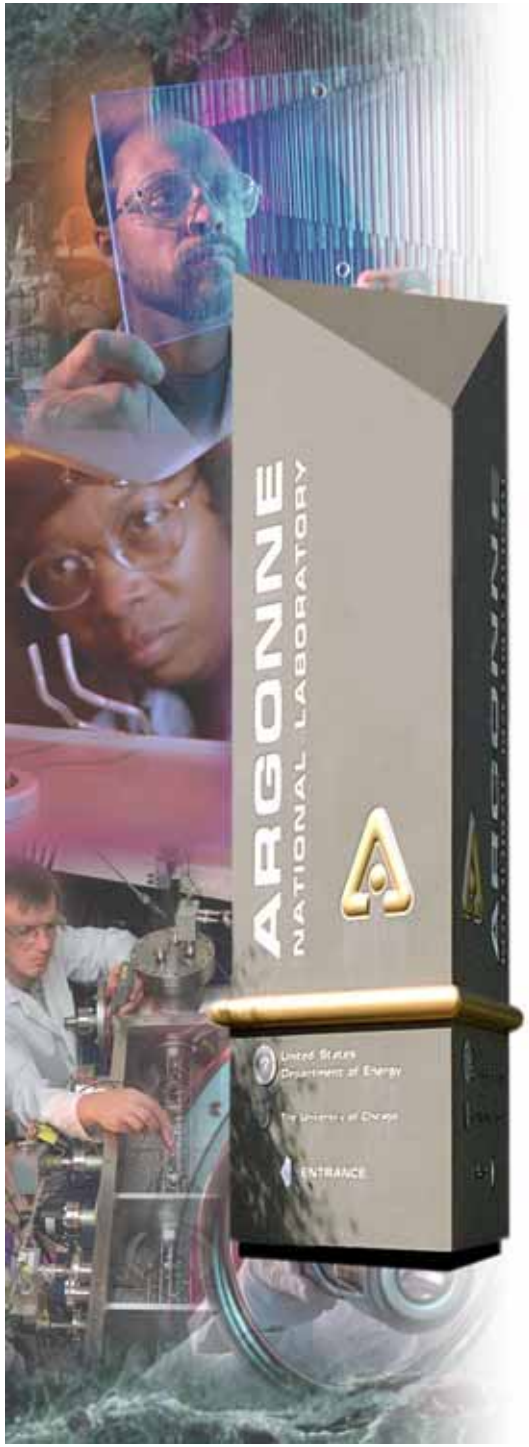

Small Modular Reactors and Their Role in Sustainable Development

Enabling Our Energy Security Through The Nuclear Fuel Cycle
Workshop for Graduate Students from the Big 10
Nuclear Engineering Departments
July 20-22, 2004

David C. Wade

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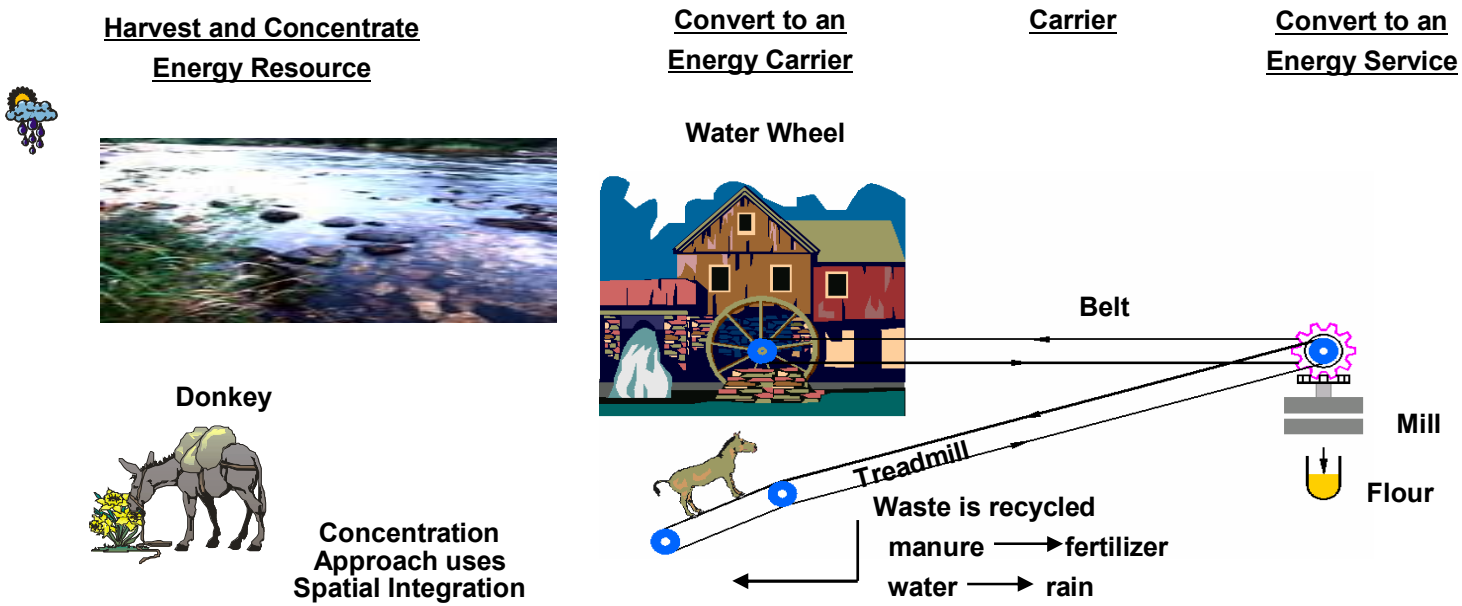
Outline of Presentation

- **Nuclear's Potential To Fuel A Sustainable Development Revolution**
  - With the Societal Impact of the Industrial Revolution
- **A New Global Energy Architecture Optimized for Nuclear**
  - The Role of Small Modular Reactors
- **Transition Strategies**
  - The Role of a Symbiotic Closed Fuel Cycle
- **Enabling Institutional Innovations and Business Plans**
- **Summary**

Nuclear's Potential to Fuel A Sustainable Development Revolution

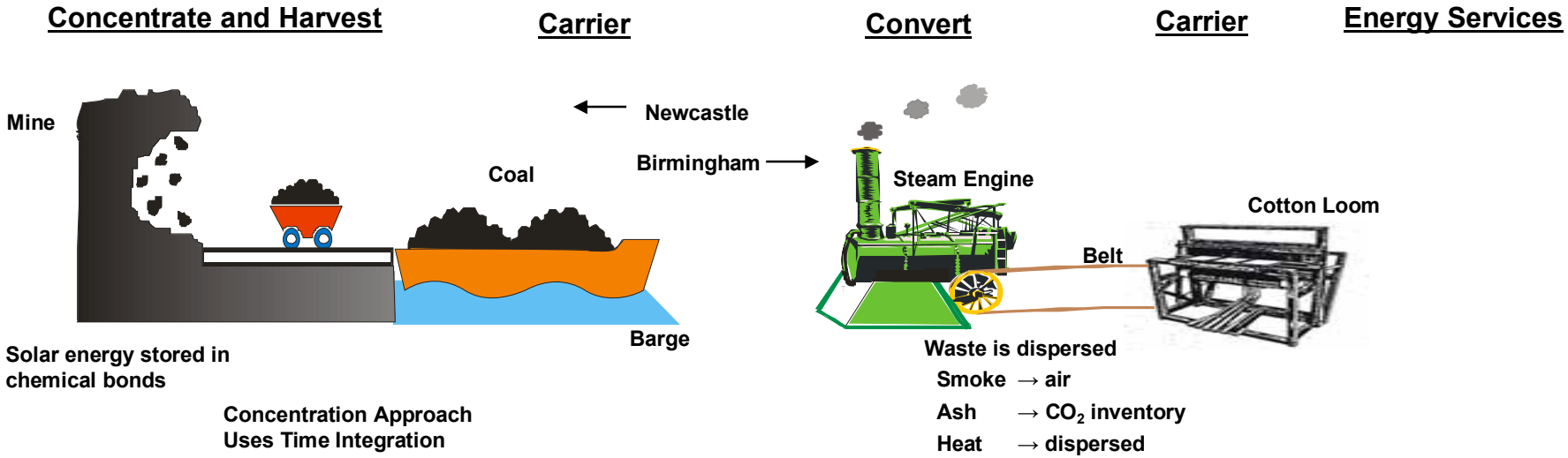
Brief History of The World's Energy Supply Architecture

- **The links in the Energy Supply Chain**
  - Harvest and concentrate the energy resource
  - Convert to an energy carrier
  - Convert energy carrier to an energy service
  - Manage the waste
- **Pre 1760: Pre-Industrial Era of Renewables Resource**



Brief History of the World's Energy Supply Architecture (cont'd.)

Post 1760: Era of Chemical Resource: Exploiting a Factor of 10^6 in Energy Density



- Energy density of one molecule of water falling 1 ft ~1 μev
- Energy density of oxidation of 1 atom of Carbon ~1 ev
- A Million times higher energy intensity became available by burning coal for energy supply

The Industrial Revolution (Circa ~1760 to ~1850)

- **Was fueled by a 10^6 increase in usable energy intensity**
  - Coal + steam engine : replaced : water wheels and animals

i.e.,

  - Stored chemical energy (Concentrated over geologic time) : replaced : renewables (concentrated over acres of space)

- **Was exploited by re-engineering the architecture and institutions of production (i.e., concentrating capital and labor to match concentrated energy input)**
  - Factories : replaced : Cottage industry
  - Division of Labor (Specialization) : replaced : Skilled crafts (Guilds)
  - Joint Stock Co. (Equity with Cap on Risk) : supplemented : Debt Financing
  - Open Markets (Free Trade) : replaced : Gov't Control of Economy (Mercantile Economy)

History of The World's Energy Supply Architecture

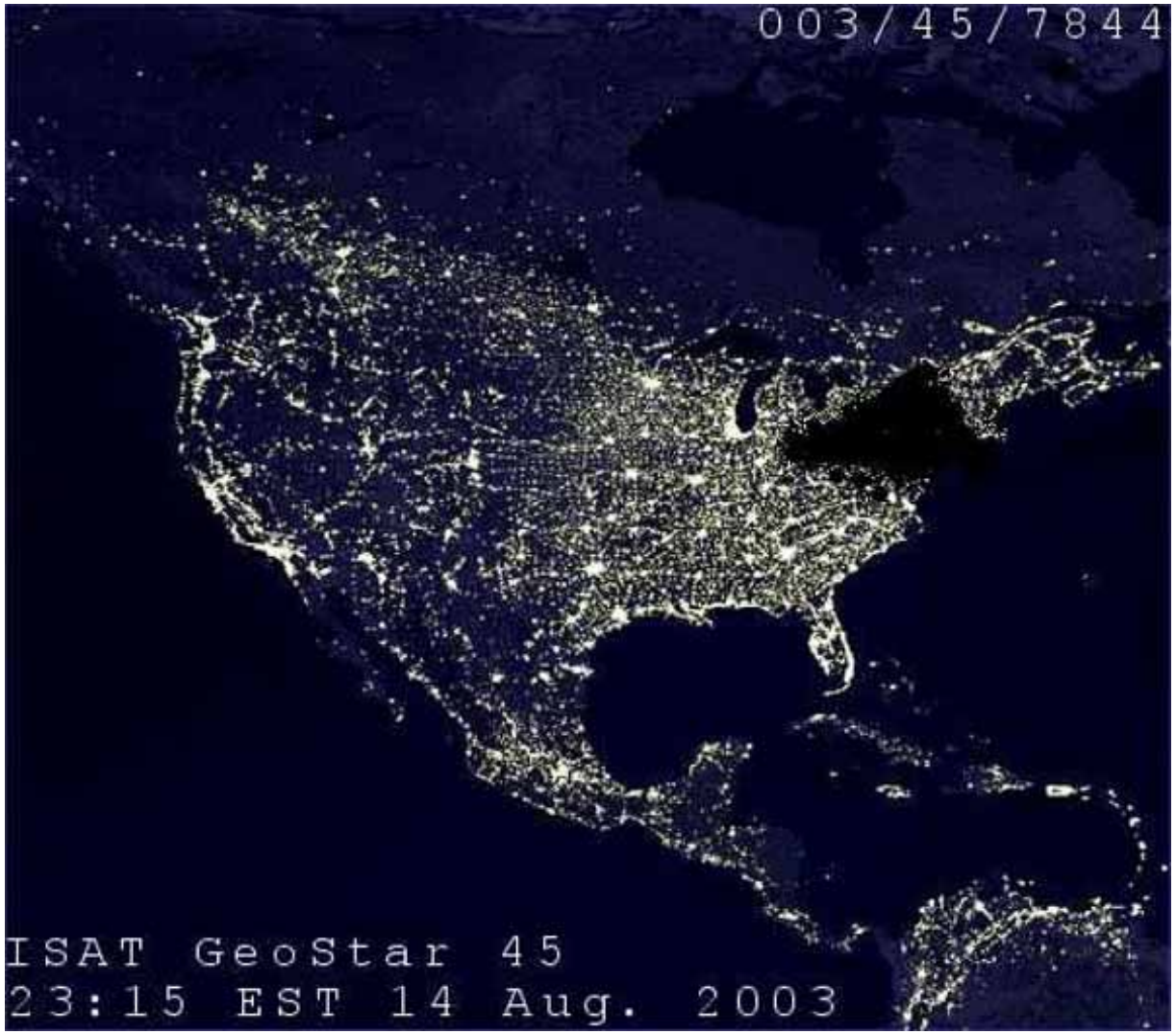
Post 1850: More "Convenient" Energy Carriers (Liquid Fuels, Electricity) and Converters (Internal Combustion Engine, Turbine/Dynamos)

	Concentrate and Harvest Resource	Converter	Carrier	Energy Services
(a)	Petroleum	Internal Combustion Engine	Gasoline	Transportation
(b)	Natural Gas	Combustion Gas Turbine + Generator	Electricity	• Lighting • Electric Motors • Information Storage

- **These new energy carriers and converters were embraced over coal, pulleys/ belts, and steam engines for delivering energy services to clients**
- **Why?**
  - More versatile
  - Cleaner
  - More "convenient"

  } i.e.," better" match to needs of the client for fulfilling his (generally unchanging) needs – light, transportation, etc.
- **They changed the "structure" of the architecture**
  - Oil's long distance transportability – leads to a world price
  - Electricity's medium distance transportability lead to economy of scale of converter,
    - *But lack of storability; leads to reduced reliability*

Reliability Vulnerability of Centralized Electricity Generation

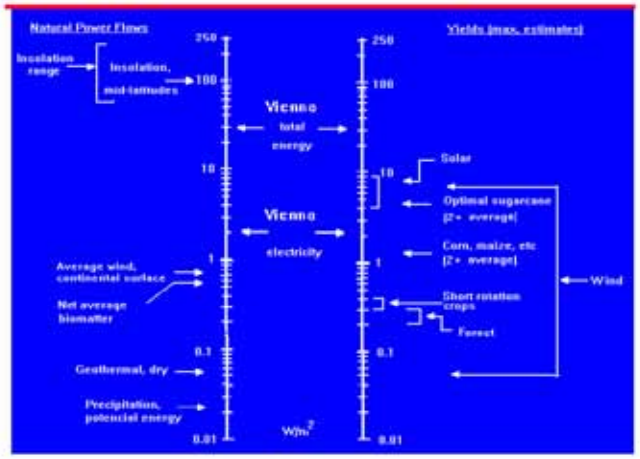


← Result of a single fault: 50 million people without electricity

Outcome of the Industrial Revolution Up to Now

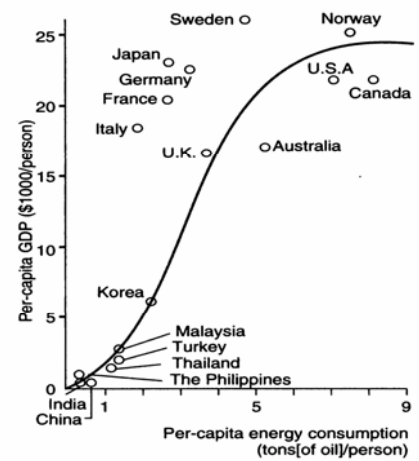
- **The Utilization of Chemical Bond Energy from a <u>Stored</u> Resource (coal, oil, gas) concentrated over eons increased energy input per capita (i.e., broke the cap on energy input derived from solar radiation/acre)**
- **Effects of Increased energy Input/Capita**
  - Drove an increase in GDP/Capita
  - Broke the 6 millennium-long Malthusian Regression to unchanging GDP/capita
  - Allowed Population and GDP/Capita to <u>Both</u> increase with Industrialization

    (world population ~ few hundred million in 1750) ~ 6 billion today
  - Facilitated the growth of Megacities



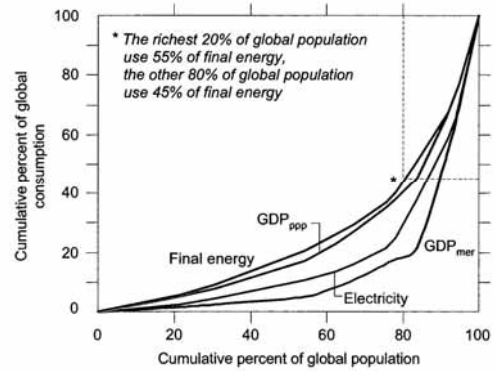
Source: *Adapted from Häfele, 1981 – International Atomic Energy Agency*

GDP/Capita
Vs
Energy Use/Capita



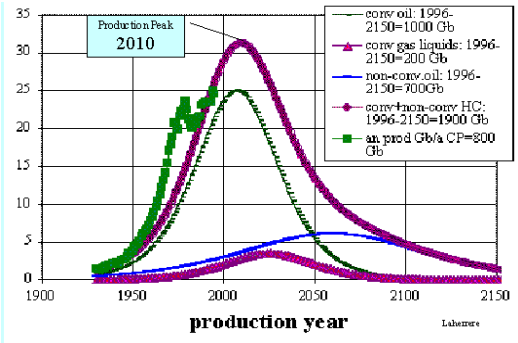
On the Other Hand

- **Only 20% of the World's Population has Benefited – 80% of World Population has access to <half of World energy**

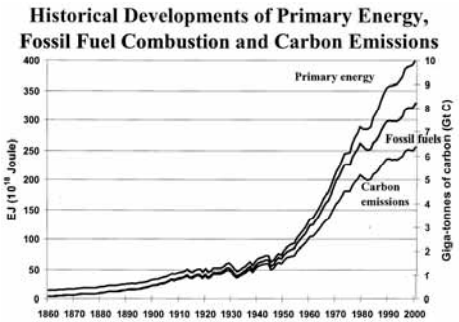


Laherrere's Oil Production Forecast, 1930-2150

- **Resource Base of fossil is finite and unsustainable**



- **Waste Management from Fossil Infrastructure is excessive, ineffective, and not sustainable**



But the Really Major Issue–

Developing Countries: The Sustainable Development Dilemma

- **The other 80% of world population will be catching up this century**
- **And demographic migrations to cities will accelerate**
  - (80% urban by 2050)

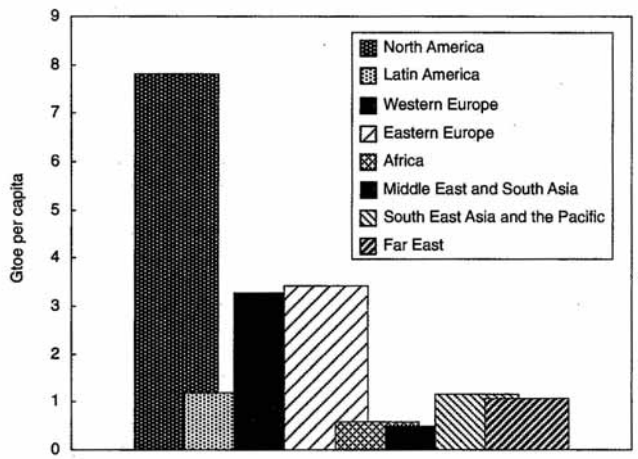


FIG. 1. Regional energy consumption (1995). [INTERNATIONAL ATOMIC ENERGY AGENCY, *Energy, Electricity and Nuclear Power Estimates for the Period up to 2015*, July 1996 Edition, IAEA, Vienna (1996)]

toe = tonnes of oil equivalent

How to Meet The Goals of Global Sustainable Development?

"Meeting The Needs of today's society without diminishing the ability of future generations to meet their needs"

- **In terms of Energy use, Sustainable Development Requires:**
  - *Supply infrastructure for a significant increase in energy use/capita – accounting for a growing world population*
  - *Longevity of Economic Resource Base*
  - *Ecological Friendliness of Waste Management*
  - *Social Acceptability*
    - Interregional and Intergenerational Equity
    - Affordability
    - Safety

The World is Searching for A Credible Means to Fuel A Sustainable Development Revolution – Dominated by Needs of Developing Countries – Especially Cities

- **The Choices are limited; and the outcomes are predictable**
  - Fossil: Business as Usual
    - *Maintain Industrial Energy Input/Capita*
    - *Increasing Competition for diminishing resources*
    - *Increasing ecological consequences*

Path for Future?

Path for Future?

- Renewables: Reversion to Pre 1760
  - *Pre-industrial energy input per capita (~current Africa)*
  - *World population decrease*
  - *De-urbanization*
  - *Medieval Lifestyle*

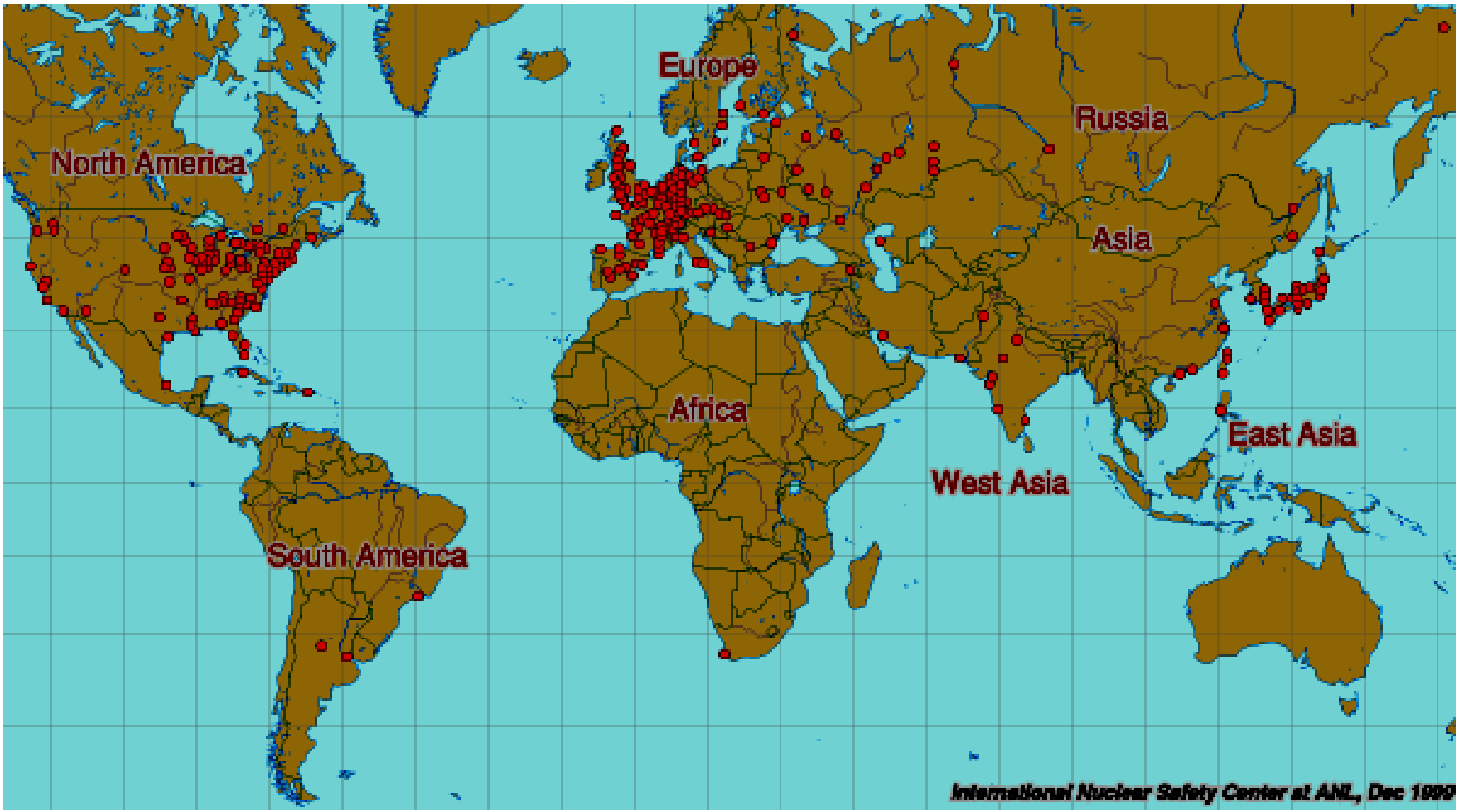
- Nuclear: Can It Fuel A Sustainable Development Revolution?
  - *Breaking one chemical bond : ~1 ev*
  - *Breaking one nuclear bond : ~ 200,000,000 ev*
  - *Can we exploit this New factor of a million to Extend Industrial - Level Energy Input/Capita to the Developing World?*

Nuclear Has Intrinsic Potential – Not Yet Exploited

- **Breaking Nuclear Bonds brings an additional factor of 10^6 over Chemical Bond Breaking**
  - Vastly less mining/shipping mass and volume per unit energy benefit
  - Vastly less mass and volume of waste per unit of energy benefit
  - Intrinsically favorable ecological features
- **The energy content of economically-recoverable uranium ore (15 million Tonnes in "Redbook")**
  - Good for ~1000 years of World Supply (Thorium extends by factor of 4)
    - *Recycle and full consumption of U238 will be needed within this century to achieve sustainability*
  - In a practical sense – this ore base provides an essentially inexhaustible energy resource
- **Nuclear Possesses Favorable Intrinsic Attributes for Both the Resource the Waste Aspects of Sustainable Development**

But they have not been exploited by the current nuclear configuration

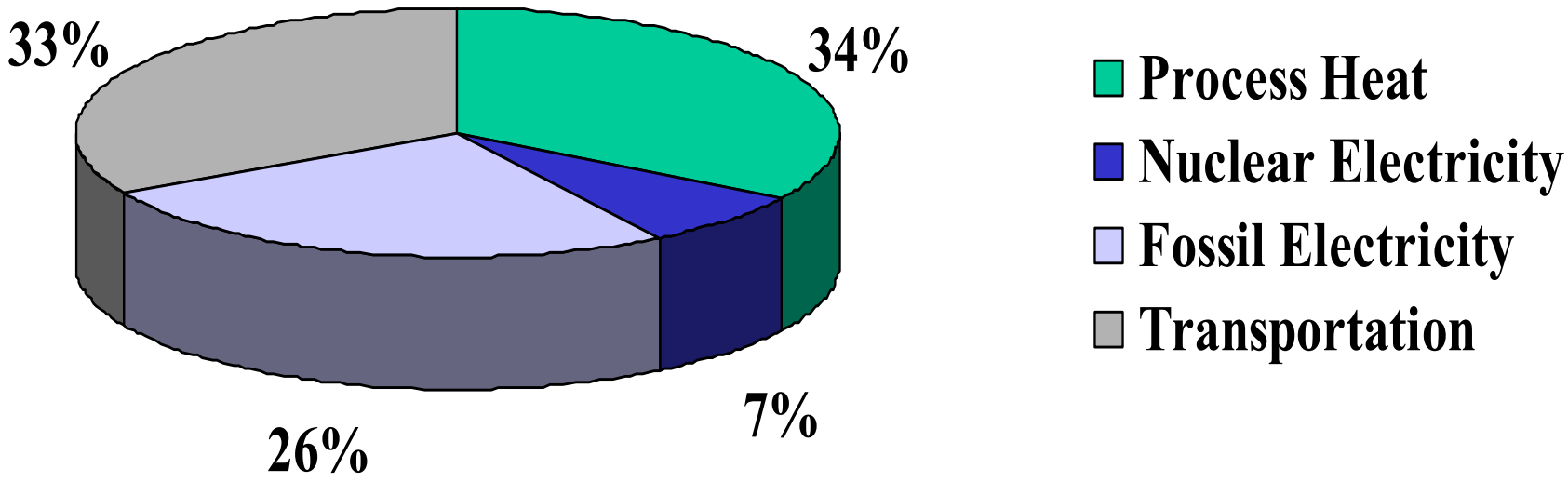
Nuclear is Currently Serving Only ~20% of The World's Population



The Dominant Future Energy Demand Growth will be in the Developing Countries

Nuclear is Currently Providing Only 7% of World Energy Utilization

(i.e., 20% of Electricity which is only 1/3 of Energy Use)



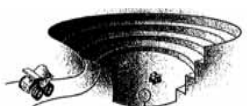
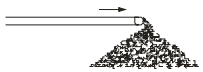
Nuclear's Ecological Benefits are Constrained:

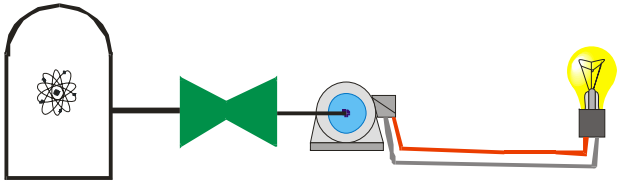
Even if Nuclear met <u>all</u> electrical needs: Only ~1/3 of Energy Use

Needed: A New Wave of Nuclear Innovation

- **Why has nuclear achieved limited market share?**
- **Because: So far we have done no more than simply place the nuclear resource and converter into the old (chemical) energy supply architecture**

Post 1950: Uranium As A New Resource/Reactor as A New Converter



- U replaces coal
- LWR replaces coal furnace
- SNF replaces ash
- Product remains electricity; payoff is no CO_2 emissions

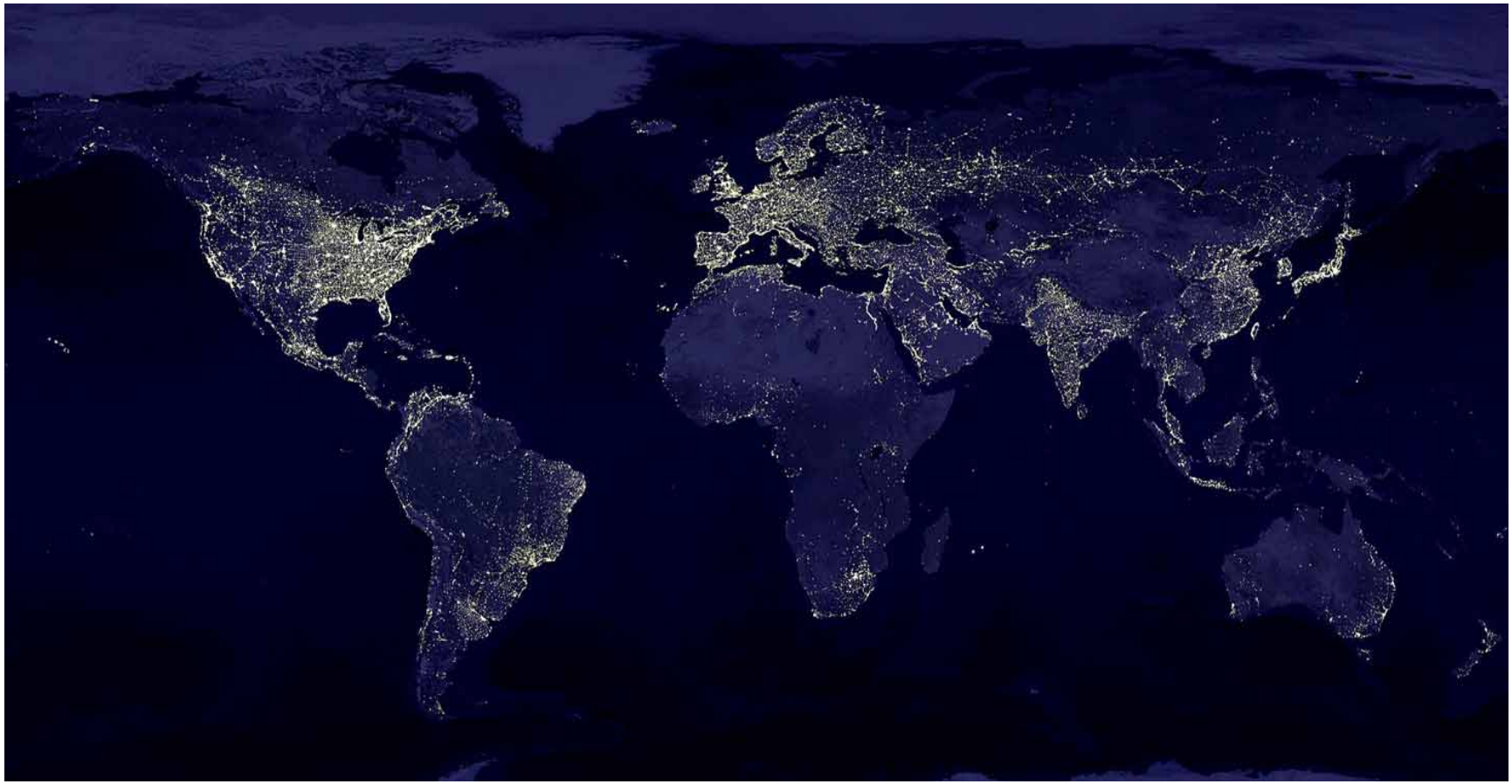
- **Nuclear energy is not chemical energy**

But

- **Unlike the Industrial Revolution, so far there has been no re-engineering of the Energy Architecture and Its Enabling Institutions to exploit nuclear's features**
- **It's Time for a New Wave of Innovation to Fully Exploit Nuclear's Intrinsic Features!**

A Proposed World Energy Architecture Optimized for Nuclear

Goal – Achieve Sustainable Development by Devising A Version of Nuclear Energy Suitable for Urban Centers in Developing Countries



Fueling A Sustainable Development Revolution

- **Re-engineer the world energy architecture -- To Exploit Nuclear's Million Fold Increase in Energy Intensity**
- **<u>First</u> – configure nuclear technology and enabling institutions such that it is available to developing countries – where demand for energy is growing the fastest**
  - Configure nuclear in a way that breaks the Energy Security/Nonproliferation dilemma
  - And – in a way that supports early stages of economic growth (limited financial and institutional capital)
  - And – in a way that ensures safety – even with a 100-1000 fold increase in deployment worldwide
- **<u>Second</u> – Close the fuel cycle – to achieve the waste self consumption and resource extension features**
- **<u>Third</u> – Use carbon-free nuclear energy to manufacture hydrogen as a synthetic chemical fuel**
  - To gradually displace fossil hydrocarbons
- **<u>Fourth</u> – Emplace enabling institutional changes to make (1) through (3) possible**

Order of Presentation

- **First describe the envisioned mid-century architecture optimized for Nuclear**
- **Then describe a transition strategy to reach it from where we are today**

Achieve Energy Security Simultaneously With Nonproliferation Assurances

First Key Step: Exploit Nuclear Fuel's Incredible Energy Density to Break The Energy Security/Nonprofileration Dilemma

- **Comparative Energy Densities**
  - Chemical fuel ~$1.4 \cdot 10^{-3}$ MW_{th} days/kg (LHV of H_2)
  - Fast reactor nuclear fuel ~100 MW_{th} days/kg (discharge burnup)
- **Zero loss of energy content over thousands of miles of shipment**
  - Low cost of nuclear fuel transport
- **Nuclear fuel is a 100,000 times "better" energy carrier than fossil**

Opportunity

- **Coalesce All Fuel Cycle and Waste Management Operations into Regional Centers operating under International Nonproliferation Oversight**
- **"Store" energy in refueling cassettes for shipment to Small Modular Reactors**

- **Derate the small fast reactor power density into the 100 kw/liter range (i.e., LWR range) so that the refueling interval can be extended from 3-5 years of LMFBR's to 15-20 years**
  - (Secure energy sources sited on sovereign territory)
  - Refueling will be done by whole core cassette replacement every 20 years
  - (By designing for internal conversion ratio of 1.0, the SMR's are fissile self sufficient – once deployed, they manufacture their reload fuel needs)
- **Support hundreds to thousands of distributed Small Modular Reactors of Long Refueling interval sited near cities throughout a significant global region**

A Dozen Regional Fuel Cycle Centers Is Enough

The World's Mid-Century Primary Energy Needs

- **At 9 toe/person year ⟹ ~12 Kw_{th} of heat energy/person deployed for <u>all</u> Energy Services:**
  (North America) **~ 1/3 for heat converted and delivered as electricity**
  (Europe is ~4 toe/person year) **~1/3 for transportation**
  ~1/3 for heating/cooling/industry
- **Assume in 2050**
  - World population = 10 Billion
  - 80% in cities
  - Urban use of energy (world average) = 3 toe/person/year

Energy Demand $10 \cdot 10^9 * 0.8 * 3/9 * 12 * 10^{-6} =$ 32,000 GW_{th} (Current use is ~12,000 GW_{th})
(More careful analyses produce 10,000 to 20,000 GW_{th} total primary energy use in 2050) **: 34 terawatt years/year**

- **Suppose Nuclear' Market Share is half of 32,000 GW_{th} of heat to service <u>all</u> primary energy sectors**
  - Annual Mass Flows of Nuclear Fuel: 1/2 * 32,000 GW_{th} * 365d/y/100,000 MWd_t/tonne = 58,400 tonnes/year
- **Using Nuclear fuel as an energy carrier: only 120,000 tonnes of shipping per year (going and returning to reactors)**
- **12 recycle/refabrication plants of 5,000 tonne/y thruput could handle half of World energy use in 2050 (32 terrawatts)**
- **Observation: (1) Economy of scale at a <u>small number</u> of Regional Fuel Cycle Service Centers could handle Global fuel cycle requirements**
  (2) Easily scaleable by adding capacity at Fuel Cycle Centers
- **21st Century Fuel Cycle Centers Become Analogous to 20th Century Oil Fields**

Nonproliferation Features of Centralized Fuel Cycle With Distributed, Infrequently - Refueled Power Plants

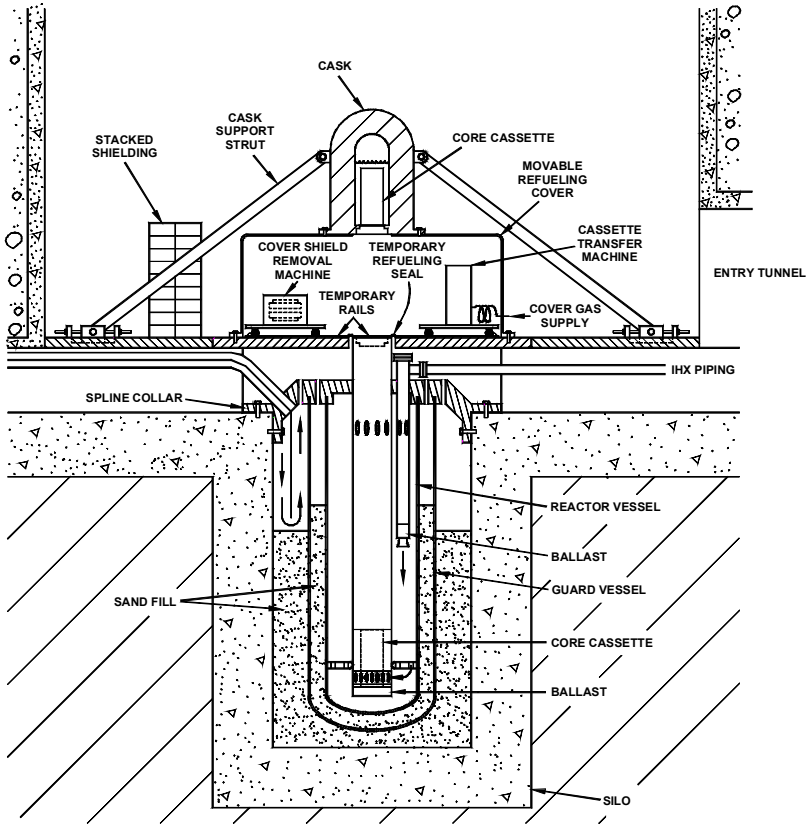
Meets ElBaradei's Criteria of November 2003

Centralized Bulk Handling of Fissile and Waste

- **Regional Fuel Cycle (and Waste Management) Center with Nonprofileration Oversight by IAEA**
  - Controlled by Consortia of Clients (interregional equity)
  - Recycle Technology produces Co-Mixed transuranic fresh fuel which is as unattractive for weapons use as LWR spent fuel
- **No Fissile goes to Waste**

Non-Accessible Distributed Fissile

- **Whole Core Cassette Refueling conducted on a 20y interval by Regional Fuel Cycle Center Personnel**
  - Refueling Equipment brought to site and taken away with Spent Cassette
- **Shipping with Cassette Entombed in Frozen Pb**
  - Several Hundred Tonne Cassette + Cask
  - GPS locator and Item Accountancy on Every Cassette during shipment

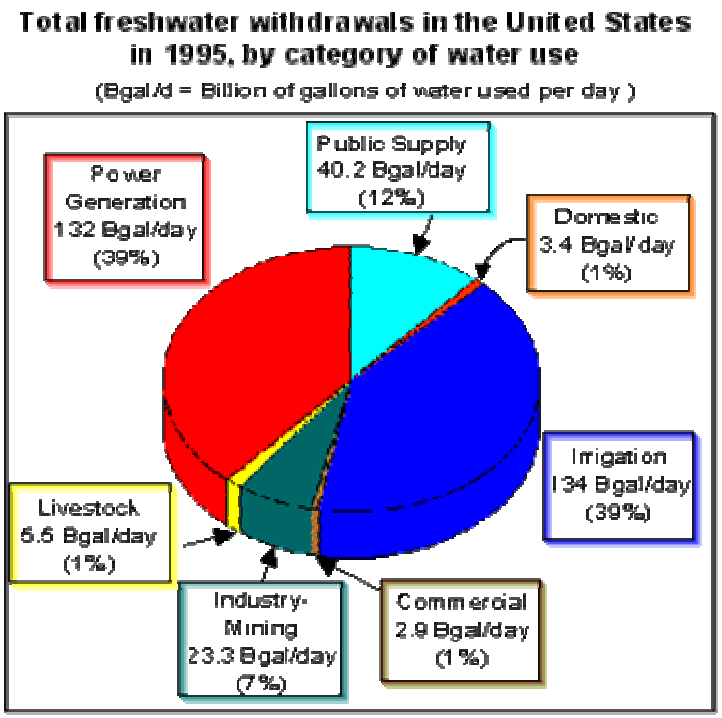


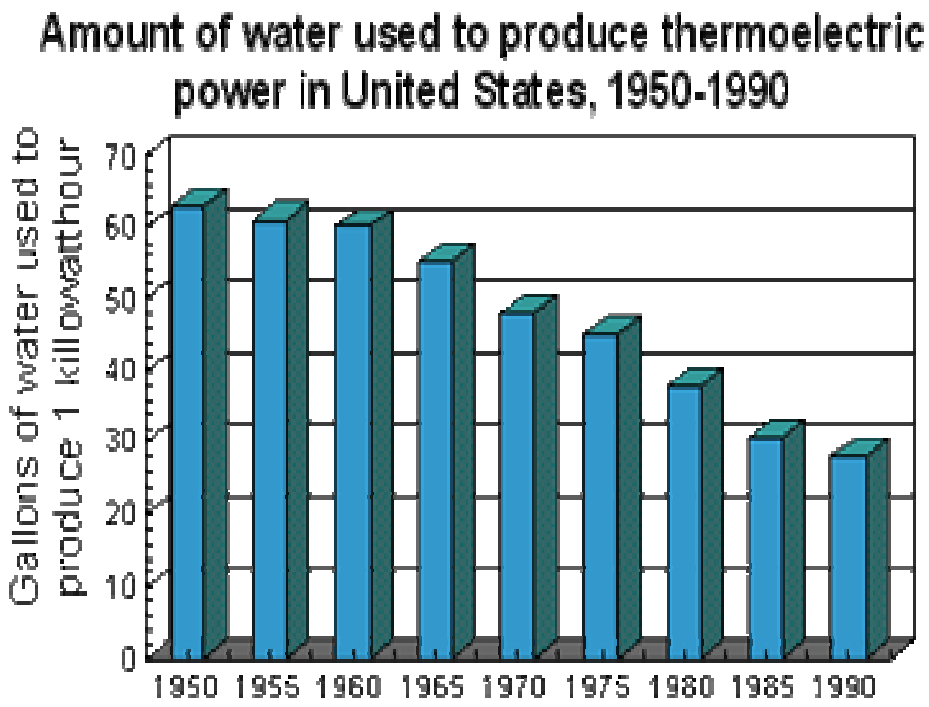
Expand Beyond Electricity To All Primary Energy

2nd Key Step: Expand The Energy Services Beyond Electricity to Hydrogen, Potable Water, and Others

- **In industrial societies, primary energy (i.e., heat) utilization is divided roughly in thirds**
  - 1/3 for electricity
  - 1/3 for transportation
  - 1/3 for industrial and domestic heat
- **Manufacture Hydrogen to enter the non-electric 2/3 of primary energy supply**
  - Using nuclear heat to manufacture hydrogen from water
- **Position nuclear to displace fossil fuels altogether**
  - *Create a carbon-free global energy architecture*
  - *Based on Electricity, Hydrogen, Microturbines and Fuel Cells*

Water Access Is A Problem for The Power Industry – New Plants Should Have Bottoming Cycles





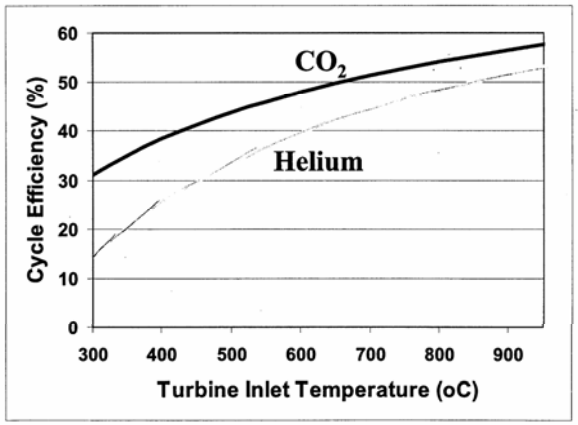
- **Water Withdrawals for Power Generation ≡ Agriculture; Each is 40% of Total**
- **Competition for Water Constrains Power Plant Siting (even though water is not <u>consumed</u>)**

Water and Energy: Critically Linked

- **Economic growth places linked demands on water/energy/and agriculture**
  - A critical issue in locating new power plants is water availability vs drinking and agriculture use
- **The demand will only increase**
  - The hydrogen economy will require additional amounts of reagent grade water
  - (Freedom Car) will require an additional 3 gallons/day per capita
- **There is no reason to create a thermal ecological footprint from energy generation**
  - We can turn the waste heat into a needed energy service
- **Opportunity: potable water can become a commodity sales product for nuclear – generated from waste heat**
- **Enter the Desalination Market in Support of Cities**

More Cost Effective Electricity Production: Super Critical CO_2 Brayton Cycle

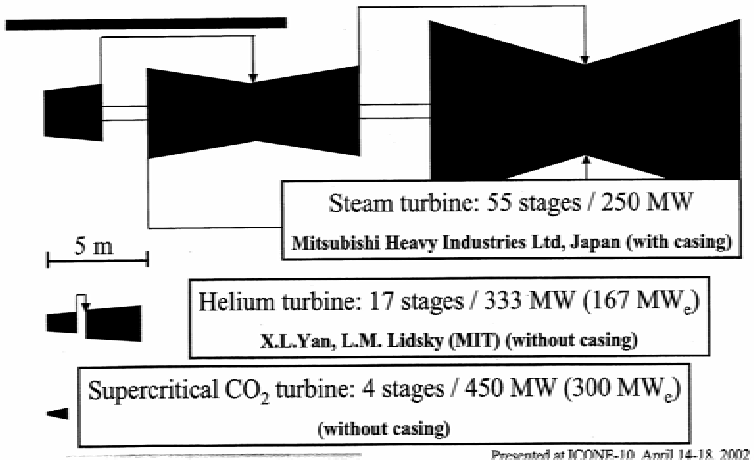
- **H_2 piped to the city**
  - 1/3 for fuel cell cars
  - 1/3 for microburbine and fuel cell distributed electricity
  - (hot water "waste" supplies buildings, offices, homes)
- **Use Improved Converters for Centralized Electricity Production**
- **Motivation for SC-CO_2 Brayton Cycle**
  - 45% Efficiency at 550ºC
  - Vastly Reduced BOP footprint compared to Rankine Cycle
  - Simpler, fewer component BOP compared to Rankine Cycle
- **If developed, Would Apply**
  - Na Reactors
  - Super Critical Water Reactors
  - Pb Reactors



Advantage of Recompression Supercritical CO_2 Brayton Cycle over the Helium Brayton Cycle

Turbine Sizes

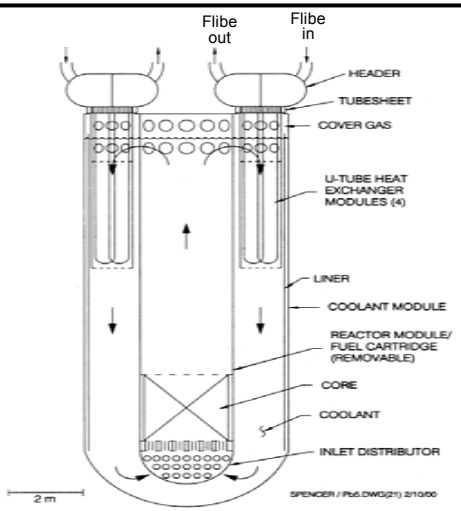
HOW SMALL IS SMALL?



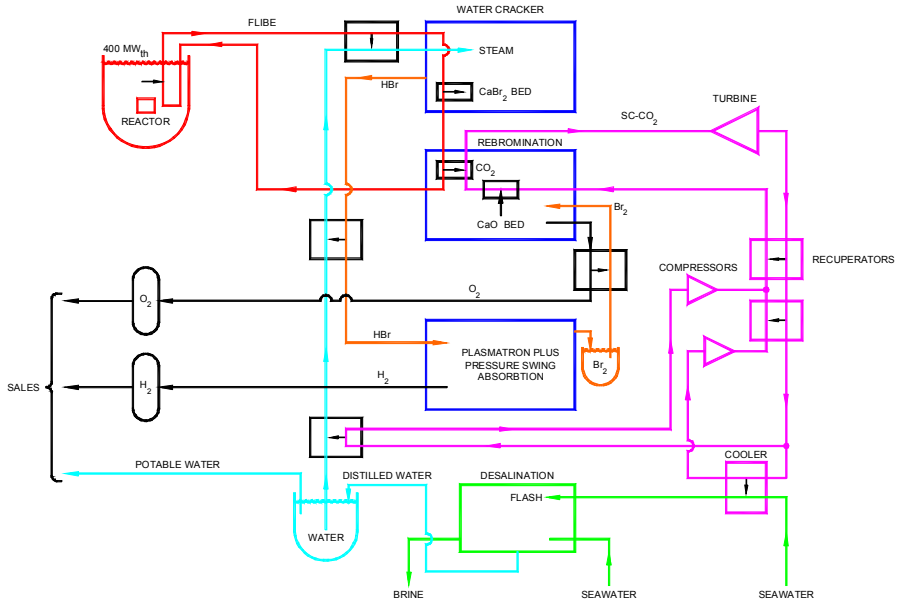
STAR-H2: A Turnkey, Pb-Cooled Natural Circulation, Derated Power Density Fast Reactor with A Long Refueling Interval

- 400 MW_{th}
- Fast Spectrum
- Pb Natural Circulation
- Low Power Density
- 20 Year Cassette Refueling Interval

- U/TRU Nitride Fuel Enrich ~8-12%
- Passive Safety
- Passive Load Follow
- T_{in} 650°C
- T_{out} 800°C
- Vessel 5 ½ x 18m (Rail Shippable)



Provides All Primary Energy and Potable Water Needs for a City of 25,000



- **Non Safety Grade Balance of Plant**
  - Built and Operated by local workforce to local standards
- **Process Heat Cascade Produces Energy Products**
  - Thermochemical Water Cracking Cycle
    - *H_2, O_2 production*
  - Supercrititcal CO_2 Brayton Cycle
    - *Electricity production*
  - Feed Forward Multi-Effects Distillation
    - *Seawater desalination*
  - Heat rejection in Brine
    - *85% of Nuclear Heat is converted to energy products*

Time Phased Market Penetration of STAR Portfolio of SMR's Without Onsite Refueling

Less Aggressive R&D: STAR Plants for Electricity and Potable Water

time

SSTAR: Early 25 to 50 MW_{th} Prototype to exercise institutional and business innovations

- License certification by test
- Licensing of passive safety; passive load follow: guard vessel containment
- Initiate licensing reciprocity arrangements among nations
- Factory Fabrication, Modularization
- Rapid Site Assembly and Connection to Non Safety Grade BOP

STAR-LM: Commercialization of electricity and potable water plant @ 400 MW_{th}

- Market entry of small plants with long refueling interval making electricity in advance of Hydrogen Economy
- Outsourced, Fuel Cycle, and Waste Management Services (perhaps prior to deployment of Regional Fuel Cycle Centers)
- Initiate leasing of Fuel Reload Cassettes

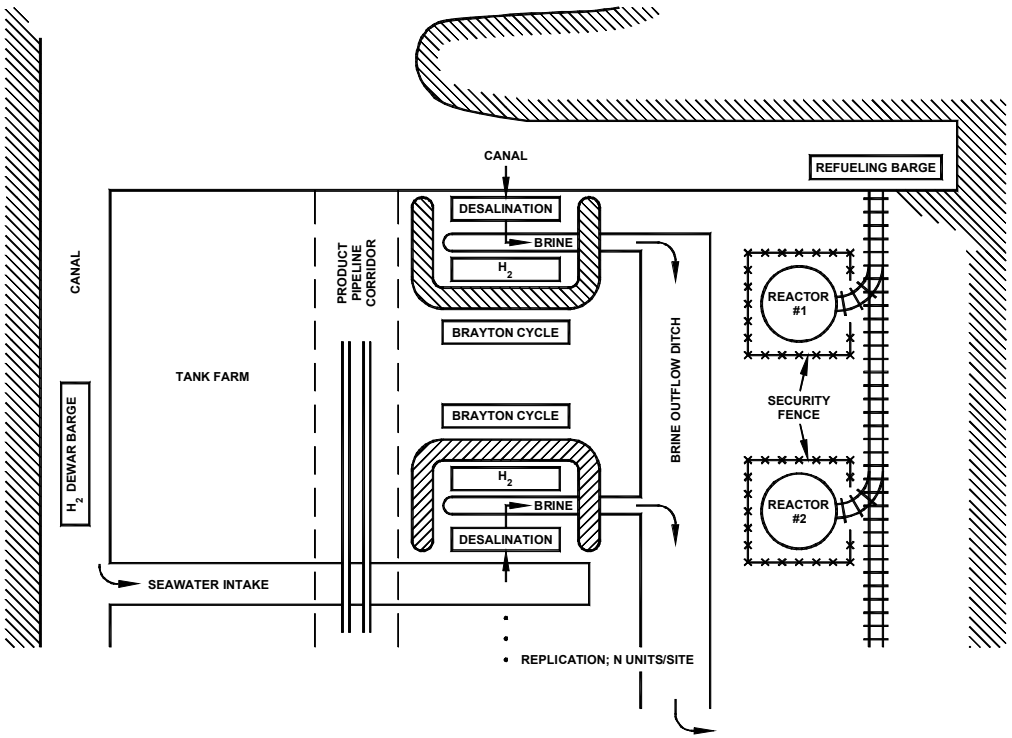
More Aggressive R&D: STAR Plants To Fuel A Hydrogen/Electricity Economy

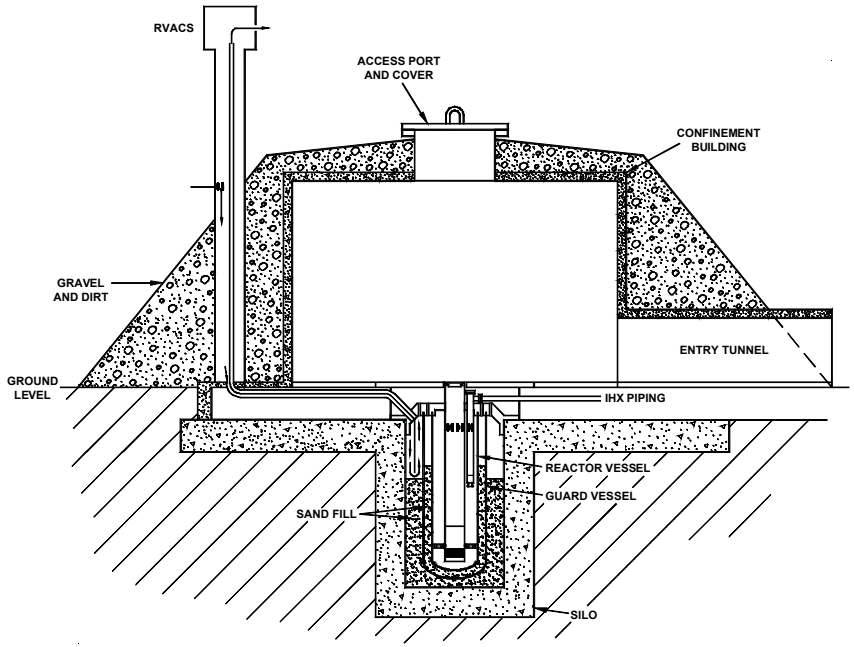
STAR-H2: Support an Emerging Nuclear-Driven Hydrogen Economy

- Commercialization of a hydrogen and potable water plant
- Deploy Multi-National Regional Fuel Cycle Centers

Achieve Unparalled Safety Performance for Tens of Thousands of Reactors Sited Near Cities Worldwide

3rd Key Step: Make The Power Plants Extraordinarily Safe: By Employing Passive Safety for Internal Hazards; Protecting STAR Reactors from External Hazards





- **Many Thousands of STAR-H2 plants Worldwide**
  - Demands Passive Safety Response to accident Initiators
  - Demands Innate protection from External Hazards
    - *Natural events – Fires, Floods, Winds, etc.*
    - *Co-sited H_2 plant*
    - *War or Terrorist*

- **Passive Safety Response to ATWS initiators**
- **Passive Decay Heat Removal**
- **Guard Vessel Containment**
  - No internal high pressure potential
  - No internal chemical explosion potential
  - Innate termination of accident initiators
- **Earthen Berm and Confinement Building**
  - Protects Guard Vessel from External Hazards

Achieve An Ecologically – Neutral Energy Supply

4th Key Step: Recycle Everything To Achieve An Ecologically Neutral Energy Supply

Nuclear/Hydrogen Based Energy Supply Chain – Eliminates Carbon

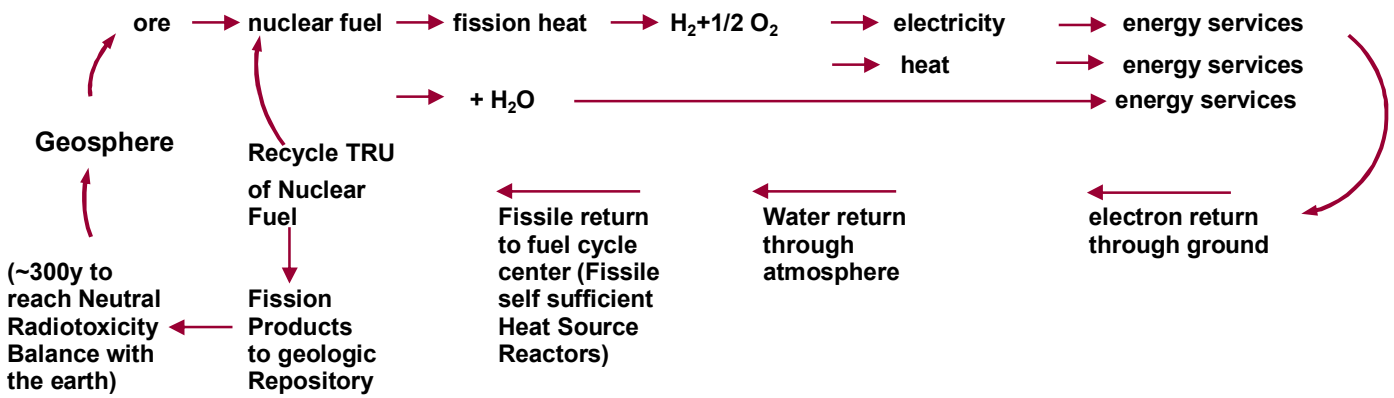
Exploit Fast Neutron Spectrum and Multi Recycle to Self-Consume Long Term Radiotoxicity

- **Energy Carriers & Converters**

		Long Distance	City & Environs	End Use
- Energy Carriers (Spokes)	:	Nuclear Fuel (100 MW_t d/kg Actinides)	Hydrogen ($1.4 \cdot 10^{-3}$ $MW_t d/kgH_2$)	Electricity Heat Potable Water
- Energy Converters (Hubs)	:	STAR Reactor Heat Source Reactors (fission to heat)	Thermochemical Water Cracking (heat to hydrogen)	Microturbines and Fuel Cells (hydrogen to electricity and water

Ecologically Neutral Recycle Chain for All Wastes Produced at Every Step of Energy Supply

- **All links in the energy supply chain can achieve ecologically neutral waste management via recycle**



Total Closure of Ecological cycles. Net global effect:

U → Fissile Product s

(all else recycles)

Provide a 1000 Year World Energy Supply

5th Key Step: Transition From a U235 Resource Base to a U238 Base by Closing The Fuel Cycle

- **The 15 million tonnes of Known + Speculative U Ore Resources Recoverable at ≤ 130$/kgU**
  - Could fuel the current world primary energy demand for a millennium if we transmute the U238 to transuranic fissile material
  - Otherwise we run out of fissile U235 within ~50 years
- **Early deployments of SMR will use TRU recovered from LWR Spent Fuel**

But 4th Key Step:

- **Emplace a symbiotic closed fuel cycle**
  - Regional Centers manage all fuel cycle operations
    - *Receive LWR Spent Fuel for waste management*
    - *Recover TRU from LWR SNF to fuel newSMR's*

Later

  - Breeder reactors centrally located at regional centers (after LWR spent fuel is used up)
    - *Manufacturing fissile for working inventories of new Breeders and SMR's <u>in a growing</u> energy supply*
    - *Using the released heat for manufacture of hydrogen*
      - Ship hydrogen to regional clients
  - SMR's sited near cities providing hydrogen and water
    - *Fissile self sufficient*

Energy Shares in A Fissile-Self Generating , Growing Global Infrastructure

- **Energy Market Share of SMR's vs Breeders**
  - Depends on demand growth rate, breeder doubling time, and SMR working inventory

F = Energy Market Share of STAR's

(1-F) = Energy Market Share of Breeders

$$F = \frac{\frac{BR-1}{I_B}\tau_D - 1}{\frac{BR-1}{I_B}\tau_D - 1 + \frac{I_S}{I_B}}$$

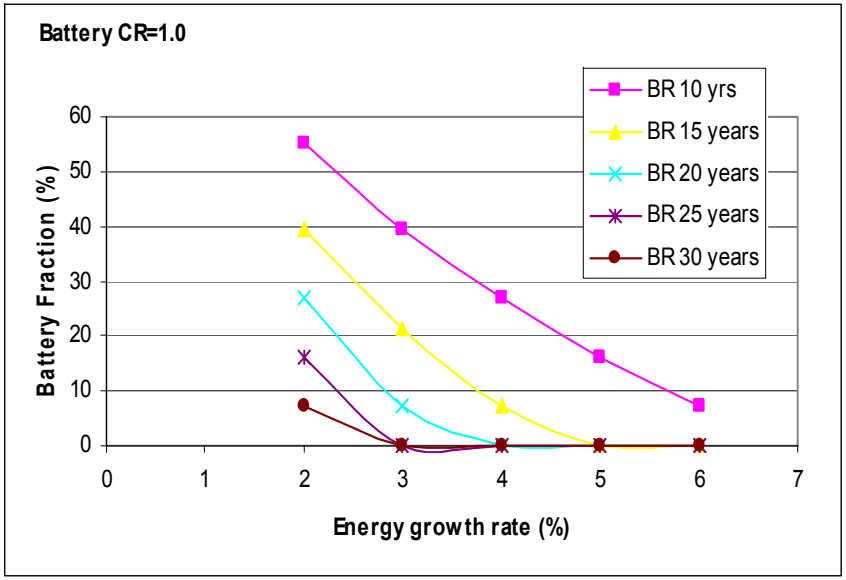
where:

τ_D = demand growth doubling time (y's)

BR = Breeding Ratio

I_B, I_S = Working Inventories of a Breeders and a STAR (including recycle pipeline)

I_S/I_B 2



Market Forces Will Maintain Fissile Supply & Demand in Balance

- **A common symbiotic fuel cycle infrastructure**
  - Integrates and mediates mass flows from diverse reactor types serving diverse market needs
    - *Big and small*
    - *Thermal and fast*
    - *Gen-III +, Gen-IV, Gen-V*
    - *Etc.*

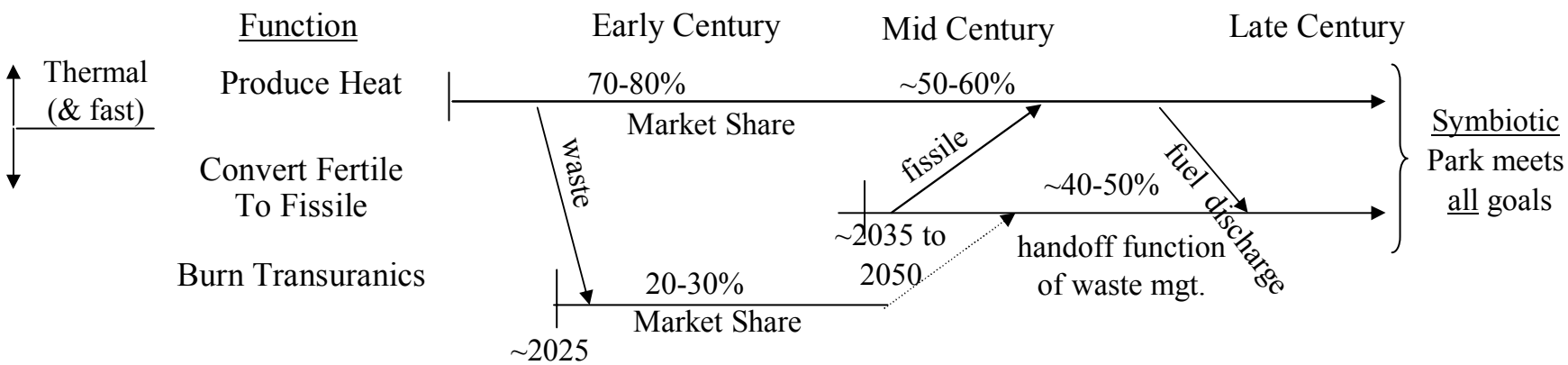
    } **The market share will be evolving in time**
- **Breeders mediate fissile production in two ways**
  - Market share
  - Breeding Ratio of Core Loading
- **A World price for fissile, and for H_2 will exist**
  - Cost effective long distance shipping of fissile cassettes; and of H_2
    - *Facilitates a world price (as currently for oil)*

Therefore

- **Open Market Financial Forces Provide Feedback – Controlling Fissile Inventories**
  - Maintain fissile demand and supply in balance
  - Mediate hydrogen production shares: central (from breeders) vs distributed (from STAR's) hydrogen production shares will be based on tradeoff:
    - *"Value" of energy security from local production vs cost of shipping from Regional Center*
- **Central (Governmental) "Control" to mediate fissile supply and demand is Not Required or Desirable**

The Global Fuel Cycle is A Dynamical System With Long Time Constants: Requires A Systems Approach to Transition Planning

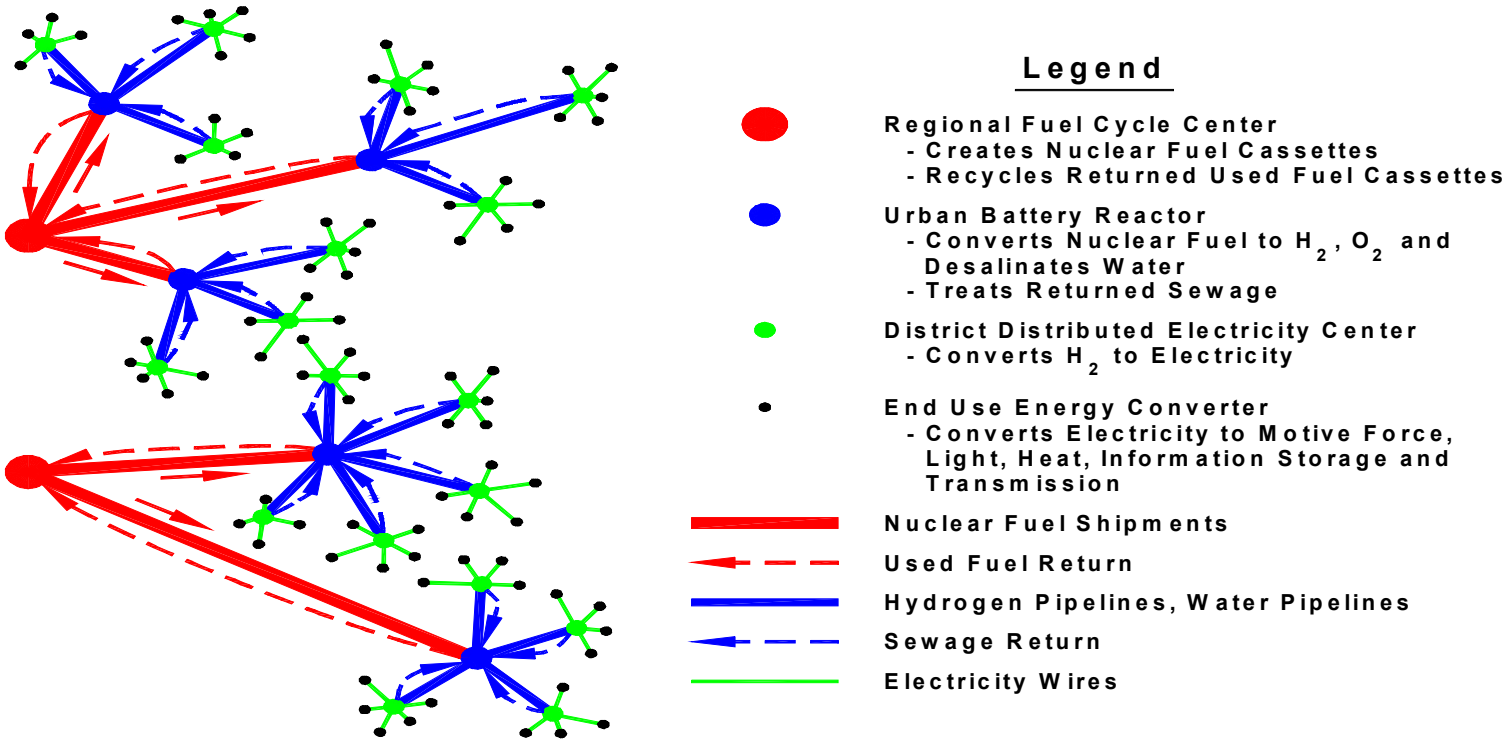
- **Symbiotic Closed Fuel Cycle Scenarios (World-Basis) were evaluated by The Gen-IV Fuel Cycle Crosscut Group**
  - Manage the transition from current Once-Thru Cycle to eventual sustainable closed cycle nuclear energy architecture



- **Results showed that**
  - A transition is technically feasible within ore constraints and repository constraints
  - Requires closing the cycle and fast reactors no later than 2020 to 2030
  - Did not address extensive expansion of market share into H_2 production

Summary:
Nuclear-Fueled Sustainable Development

The Proposed Mid Century Hierarchical Hub-Spoke Energy Architecture – Optimized for Nuclear



Exceptional Reliability of Supply

- **Connections of Hubs to Redundant Supplier Hubs; Storage of Every Hub**
- **Distributed generation of energy services; cross connection of Hubs at each hierarchal level**
- **This Architecture is Extremely Robust – to diversity and to evolution**
  - The Hierarchal Hub-Spoke Architecture is used by nature for cell metabolism (Science, Vol. 297, p.1551, Aug 2002)

Could This Architecture Fuel a Sustainable Development Revolution?

Humanity's Top Ten Problems for Next 50 Years

- **Richard Smalley Nobel Laureate (Chemistry 1996)**
  - "Energy Can Help Solve Most of Them!"

1. **ENERGY**
2. **WATER**
3. **FOOD**
4. **ENVIRONMENT**
5. **POVERTY**
6. **TERRORISM & WAR**
7. **DISEASE**
8. **EDUCATION**
9. **DEMOCRACY**
10. **POPULATION**

2003	**6.3**	**Billion People**
2050	**8-10**	**Billion People**

- **Bjorn Lomborg's Copenhagen Consensus Ranked Many Issues more urgent than Climate Change**
  - Malaria, HIV/AIDS, Water, Sanitation, etc.

But:

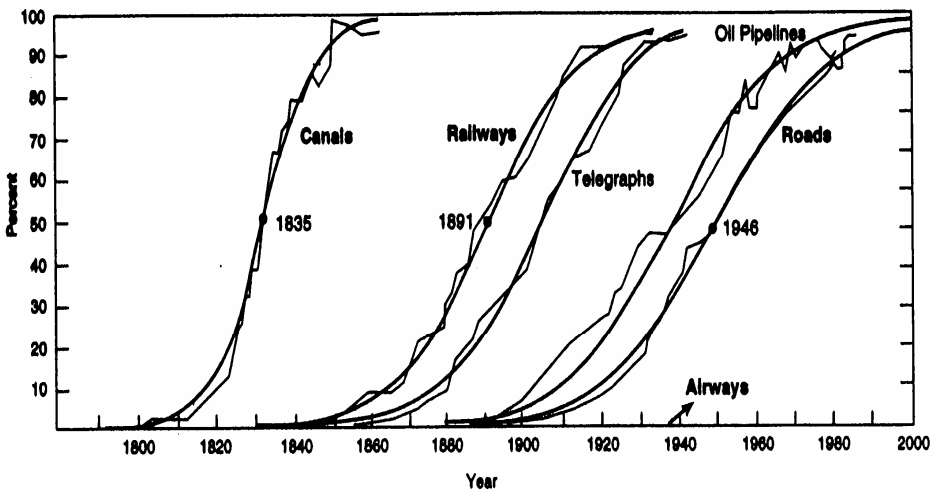
- **Copious quantities of clean, affordable energy will help with manifold aspects of Sustainable Development**
  - Disease, hunger and lack of sanitation can be ameliorated by energy input and potable water
  - Water stress and energy stress as sources of conflict can be eased by providing energy security
- **Population growth rate will tend to decrease wherever GDP/capita rises to the industrial range (as in Europe, N. America) → helping to ameliorate human impact on environment, biodiversity**

Answer: Yes it Could!

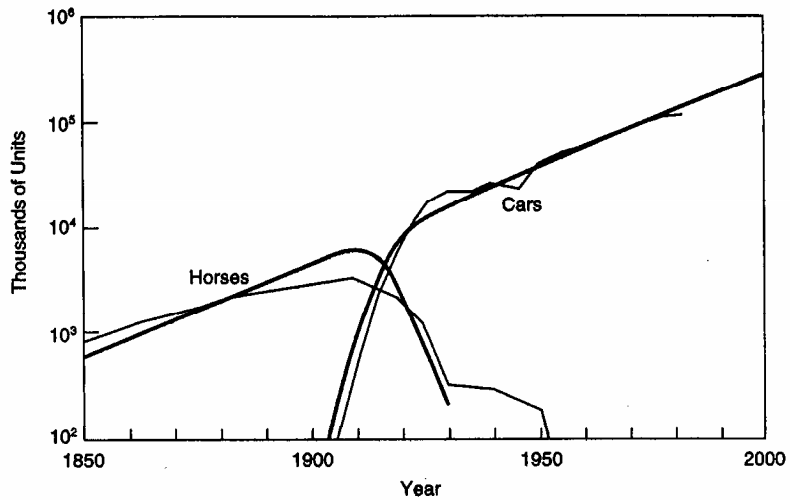
Transition Strategies

Transitions to New Infrastructures Take Multi Decades

Filling The Same Need With Something "Better"



Growth of infrastructures in the United States as a percentage of their maximum network size.
SOURCE: Grübler and Nakićenović (1991).

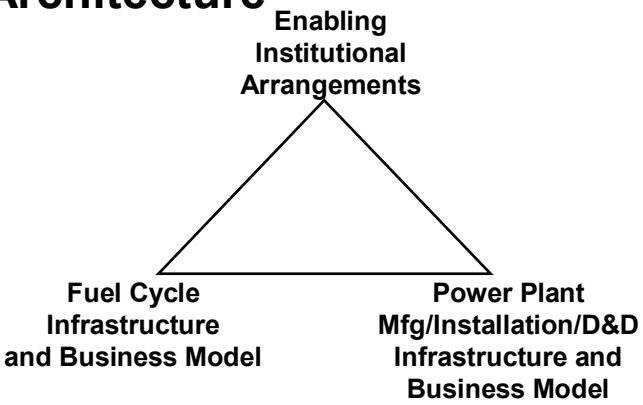


Number of nonfarm draft animals and automobiles.
SOURCE: Nakićenović (1986).

- **To be completed by mid century: The transition needs to start immediately**
- **What steps can we take Near and Mid Term?**

Emplacing The Structural Elements of the New Energy Architecture

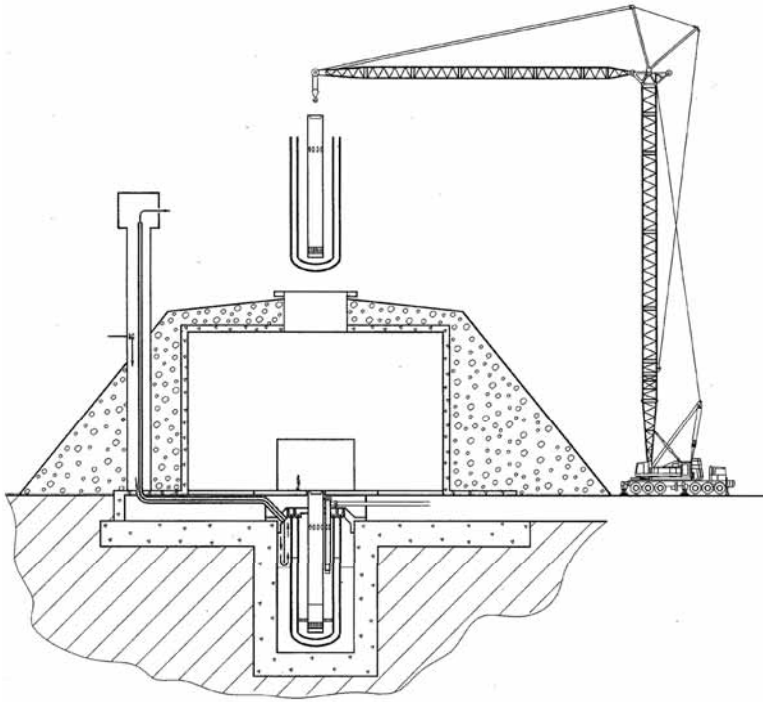
- **We will have to emplace three main structural elements of the Architecture**



- **Enabling Institutional Arrangements**
  - International Regimes for Commerce in Nuclear Technology
  - Multi-National Legal Arrangements for Fuel Cycle Centers
- **Power Plant Mfg/Installation/D&D Infrastructure**
  - Risk transferred from buyer to supplier
  - Move from an Economy of Scale to Economy of Mass Production Business Model
  - Uses an Airplane or Heavy Equipment Business Model
- **Closed Fuel Cycle Infrastructure**
  - The Mass Flow Infrastructure for the Overall Nuclear Enterprise
  - Managing the Waste via Symbiotic Mass Flows
  - Managing and Balancing Fissile creation and destruction as the Enterprise Evolves in Time
  - Use a Petroleum Industry Business Model

Emplacing The Power Plant Structural Element

- **Use Passive Safety To Eliminate a Main Driver for Economy of Scale**
  - No High Pressure; No severe accidents
  - Large conventional containment can be eliminated
  - Therefore economy of scale can be replaced by SMR economy of mass production
- **Reverse the Historical Nuclear Business Paradigm to Meet Needs of Developing Countries and IPP's**
  - Transfer Financial Risk from Client to Supplier
  - Client preconstructs a non-safety-grade balance of plant
  - Client receives a Replicate, Turnkey, Pre-licensed Heat Source Reactor
  - Client outsources fuel cycle & waste management services
  - Supplier conducts rapid transport/install/startup of Heat Source Reactor
    - *Client receives revenue stream quickly*
  - Supplier spreads his cost of risk over hundreds of replicates (business model of airplane sales; heavy equipment sales)
- **Configure for Developing Country Institutional Maturity**
  - Non-safety Grade Balance of Plant
    - *Built by indigenous labor to indigenous standards*
  - Reduced Staffing and Skill Levels
    - *Passive Load Follow*
    - *Passive safety Response*



Emplace a Broadened Product Slate – Incrementally: Market Penetration via Nuclear Hydrogen

Incremental Steps Using Existing and Near-Mid Term Technology

- Current Water Reactors and Near-Term Gas Reactors
- Electrolysis, steam/methane reforming
- Open fuel cycle

Near Term: Help Launch A H_2 Economy Using Existing Technology

- **Use nuclear electricity for distributed electrolysis of water**
  - Break the Chicken and Egg Dilemma of lacking a hydrogen distribution infrastructure
  - Studies by Alistair Miller and Romney Duffey show economic feasibility

Near-Mid Term: Develop Win-Win Symbiosis With Fossil

- **Extending/Enriching Fossil Reserves**
  - Site a dedicated H_2 nuclear production plant next to a refinery (no distribution of H_2 required)
    - *Lighten and sweeten the degrading petroleum feedstock*
  - Site a dedicated steam and H_2 nuclear production plant in a tar sands field
    - *Steam to extract the crude petroleum*
    - *H_2 to lighten and sweeten the crude petroleum*
- **Closing the Carbon Cycle**
  - Use nuclear process heat to manufacture commodity chemicals from coal-fired plant CO_2 emissions

In the Meantime

- **Develop reactors and chemical cycles for higher temperature nuclear production of H_2**

Emplacing A Symbiotic Fuel Cycle for Managing The Global Fissile Inventory

- **LWR's will dominate for several decades**
- **Many forms of SMR's will be introduced by competing suppliers (STAR is just one choice)**

But

- **One shared Fuel Cycle <u>Integrates/Mediates</u> <u>ALL</u> Fissile flows and Waste Management!**

<u>Initial Decades</u>

- **Working Inventories for STAR deployments**
  - Obtained by processing LWR Spent Fuel
- **A Win-Win Symbiotic Fuel Cycle**
  - LWR spent fuel "waste" converted to
    - *Fission Product (only) waste forms*
    - *Transuranics to fuel STAR working inventories*
    - *U238 feedstock supply for sustainable development*
  - STAR's, once started, are fissile self sufficient

<u>Later Decades:</u> After LWR spent fuel supply diminished (cheap U ore depleted)

- **Breeder Reactors Sited at Regional Fuel Cycle Centers Fuel a Growing World Economy**
  - Breeders Generate working inventories for growing deployment of STARS
  - Heat from Breeders used to manufacture H_2 for regional clients

<u>Benefits</u>

- **Only fission products go to waste**
- **15 million tonnes of U ore at ≤ 130 $/kg can fuel a millennium of global energy needs**

Emplacing Enabling Institutional Arrangements

Just as for the Industrial Revolution, Technology is not Enough – Old Institutional and Business Models Cannot Exploit the 10^6 Increase in Energy Intensity Attendant the switch to Nuclear From Chemical fuel

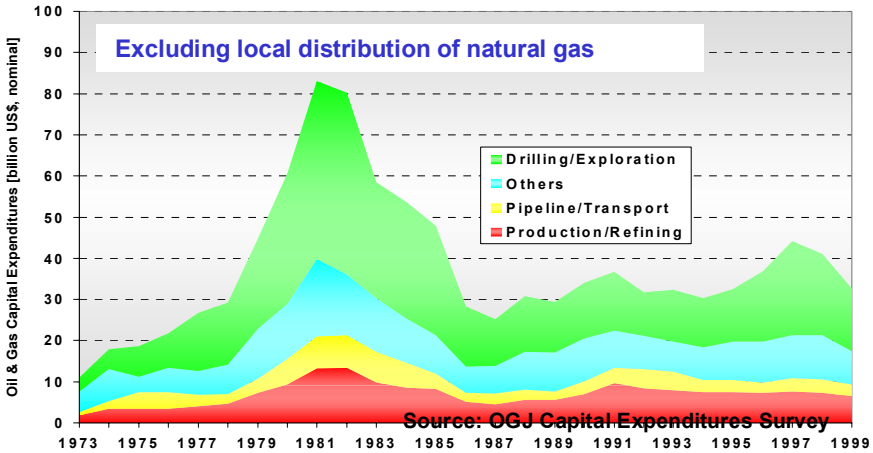
- **Introduce Business Plan Innovations (replace LWR Economy of Scale with STAR Economy of Mass Production)**
  - Standardized Commodity Plants delivered Turnkey
  - Outsourced Fuel Cycle and Waste Services
  - Risk transferred from client to supplier
    - *Business Model of Airplane, heavy equipment sales*
- **Emplace enabling institutional changes for multi-national Fuel Cycle Centers**
  - Multinational legal arrangements for Regional fuel Cycle Centers
    - *Owned and Operated by Consortia of Clients*
    - *Overseen by international Nonproliferation Authorities*
    - *Legally-binding access to services and seat on Board of Directors in exchange for commitment to forego an indigenous fuel cycle infrastructure*
- **Emplace Enabling Institutional changes for International Norms on Safety and Nuclear Operations**
  - International Norms on
    - *Safety, Radiological Safety, Early Notification of Accidents*
    - *Mutual Aid Pacts in Event of shipping Accidents*
    - *NPT Treaty, etc., etc.*
  - Reciprocity Arrangements Among National Safety Licensing Authorities

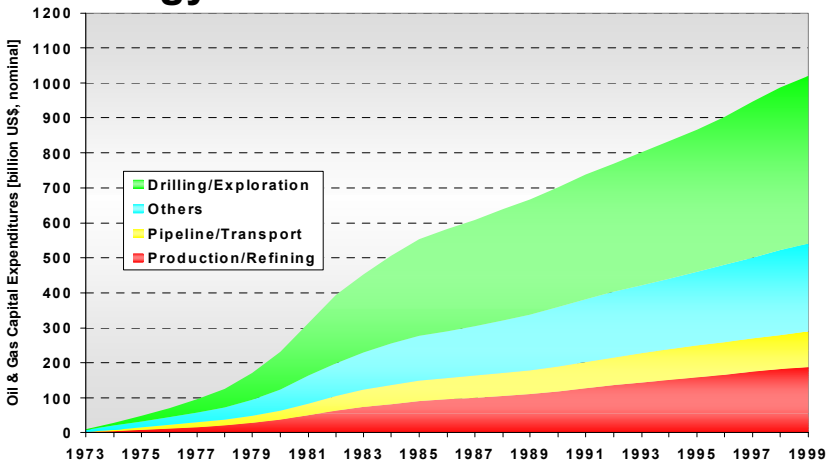
Who Will Build/Operate The Fuel Cycle Centers?

- **Client Outsources fuel/waste services to a Regional Fuel Cycle Center**
  - Receives Guaranteed-by-law access to services in exchange for commitment to forego emplacing an indigenous fuel cycle – a supplement to NPT
- **Multi-National Control of Regional Centers**
  - Consortia of Clients Controls – Chartered Under International Law
    - *Provides Energy Security to Clients via access to services guaranteed by law*
  - IAEA Nonproliferation Oversight
- **Use Petroleum Business Model for Fuel and Waste Services**
  - Consortia is like Board of Directors of a Corporation
  - Consortia Contracts a Professional Manager/Operator to Build and Conduct Operations under a risk and profit sharing arrangement
    - *Clients provide Long-Term Contract for Services:*
    - *Builder/operator spreads his cost of risk over large and growing volume of business (The multi national oil company model – an energy company)*

Is This Economically Plausible?!
Energy – The World's Largest Business

- **Capital Investments to Re-Engineer the Energy Architecture**
  - Will be many tens of Billions of Dollars
- **These outlays are Routinely Made in the Energy Business**





Source: OGJ Capital Expenditures Survey

- **Deployment Rates of STAR's will be ~1000 or more plants/year; can we build them?**
  - US manufacturing capacity in WW-II exceeded this
    - *2610 Liberty Ships built (April 41 to 1944) 441 ft. long, 10,390 ton displacement (record rate was 10 days from laying keel to launch!)*
  - There will be several dozen suppliers worldwide offering SMR of diverse designs
    - *Deployment of thousands of plants/year is feasible*

Closing Thoughts

- **250 years after the Transition From Renewables to Chemical (Fossil) Energy**
  - The 21st century will see massive growth in energy demand in developing economies
  - Resources are diminishing and ecological impacts are increasing
- **~50 years after discovery of fission, the first wave of nuclear energy technology**
  - Produces 18% of the world's electricity (primarily OECD nations)
  - Has matured – with exceptional performance routinely attained -- >90% CF
- **The time is ripe for a second burst of innovation to further extend nuclear's role by fully exploiting its 10^6 advantage over fossil**
  - Contribute to a sustainable world energy infrastructure
    - *Servicing the other 80% of the world's population in Non-OECD nations*
    - *Providing a slate of ecologically superior energy products (H_2, potable water, electricity)*
- **We need to reconfigure nuclear to fully exploit its innate differences from chemical energy**
- **We need to re-engineer the overall world energy architecture – optimize for nuclear**
- **We need to initiate a Multi-Decade Transition Process to the New Architecture**

A Call To Youth – To Lead The Revolution

- **Nuclear Holds The Potential To Fuel A Sustainable Development Revolution**
- **The Transition Must have taken Place By Mid Century**
  - Requires a "Systems Approach" to:
    - *Match the structural elements of the architecture to the innate features of nuclear*
    - *Plan/coordinate to ponderous dynamics of transition*
- **A Revolutionary Re-engineering of The World Energy Architecture is Needed**
  - On the scale of the Industrial Revolution
  - Requires Special Attention To Meeting Needs of Developing Countries
  - Revolutionary – but achieved through incremental market penetration
- **Requires Technical Innovation Across The Board**
  - Reactor Design
  - Balance of Plant Design; new energy converters
  - Fuel Cycle Design
- **Requires Institutional and Business Innovations**
  - New Business Plans
  - New Institutional Arrangements
  - Public Communication
- **Although Not Knowing It – The World is depending on YOU for this revolution**
  - You -- the Next generation of Nuclear Engineers
  - To be the James Watt's, Eli Whitney's, Adam Smith's, John Adams' of a 21st Century Sustainability Revolution