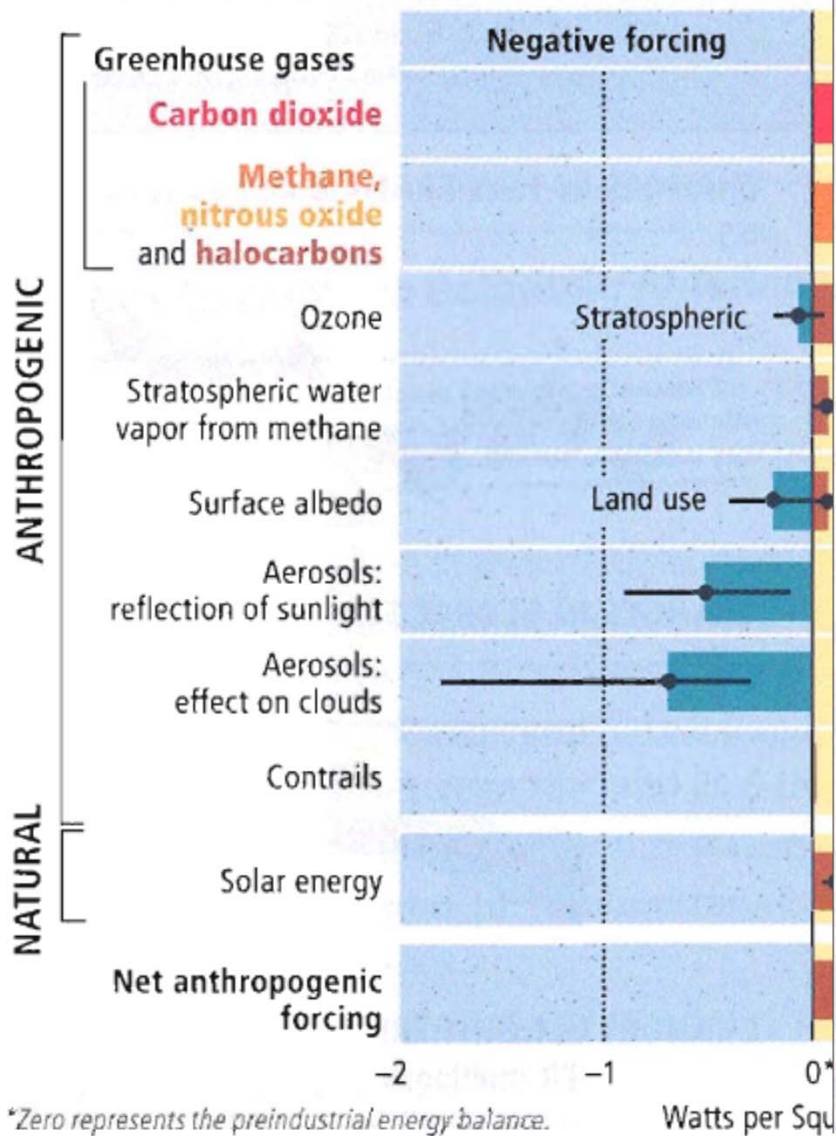
**Diagram 1. Energy Flow, 2006**  
(Quadrillion Btu)



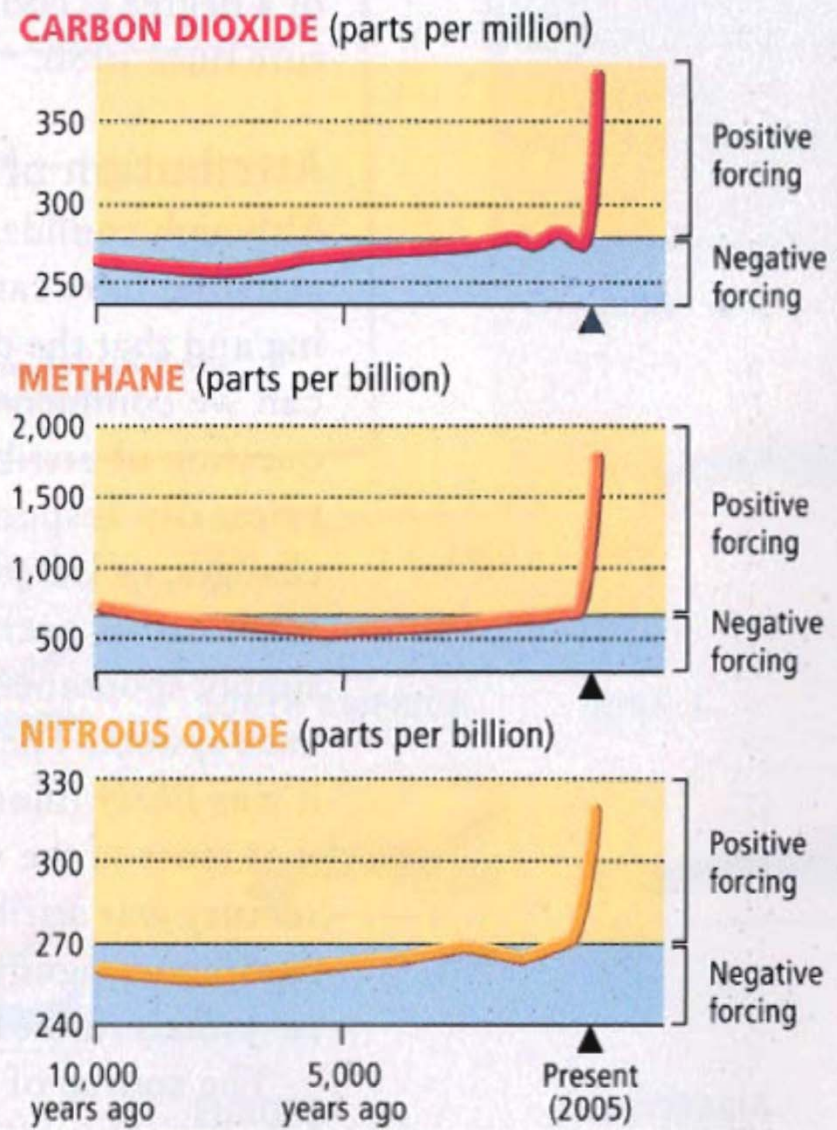


# SciAm – August, 2007 Issue

## Radiative Forcing: The Overview



## Greenhouse Gases: The Major Forcings

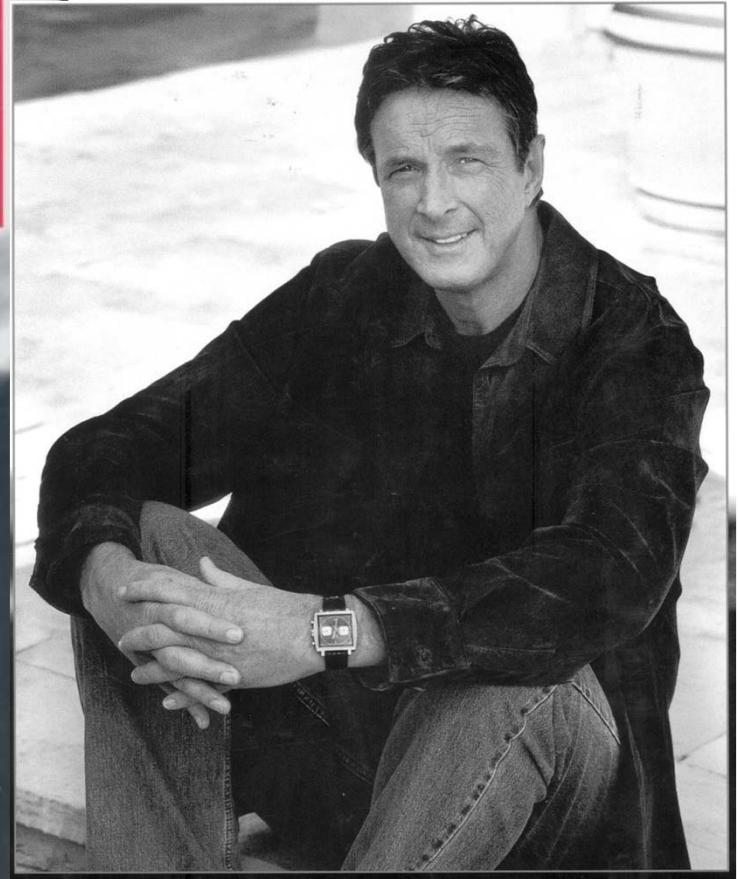
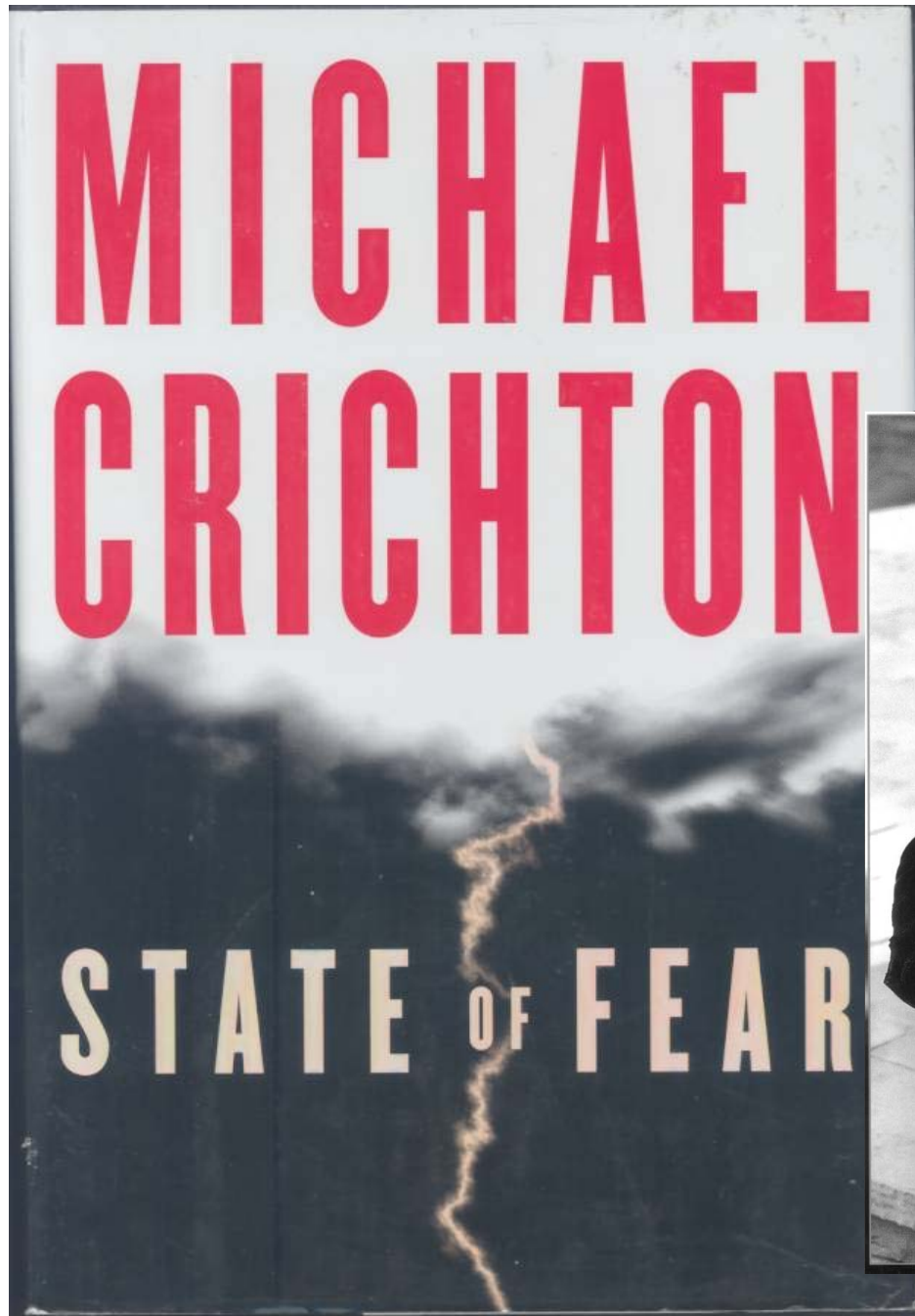


# The Day After Tomorrow



# An Inconvenient Truth





# “Greenhouse Gases”



# “Expert Opinion”

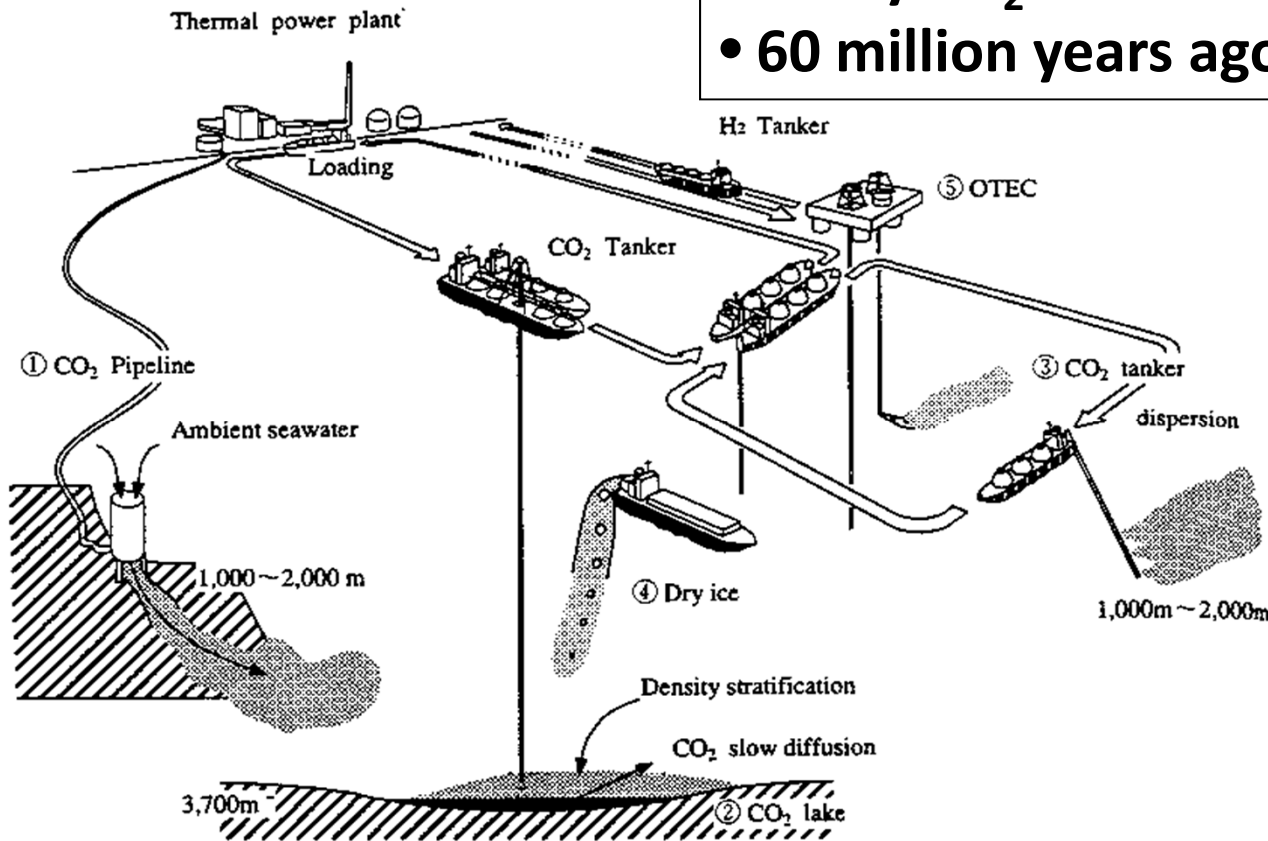
- Nate Lewis
  - Mitigation is more or less hopeless without massive skewing of the “laws of economics” through government intervention
- Bill Nordhaus
  - By 2100, the global economy will be rich enough to afford adapting to 500-600 ppm CO<sub>2</sub>
- Fred Singer
  - No problem (GCC is good for you...)
- William Ruddiman
  - Invention of agriculture 8000 years ago and subsequent methane emissions saved the planet from undergoing a “scheduled cyclic ice age.”
- Jesse Ausubel
  - To propose significant deployment of renewables is a “heresy.”
- Sean Hannity
  - It’s all due to Al Gore, Sean Penn and Leonardo DiCaprio flying around in private jets.

# “Not-so-Expert Opinion”

- Exactly what is “clean coal?”
  - Is it “heavy metal free?”
  - Is it “sulfur free?”
  - Is it “zero emissions?”
  - Is it “all of the above?”
- Don’t ask any American politician, because they haven’t a clue

# Carbon Dioxide – Where do we put it?

- Today CO<sub>2</sub> is at 400 ppm
- 60 million years ago, it was 7000!



...maybe the best place is in the atmosphere 😊

## Carbon dioxide ocean disposal options

(Adapted from Fujioka et al, 1997)

# Theory of Everything

$$\mathcal{H} = - \sum_j \frac{\hbar^2}{2m} \nabla_j^2 - \sum_a \frac{\hbar^2}{2M_a} \nabla_a^2 - \sum_{j,a} \frac{Z_a e^2}{|r_j - R_a|} + \sum_{j,k} \frac{e^2}{|r_j - r_k|} + \sum_{a,b} \frac{Z_a Z_b e^2}{|R_a - R_b|}$$

- Hydrogen atom
- Methane molecule
- Water
- Air
- Rocks
- Concrete
- Steel
- Glass
- Plastic
- Buildings
- Cities
- Continents

- Proteins
- DNA
- Viruses
- Bacteria
- Yeast
- Slime mold
- Butterflies
- Sharks
- Rats
- Lawyers
- Ebola virus
- Legislatures
- Civilizations

- Flowers
- Trees
- Cows
- Cheese
- Sauce Bernaise
- Computers
- Television
- Cars
- Jets
- Lawnmowers
- Sewage
- Spotted Oats
- ...

# Bob Laughlin's "Theory of Everything" (that's important!)

- 3 -> 10<sup>2</sup>
  - Chemistry
- 10<sup>2</sup> <-> 10<sup>3</sup>
  - Thermodynamics
- 10<sup>3</sup> <-> 10<sup>10</sup>
  - Cooperative Phenomena
- 10<sup>10</sup> <-> 10<sup>20</sup>
  - Emergent Behavior (Us)



- > 10<sup>20</sup>
  - CLIMATE !
- **SIZE MATTERS !**

# Overture

# The 21<sup>st</sup> 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*

# Boundary Conditions

- Carbonless
  - No CO<sub>2</sub>
- Non-Eco-Invasive
  - Minimal land/ecology impact
- Off-the-table
  - Large scale renewables (wind, solar, bio)
  - Sequestration

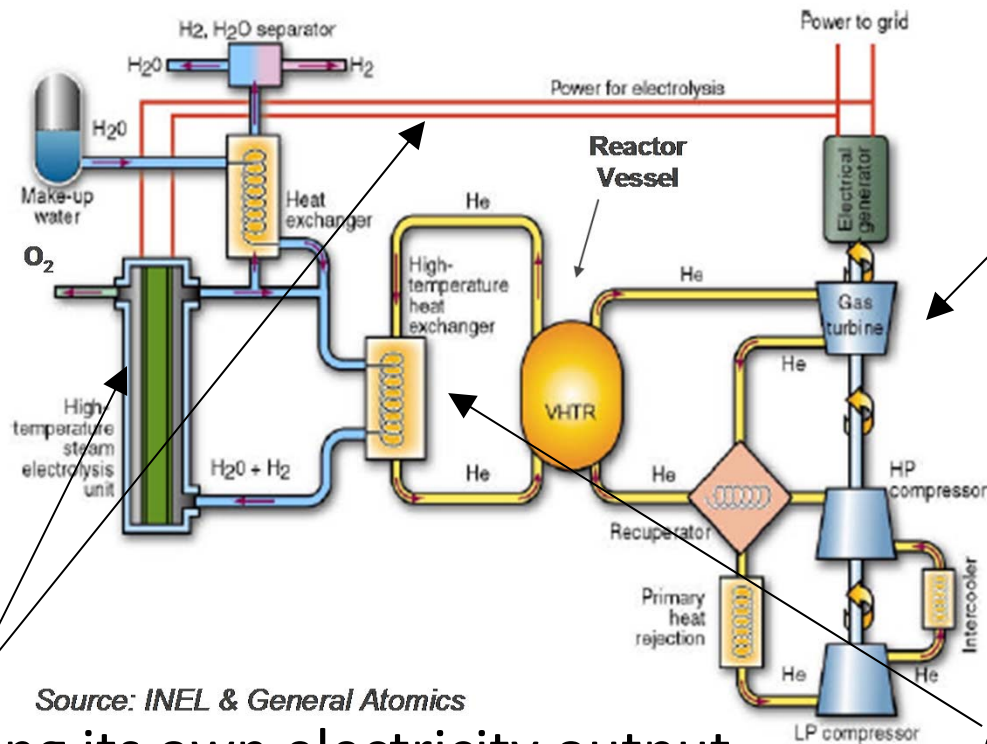
# Technology Menu

- Generation
  - HTGCR Nuclear (80%)
    - electrons
    - protons
  - PV Solar Roofs (20%)
- Transmission
  - Hydricity SuperCable
- Storage
  - Hydrogen + Hydricity Fuel Cell
- End Use Power
  - Electricity
  - Hydrogen

# Implementation Technology I

## HTGCR Nuclear Power

- Gen IV High Temperature Gas-Cooled Reactors can make electricity the old fashioned way by spinning turbines
- The same reactor can make hydrogen from water in *two* ways...



Source: INEL & General Atomics

Using its own electricity output to perform electrolysis...



Or with heat drawn from the reactor...



# Implementation Technology II

## The Hydricity Economy



### Hydrogen for:

- Personal Transportation
- Storage of Electricity
- Industrial Thermal/Chemical Processing
- Residential/Commercial Heating

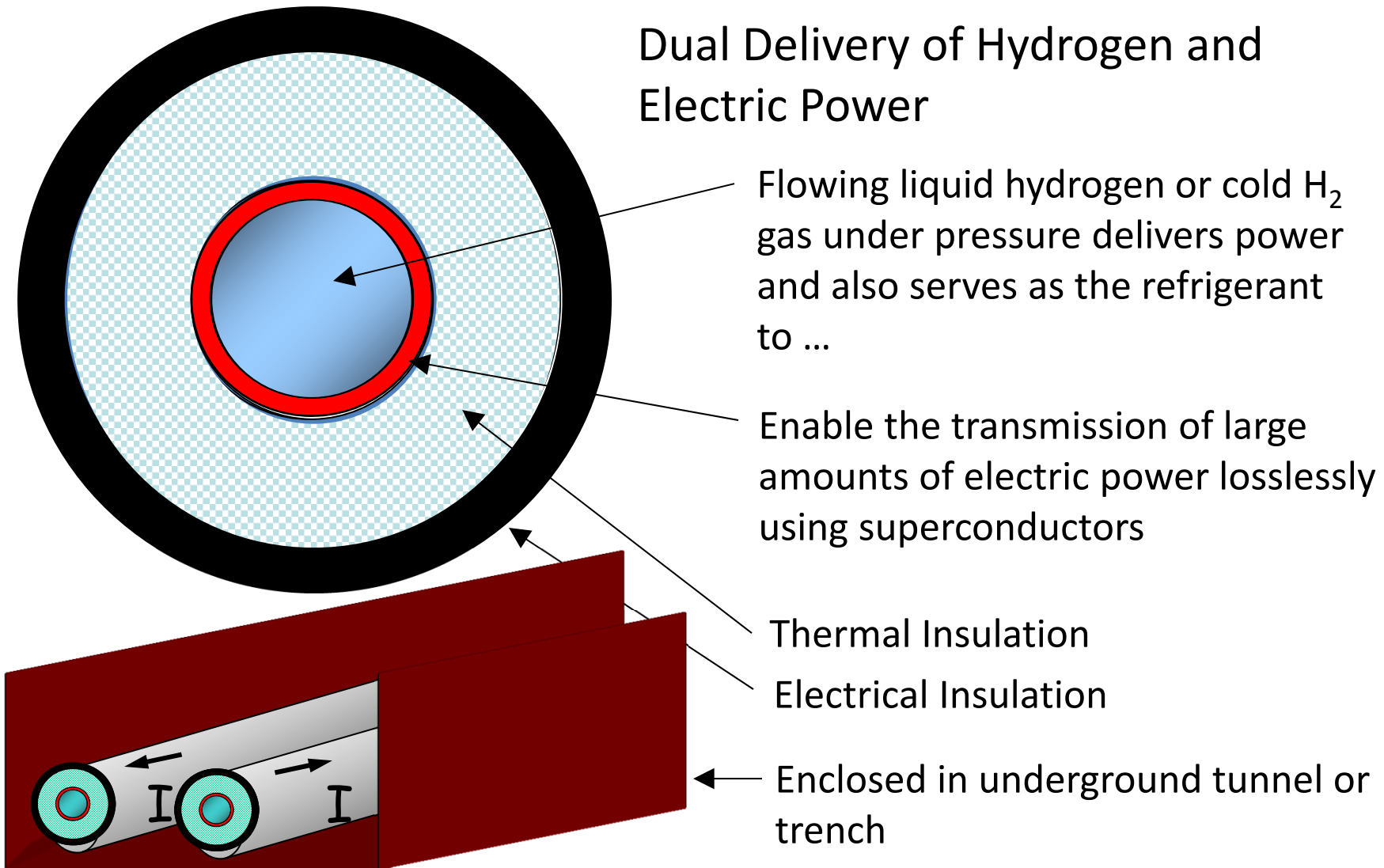


### Electricity for:

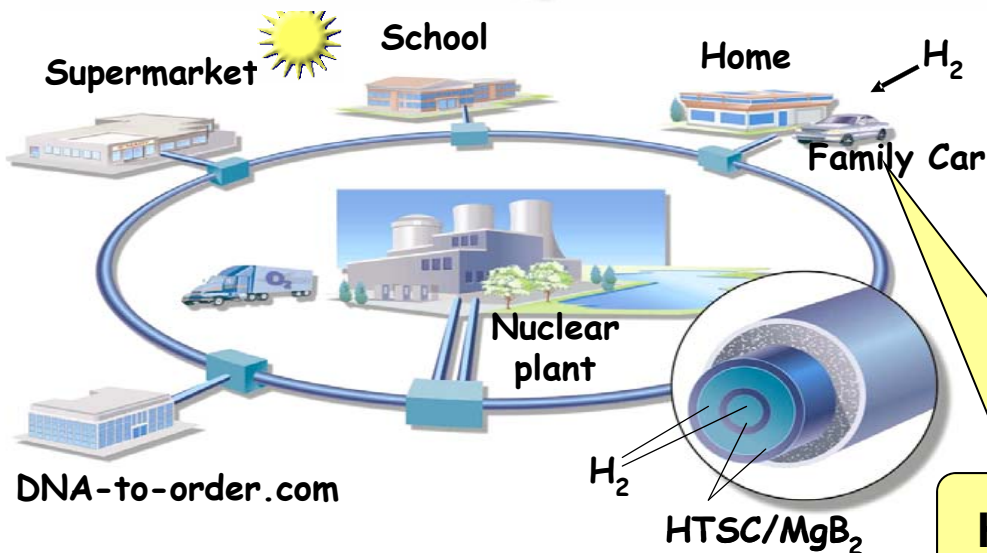
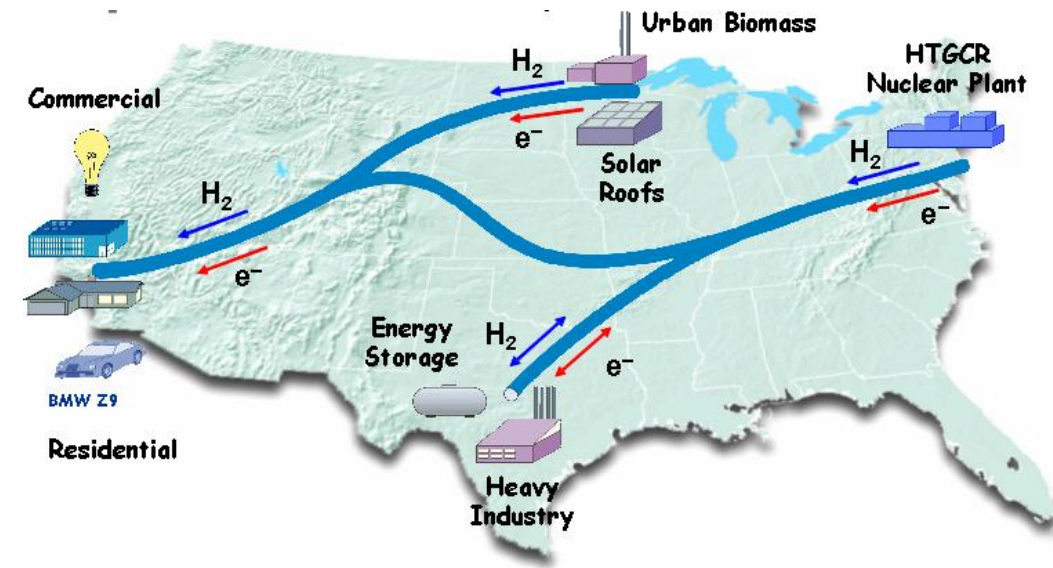
*-Just about everything else!  
(maybe even space heating, as well)*

# Implementation Technology III

## *The Hydricity SuperCable*

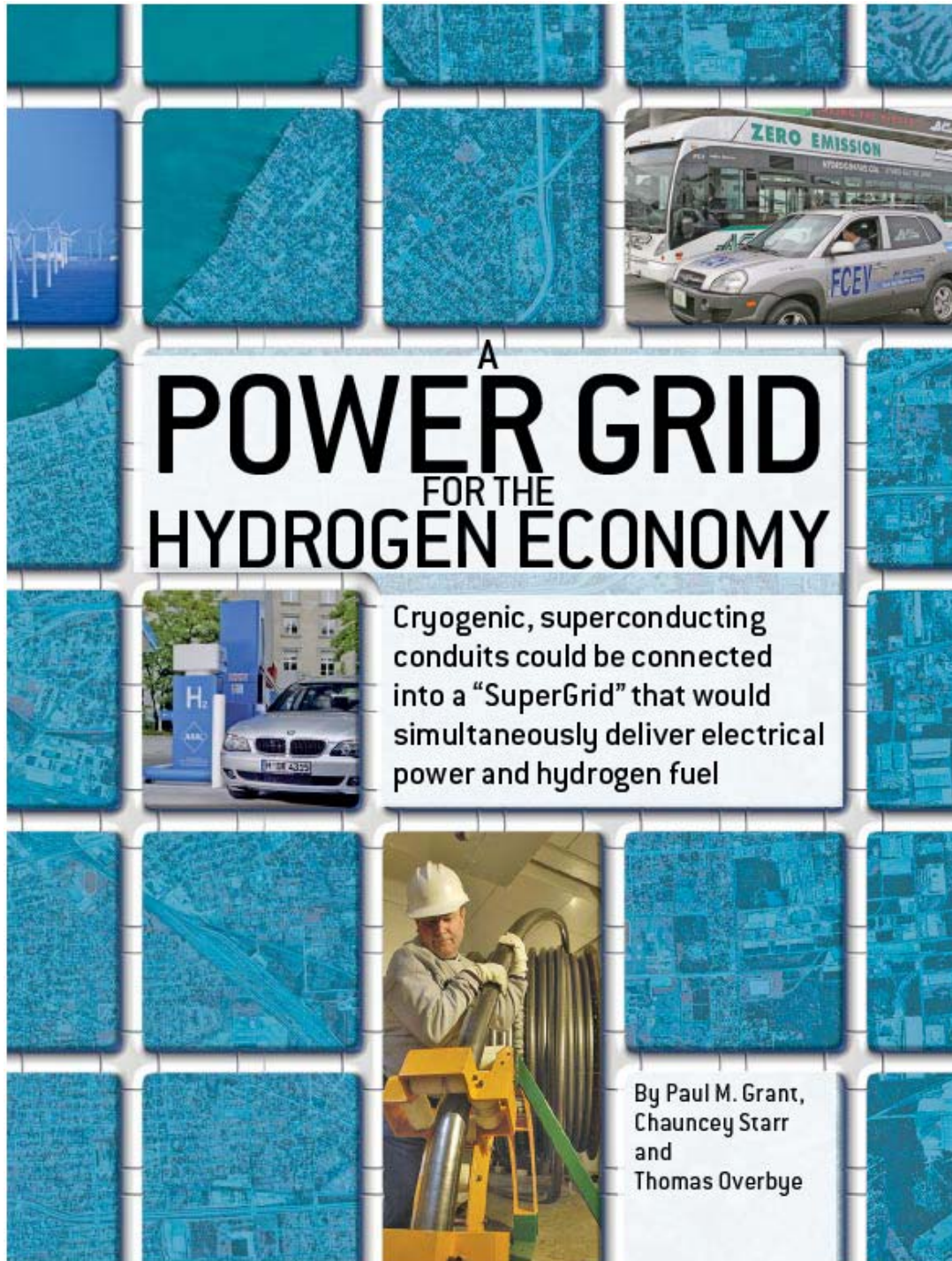


# SuperCities & SuperGrids



- Nuclear Power can generate both electricity and hydrogen – “Hydricity”
- Hydricity can be distributed in underground pipelines like natural gas
- The infrastructure can take the form of a **SuperGrid**
- ...or a **SuperCity**

**Honda Civic H2!**



On the afternoon of August 14, 2003, electricity failed to arrive in New York City, plunging the 10 million inhabitants of the Big Apple—along with 40 million other people throughout the northeastern U.S. and Ontario—into a tense night of darkness. After one power plant in

Published in

**SCIENTIFIC  
AMERICAN**

July, 2006

**“System Crash”**

Omni Productions,  
Vancouver, BC

CBC Broadcast October, 2008

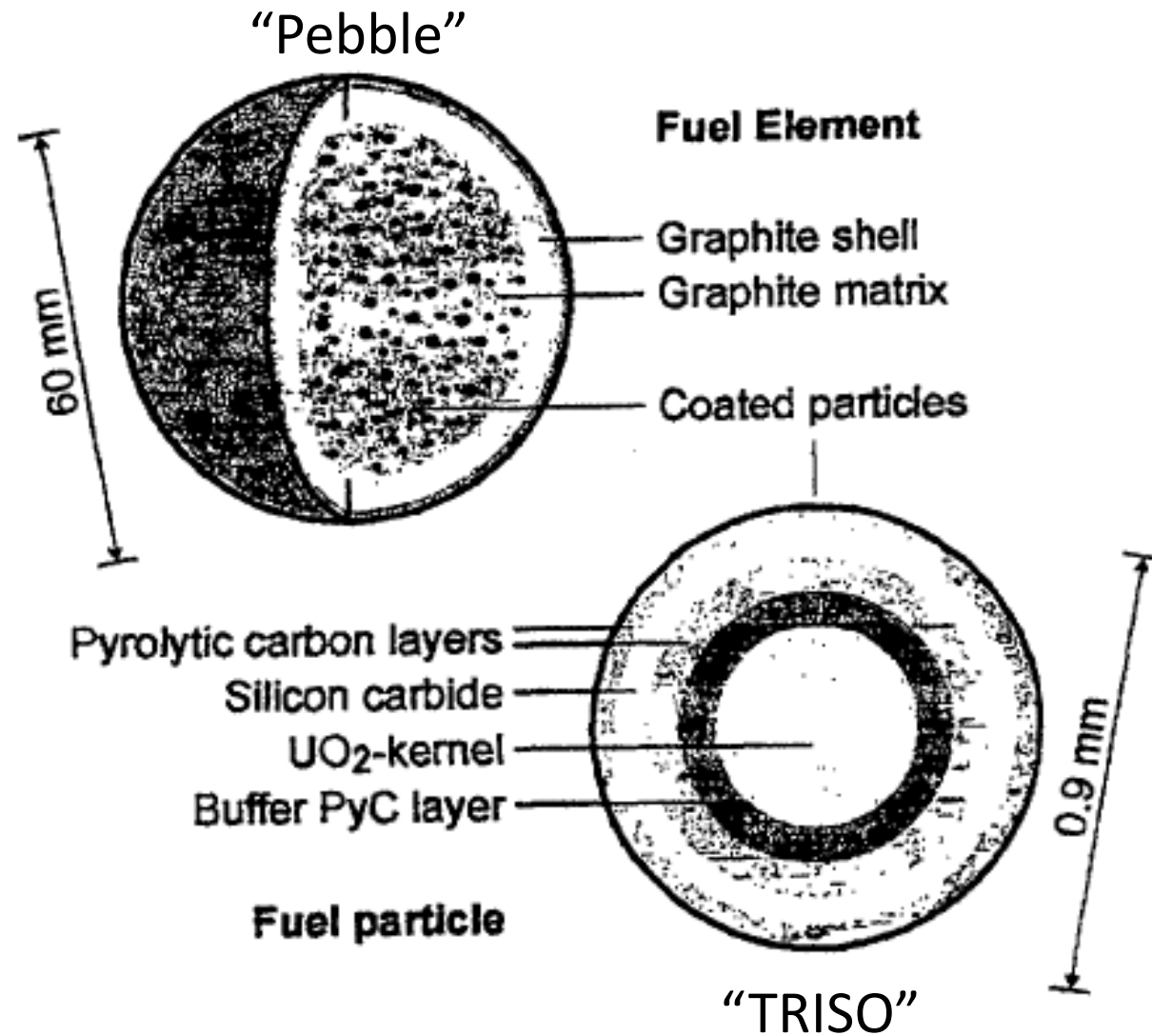
**Nuclear**

# Oklo “Natural” Reactor



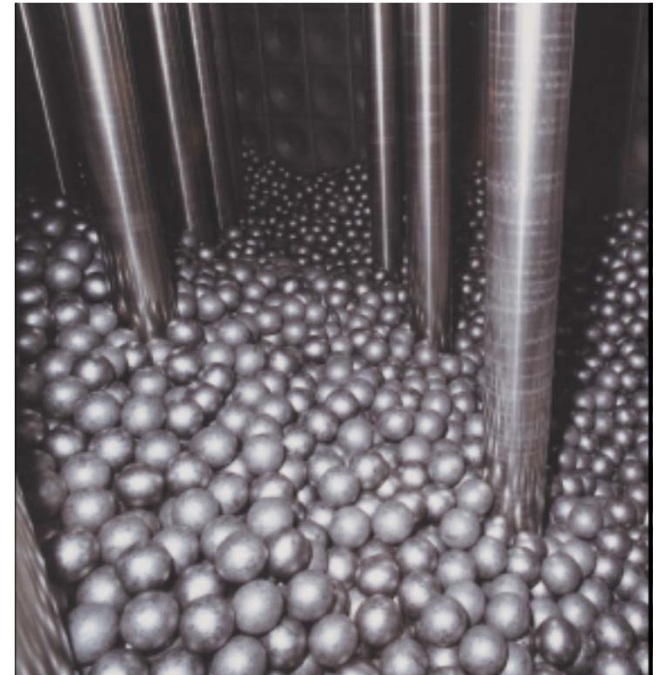
- Pu was created 2 billion years ago!
- Reactor produced 100 kW of power for 500,000 years!
- “Waste” has moved less than one meter.

# Particle/Pebble Nuclear Fuel



# Eskom Pebble Bed Modular Reactor

- Helium gas cooled (Brayton Cycle)
  - Won't melt down
  - Direct turbine drive
- “Baseball” packaged fuel
  - Continuous fuel replenishment and removal
  - Theoretical 100% availability
- Modular Design
  - Scalable: 100 – 500 MW units
  - High safety and security factor
- Economical
  - 1.2 cents/kWh ... cheaper than coal

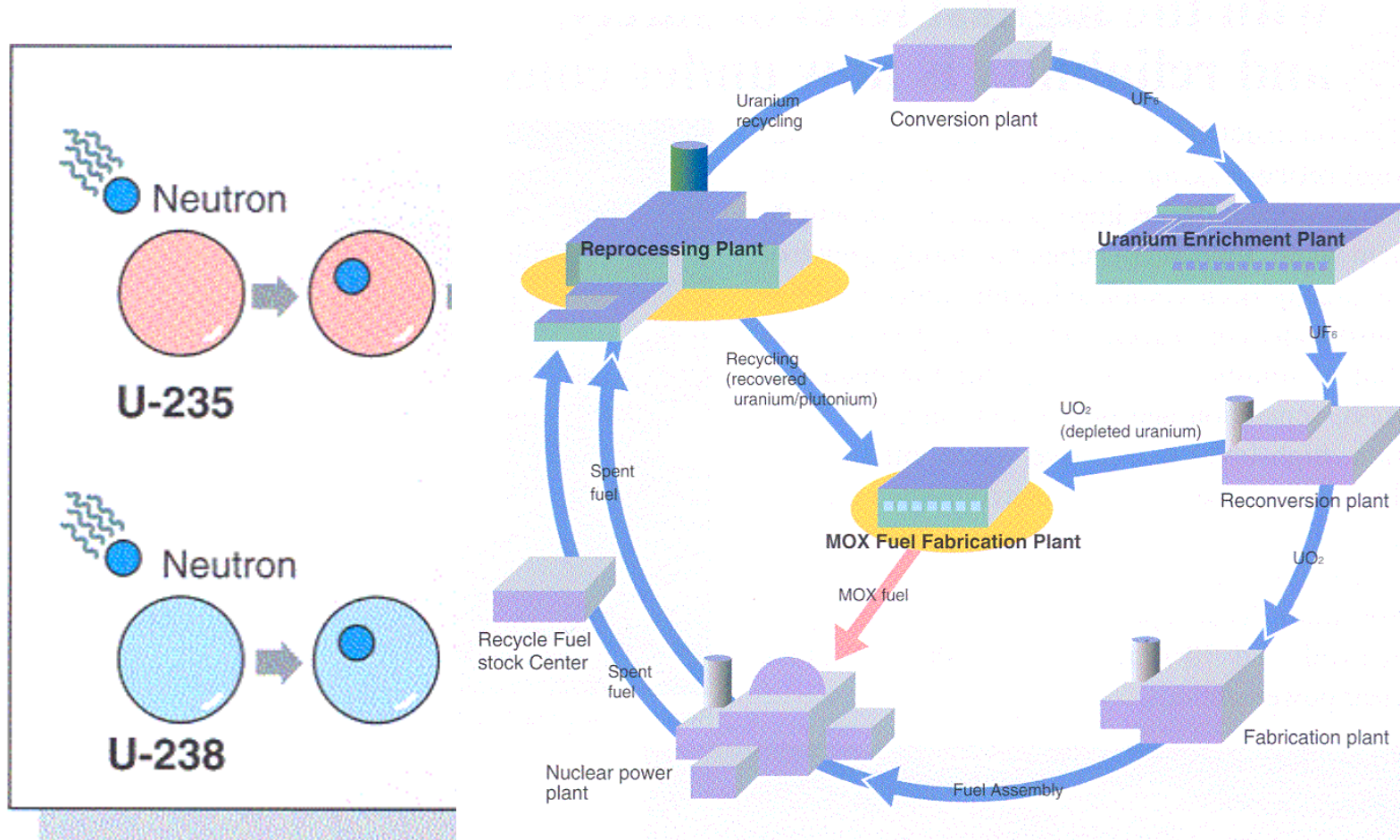


# Yucca Mountain

Created by Emma Hill, 2002



# Reprocessing "Spent" Fuel

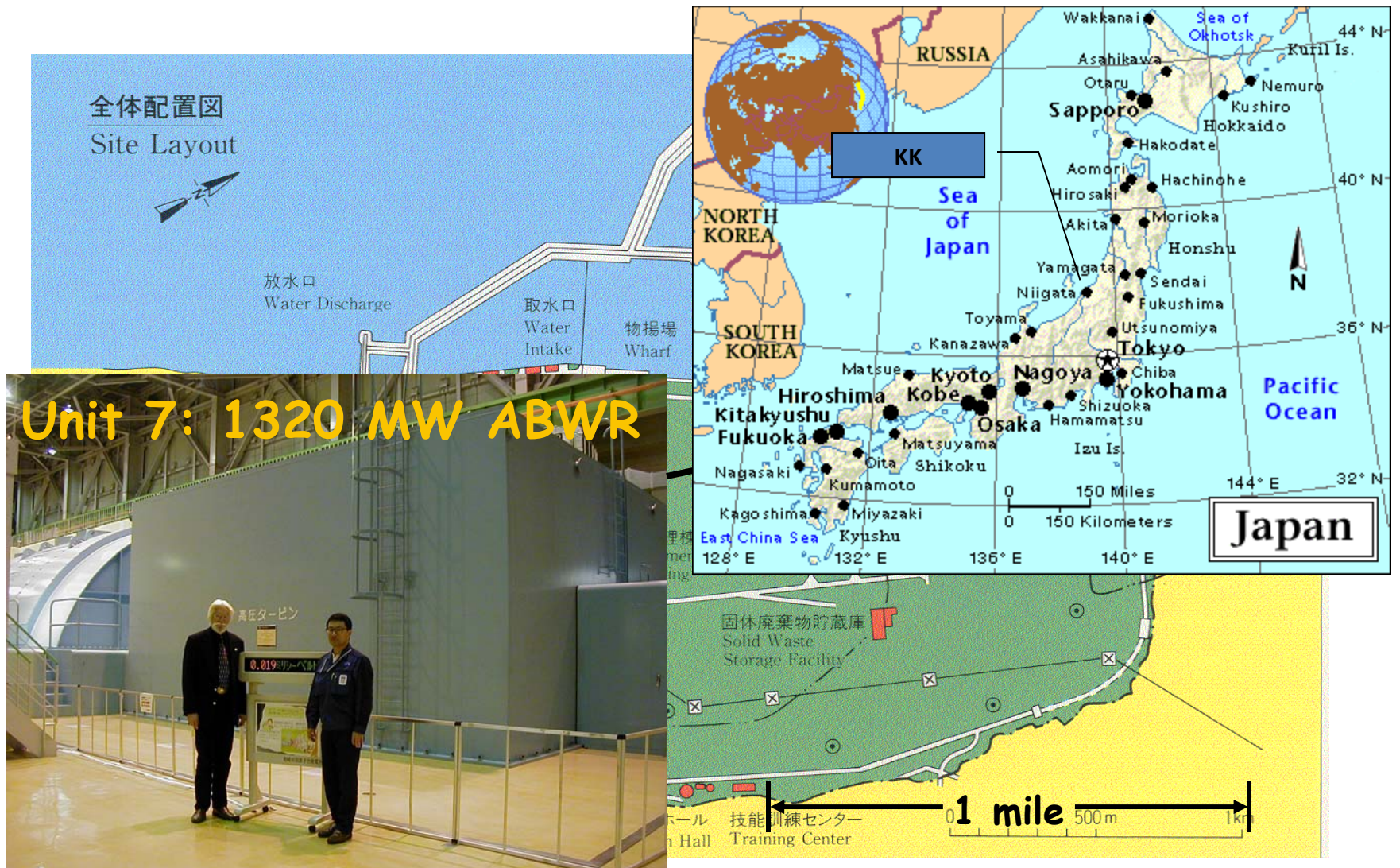


# JNFL Rokkasho Reprocessing Plant



<http://www.jnfl.co.jp/english/contact/visitor-center.html>

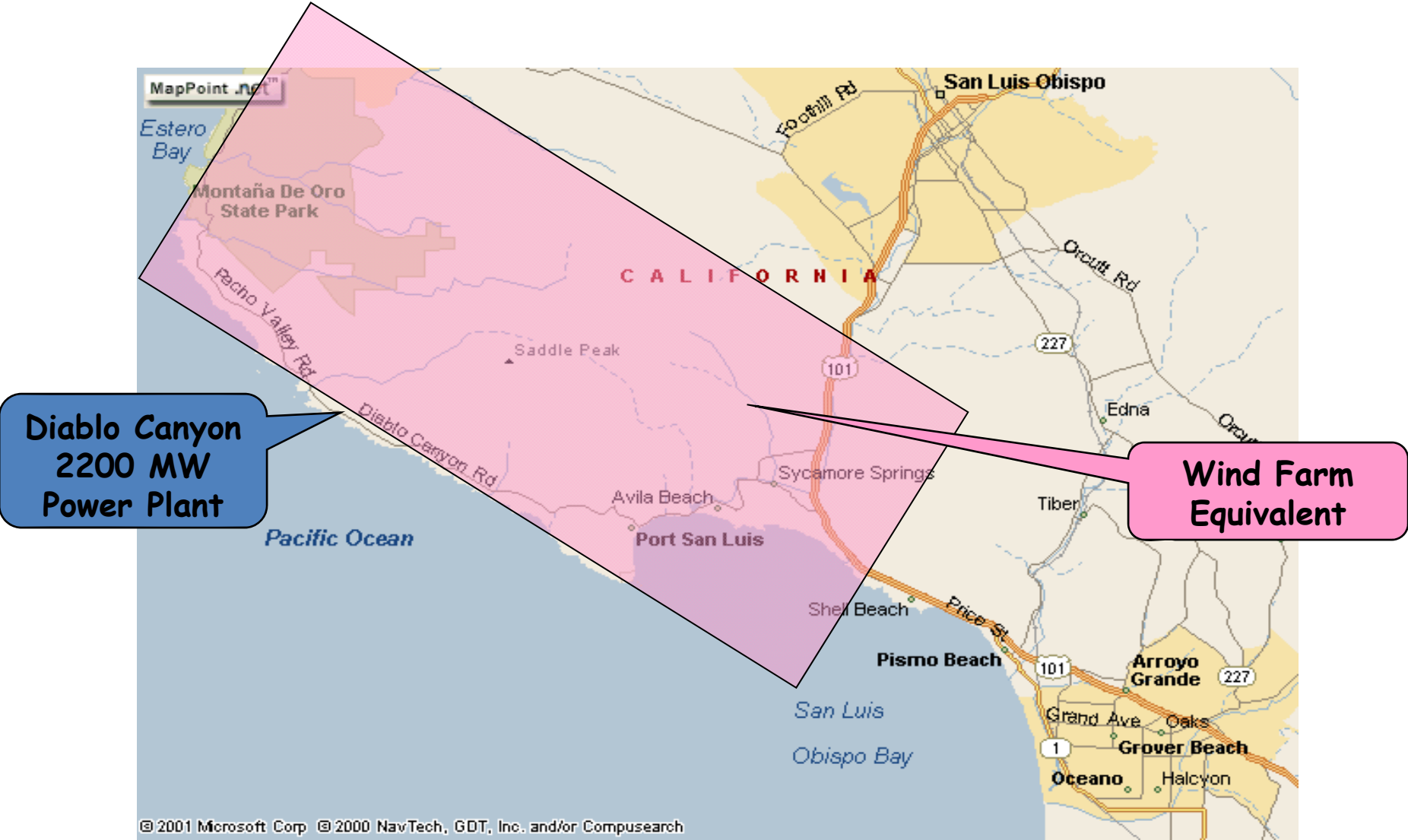
# Kashiwazaki Kariwa: 8000 MW



# Diablo Canyon



# California Coast Power



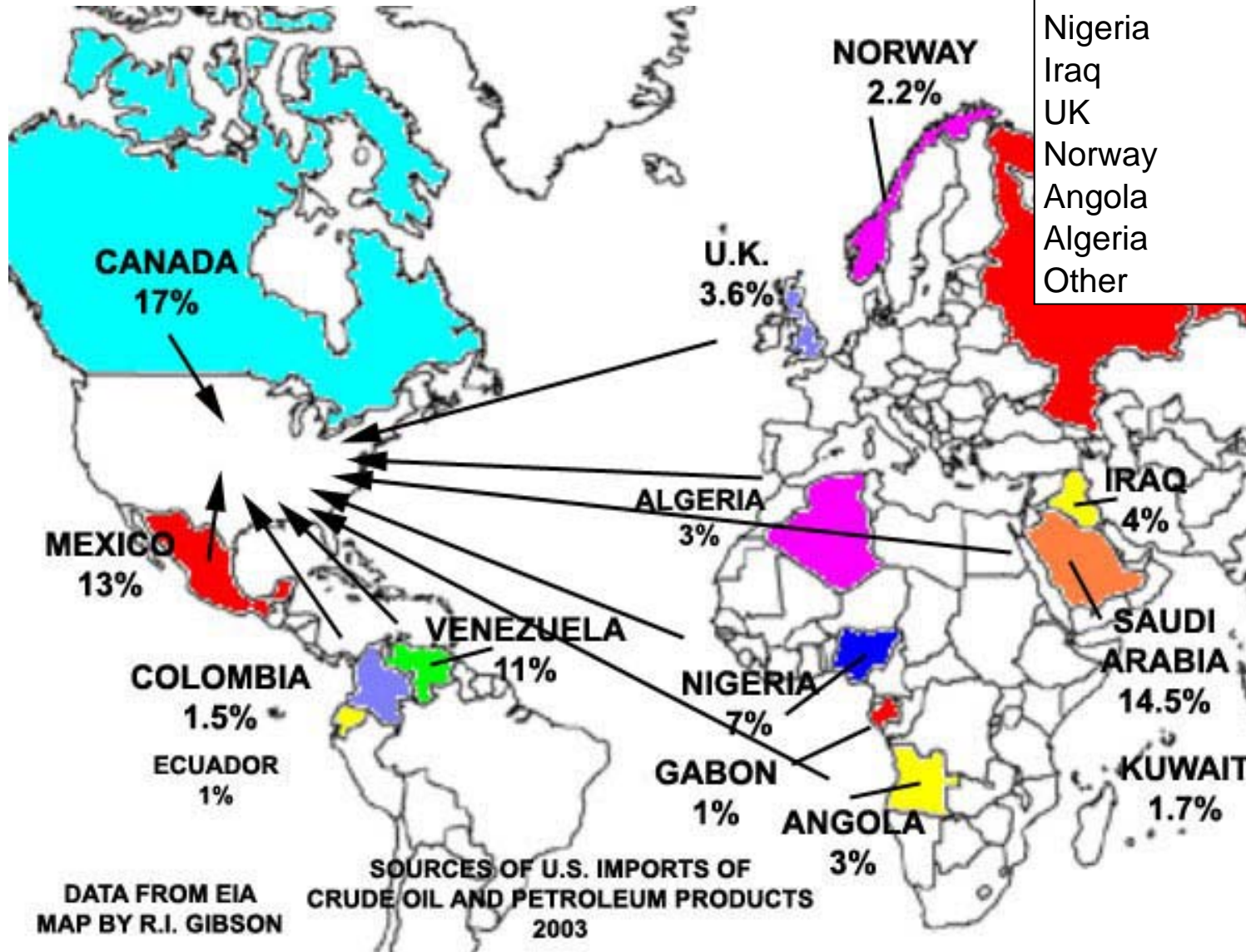
# Hydrogen

# Overview of a Hydrogen Economy

P.M. Grant, "Hydrogen lifts off...with a heavy load," *Nature* 424, 129 (2003)

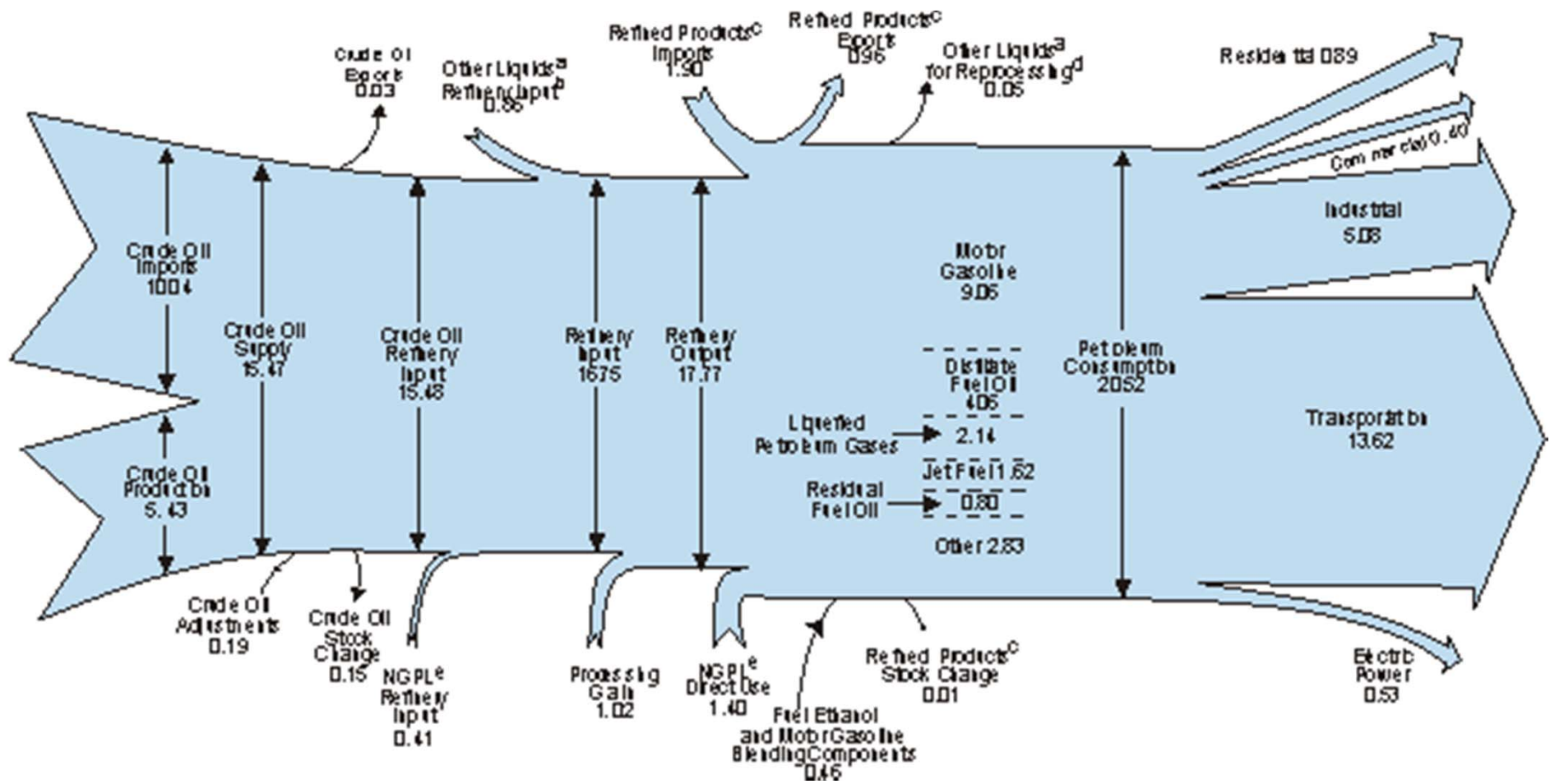
- How much oil do we produce and import?
- Can we replace the portion used for domestic surface transportation with hydrogen?
  - You're going to have to make a lot of hydrogen!
  - How will we make it?
  - Obviously from water, but from how much water?
  - Any side effects?

# US Oil Imports (2003)

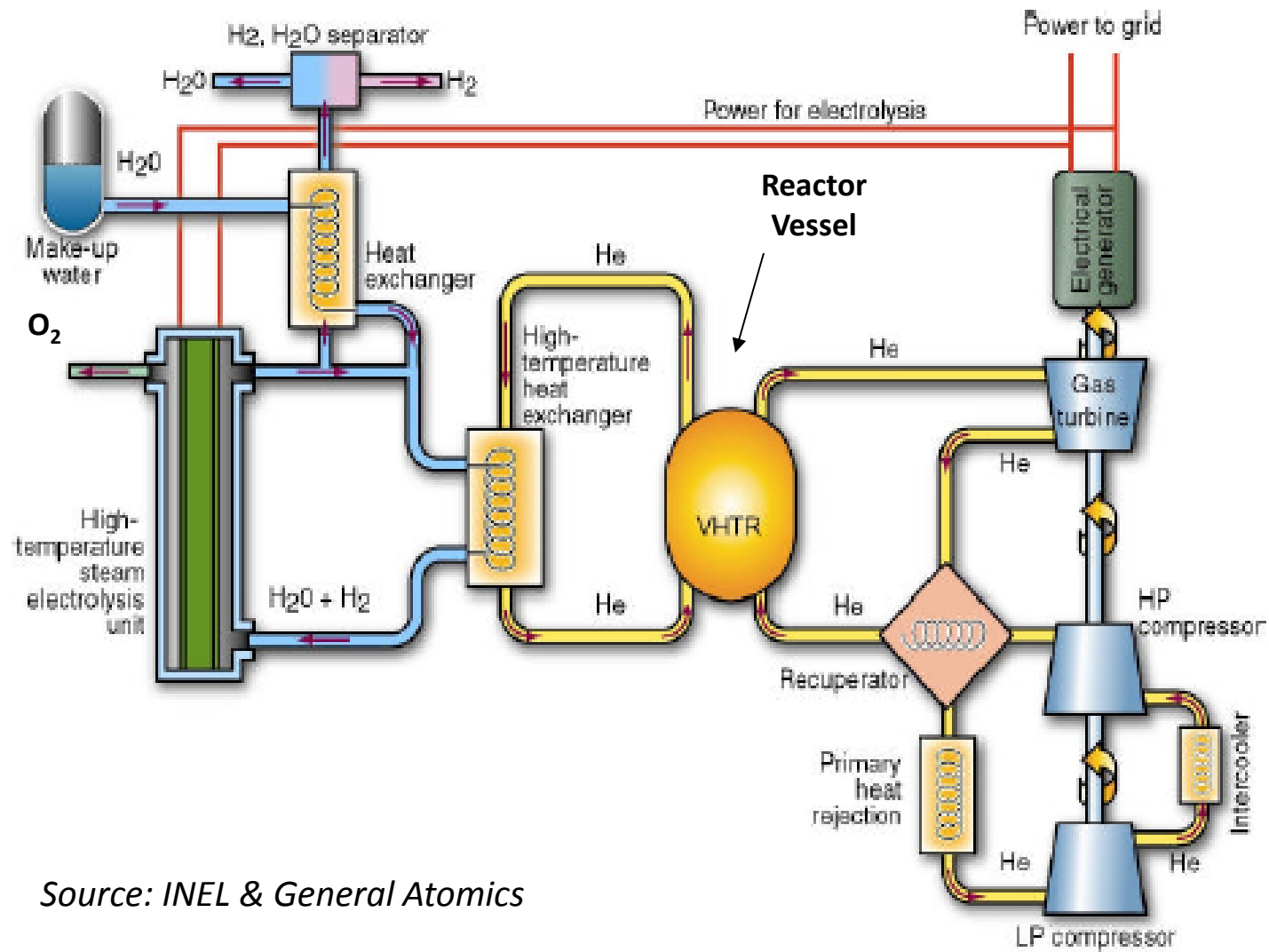


US	39%
Canada	13%
Saudi Arabia	10%
Mexico	10%
Venezuela	9%
Nigeria	4%
Iraq	4%
UK	3%
Norway	3%
Angola	2%
Algeria	2%
Other	2%

# Oil: Source to End Use (2005)



# Co-Production of Hydrogen and Electricity



Source: INEL & General Atomics

# Hydrogen for US Surface Transportation

“You have to make a lot of it”

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

P.M. Grant, “Hydrogen lifts off...with a heavy load,” *Nature* 424, 129 (2003)

### Factoids & Assumptions

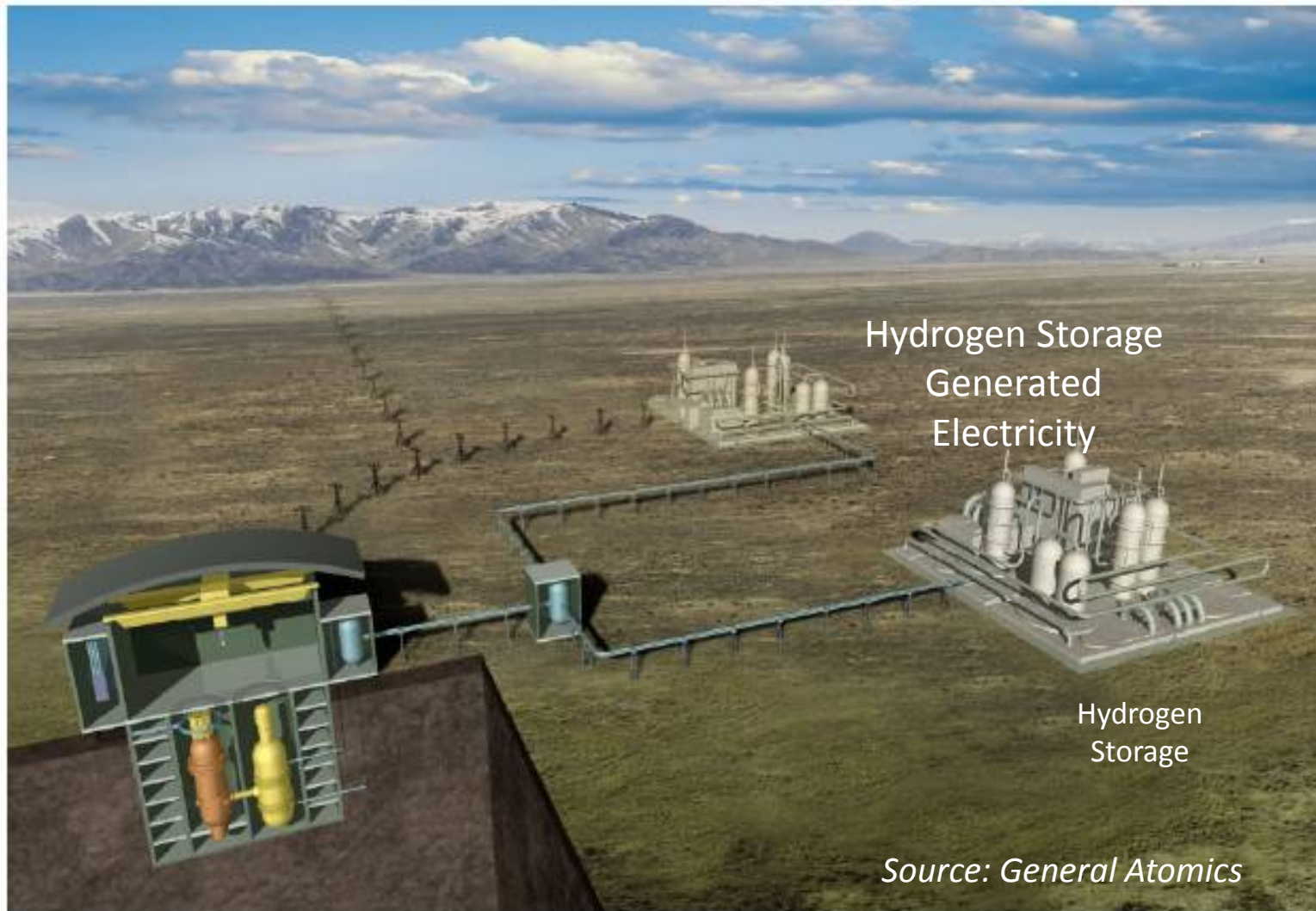
Daily consumption of gasoline and diesel by US cars & Trucks	8.6 Billion barrels/day
Effective Otto Cycle Efficiency (Useful conversion to drive chain)	25 %
Water Electrolysis Efficiency (Source Electricity-to-Hydrogen)	80 % (aggressive)
Fuel Cell Efficiency (Onboard Hydrogen-to-Electricity)	80 % (very aggressive)
Conversion/drive chain Efficiency	80 % (nominal)
Additional Electric Generation Plant Capacity for Hydrogen Vehicles	<b>400 GW</b>

# Hydrogen for US Surface Transportation: Generation by Renewable Electricity

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

Land Area Required to Supply by Renewables		
Technology	Area (km <sup>2</sup> )	Equivalent
Wind	130,000	New York State
Solar	20,000	50% Denmark Death Valley + Mojave
Biomass	271,915	3% USA State of Nevada

# Nuclear “Hydricity” Production Farm



# Hydrogen for US Surface Transportation: Water Requirements

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

Hydrogen per	
Tonnes	Shuttles
230,000	2,225

Water per D	
Tonnes	Surface
2,055,383	



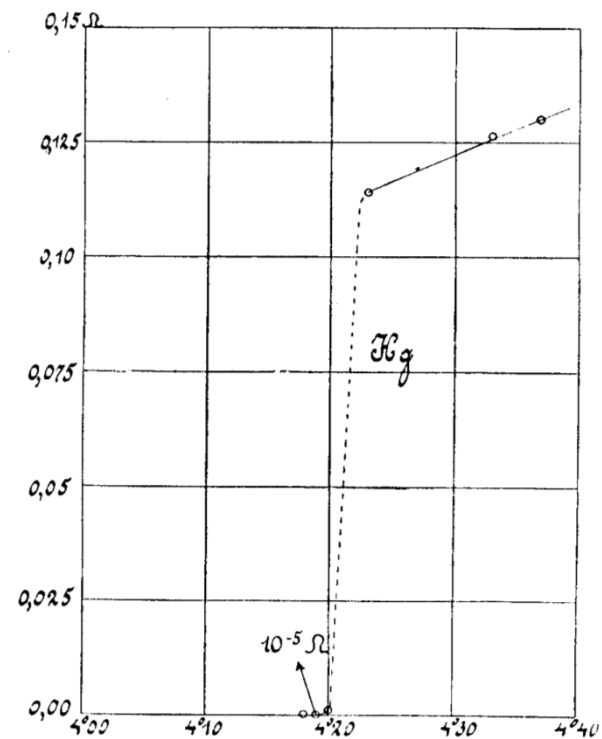
# Super Conductors

# 1911: A Big Surprise!

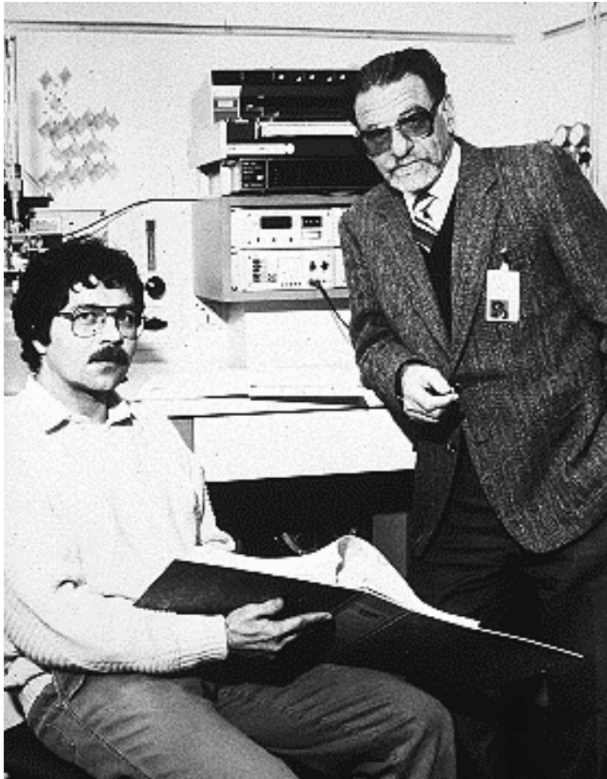


Thus the mercury at 4.2 K has entered a new state, which, owing to its particular electrical properties, can be called the state of *superconductivity*

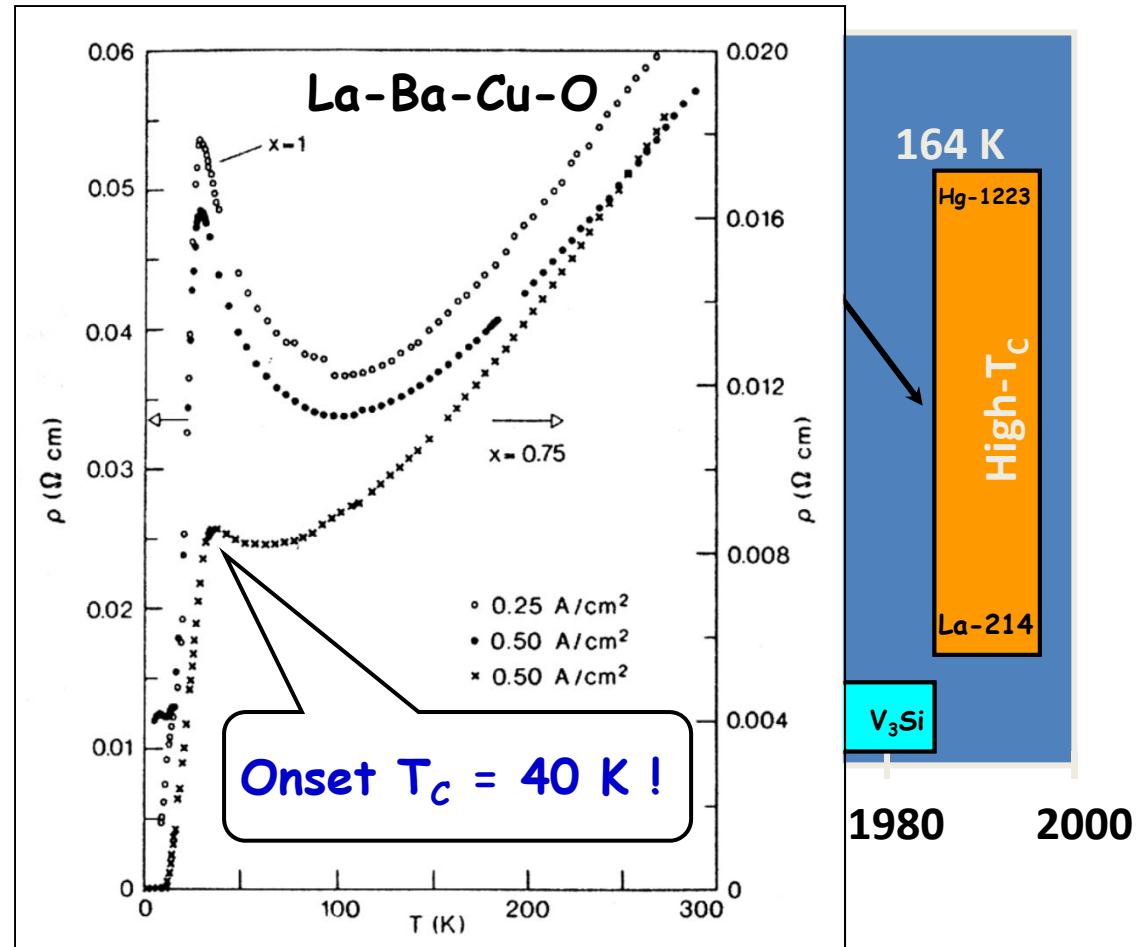
H. Kamerlingh-Onnes (1911)



# 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*

# Woodstock of Physics NYC, 1987

## Physicists' Night Out!

WHAT IS MORE EXCITING THAN  
**High T<sub>c</sub> — Physics Art!**

PAM DAVIS  
STEVE KIVELSON  
DAN ROXBAR and  
SHAHAB ETEMAD

**LIMELIGHT**

FOR DANCING  
AT NEW YORK'S MOST FASHIONABLE NIGHTCLUB

● ● ● ● THURSDAY, MARCH 19, 1987 ● ● ● ●

DOORS OPEN 10:00 PM SHARP  
DANCING ALL NIGHT

COMPLIMENTARY ADMISSION FOR YOU AND A GUEST WITH THIS INVITATION  
212 671-16-3000

THIS INVITATION CANNOT BE SOLD OR TRANSFERRED

## Woodstock of physics revisited

commentary

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 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 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



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

intensely human pursuit—something they do not teach you in graduate school.

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 Cal-

ifornia, 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.

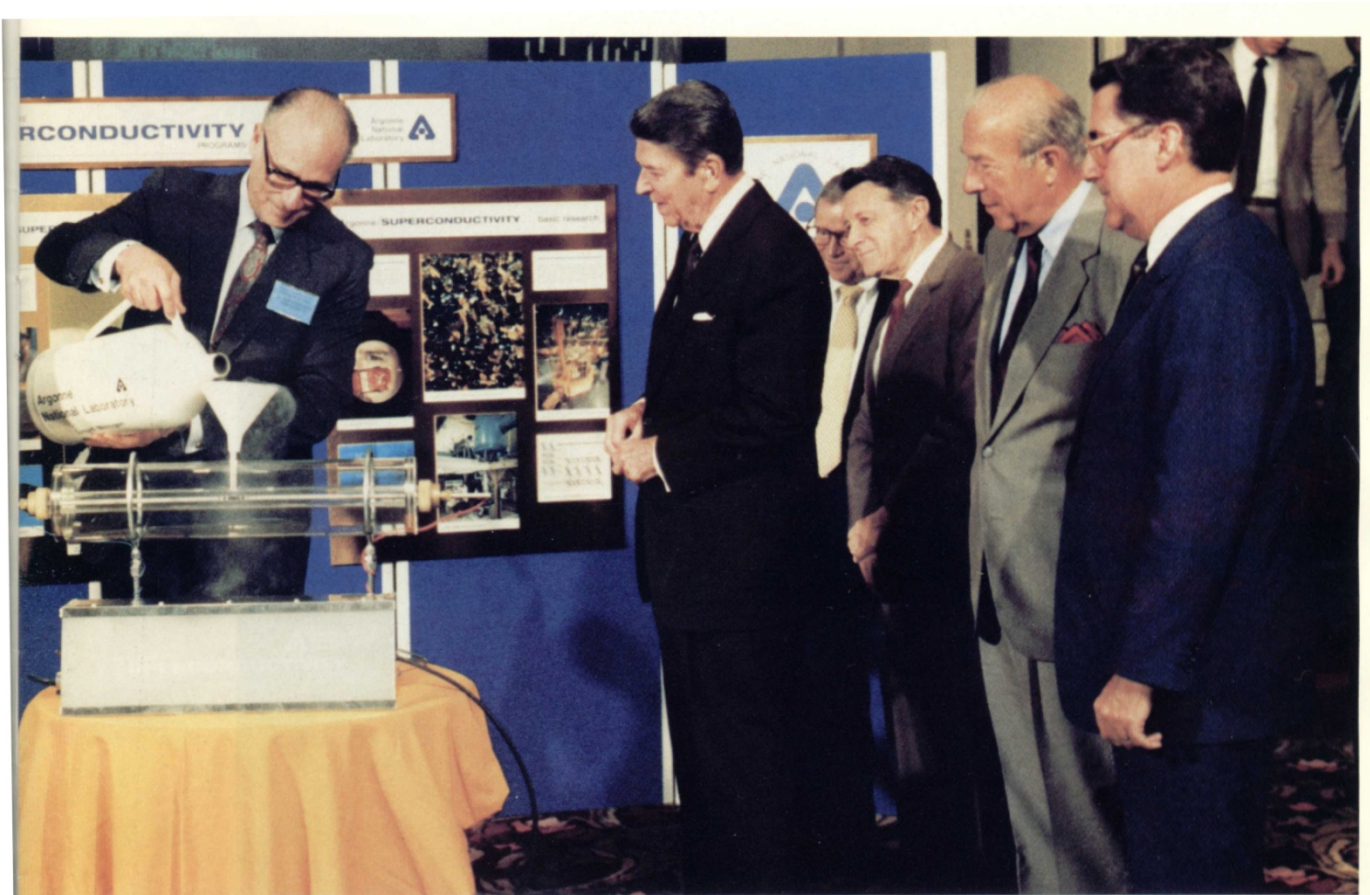
### Opening act

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.



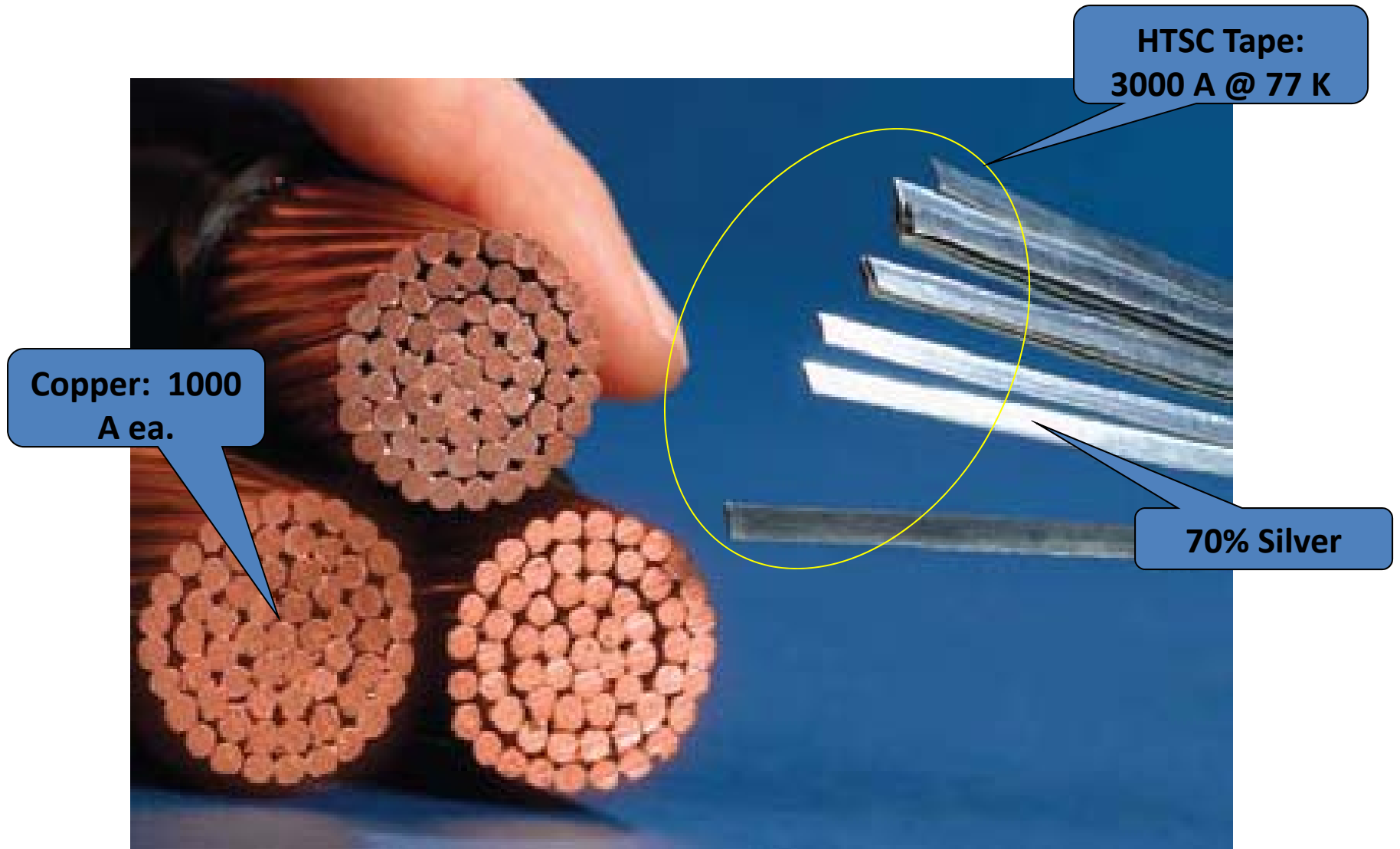
Fever pitch: the room filled with physicists eager for news of superconductivity.

# “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.*

# HTSC Tape (AMSC)



# Finished Cable



# Puji Substation (Kunming City)



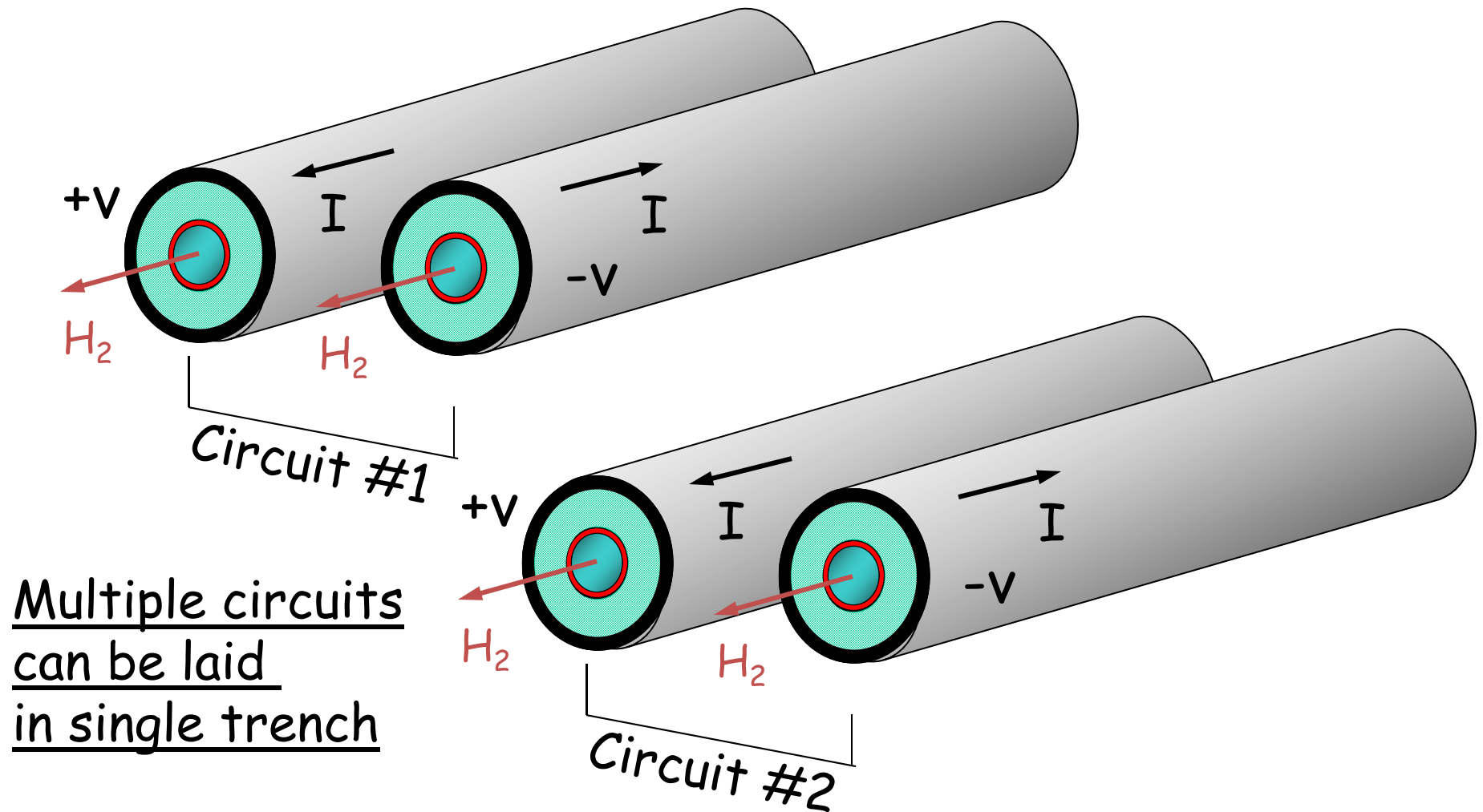
# Requies Jes' Minimal Skill Level



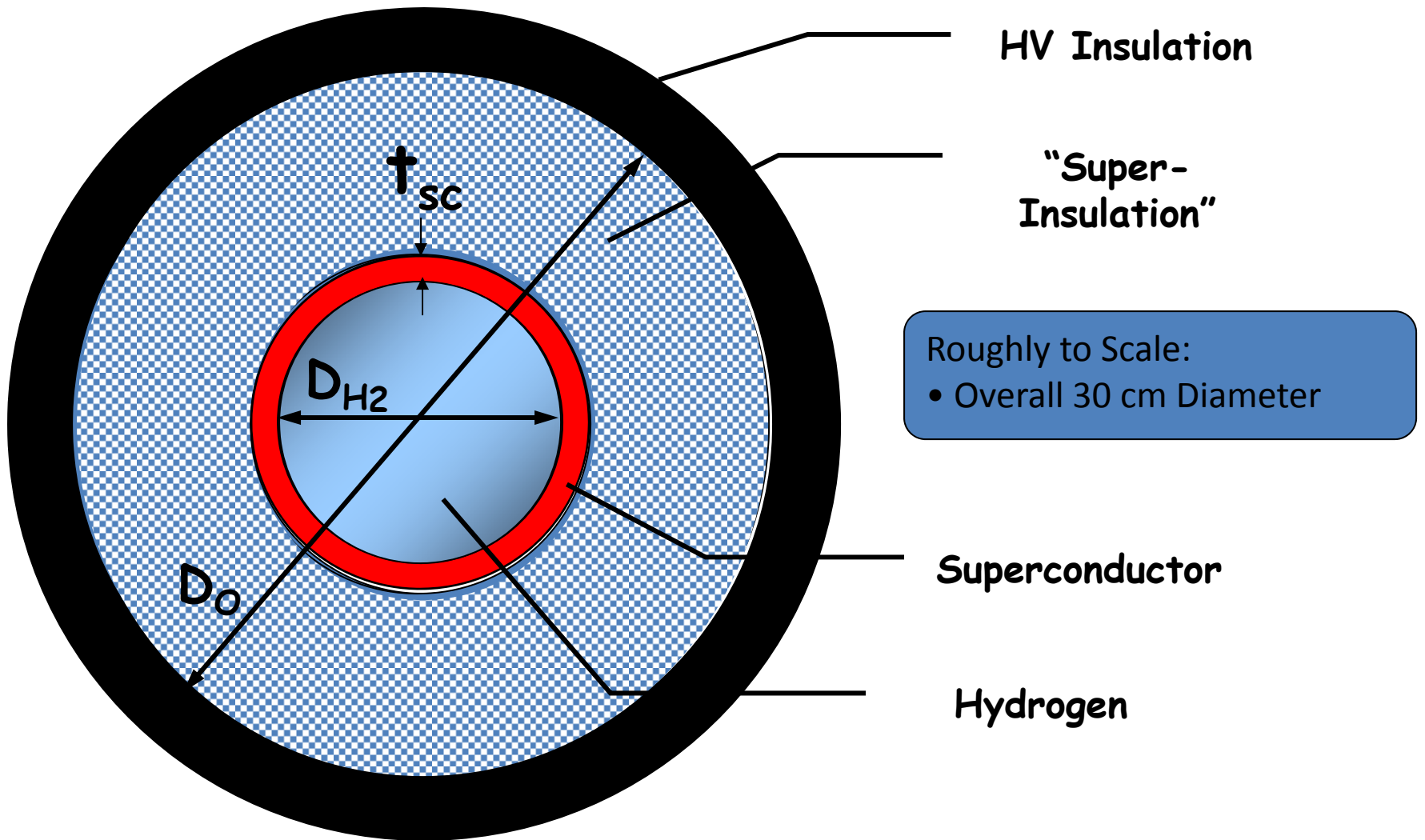
- Harvard PhD...OK
- But...
- Ya gotta pass the IBEW apprentice exam too!

# Hydricity SuperCables

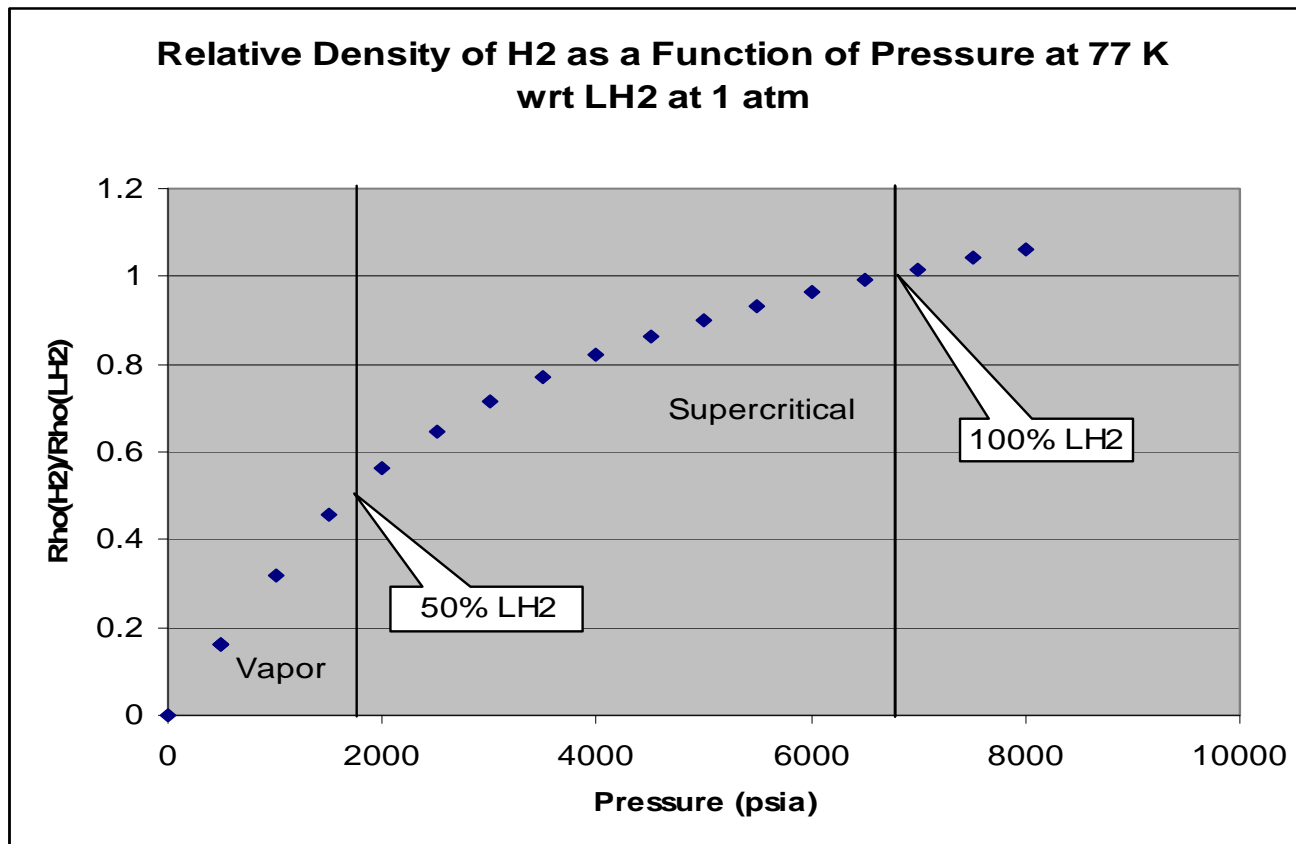
# “Hydricity” SuperCables: “Proton/Electron Power (PEP) to the People”



# LH<sub>2</sub> SuperCable

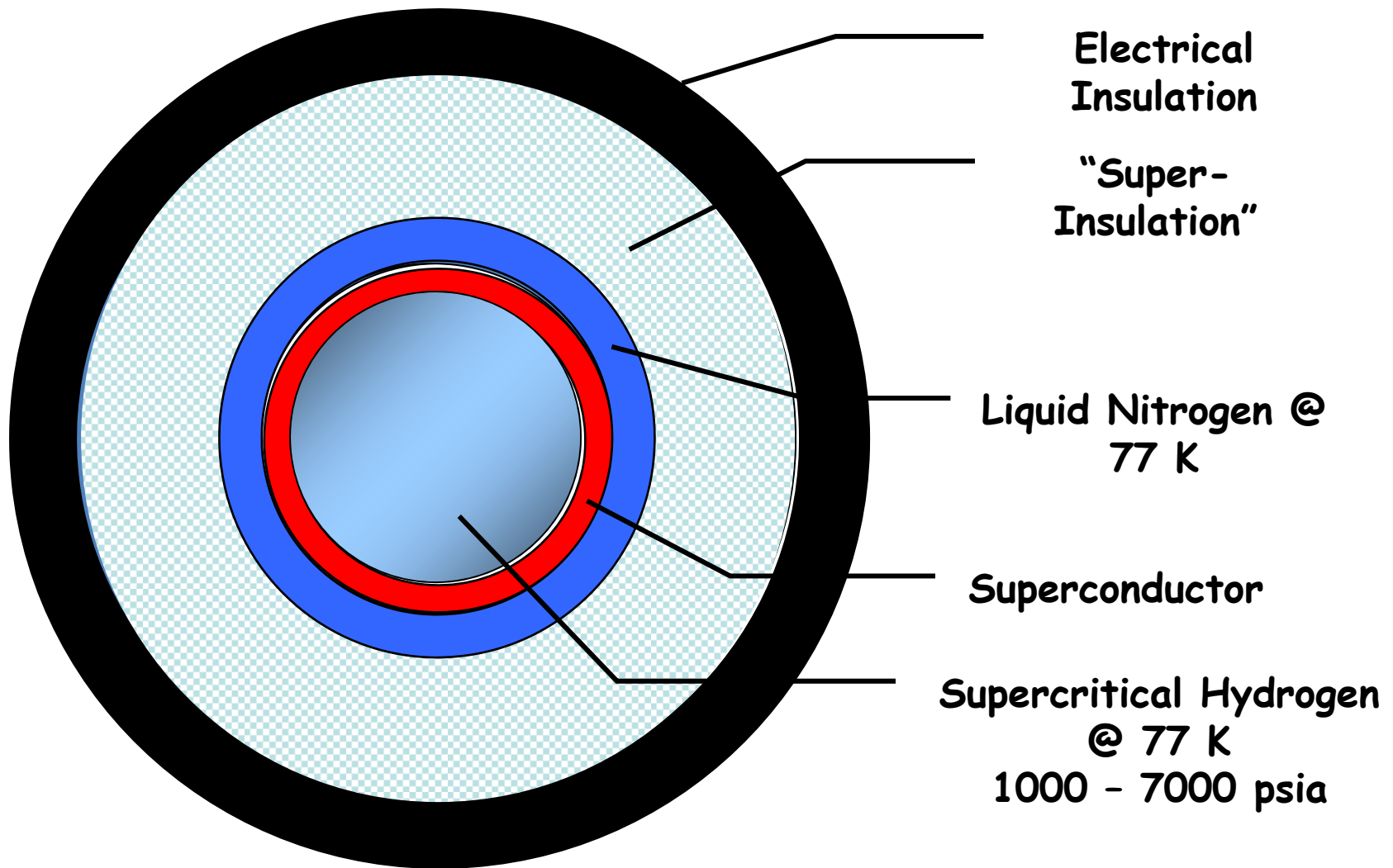


# Hydrogen Mass-Density Energy Content



**H<sub>2</sub> Gas at 77 K and 1850 psia has 50% of the energy content of liquid H<sub>2</sub> and 100% at 6800 psia**

# Supercritical H<sub>2</sub> SuperCable



# Relative Power Flows

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

Electricity

$P_{SC}$  = Electric power flow

$V$  = Voltage to neutral (ground)

$J$  = Supercurrent density

$A_{SC}$  = 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  $H_2$ )

$\rho$  =  $H_2$  Density

$v$  =  $H_2$  Flow Rate

$A$  = Cross-sectional area of  $H_2$  cryotube

# Hydricity Scaling Factor

Dimensionless, geometry-independent scaling factor defines relative amounts of electricity/hydrogen power flow in the SuperCable:

$$R_{e/h} \equiv (J / Q\rho)(|V| / v)$$

“Energy Density”

“Pressure”

# SuperCable H<sub>2</sub> 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 LH<sub>2</sub>**

**LH<sub>2</sub> in 10 cm diameter,  
250 mile bipolar SuperCable  
= Raccoon Mountain**



# Super Grids

# US Natural Gas Imports (BCF – 2003)

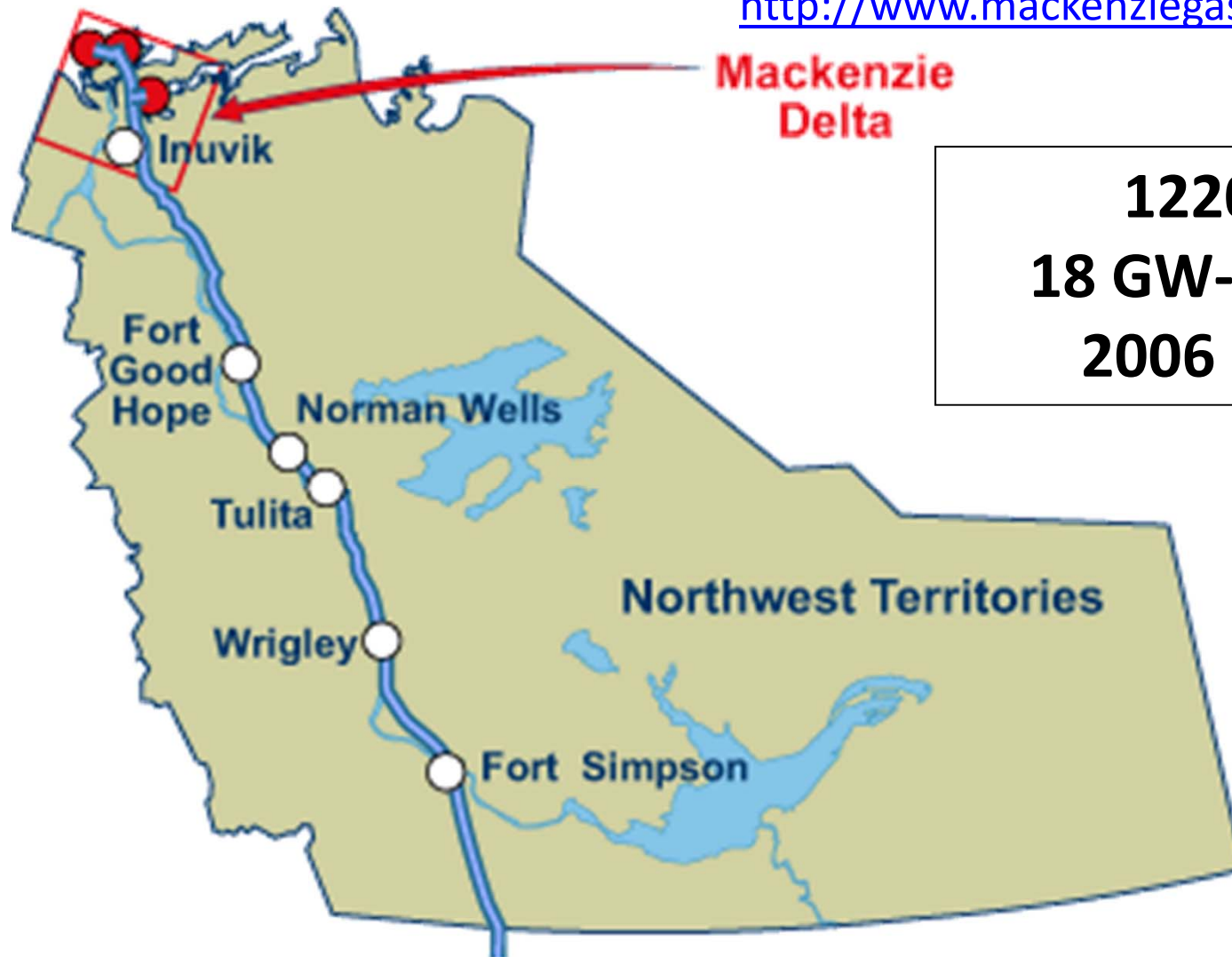


# A Canadian's View of the World



# The Mackenzie Valley Pipeline

<http://www.mackenziegasproject.com>



**1220 km**  
**18 GW-thermal**  
**2006 - 2010**

## MVP Specs

Pipeline Length	1220 km (760 mi)
Diameter	30 in (76 cm)
Gas Pressure	177 atm (2600 psia)
Pressurization Stations	~250 km apart
Flow Velocity	5.3 m/s (12 mph)
Mass Flow	345 kg/s
Volume Flow	1.6 Bcf/d (525 m <sup>3</sup> /s)
Power Flow	18 GW (HHV Thermal)
Construction Schedule	2006 - 2010
Employment	25,000
Partners	Esso, APG, C-P, Shell, Exxon
Cost	\$18 B (all private)

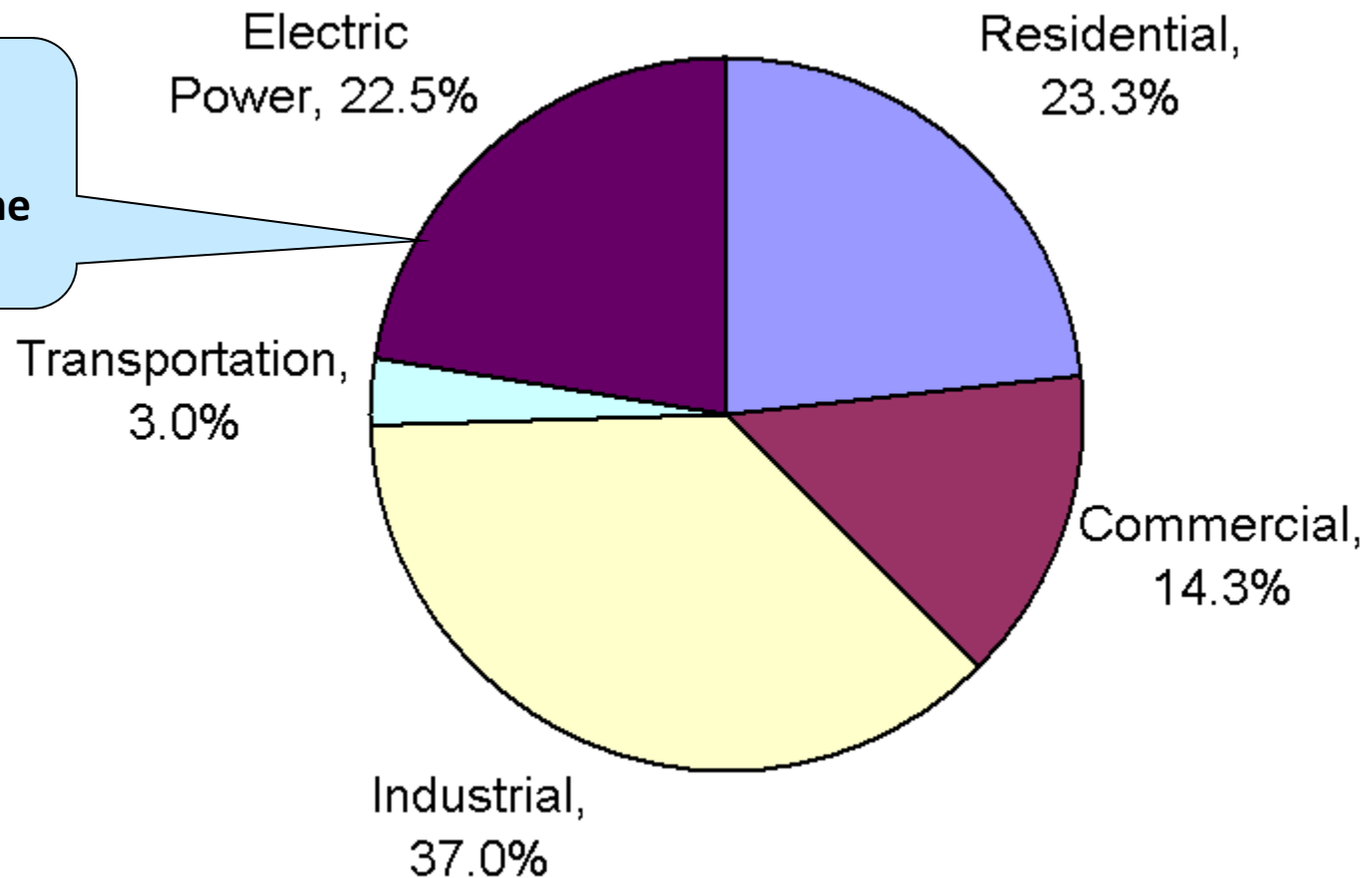
# Constructing Gas Pipelines



# 2004 Natural Gas End Use

Schoenung, Hassenzahl and Grant, 1997  
(5 GW on HTSC @ LN<sub>2</sub>, 1000 km)

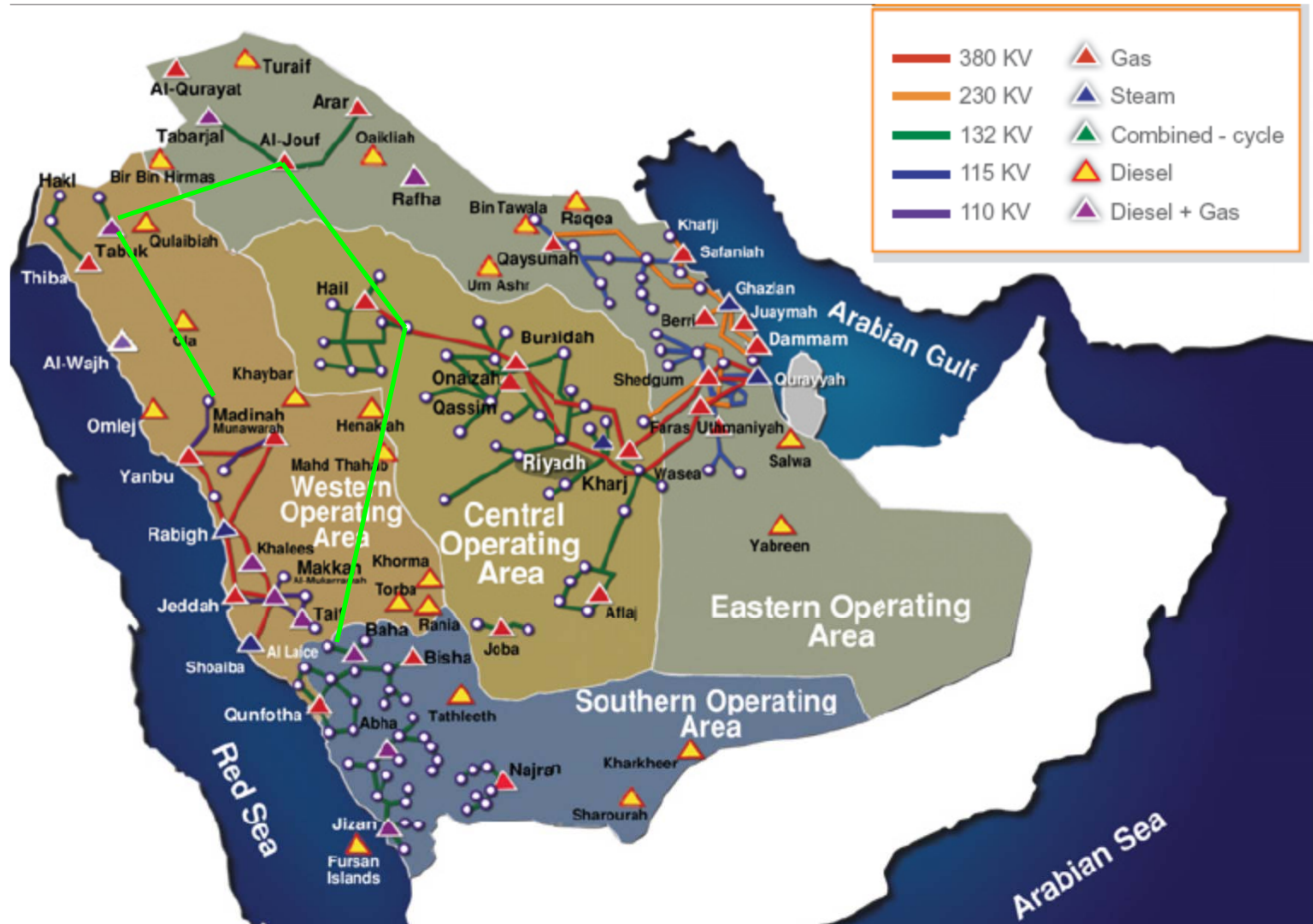
Why not  
generate this  
electricity at the  
wellhead?



# It's 2030

- *The Gas runs out!*
- We have built the LNG SuperCable years before
- Put HTCGR Nukes on the now empty gas fields to make hydrogen and electricity (some of the electricity infrastructure, e.g., I/C stations, already in place)
- Enable the pre-engineered hydrogen capabilities of the LNG SuperCable to now transport protons and electrons.

# It's 2010...And the Oil is Running Out

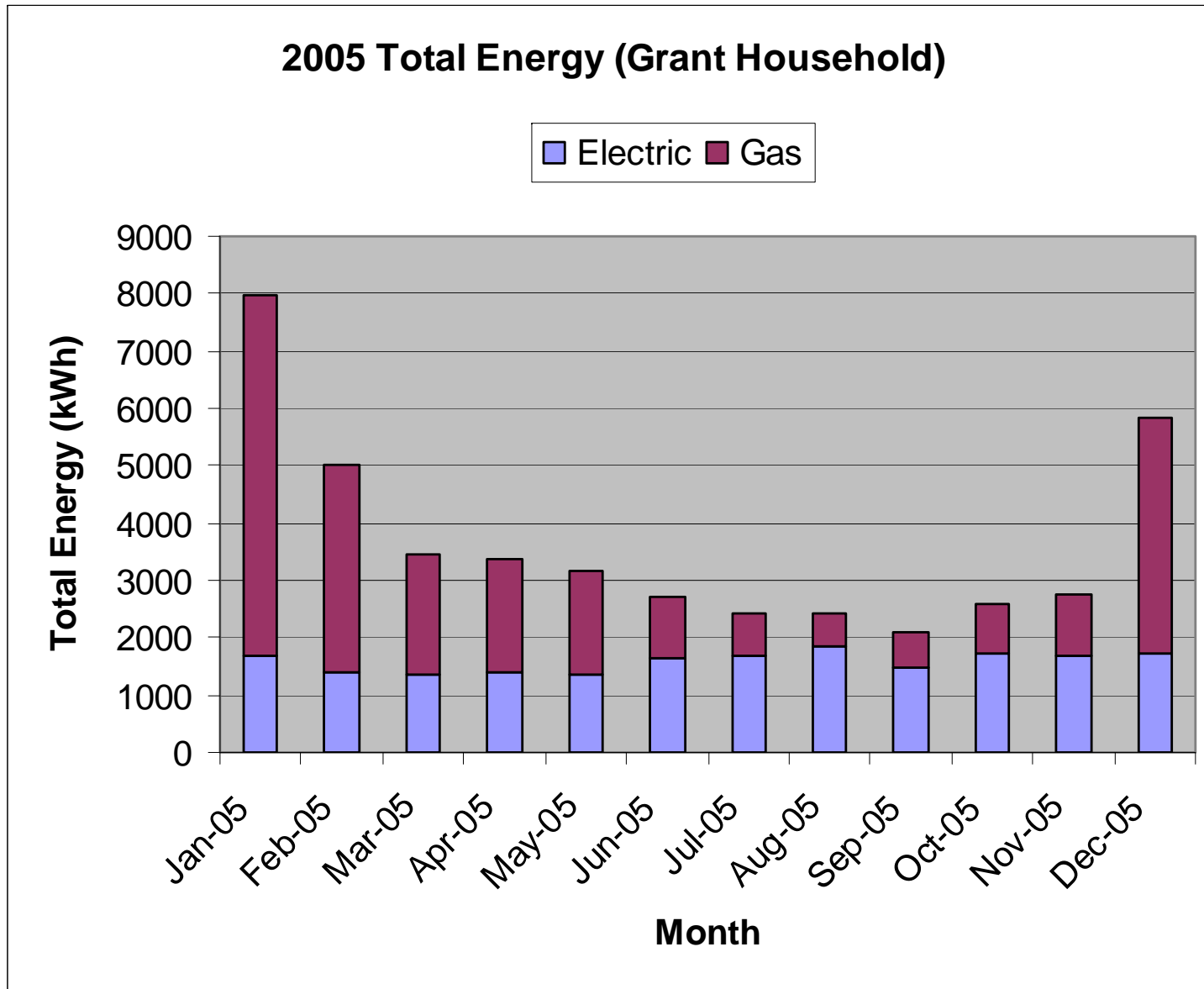


# SuperCities & SuperSuburbs

# SuperSuburb Parameters

- Electricity for residential appliances, lighting, space conditioning and cooking
- Hydrogen for storage of electricity and personal transportation
- Off the Agenda:
  - Commercial business; shopping centers
  - Electric rail/rapid transport
  - Street lighting

# California Living!



## Baseline Electric Power and Energy Storage Requirements per GHE in SuperSuburb

Baseline Power (kW)	Energy Stored (kWh)	Hydrogen Mass Equivalent (kg)	Volume as Liquid (21 K, 14.7 psia) (cube edge in meters)	Volume as Gas (300 K, 2000 psia) (cube edge in meters)
5.99	6129	187	1.38	2.63

## GHE Transportation Energy Consumed

Miles/Year	DOE H <sub>2</sub> Mileage (kWh/mile)	H <sub>2</sub> Daily Mass Consumption (kg)	SuperCable H <sub>2</sub> Delivery Power (kW)
30,000	0.76	1.91	2.61

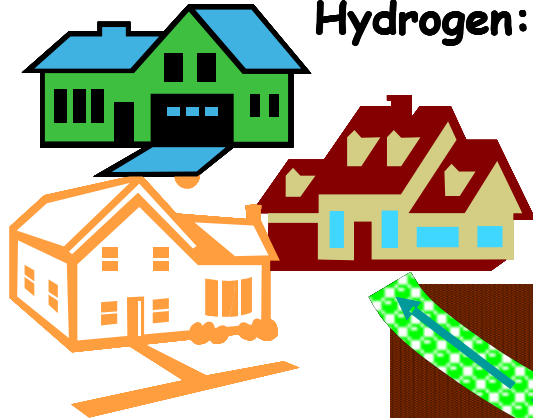
## Baseline Electric and Hydrogen Power Needs of a “San Jose” SuperSuburb of GHEs

GHE Households	Base Electric Power (MW)	Electricity to be Stored as H <sub>2</sub> (tonnes)	Base H <sub>2</sub> Power (MW)	H <sub>2</sub> Stations
300,000	1798	56,104	782	748

# The Cryogenic Neighborhood

## SuperSuburb

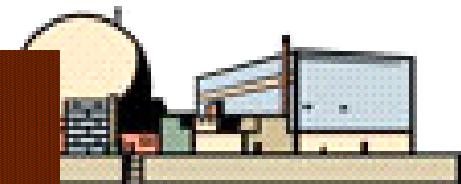
Households: 300,000  
Electricity: 1800 MW  
Hydrogen: 800 MW



~ "San Jose"

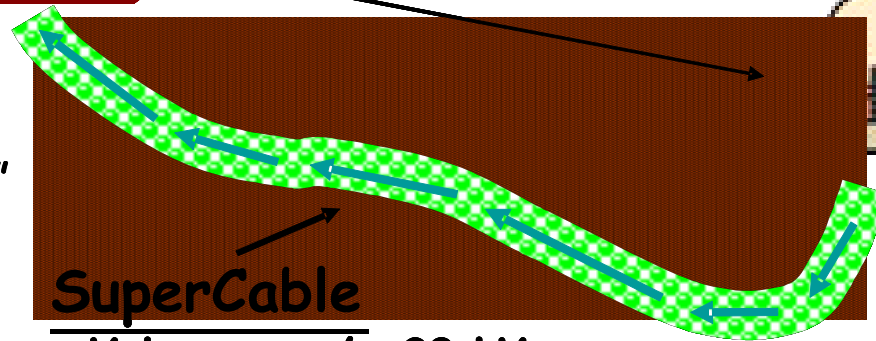
## SuperNuke

electrons + protons  
=> 2600 MW



~ "Diablo Canyon"

250 km

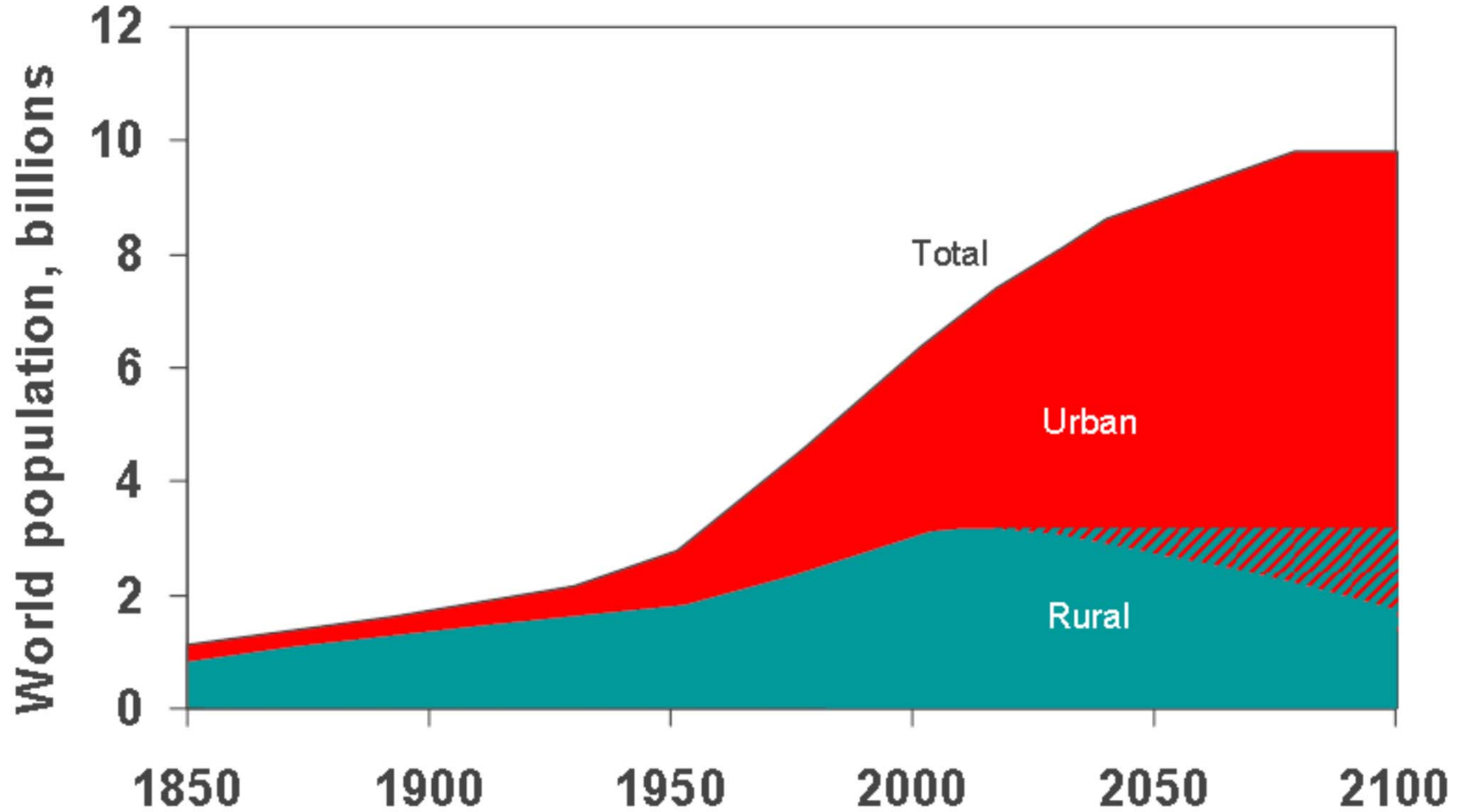


## SuperCable

Voltage: +/- 20 kV  
Current: 45 kA  
H<sub>2</sub> Storage: 28 GWh  
H<sub>2</sub> Flow: 2 m/s => 6.8 kg/s

**Finale**

# World Population: 1850 - 2100



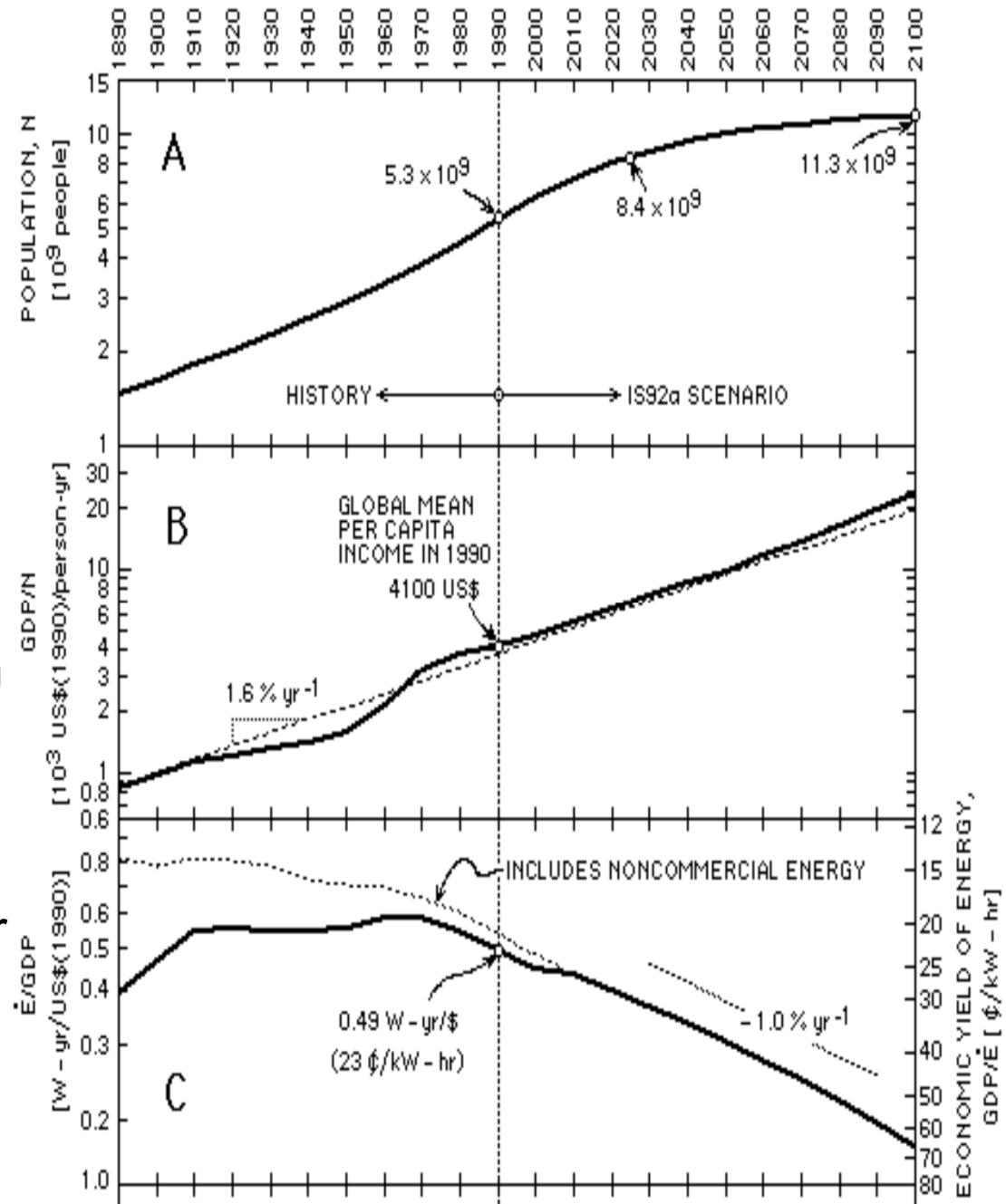
From Global Energy  
Perspective – 2007

Nate Lewis, Cal Tech

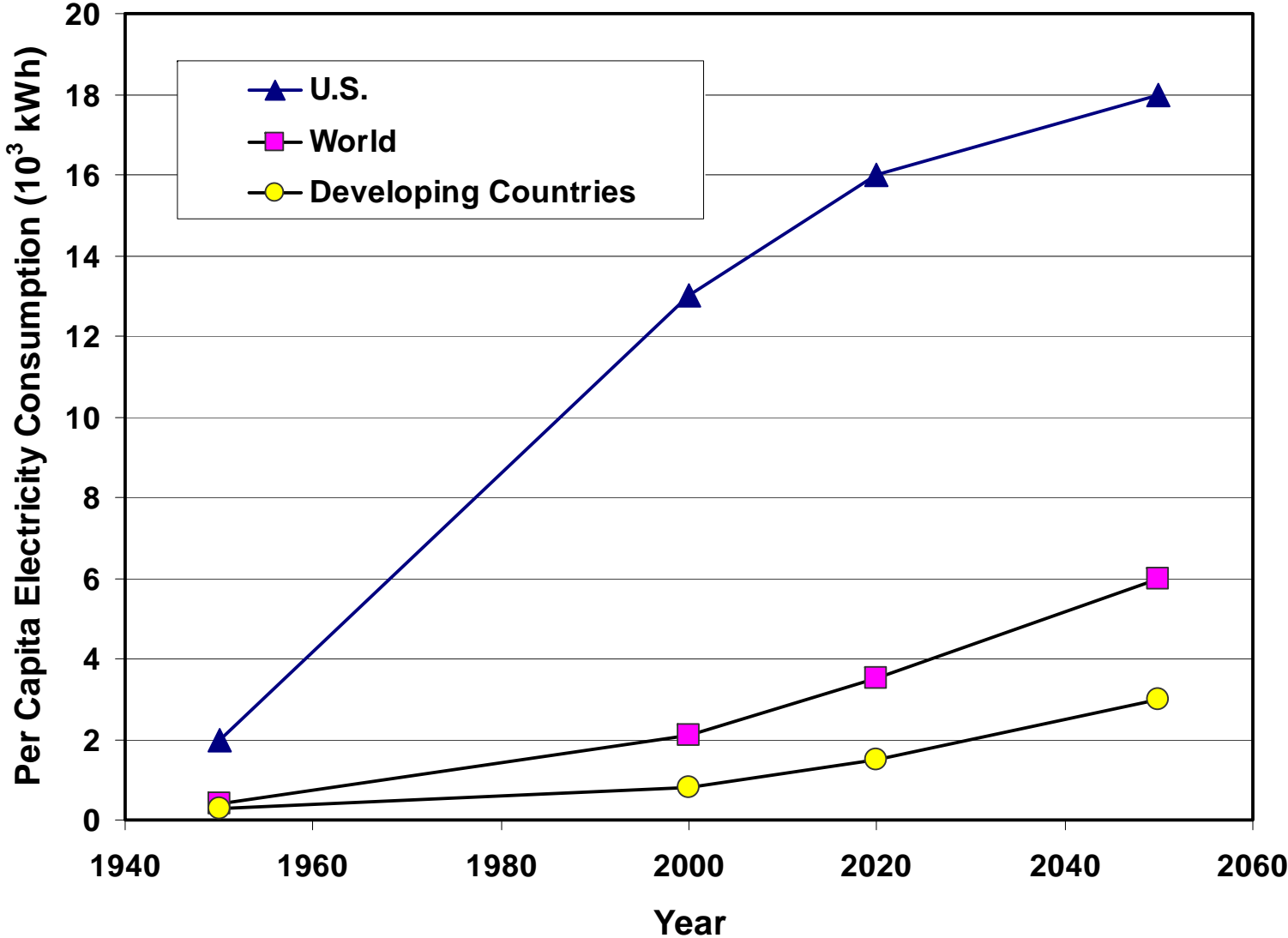
Population Growth to  
10 - 11 Billion People  
in 2050

Per Capita GDP Growth  
at 1.6% yr<sup>-1</sup>

Energy consumption per  
Unit of GDP declines  
at 1.0% yr<sup>-1</sup>



# Trends in Per Capita Electricity Consumption



# Enfranchisement of Women



...But There Are Always Exceptions!



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

*Proverbs 29:18*

“You can’t always get what you want...”

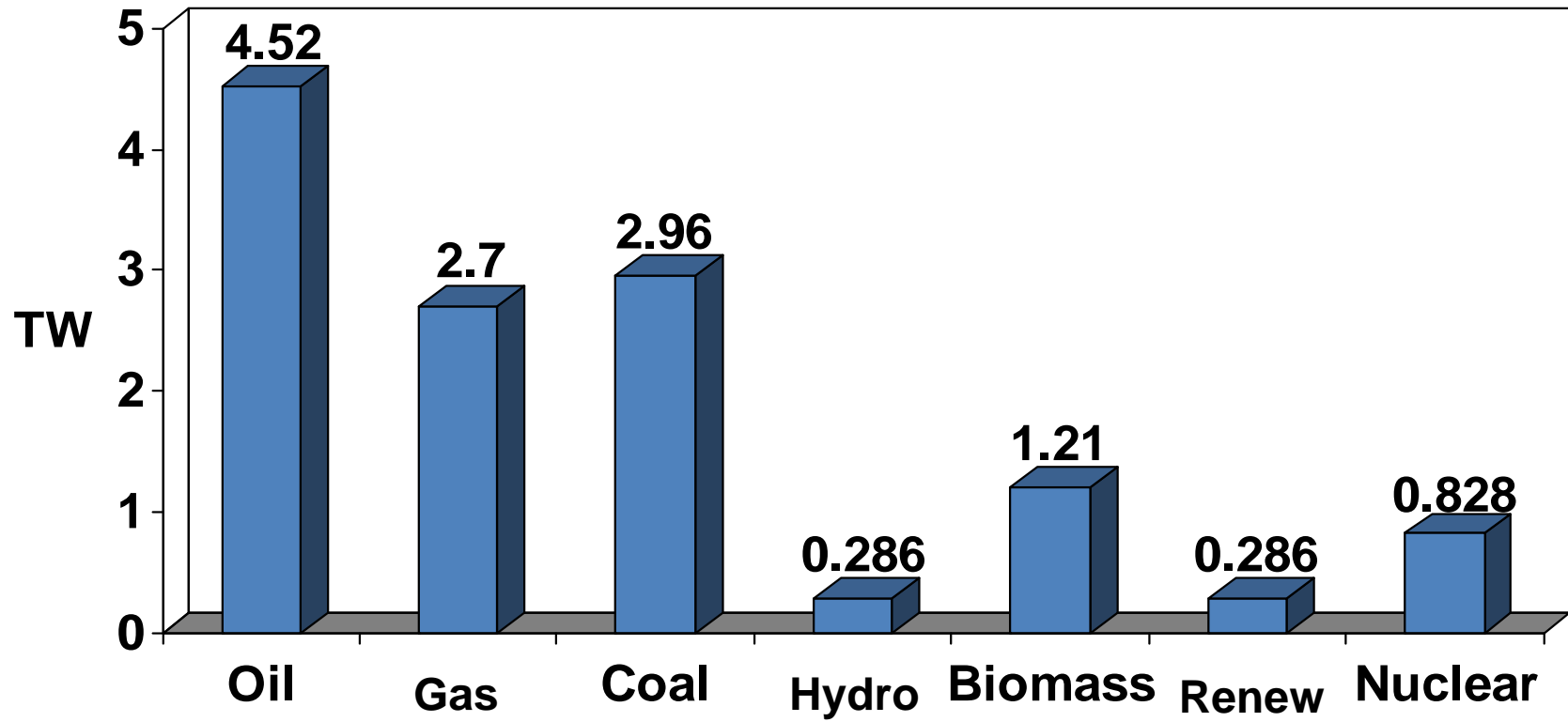


“...you get what you need!”



**Extras**

# Mean Global Energy Consumption 1998



Global Total: 12.8 TW

US: 3.3 TW (99 Quads)

(1 TW Electricity)

# The Trioka Challenge of GCC

- Mitigation
  - If GCC is principally CO<sub>2</sub> emissions-driven:
    - How do we stop or stabilize them?
    - Can we stop or stabilize them?
    - *Does superconductivity have a role?*
- Impact
  - In any event, heat already stored in the oceans will continue to warm the planet?
  - What impact will this have on the human condition?
    - Massive redistribution of land and water resources?
- Adaptation
  - Since continuing warming is inevitable, what technologies need to be developed to ameliorate its impact?
    - *Does superconductivity have a role?*

# Mitigation

- SuperGrid
  - Nuclear
  - Hydrogen
  - Superconductivity (efficiency!)
- DOE PR 1997
  - Transmission savings
  - Rotating machinery
  - Transformers

# A North American Pipedream?



**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).

# 2005 GHE Energy Consumption Statistics

<i>Energy (kWh)</i>	<i>Electricity</i>	<i>CH<sub>4</sub></i>	<i>Total</i>
Annual Total	18894	24882	43776
Monthly Average	1575	2073	3648
Standard Deviation	174	1747	1748
Skewness	-0.15	1.51	1.69
Kurtosis	-1.57	1.88	2.42

# Monthly GHE Consumption

<i>Power (kW)</i>	<i>Electricity</i>	<i>Natural Gas</i>	<i>Total</i>
Monthly Mean	2.16	2.84	4.99
Standard Deviation	0.24	2.39	2.39
Mean + STD	2.39	5.23	7.39
Mean - STD	1.92	0.45	2.60

## Number of GHEs per H<sub>2</sub> Station and Individual Station Capacity

US Households (2005)	Number of Stations (1998)	Households per Station	Turnover Rate (days)	H <sub>2</sub> Mass (kg)	Liquid “cube” (meter)	Gas “cube” (meters)
75,000,000	187,000	401	3	2298	3.2	6.1

## SuperSuburb SuperCable Monopole Minutia and Costs)

HTSC Tape Parameters							
Width (mm)	Thickness (mm)	Length (m)	Total No. Tapes	Tape Req'd (km)	Approx. No. Splices	Tape C/P (\$/kA×m)	HTSC Cost (M\$)
4	0.25	800	~300	~80,000	~100,000	50	591

## SuperSuburb SuperCable Thermal Loss Budget (W/m)

Radiation	Flow Friction	Addenda Loss	1.0 % Ripple	Total
0.70	0.49	0.20	0.09	1.48

## SuperSuburb SuperCable Refrigeration Requirements

Temperature Rise (K/km)	Total Rise for 250 km SuperCable (K)	Permissible Rise Prior to Re-Cool (K)	Total Number of Cooling Stations Required	
0.045	11	1	11	
Station Spacing (km)	Cooling Power per Station (kW)	Cost of Heat Uplift (\$/kW)	Per Station Cost (K\$)	Total Station Cost (M\$)
22.25	32.9	5	164	1.85

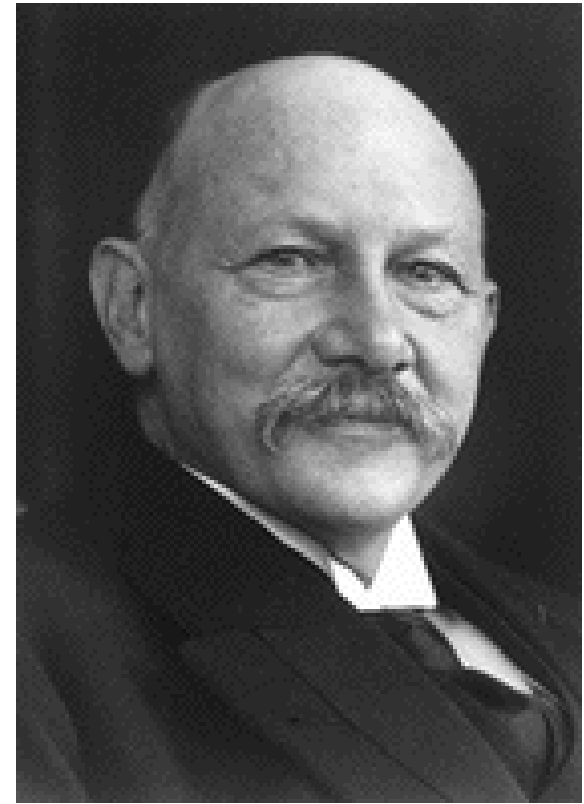
# Fathers of Cryogenics



*James Dewar*

**Dewar**

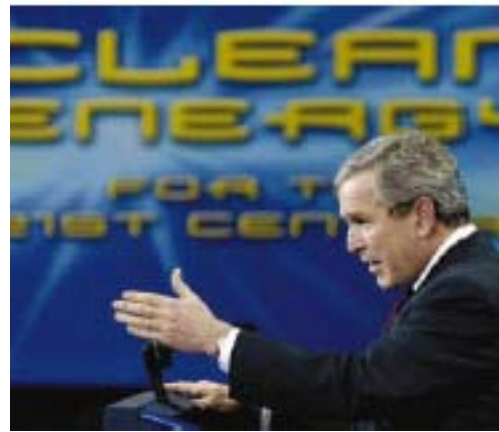
CH <sub>4</sub>	112 K
O	90
N <sub>2</sub>	77
Ne	27
H <sub>2</sub>	20
He	4.2



**Kammerlingh-Onnes**

# Hydrogen

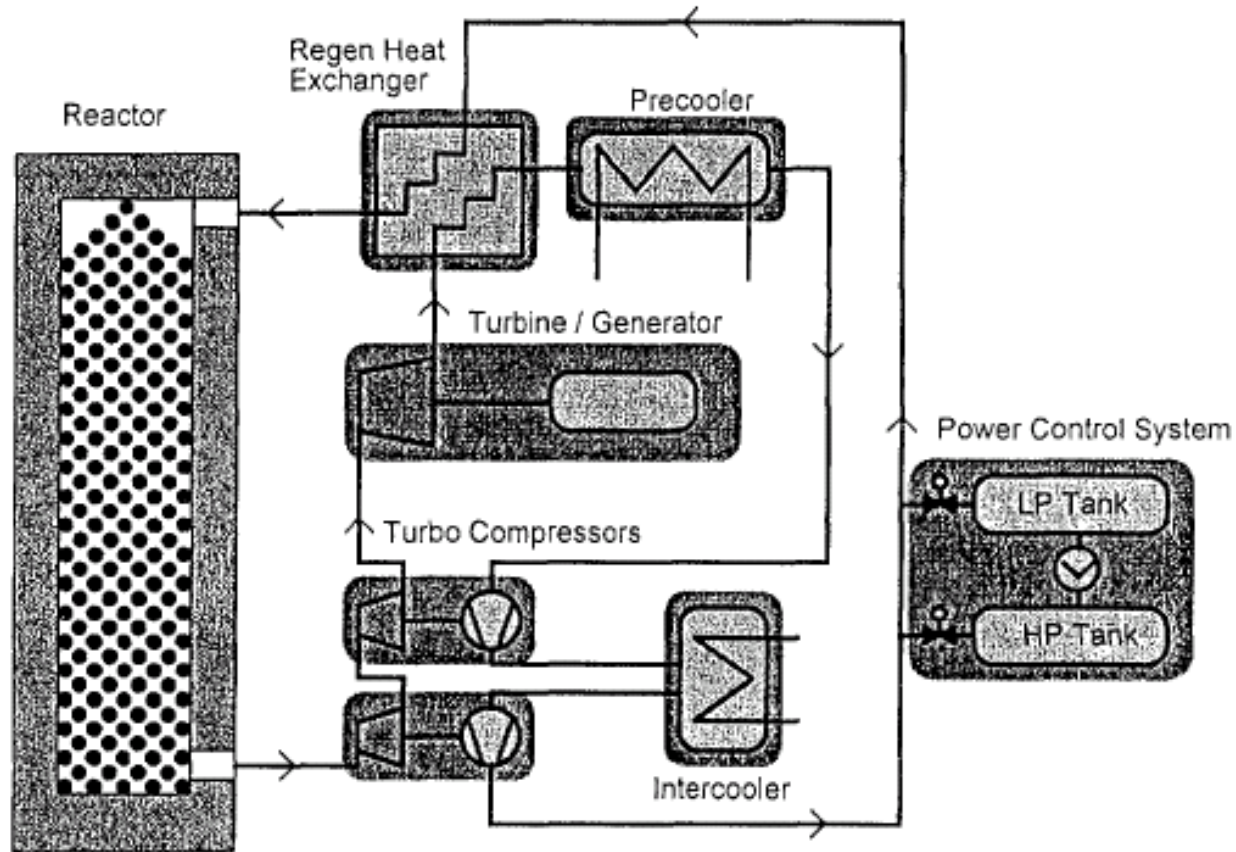
## The Hydrogen Economy



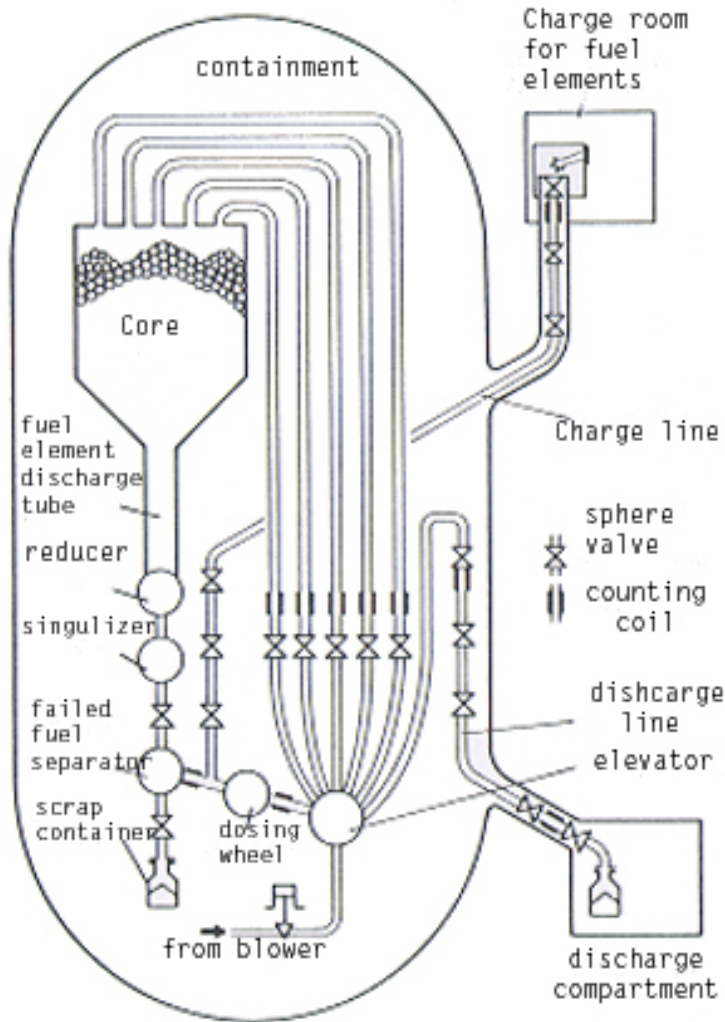
- You have to make it, just like electricity
- Electricity can make H<sub>2</sub>, and H<sub>2</sub> can make electricity ( $2\text{H}_2\text{O} \rightleftharpoons 2\text{H}_2 + \text{O}_2$ )
- You have to make a lot of it
- You can make it cold, - 419 F (21 K)

P.M. Grant, "Hydrogen lifts off...with a heavy load," *Nature* 424, 129 (2003)

# High Temperature Gas Cooled Reactor



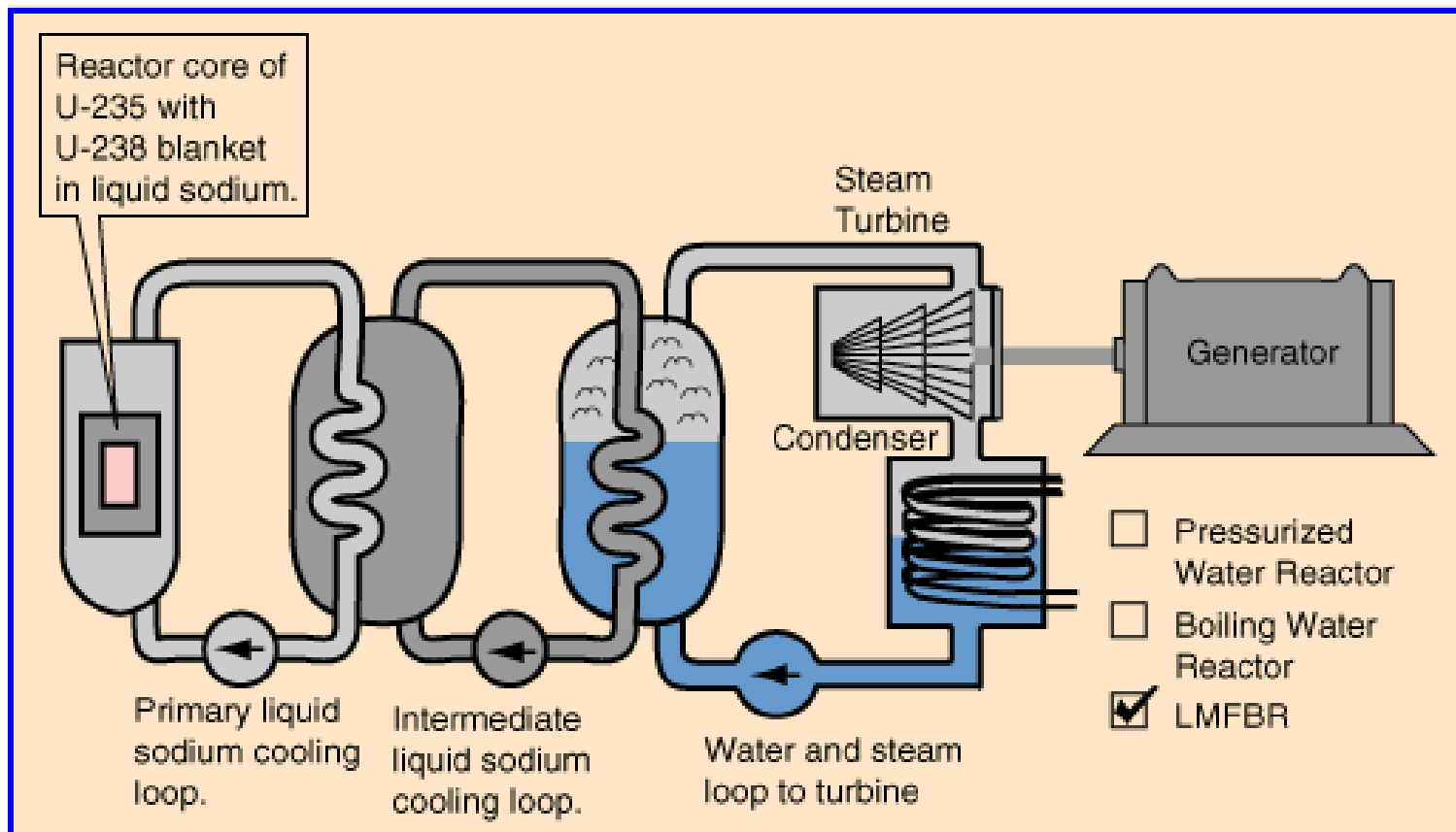
# What is a Pebble Bed Reactor (MIT)?



- 360,000 pebbles in core
- about 3,000 pebbles handled in FHS every day
- about 350 pebbles discarded daily
- one pebble discharged every 30 seconds
- average pebble cycles through core 15 times
- fuel-handling most intensive part of plant

<http://web.mit.edu/pebble-bed/>

# Fast Breeder Technologies



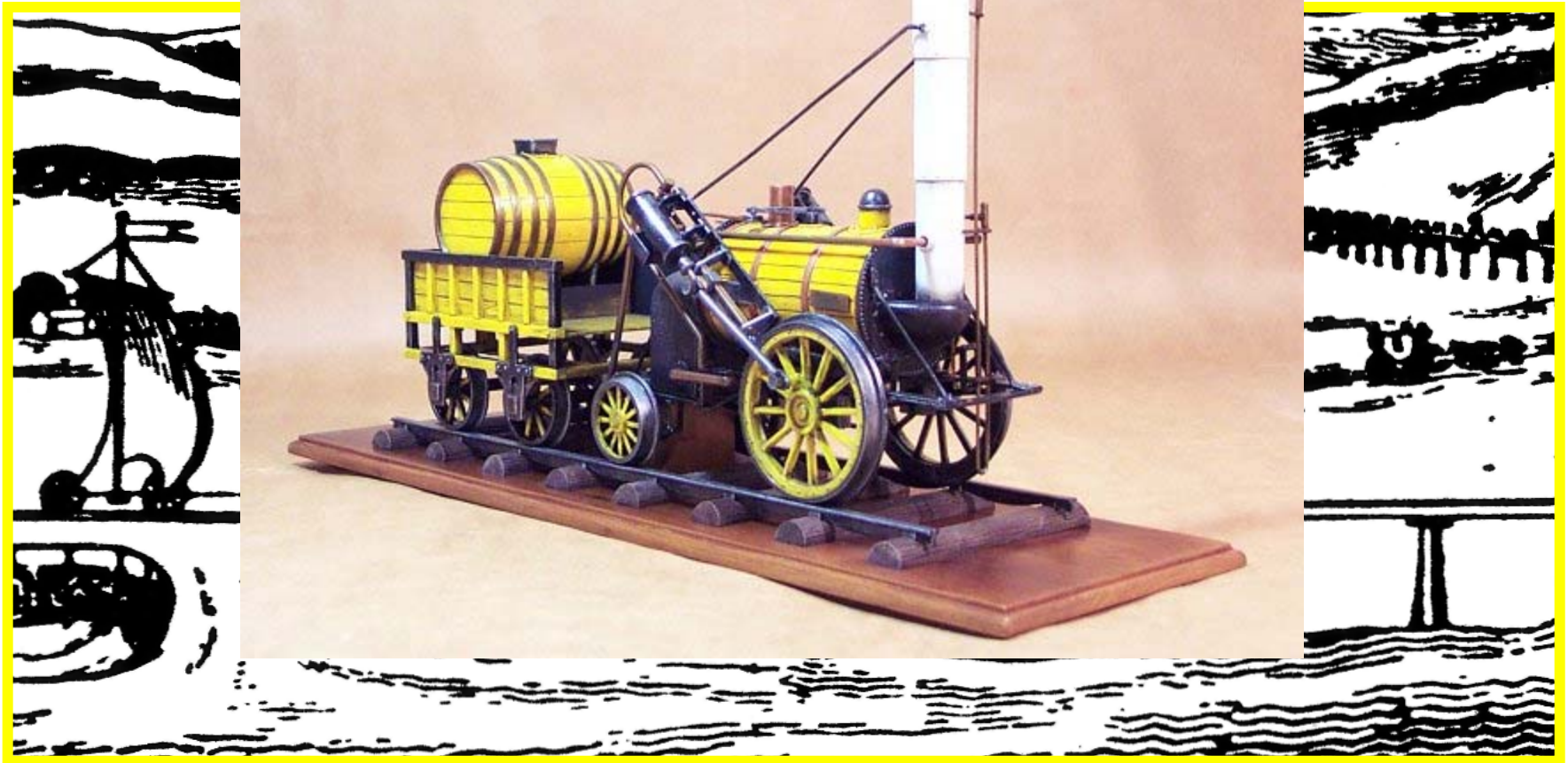
<http://hyperphysics.phy-astr.gsu.edu/hbase/nucene/reactor.html#c5>

# Vision of a Sailing Railway

Mon

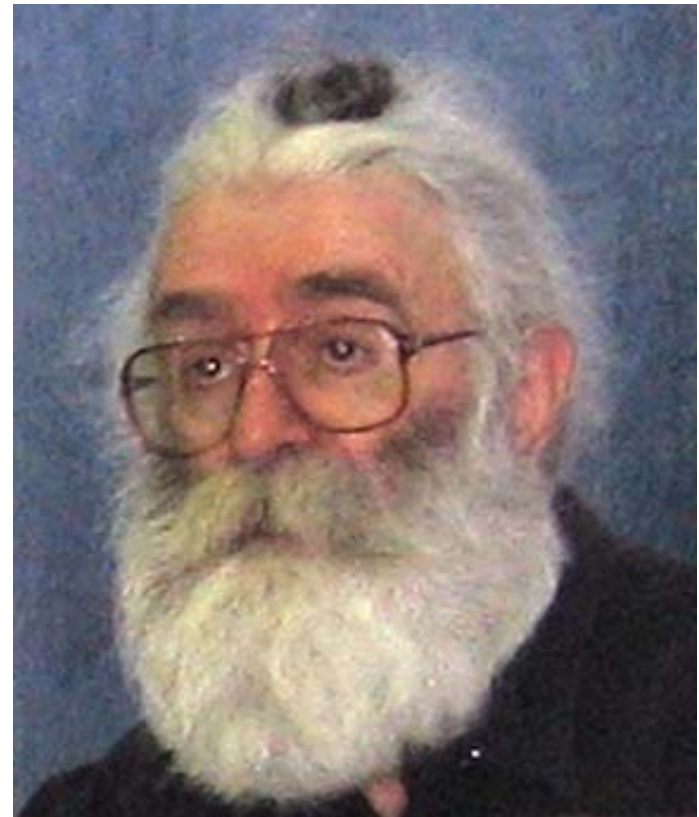
n 1828

George Stephenson - 1825



Source: Marshall, 1938

**I AM NOT Radovan Karadzic!**





# Physics Colloquium

SuperCities and SuperGrids

A Vision for Long-term Sustainable and Environmentally Compatible Energy Independence for North America

## SuperCities and SuperGrids

A Vision for Long-term Sustainable and  
Environmentally Compatible Energy  
Independence for North America

Paul M Grant

[w2agz@pacbell.net](mailto:w2agz@pacbell.net)

<http://www.w2agz.com>

<http://www.w2agz.com/ucdpc08.htm>

Aging IBM Pensioner

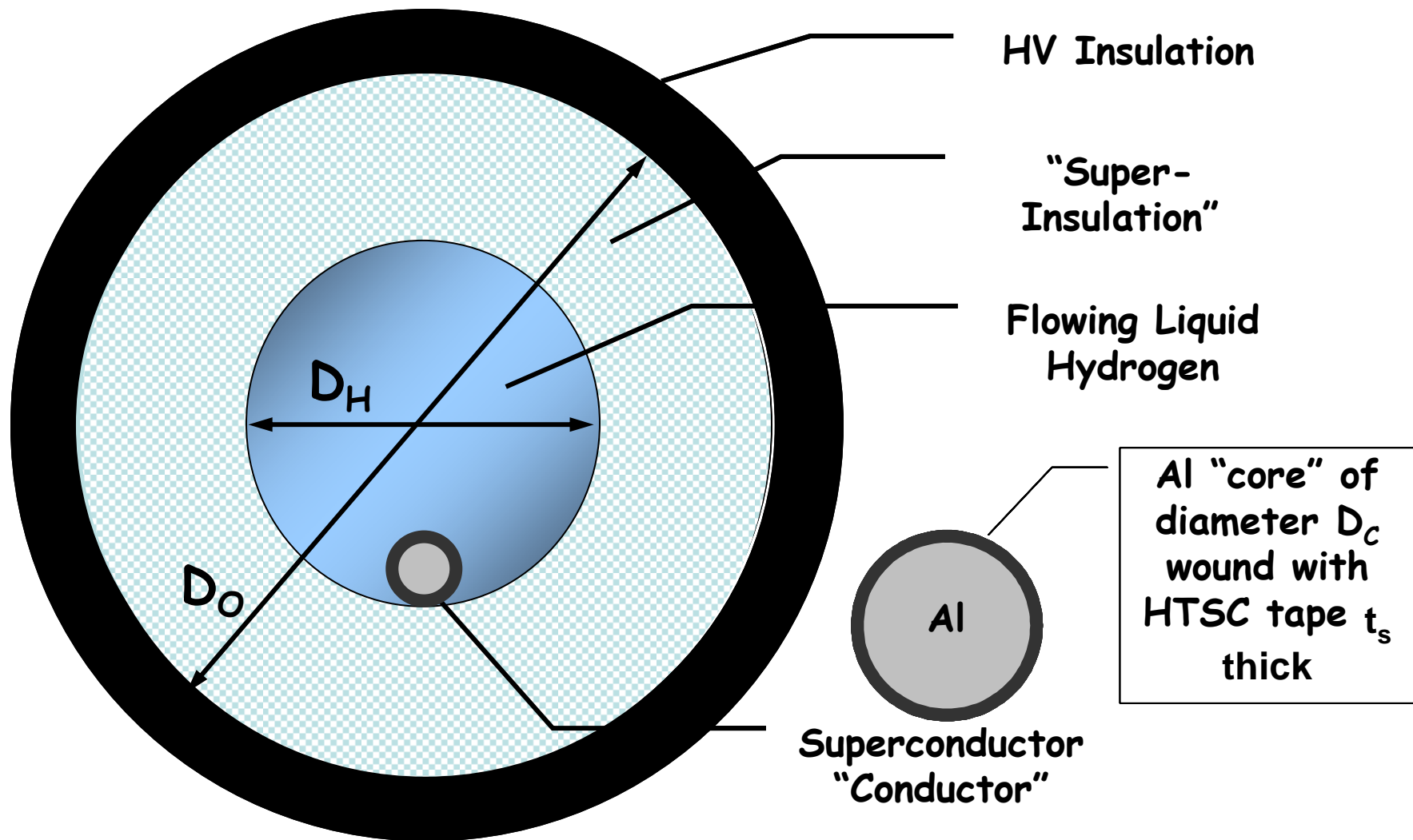
# Chauncey Starr

1912 - 2007

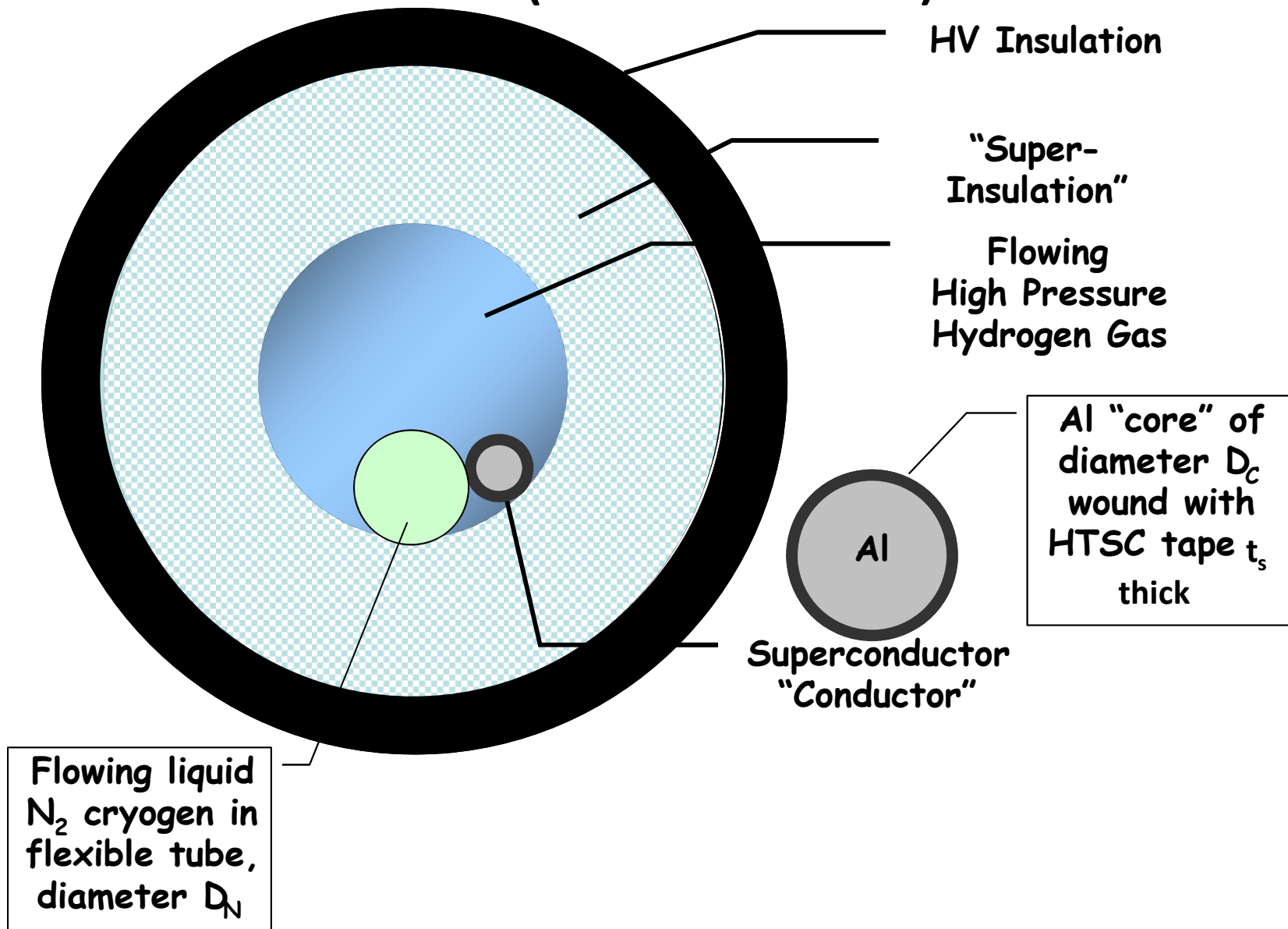


*Obituary, Nature, 14 June 2007*

# SuperCable Monopole (Alternative)

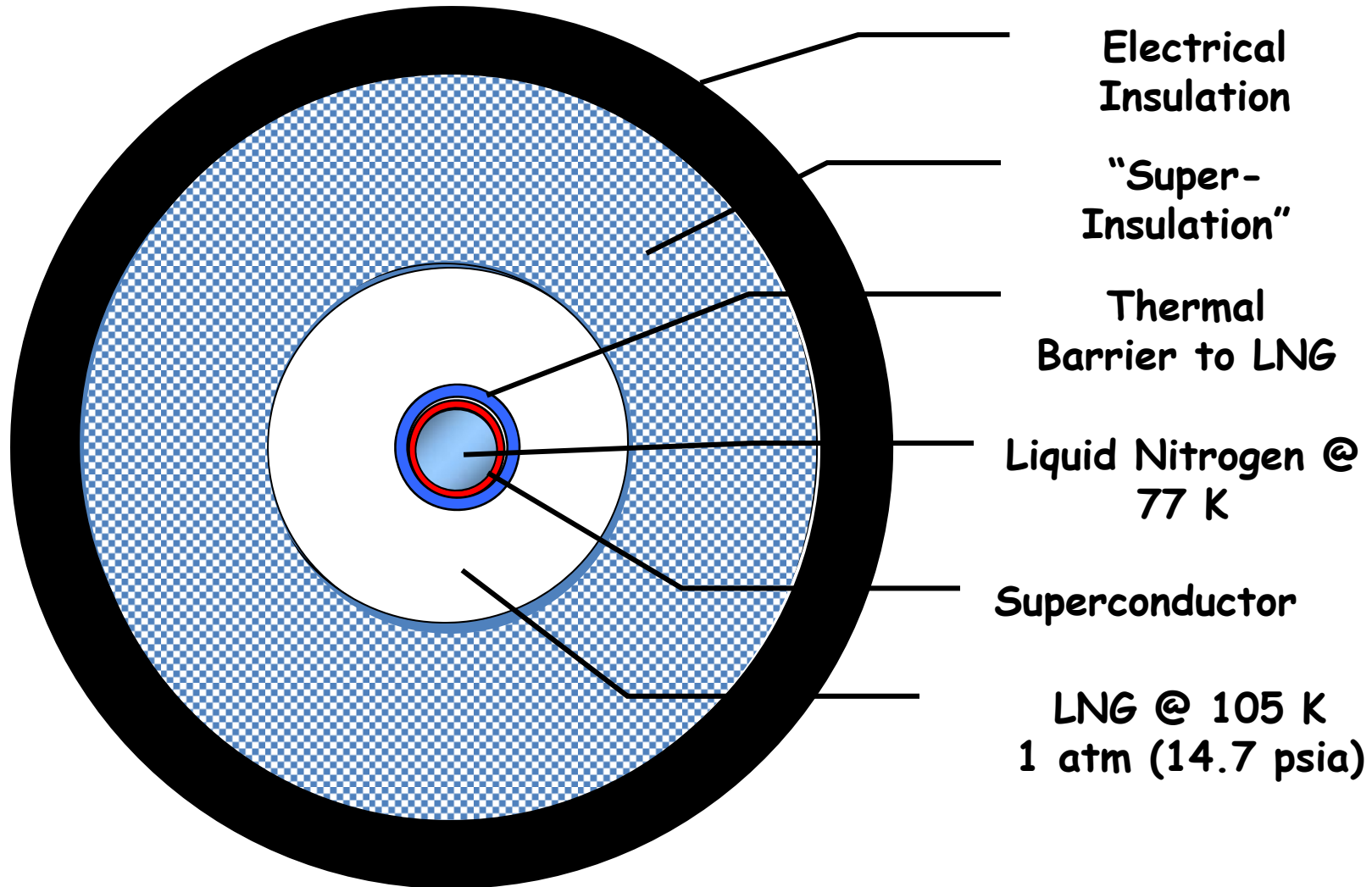


# Supercritical H<sub>2</sub> SuperCable (Alternative)



Design for eventual  
conversion to high  
pressure cold or liquid  $H_2$

# LNG SuperCable



# 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

$\rho$  =  $H_2$  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

## Fluid Properties Comparison of Liquid to Gaseous Hydrogen Transporting 500 MW<sub>t</sub> in a 10-cm Diameter Pipe

T °K	P psia	ρ kg/m <sup>3</sup>	μ μPaxs	μ <sup>2</sup> /ρ ndyne	V m/s	Re 10 <sup>6</sup>
20	14.7	70.8	13.6	261	4	2.08
77	1850	35.4	5.6	87	8	5.06

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

*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<sup>2</sup>)

$\lambda$  = 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

$\rho$  = fluid density

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

## Colebrook's Equation

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

# Wellhead LNG + Electricity

## MVP Scenario

### Electricity Conversion Assumptions

Wellhead Power Capacity	18 GW (HHV)
Fraction Making Electricity	33%
Thermal Power Consumed	6 GW (HHV)
Left to Transmit as LNG	12 GW (HHV)
CCGT Efficiency	60%
Electricity Output	3.6 GW (+/- 18 kV, 100 kA)

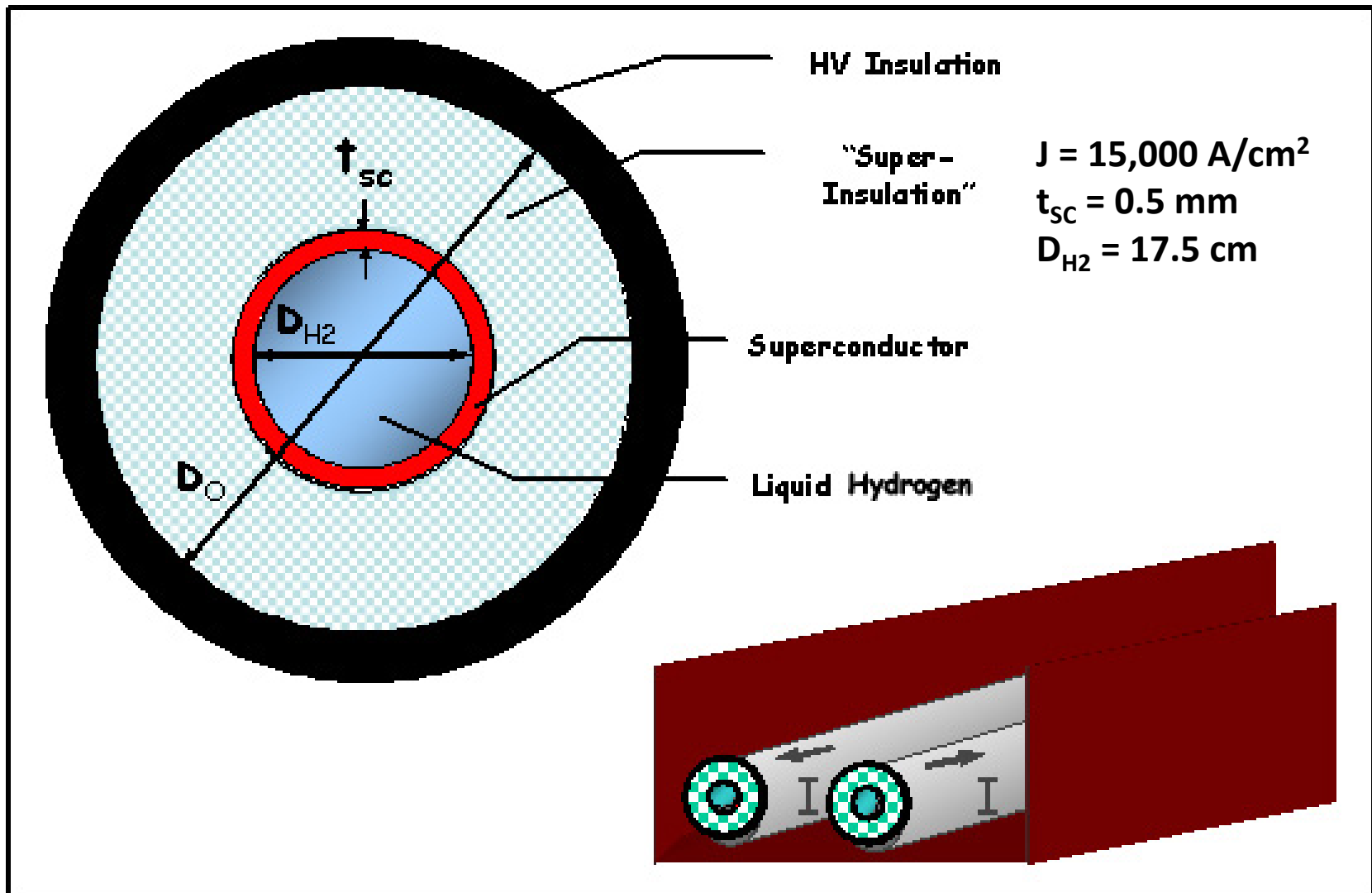
### SuperCable Parameters for LNG Transport

CH <sub>4</sub> Mass Flow (12 GW (HHV))	230 kg/s @ 5.3 m/s
LNG Density (100 K)	440 kg/m <sup>3</sup>
LNG Volume Flow	0.53 m <sup>3</sup> /s @ 5.3 m/s
Effective Pipe Cross-section	0.1 m <sup>2</sup>
Effective Pipe Diameter	0.35 m (14 in)

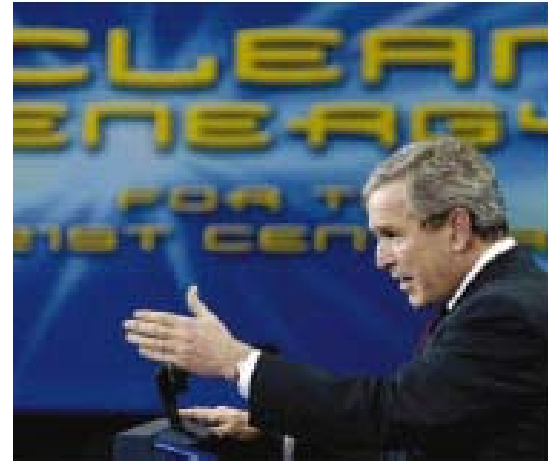
# SuperCities (SuperSuburbs)

ICEC-ICMC, Seoul, 2008

# The CryoNet



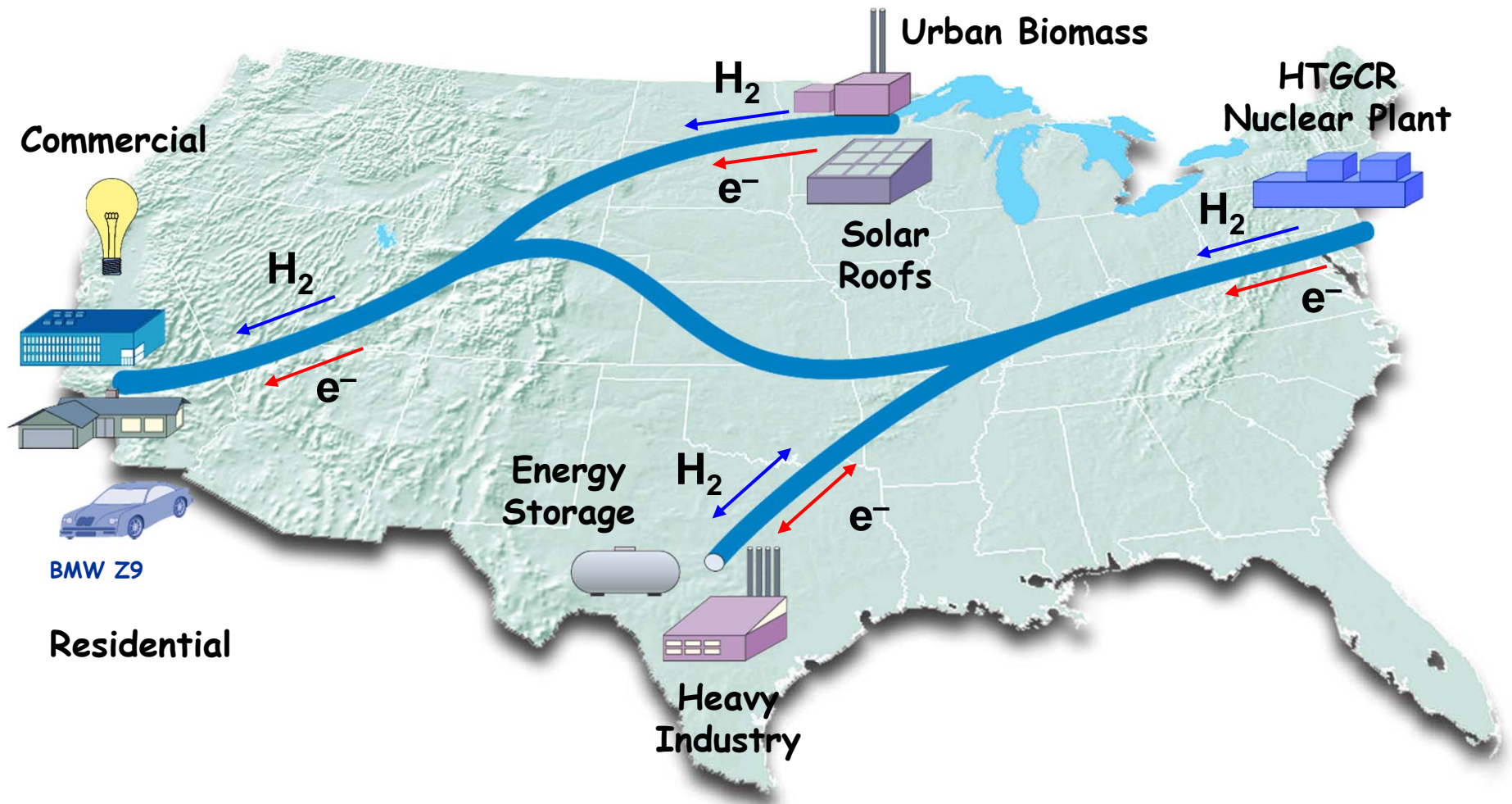
# The Hydrogen Economy



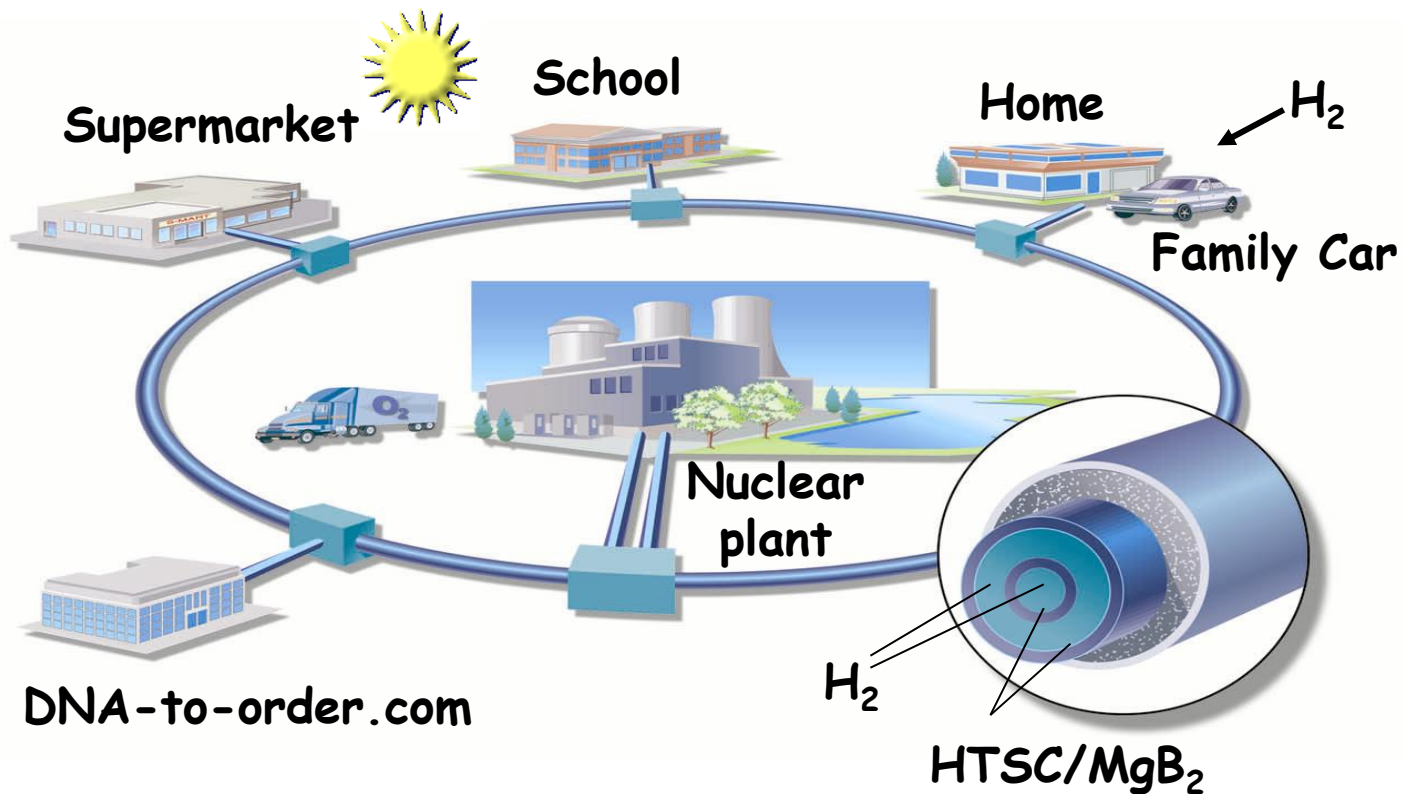
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**P.M. Grant, "Hydrogen lifts off...with a heavy load," Nature 424, 129 (2003)**

# North American 21st Century *Energy SuperGrid*



# SuperCity



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

# SuperCable Physical Parameters

Operating Current Density, J (A/cm <sup>2</sup> )	t <sub>sc</sub> (cm)	Hydrogen Flow Rate (m/s)	D <sub>H2</sub> (cm)	Maximum Magnetic Field (T)
15,000	0.05	2	17.5	0.10

# Bottom Line

## SuperSuburb SuperCable Economic Factors.

Cost of Electricity (\$/kWh)	Line Losses in Conventional Transmission (%)	Annual Value of Losses on 1800 MW Transmission Line (M\$)	Additional Capital Costs for HTSC and Refrigeration (M\$)	FRB Discount Rate (%)	Period for ROI (Years)
0.05	5 %	39.4	1185	5.5 %	18