Why Fuel Cycle Choices Will Vary With Time

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The MIT *Future of The Nuclear Fuel Cycle*[1] Study Examined Fuel Cycles in the Context of Growing Energy Demand and Greenhouse Gas Restrictions

- World population is 7 billion; going to ≥10 billion
- How can we supply 3-6 times more energy without running out of resources or seriously impairing the planetary environment?

MIT Fuel Cycle Conclusions

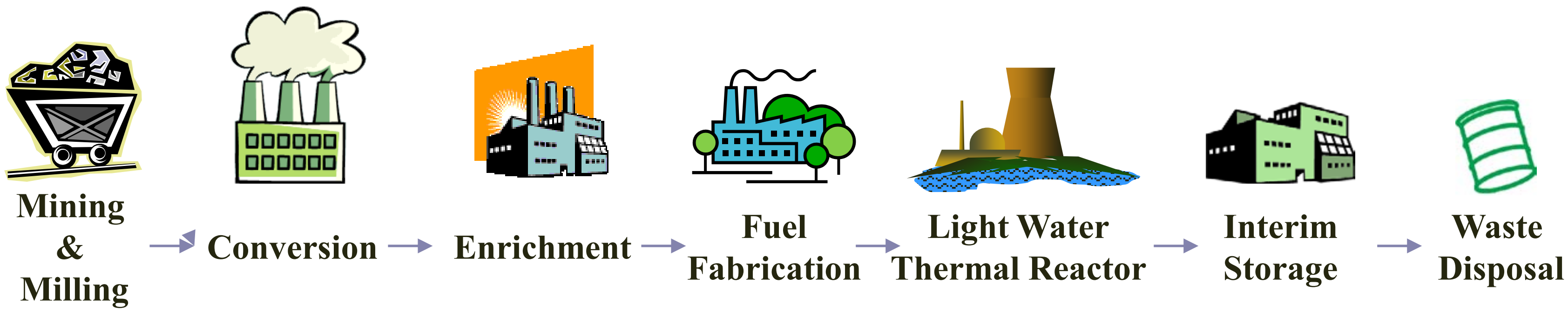
- We do not know if Light-Water Reactor (LWR) spent nuclear fuel (SNF) is a waste or valuable resource
- Lead to recommendation to store SNF to provide options for future generations.
- Three storage options for SNF
  - Reactor
  - Central site
  - In repository with option for future recovery

Why Are Fuel Cycle Futures Unknown ?

Light Water Reactors

Today’s Reactors

The U.S. and Sweden Use a Once-Through Fuel Cycle



Production of Nuclear Fuel

Electricity Generation

Waste Management

Need Only 200 Tons of Uranium / Reactor Year

Conventional Uranium Mining is the Economic Fuel Choice Today

This is Likely to Remain True for Most of the Century[1]

Photo Courtesy Energy Resources of Australia: Ranger Mine in Australia

Advances in Drilling Technologies (Solution mining) and Carbon Dioxide Sequestration[2] May Expand Uranium Resources

The Mega Resource of Uranium is the Ocean

- 10,000 times conventional resources
- The challenge is the low concentrations (3.3 ppm)
- Black current off Japan carries 5.2 million tons per year

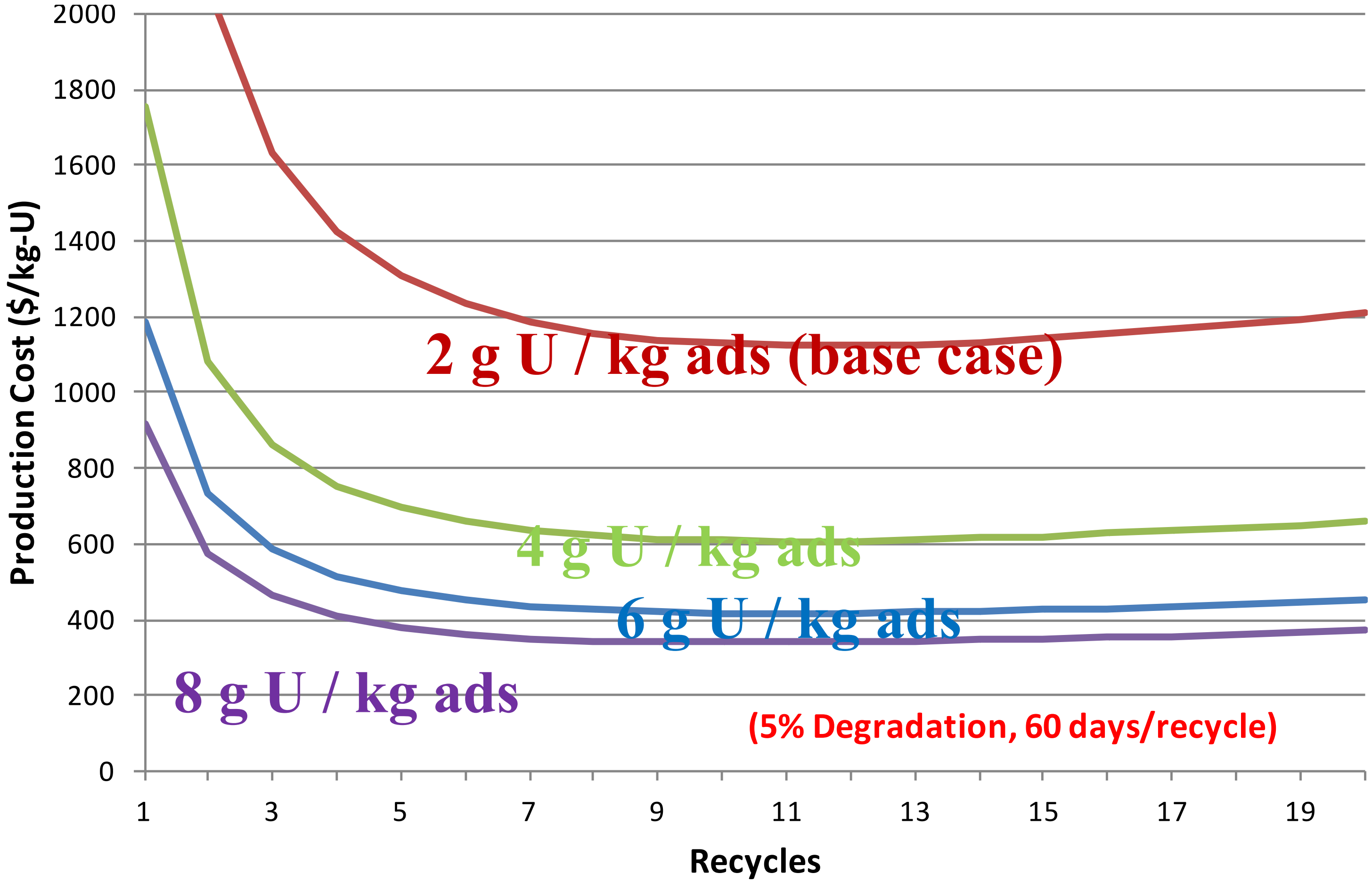
Recent Advances[3] in Chemistry May Make Seawater Uranium Competitive with Expensive Conventional Uranium

Recovery operation of adsorbent

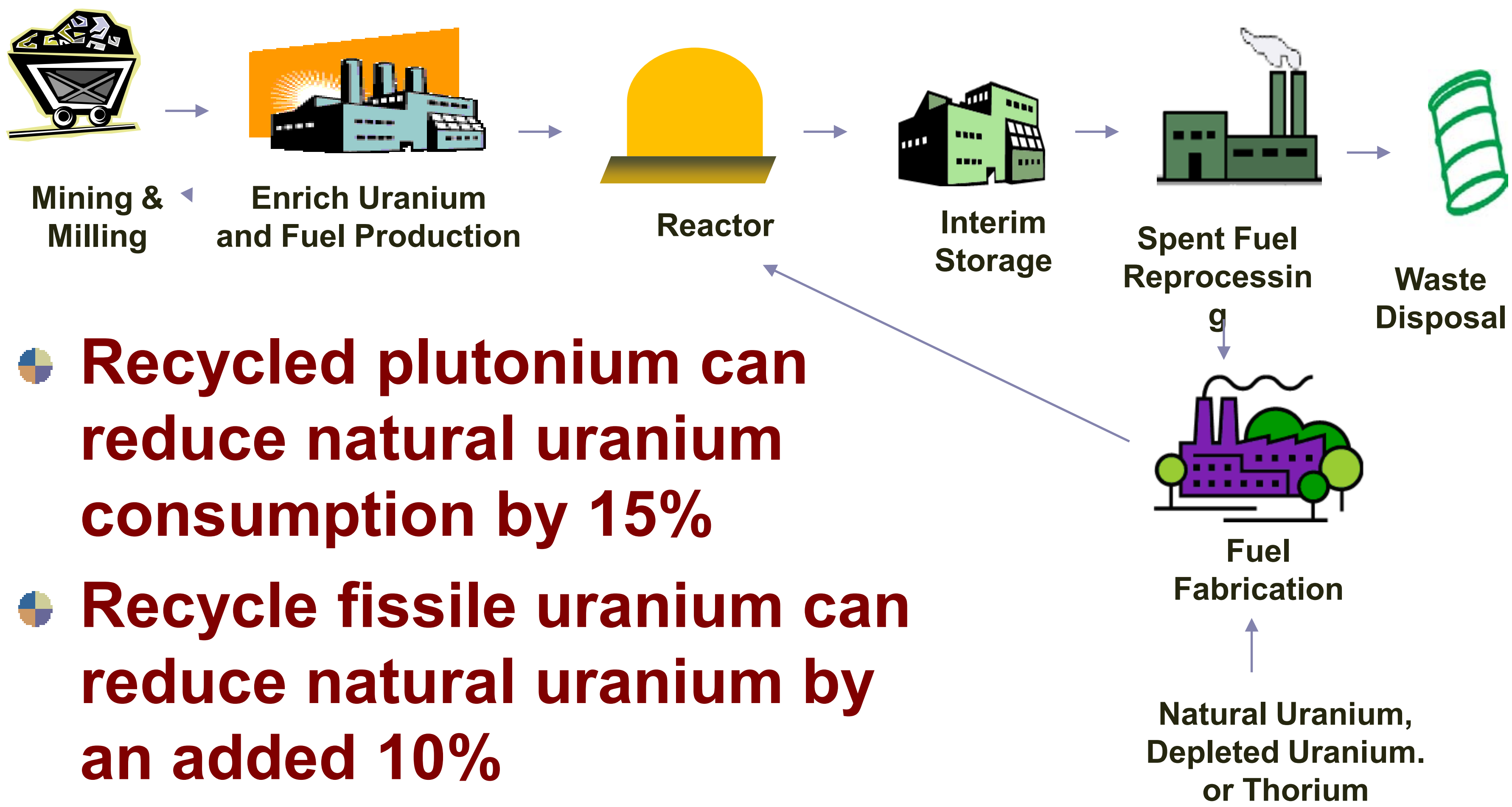
- Synthetic "kelp" with selective absorption for uranium
- Anchored on sea bottom for several months in currents
- Harvest uranium and recycle absorber

Cost of Seawater Uranium Dependent Upon Absorber Capacity[3]: Still Expensive U

Recent Advances at Oak Ridge National Laboratory Have Increased Absorption Capacity / Lowered Costs



LWR SNF Contains ~1% Plutonium: Can Recover and Recycle Back to LWR



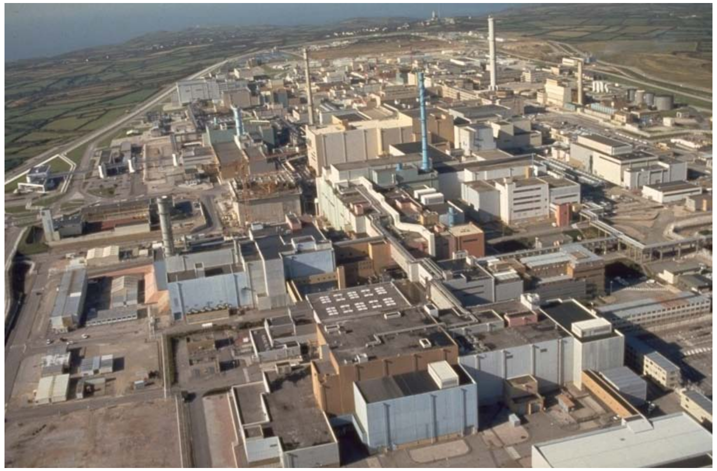
- Recycled plutonium can reduce natural uranium consumption by 15%
- Recycle fissile uranium can reduce natural uranium by an added 10%

Recycling LWR SNF Is Uneconomic But That Could Change[4]

Hanford (Washington State)

- 1960s weapons complex with on-site waste disposal
- 5000-7000 MTU/y (33 MTU/day maximum)
- Defense SNF
- Large facility

LaHague (France)



Courtesy of COGEMA

- Commercial with off-site waste disposal and waste treatment plants
- 2 x 800 MTU/y
- Commercial SNF
- **Much larger facility**

History of Reprocessing May Indicate a Route to Economic Reprocessing

- Much of the cost of reprocessing is associated with waste management
- Defense reprocessing did on-site disposal with major cost savings but made a mess
- What if integrated reprocessing and the repository into a single facility with advanced technologies?
- Potential for major cost savings but implies major changes in technology

Technology Advances Will Determine Which Options Supply Nuclear Fuel

Conventional Uranium

Seawater Uranium

Reprocessing SNF

Preferred Option or Options May Change with Time

Fast Reactors

Future Reactors That Reduce Uranium Consumption by 10 to 100 Times

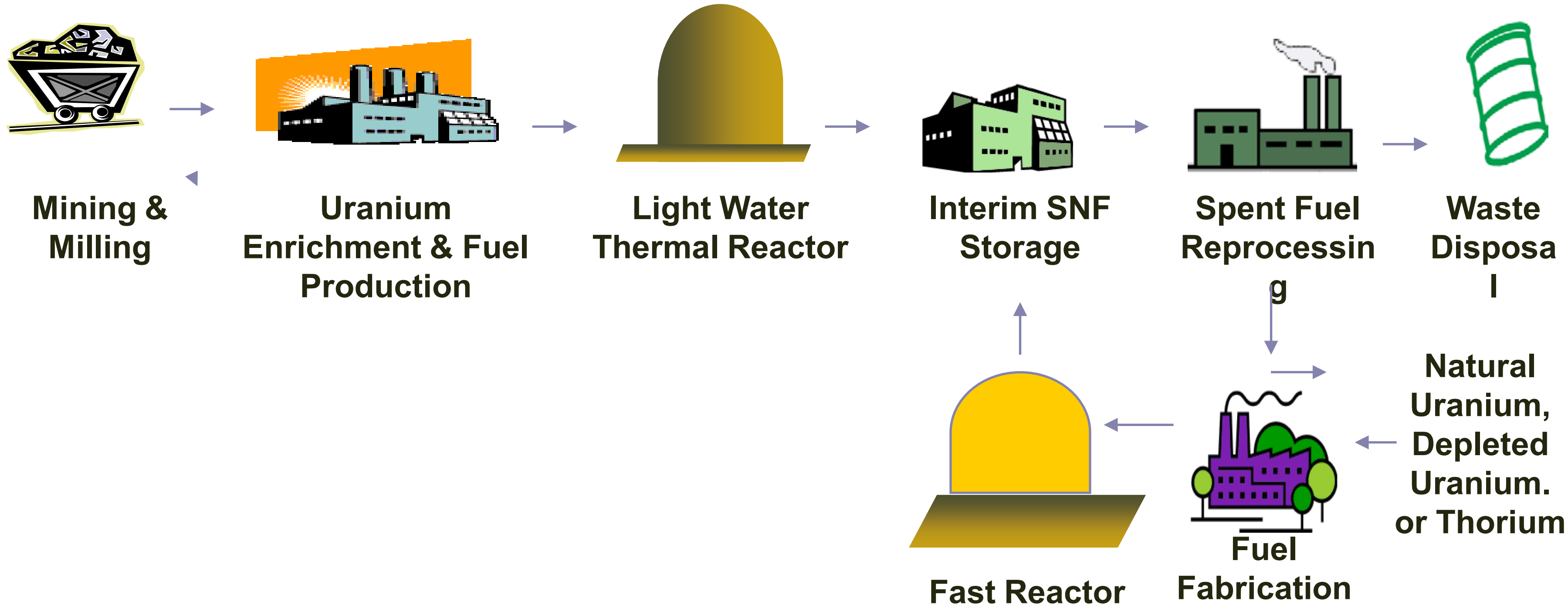
Fundamental Difference Between LWRs and Fast Reactors (FRs)

- Natural uranium contains ~0.7% fissile ^{235}U and 99.3% non-fuel ^{238}U
- LWRs consume ~1% of uranium energy
- Fast reactors
  - Convert fertile (Non-fuel) ^{238}U to fissile ^{239}Pu (fuel) as fast as burn ^{239}Pu
  - **Get 10 to 50 times more energy per kg natural uranium starting material**
  - With efficient use of uranium, could even mine uranium from granite

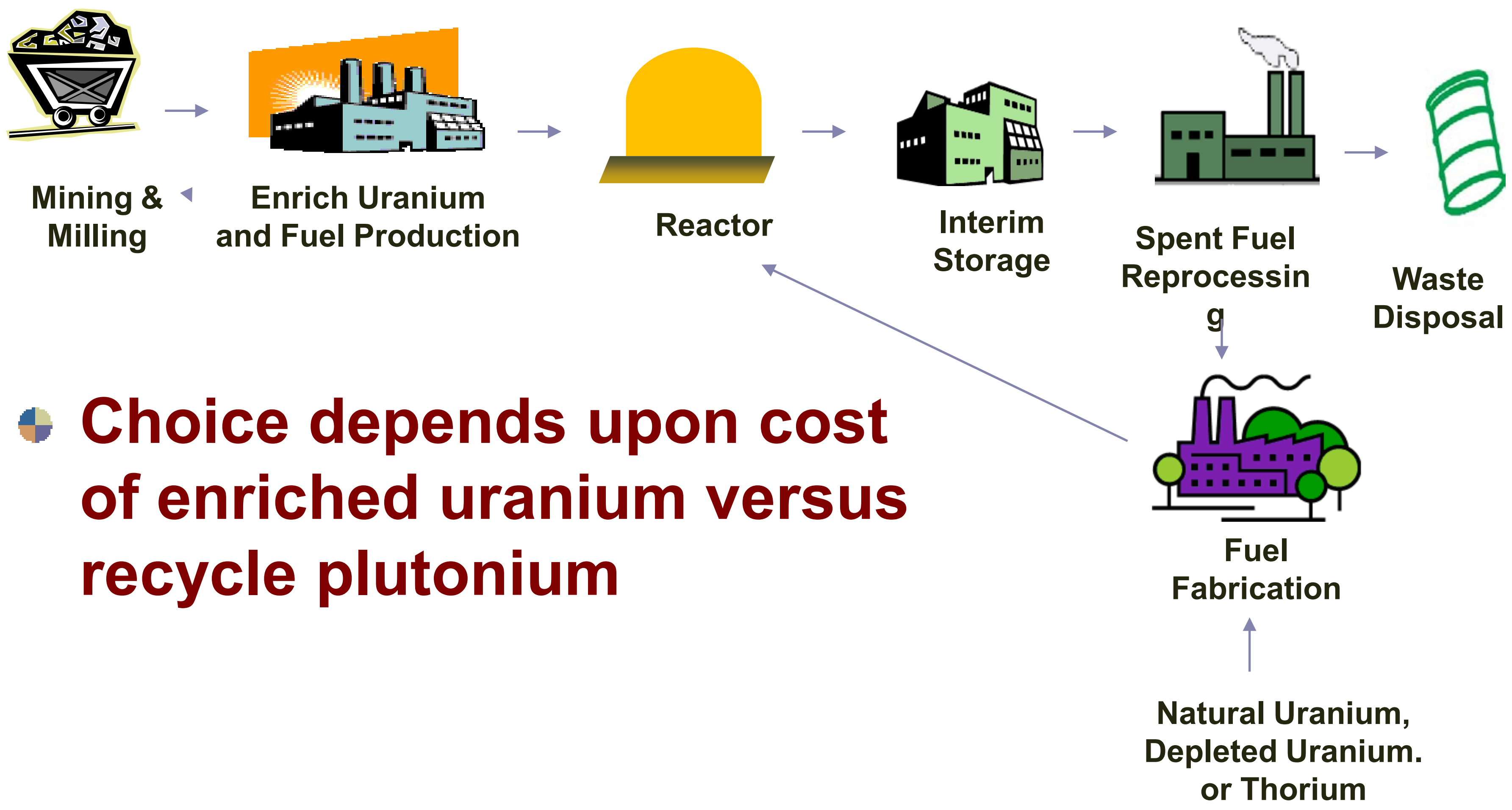
Fast Reactor Physics Implies Reactor Cores with High Fissile Content

- LWR fuel
  - New fuel: ~5% ^{235}U fissile fuel (Rest ^{238}U)
  - Burns down to ~1%
  - **Fissile material burnout determines when SNF**
- Fast Reactor (FR) fuel
  - New fuel is 15 to 35% fissile (^{235}U or ^{239}Pu), the rest is ^{238}U—Expensive fuel.
  - Make fissile fuel as fast as consume fissile fuel so fissile content of SNF ~same as new fuel
  - **Radiation damage determines when SNF**

Traditional Strategy to Start up FRs is Recycle Pu from LWRs



Can Startup Fast Reactor on Enriched Uranium and Recycle FR SNF



- Choice depends upon cost of enriched uranium versus recycle plutonium

Fast Reactor SNF Is Recycled Because of its High Fissile Content

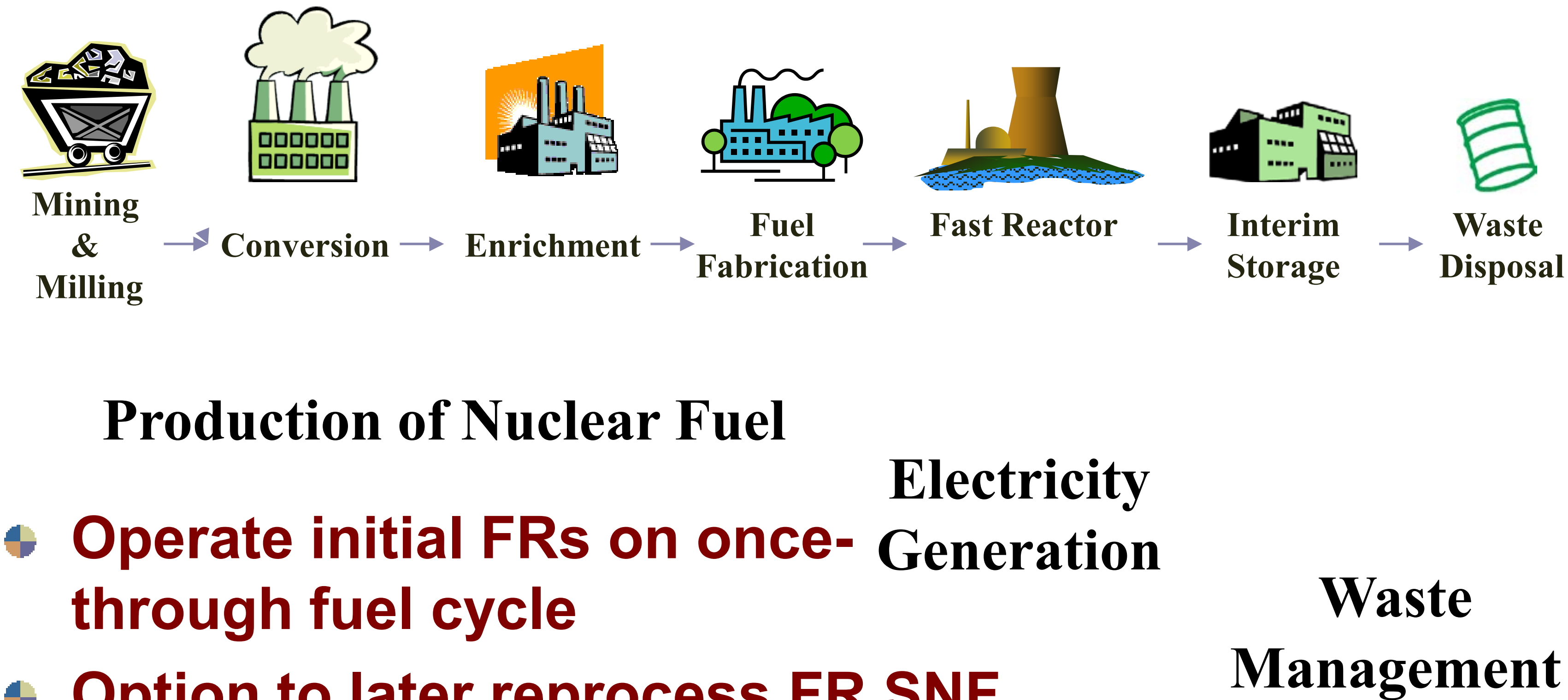
- Fuel replaced because radiation damage to fuel—clad becomes weak and will fail
- Not recycled because out of fuel (LWR case)
- **Economics could favor FR SNF recycle but not LWR recycle because FR SNF has 10 times as much fissile material (Higher assay source of fissile material) per ton of SNF**

Improvements in Technology Open New Fast Reactor Options

- Recent improvements are reducing the initial fissile content of fast reactor fresh fuel
  - Initial fuel value is less
  - Value of SNF is less
- Potential for better materials to increase clad lifetimes (More energy per fuel assembly)

Advancing FR Design Suggests[5] a Once-through FR Fuel Cycle with Same Fuel-Cycle Cost as LWR

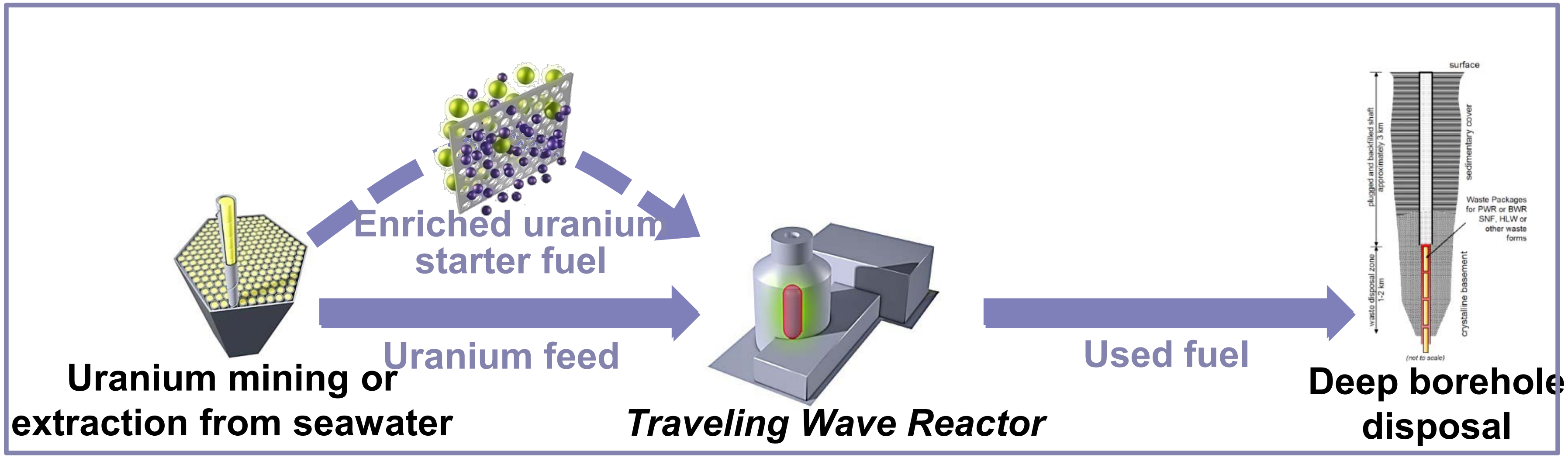
Get More Energy Per Fissile Material in Reactor Core



- Operate initial FRs on once-through fuel cycle
- Option to later reprocess FR SNF
- Low-fissile LWR SNF may become a waste

Terra Power[6] Developing FR With Extreme Fuel Burnup

- Startup on enriched uranium
- Replacement fuel is natural or depleted uranium
- 20 times better fuel utilization than LWR
- May not be worth recycle SNF because high fission product content and low cost initial fuel



Unclear If Possible: Major Technological Challenge

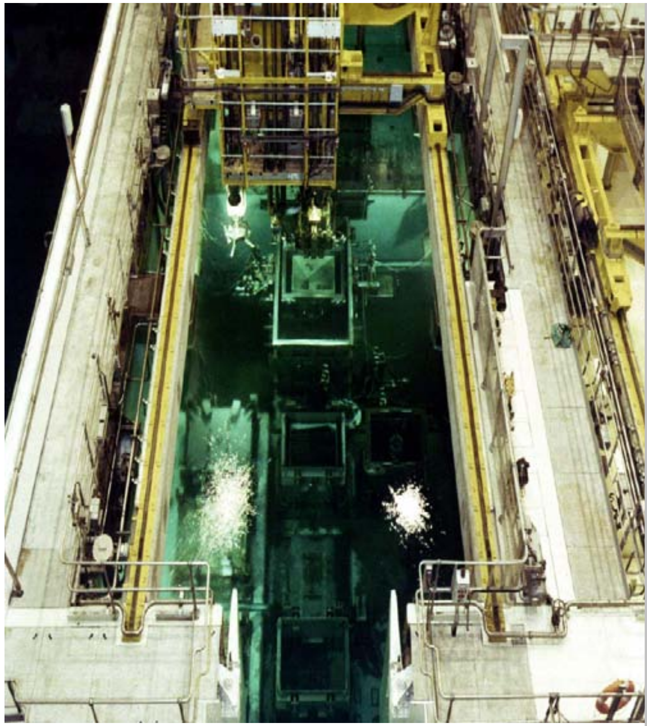
Fuel Cycle Conclusions

Technology Developments will Determine Economic Fuel Cycles

LWR SNR May or May Not Be a Valuable Resource

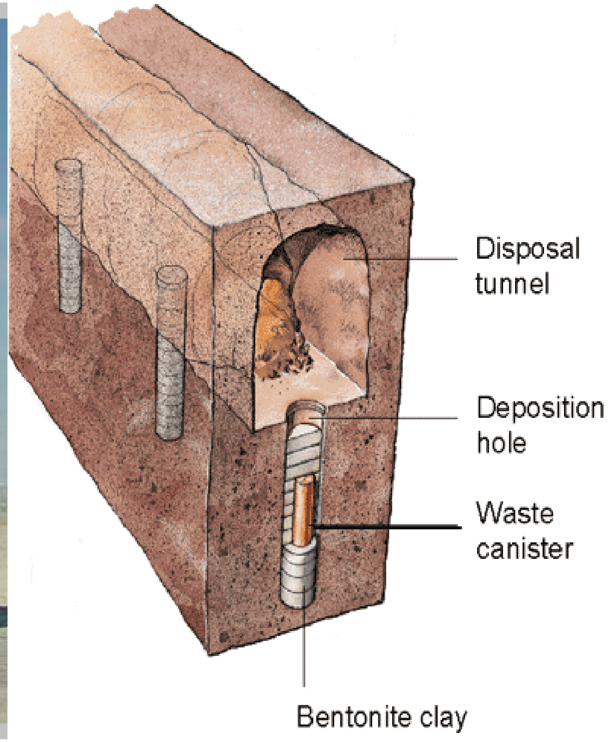
Implications for Repositories

Do Not Know if SNF Is a Resource or Waste: Leads to Conclusion to Store SNF to Maintain Options for Future Generations



At Reactor

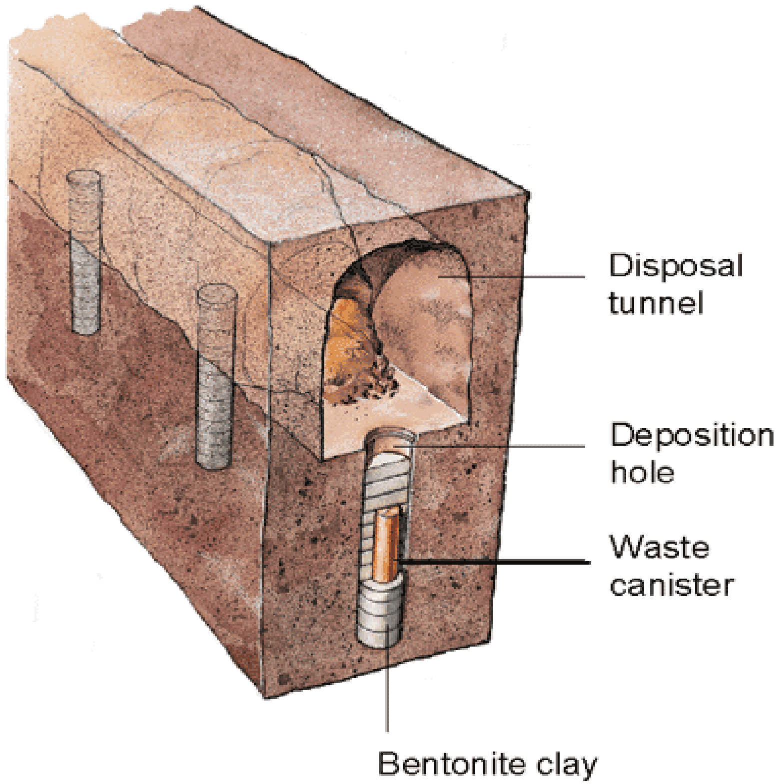
Centralized Storage



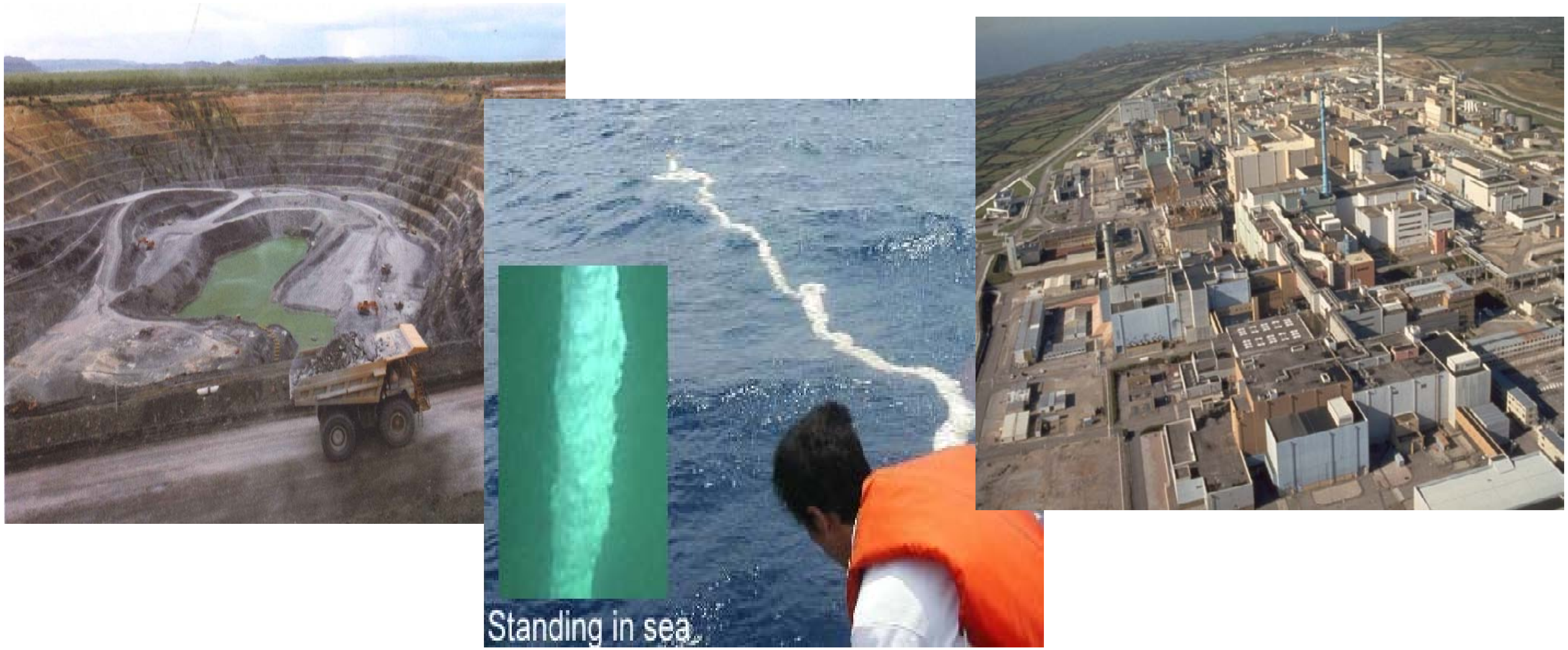
In Repository With Recovery Option

SNF Disposal with the Option of Future Recovery is a Preferred Option

- Intergenerational equity with disposal today and options for future
- Excellent security and nonproliferation
- Insurance against unexpected events



Conclusions



Fuel Cycle Choices will Likely Vary Over Time

Biography: Charles Forsberg

Dr. Charles Forsberg is the Executive Director of the Massachusetts Institute of Technology Nuclear Fuel Cycle Study, Director and principle investigator of the Fluoride-salt-cooled High-temperature Reactor (FHR) Project, and University Lead for Idaho National Laboratory Institute for Nuclear Energy and Science (INEST) Nuclear Hybrid Energy Systems program. Before joining MIT, he was a Corporate Fellow at Oak Ridge National Laboratory. He is a Fellow of the American Nuclear Society, a Fellow of the American Association for the Advancement of Science, and recipient of the 2005 Robert E. Wilson Award from the American Institute of Chemical Engineers for outstanding chemical engineering contributions to nuclear energy, including his work in hydrogen production and nuclear-renewable energy futures. He received the American Nuclear Society special award for innovative nuclear reactor design on salt-cooled reactors. Dr. Forsberg earned his bachelor's degree in chemical engineering from the University of Minnesota and his doctorate in Nuclear Engineering from MIT. He has been awarded 11 patents and has published over 200 papers.

http://web.mit.edu/nse/people/research/forsberg.html

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The Massachusetts Institute of Technology (MIT) report "The Future of the Nuclear Fuel Cycle" concluded that today we do not have a basis for deciding on a long-term fuel cycle (FC). That conclusion led to the recommendation for interim storage of spent nuclear fuel (SNF). SNF storage could be at the reactor, at a centralized facility, or in a repository with the option for future recovery.

There are many criteria for the selection of FCs: economics, efficient resource utilization, energy independence, waste management, and non-proliferation. Different countries have made different choices because of different weighting of these criteria. Our analysis indicates that if economics is the basis for fuel cycle selection, the optimum fuel cycle may change back and forth over time between open and closed fuel cycles. This conclusion and more recent studies *support the idea of a repository as the center of the backend of the fuel cycle: a disposal site today, a facility that allows future SNF recovery, and the site of any future reprocessing facility if future decisions are made for recycle for fissile recovery, waste management, or other purposes.*

In terms of economics, the preferred source of fissile fuel depends upon relative progress in uranium mining (including seawater uranium), recycle technologies, and fast reactors. The difficulty in predicting the future can be seen by considering one part of the challenge: development of fast-neutron-spectrum reactors (FRs). Existing light-water reactors (LWRs) consume ~1% of the energy value of uranium (primarily the 0.7% ^{235}U). In a FR with a conversion ratio greater than one, fissile ^{239}Pu or ^{233}U is generated from ^{238}U or ^{228}Th as fast as it is consumed. This enables full use of the uranium if the SNF is recycled, drastically lowers impacts from mining, and broadens the resource base. However, the FR fuel element does not run out of fissile material, rather the fuel lifetime and the need to reprocess is determined by fuel clad burnup. Future technology developments on improving fuel clad performance may determine the preferred fuel cycle.

- *Low burnup FR SNF*. The startup fuel for a FR is expensive because of its high fissile loading. If the SNF burnup is low (current limits), it is economically required to recycle FR SNF to recover expensive fissile fuel for reuse. As the burnup increases, the fuel cycle costs go down per unit of electricity because less fuel is fabricated and recycled. If fuel is reprocessed, there are options for actinides including transmutation in special reactors or selective disposal of long-lived radionuclides in deep boreholes.
- *High burnup FR SNF*. If very high fuel burnups are achieved, it is possible to build FRs that startup on low-enriched uranium with replacement fuel made of natural or depleted uranium. The depleted uranium is converted to ^{239}Pu that is then fissioned in situ—all without reprocessing. This is the strategy of breed and burn FRs such as proposed by Terra Power® where more than 20% of the total uranium would be burned in a once-through fuel cycle. The FR would be more than 20 times as efficient in uranium usage as an LWR. In such a system one would expect reprocessing to be uneconomic. It is much less expensive with lower risks (health, nonproliferation, etc.) to fabricate a fuel assembly out of depleted uranium than plutonium.

One can make reasonable arguments that the future is (1) the open FC, (2) the open FC evolving to closed FC, or (3) the open FC evolving to a closed FC and then back to an open FC as technology progresses.

The costs and risks from future recycling of SNF have equally large uncertainties. Recent assessments indicate the possibility of much lower reprocessing costs if reprocessing is collocated with the repository. While waste partitioning and transmutation has been extensively investigated, other closed FC options such as waste partitioning and deep borehole disposal have not been examined in depth.

The conclusion is that we can't credibly make 100-year decisions on fuel cycles. What we can do is organize a system that is (1) adaptive, (2) meets near-term requirements and (3) leaves us options for the future. One option that clearly meets that objective is a repository designed for

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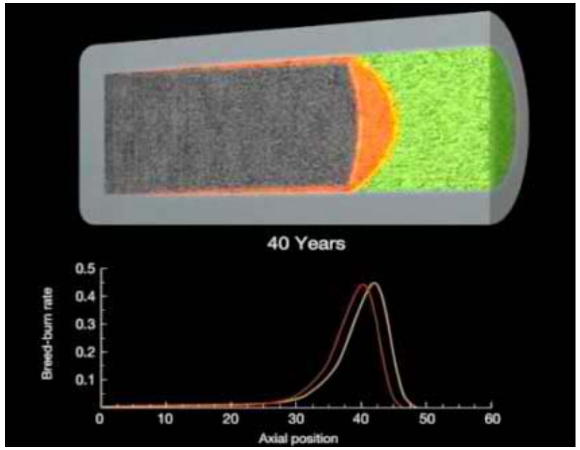
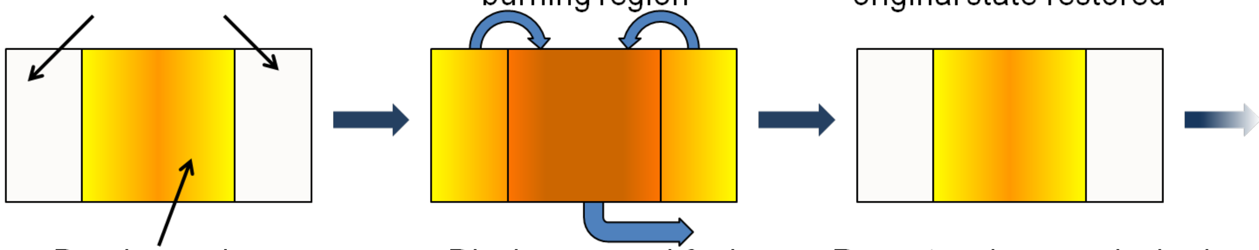
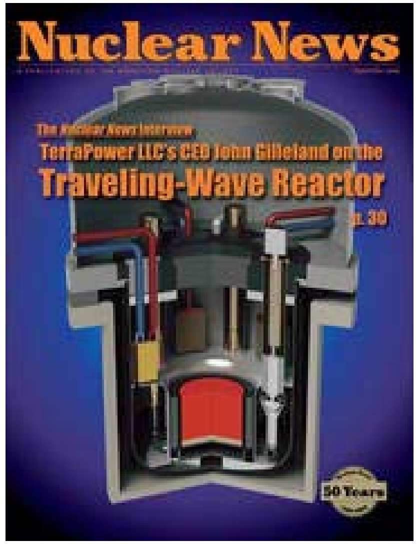
Traveling Wave Reactor

The Traveling Wave Reactor (TWR) is a sodium-cooled Breed-and-Burn (B&B) reactor being developed by TerraPower

- A ***breed-and-burn*** reactor is a fast breeder reactor that does not use reprocessing
  - Fissile Pu-239 is bred in depleted uranium fuel, using leakage flux from burning region
  - Newly bred fuel ***directly replaces*** discharged fuel in burning region and sustains criticality







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