The Nuclear Fuel Cycle from Back to Front: A Waste Management Perspective during the Nuclear Renaissance

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Introduction to Nuclear Fuel Cycle Chemistry
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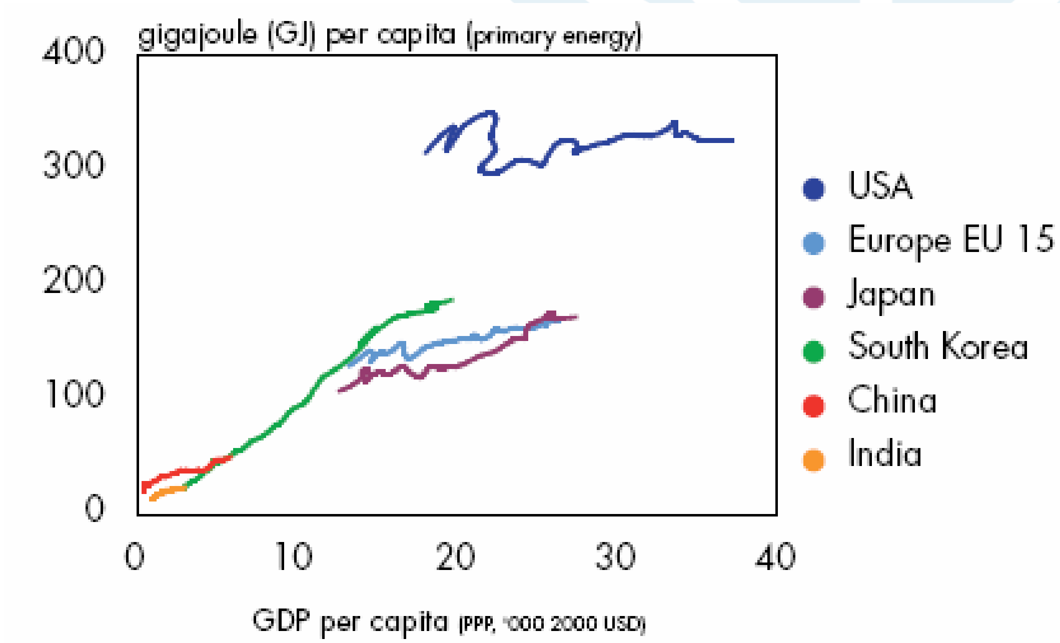
Fueling National Prosperity

Energy demand is an accurate historical indicator of economic prosperity

A reliable and affordable energy supply is the cornerstone of sustained economic growth and prosperity



[Source – Royal Dutch Shell, “Shell Energy Scenarios to 2050,” 2008.]

Global Demand Doubles by 2050

World energy demand will double by 2050

World net electricity and nuclear energy consumption by region, 1990-2025 (Billion Kw-h)

Region/Country	History 1990	2001	2002	Projections 2010	2015	2020	2025	Avg. Annual Change (%)
Electricity Consumption								
Mature Economies	6368	7934	8086	9079	9837	10514	11319	1.5
Transitional Economies	1906	1520	1544	2334	2654	2917	3145	3.1
Emerging Economies	2272	4383	4645	7462	8909	10246	11554	4.0
Total World	*10546*	*13836*	*14275*	*18875*	*21400*	*23677*	*26018*	*2.6*
Nuclear Energy Consumption								
Mature Economies	1544	2024	2032	2120	2136	2110	2083	0.1
Transitional Economies	256	282	302	364	376	437	512	2.3
Emerging Economies	105	209	225	406	519	605	675	4.9
Total World	*1905*	*2515*	*2560*	*2890*	*3032*	*3152*	*3270*	*1.1*

[Source – United States Department of Energy, "International Energy Outlook 2005," DOE/EIA-0484, July 2005]

Global Demand Drives Alternative Energy

Nuclear energy is a true 'cradle-to-cradle' technology

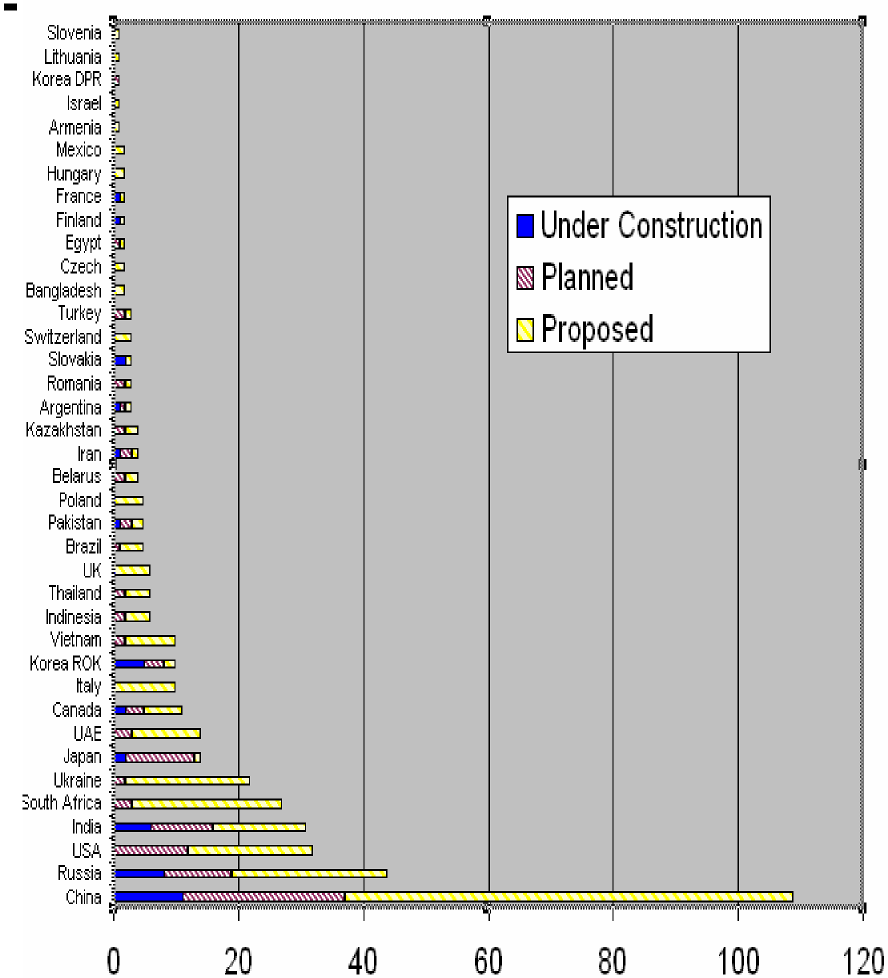
- **'CO_2-free' energy**
- **Sustainable fuel cycles**

Nuclear power used worldwide

- **436 Operating reactors**
- **43 under construction**
- **106 planned or ordered**
- **266 proposed**

Considerations for the nuclear renaissance:

- ***Safety***
- ***Waste disposal***
- **Proliferation-resistance**



Source: World Nuclear Association – Reactor Data – January 2009 (see http://www.world-nuclear.org/info/reactors.html)

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Waste Management is *Critical* Part of the Fuel Cycle

Effectively learn from the past experience in defense and civilian nuclear waste management to develop optimized processes and systems

Type
Specifications
Schedule
Shipping

Reactor Design/Operation

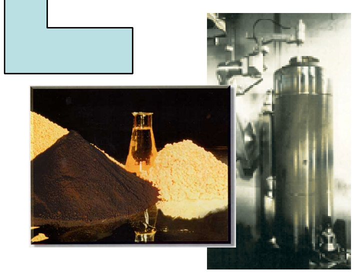
Schedule
Burnup
Conversion Ratio
Shipping

Irradiated fuel storage

Type
Age
Schedule
Shipping

Fuel Processing

Inventory Control
Product Purity
Safeguards
Separation Efficiency
Disposition Path
Shipping



Material Recycle/Disposition

WAC
Waste Form
Technology
Shipping

Isotopes
Safeguards
Schedule
Shipping

Fuel Fabrication

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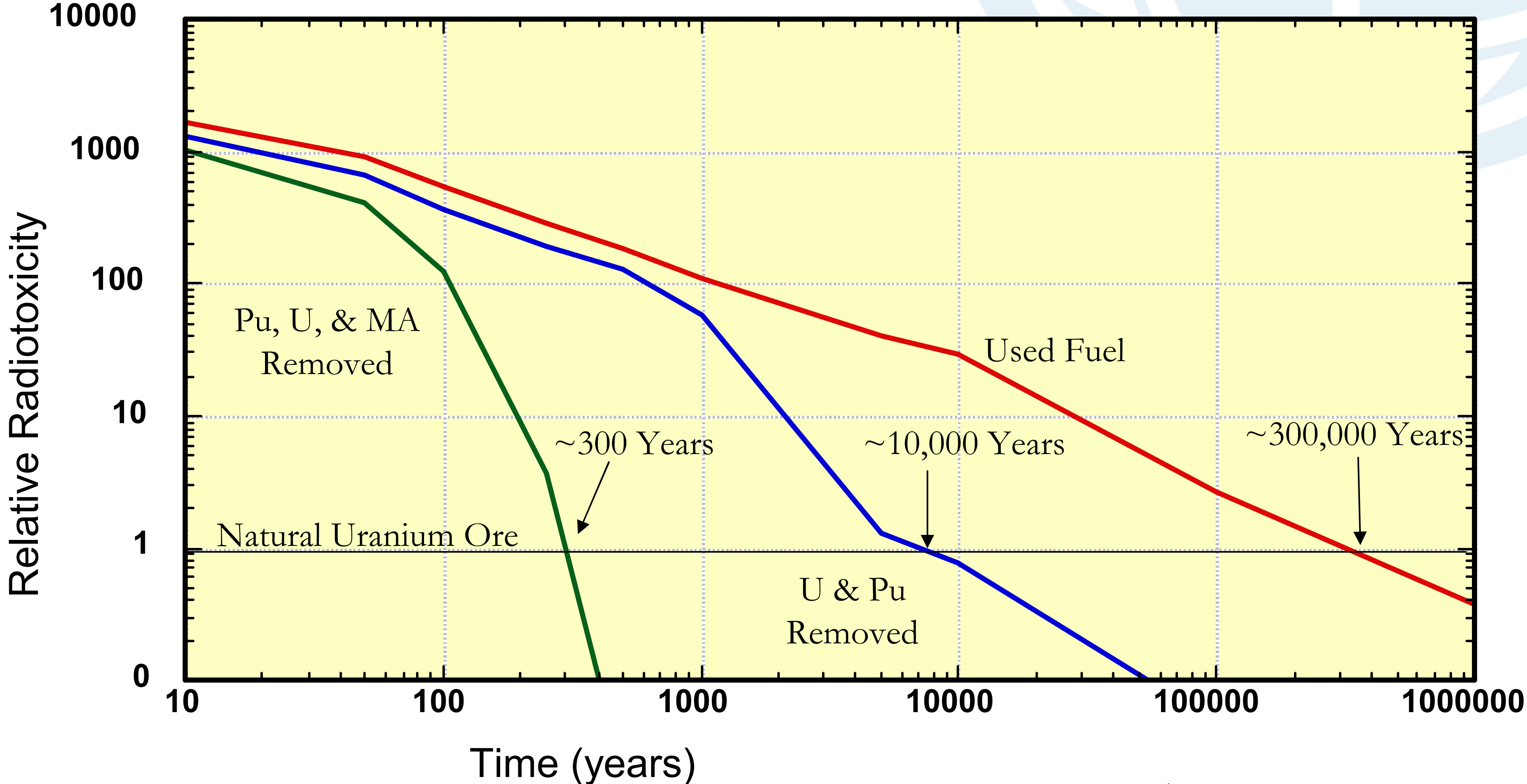
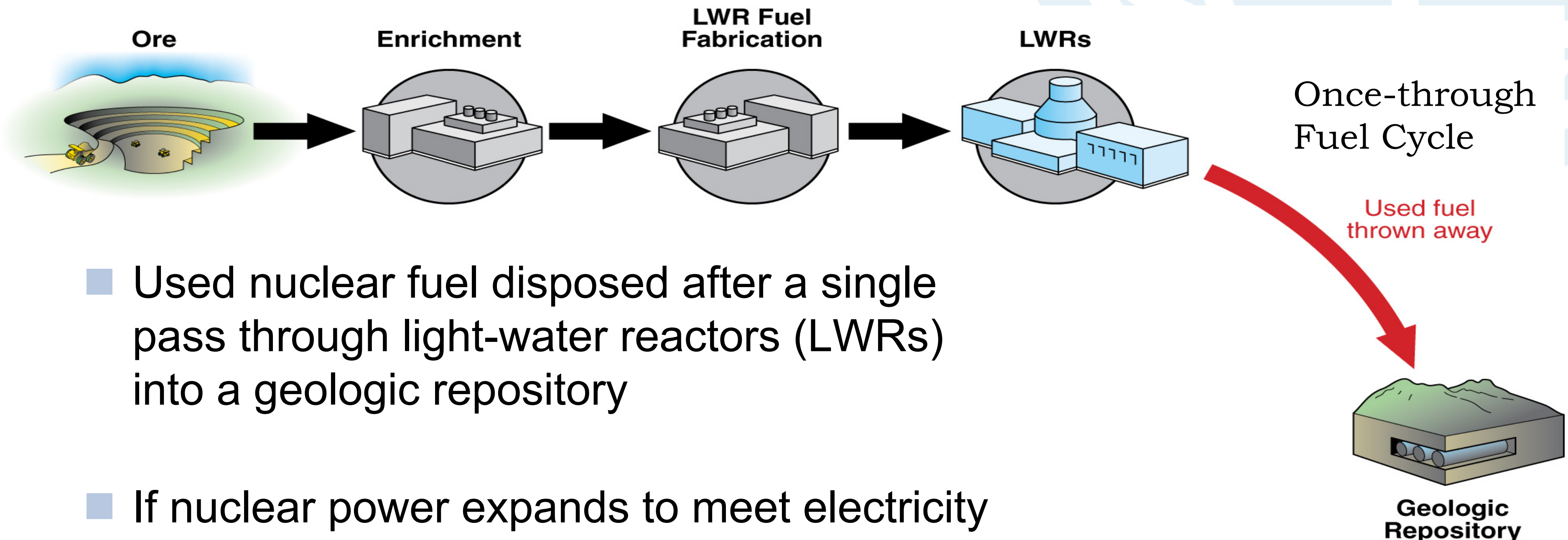
Recycling Can Greatly Reduce Long-term Radiotoxicity of Nuclear Waste



LWR Fuel 50 GWd/MT, 5 Years Cooling

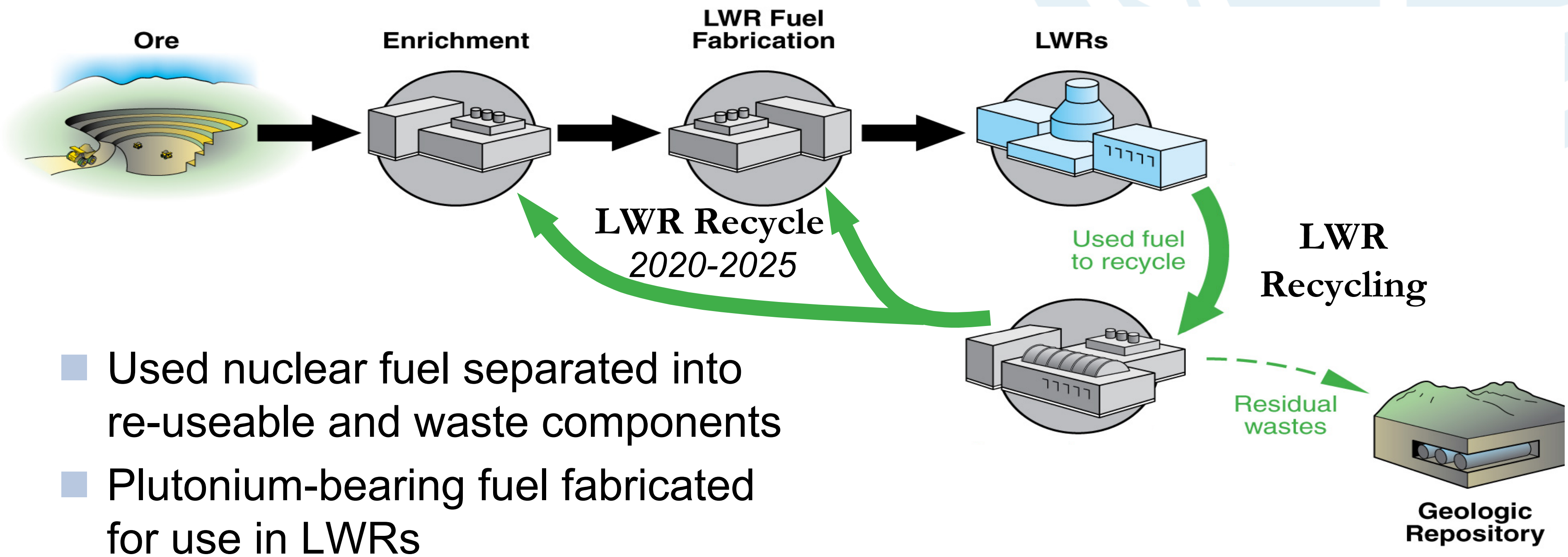
The “Once-Through” Fuel Cycle
– Approximately 300,000 year waste –



- Used nuclear fuel disposed after a single pass through light-water reactors (LWRs) into a geologic repository
- If nuclear power expands to meet electricity demand, the U.S. would need multiple repositories (the size of Yucca Mountain at current statutory capacity) by the end of the century with the once-through fuel cycle

Light-Water Reactor (LWR) Recycling

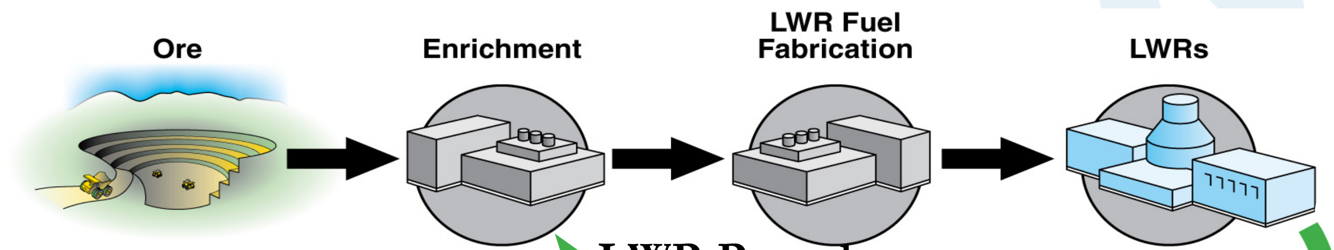
– Approximately 10,000 year waste –



- Used nuclear fuel separated into re-useable and waste components
- Plutonium-bearing fuel fabricated for use in LWRs
- Residual wastes sent to a geologic repository
- Must address used MOX fuel

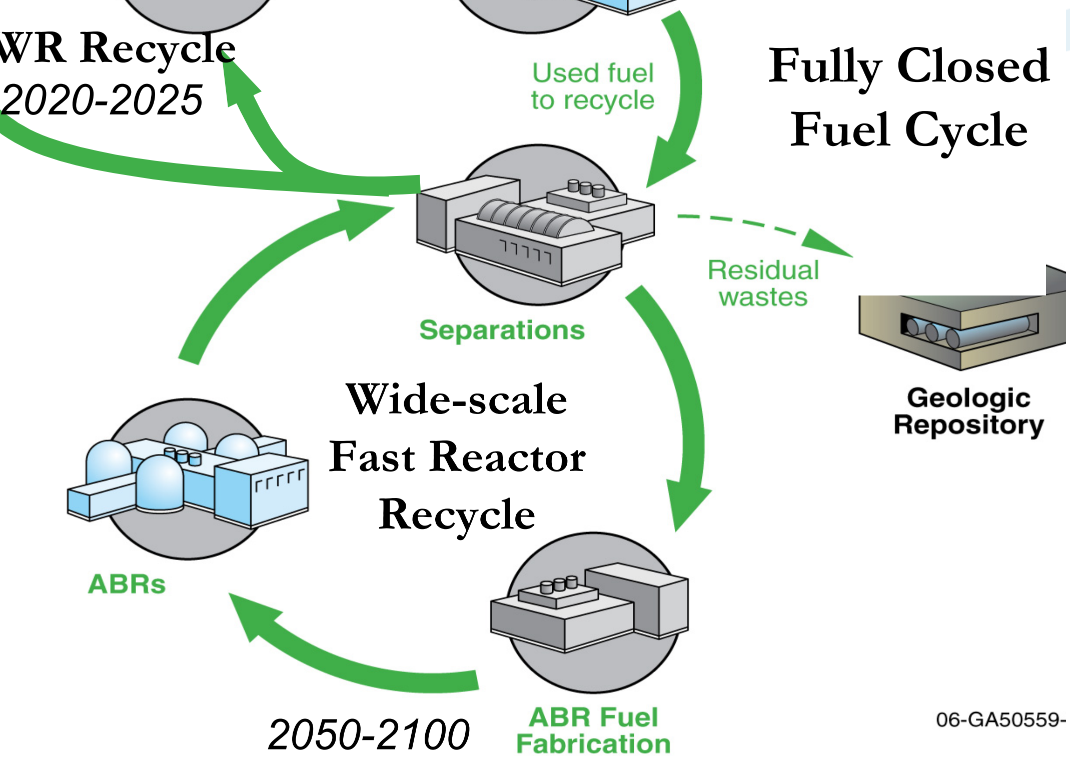
Light-Water + Fast Reactor Recycling

– Approximately 300 year waste –



Key elements of two-step approach:

- Recognizes technology readiness – commercial facilities use proven, best available technologies
- Recognizes funding and market realities – it will be second half of century before wide-scale use of fast reactors available
- Enables reliable fuel services (take back) capability sooner
- Begins conserving valuable resources sooner
- Begins reducing repository burden sooner – *optimized waste management*
- Ultimately achieves all objectives of fully closed fuel cycle



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Traditional Approach to Development

- Incremental improvement of existing technologies to allow for short-term (~20 years) deployment, driven by better utilization of Yucca Mountain
  - Specific choice of technologies and integrated system (dictated by time frame and Yucca Mountain characteristics)
  - Challenges had been well identified
  - Engineering approaches were chosen to address these challenges
  - Fundamental challenges had also been identified (2006 workshops), but were marginally acted upon (e.g., modeling and simulation)
- The incremental approach resulted in very limited investment in the tools needed to develop a better understanding of the fundamentals

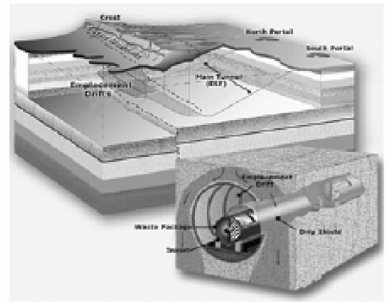
Deep Geologic Disposal

- There are many options for deep geologic disposal

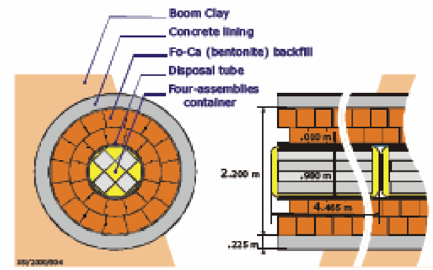
Mined geologic repositories –
Saturated rock
Hard rock – granite, basalt, …
Soft rock – shale, sedimentary rocks, …
Unsaturated rock
Volcanic tuff
Clay (saturated)
Salt (dry)

Isolation is provided by engineered systems, chemical environment, geologic stability, …

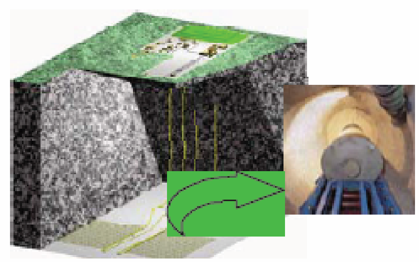
Deep boreholes
Isolation is provided by depth



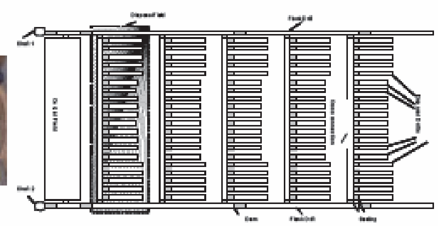
Yucca Mountain



Saturated Clay Layer



Granite



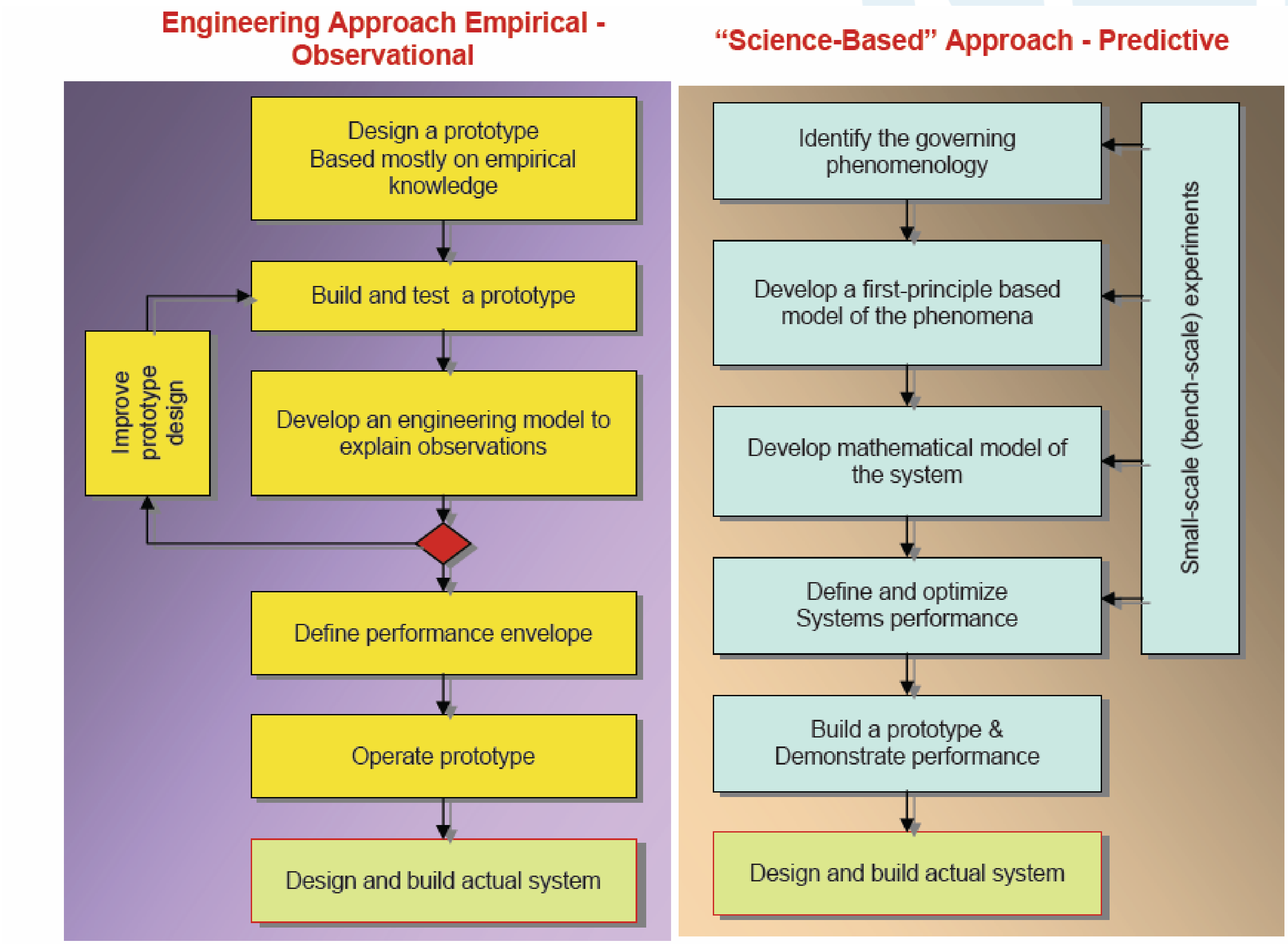
Salt

Seabed/sub-seabed, Subduction Zone, Rock melt, Island (intentional dilution in ocean), Ice sheet, Space, … Many issues - isolation potential, international law, geology, …

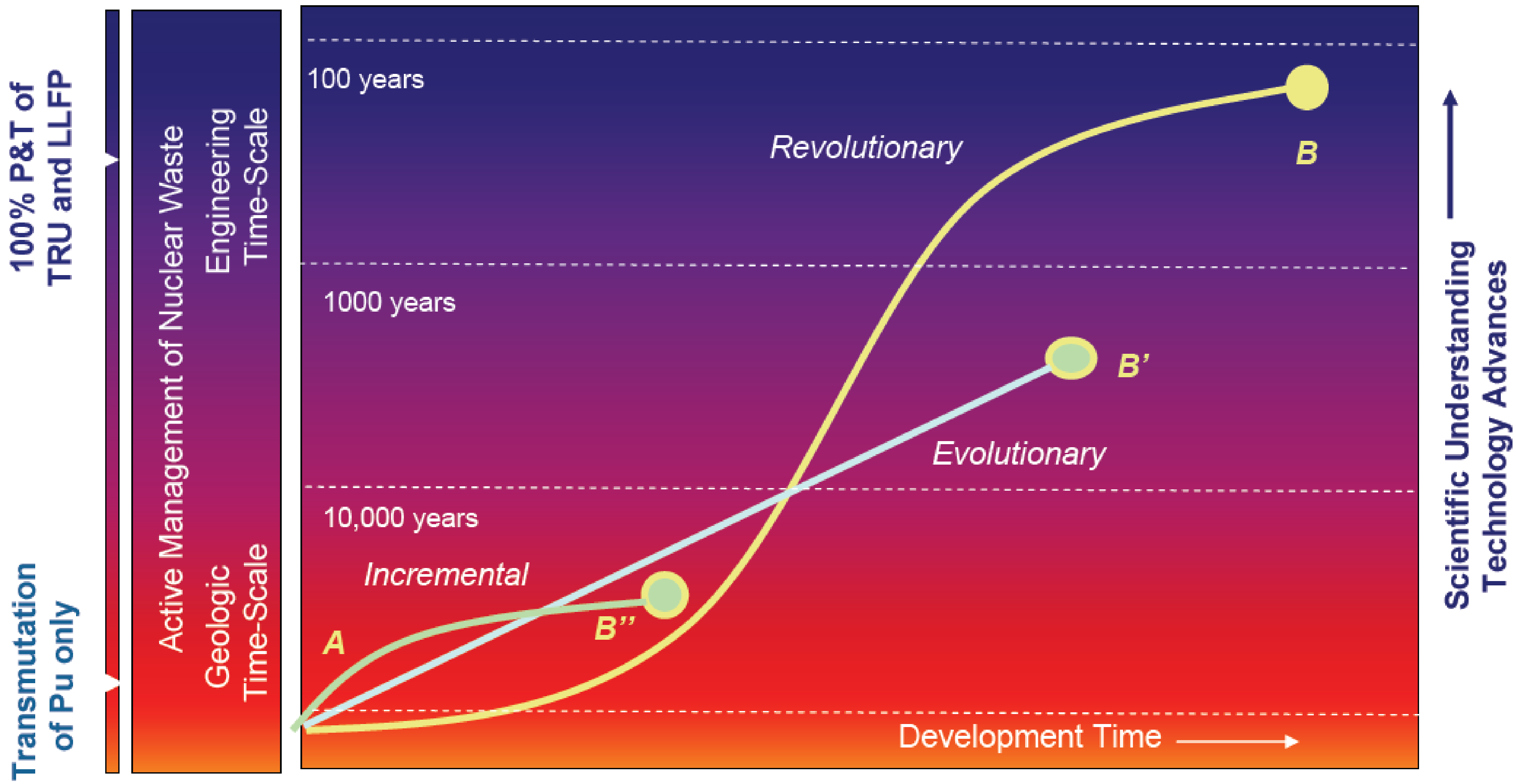
'Thinking from the Back'

- **Postulate a desired goal to avoid the need for a mined geologic repository**
- **Options for waste characteristics**
  - **Remove all elements from waste stream that require waste to be disposed in a mined geologic repository**
    - Transmutation or other treatment needed to convert all of the hazardous elements
  - **Remove sufficient elements from waste stream so that other waste isolation approaches can be used for the remaining elements, such as deep boreholes**
    - Remove decay-heat producing elements since they limit borehole disposal capability
    - Transmutation only required for elements not destined for disposal without treatment
- **Technology Requirements ➽ Technology Options ➽ R&D Program**

Observational vs. Predictive Approach



Transformational Approach



Waste Management Approach

Today's Technology Challenges

- Storing and disposing spent fuel, HLW, GTCC, and LLW from a range of fuel cycles
  - Understanding and predicting geologic repository performance.
  - Safe, secure, and cost effective storage and disposal.

Grand Challenge/Transformational Result:

- Integrated waste management with zero radionuclide release from storage and disposal system
- Predictive capability for performance of storage and disposal options for a range of fuel cycles

Development Path

- Develop an understanding of geologic repository performance
  - Review extensive technical basis developed in the U.S. and internationally over the past several decades
  - Explore range of geologic settings, including granite, salt, clay, and tuff, and range of disposal concepts, including shaft-room, ramp-drift, borehole, and shallow land burial.
  - Investigate storage concepts for a range of waste streams.
  - Develop an integrated waste management strategy applicable to a range of fuel cycle options

Volatile/Semi-Volatile Fission Products

Domestic deployment of used nuclear fuel recycling will likely require revised treatment approaches

- **Aqueous discharge unlikely**
- **Candidate treatment options**
  - Iodine captured on silver zeolite
  - Tritium captured in molecular sieve
  - Krypton and Xenon captured zeolite/mordenite
  - Carbon as carbon dioxide captured in/on caustic

Long Lived Fission Products – I, Tc, C

- **Waste Forms must sequester or delay release of radionuclides for at least 50,000 – 150,000,000 years**
- **Form highly mobile anionic species in environment**
- **Initial approach:**
  - AgI displaced by sulfide, need to protect from reducing groundwater and heat
  - Tc as metal alloy requires sacrificial species to protect from oxidation
  - Carbonate species as grout requires specialized formulation and packaging

Short Lived Fission Products – H, Kr, Xe, Cs, Sr

- **Strategy includes potential for decay storage**
  - Monitored engineered storage for ~10x $t_{1/2}$
  - Ultimate disposal as LLW
- **Must dissipate heat**
- **Must contain gases (H, Kr, Xe, radiolysis products)**
- **Waste forms must accommodate:**
  - Radiation exposure
  - Chemical (valence) change
  - Physical (size) change
  - Leachability of radionuclides and any hazardous metals

Lanthanides and Balance of Fission Products

- Default is glass
- Good opportunity to reconsider US waste regulations
- Is this remaining fraction still HLW?
- Consider waste in terms of characteristics instead of origin
- Can this stream be disposed as Greater than Class C or Intermediate Level Waste?
- If so, what should waste form performance requirements be?

Undissolved solids, Hulls and Hardware

- Noble metal Fission Products
- Activated metals
- Residual TRU contamination
- Some metal used in making Tc-alloy waste form
- Balance could be considered HLW, Greater than Class C or Intermediate Level Waste
- Performance assessment for disposal or Geologic Repository

General Low-Activity Waste

- ***Significant growth in nuclear will stress infrastructure***
- **Wastes are all classes, many physical and chemical forms**
- **Magnitude of wastes may make cutting-edge technologies economical**
  - Organic destruction
  - Decontamination
  - Size reduction
  - Contaminated recycle market?

An Integrated Waste Management Strategy

- Expansion of nuclear energy worldwide requires answers to safety, regulatory, and *waste management* issues
- Additional work is needed to define waste treatment, waste forms, and disposition pathways
  - Develop quantifiable waste form performance requirements
  - Standard tests to measure durability
- Options should be considered for work with minimal regulatory change as well as potential opportunities for changing regulations and policy
- Consider beneficial reuse/recycle
- Large opportunity for collaboration
- ***Learn*** from previous defense & civilian experience