Actinide Burning in Reactors: Options and Outcomes

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In Memory of Manson Benedict:
A plenary session on the Nuclear Fuel Cycle
at the ANS Meeting in Boston
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Scope of Talk

- Is there a need for actinide burning and recycling?
  - Resource extension, Waste management, Stockpile Reduction
- Approaches to reduction of transuranic actinides in the fuel cycle
  - Reduce TRU in LWR uranium fuel cycle
  - Transmute the TRU actinides through recycling (involves actinide separation form UO2, fuel manufacturing, irradiation in core and recycling)
- Effect of actinide burning technology choice on
  - U needs, TRU accumulation, potential costs.
- Implications for the repository, using quantification from the AFCI work at ANL.

Transuranic Element Buildup

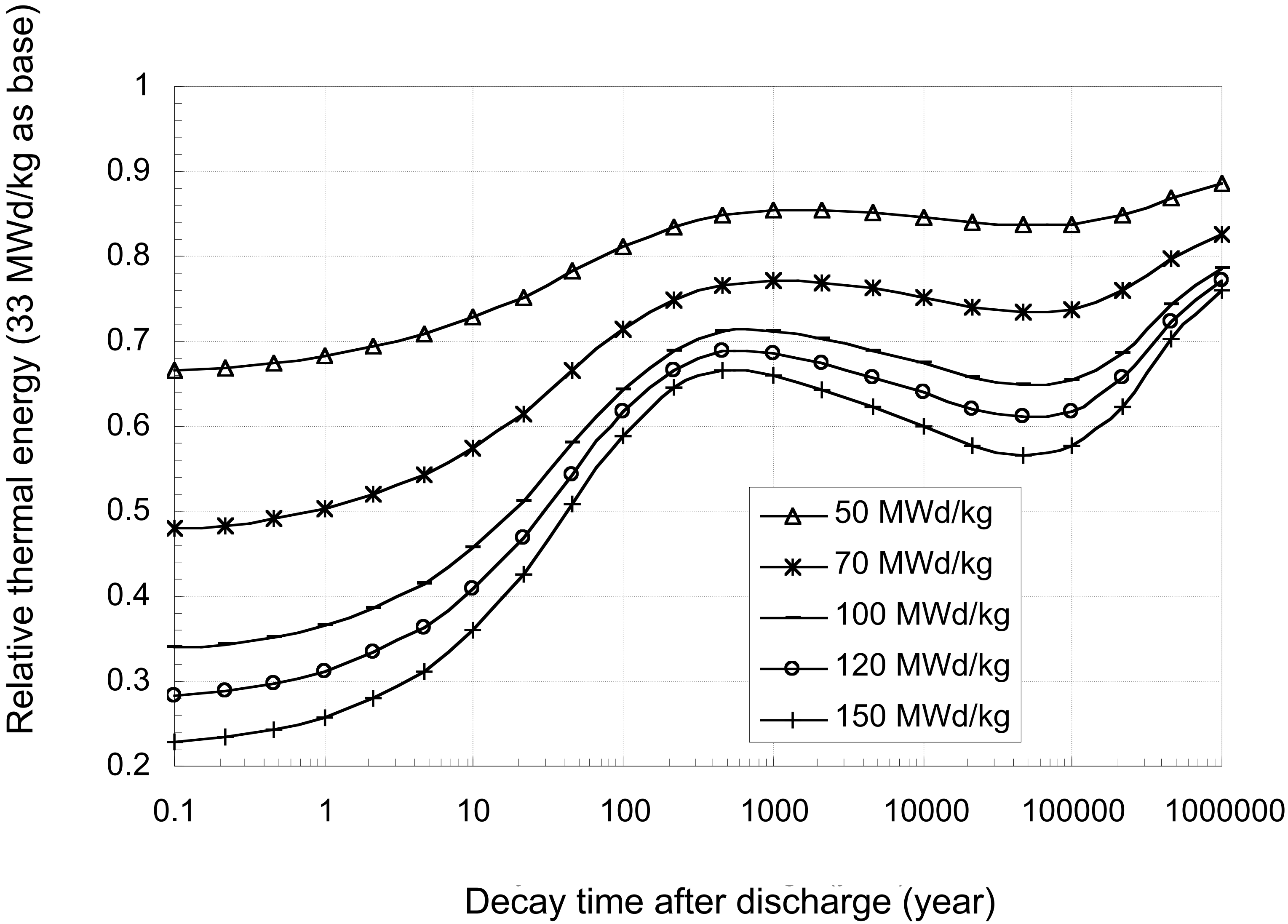
- Production of Pu and minor actinides is a byproduct of using U as nuclear fuel
  - Roughly 2000 (8000) tons of spent fuel are discharged annually in the US (world)
  - About 50,000 (130,000) tons have been discharged in the US (world)
  - Mostly uranium (about 95%, at 0.5 to 0.8% ^{235}U) with:

    1% plutonium, 0.1% minor actinides, 3-5 % fission products.
- Pu and higher actinides are accumulating in spent fuel storage or reprocessing output storage.
  - In the US, and some countries like Sweden, S. Korea, Spain and Finland, spent fuel is currently stored at the reactor sites, but destined for a repository.
  - In France, Japan and other countries one recycle of Pu in LWRs as mixed oxide (MOX) is planned, then fuel is stored until it is needed for future fast reactors.
- Add to that discarded weapons Pu, about 10% of civilian Pu to date, or 150 tons, with more potentially coming

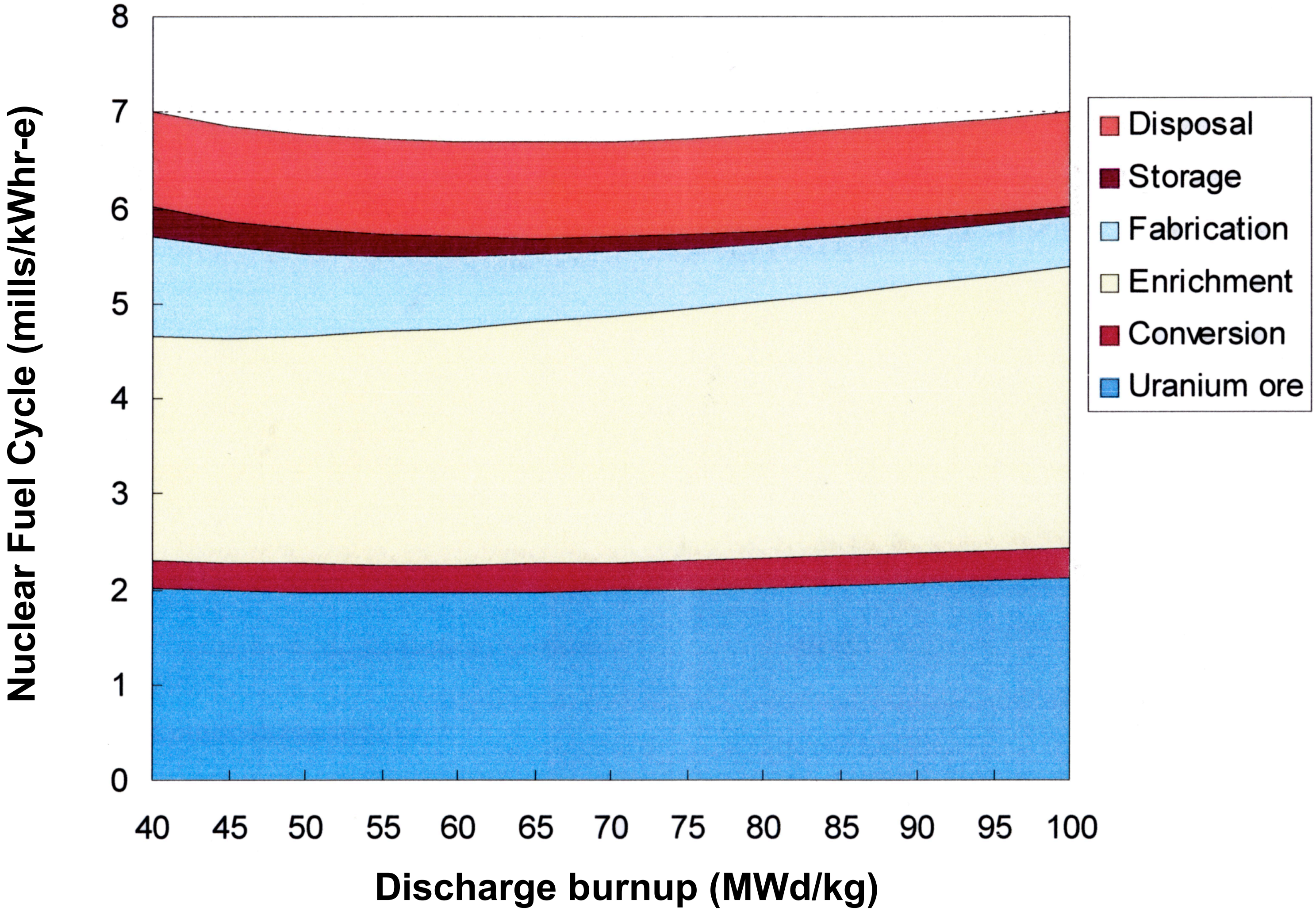
LWRs as a Source of Actinides

- **Once-Through Uranium Cycle**
  - HEU avoids Pu and higher actinide in LWR spent fuel, but proliferation concerns limit enrichment below 20%
  - LEU cycle is more efficient in U utilization and SWU utilization
  - LWR spectrum maximizes Pu-238 content in Pu
  - High burnup reduces Pu production per unit energy derived
    - Discharged Pu is proportional to $B^{0.5}$
    - Discharged ^{238}Pu is proportional to $B^{2.2}$
  - High burnup reduces spent fuel volume per unit energy
  - High burnup reduces decay heat production in most of the important periods of up to 10 years and from 100 to 10,000 year
  - Fuel cycle cost is not sensitive to burnup given a fixed 18 month cycle.   A shallow optimum around 70 MWd/kg.

Decay Thermal Energy per GW-yr(e)



Fuel Cycle Economics



*Fixed 18-month cycle,

Closed Cycle with Transuranic Burning

☆ Many options to burn (transmute) Pu and higher actinides have been proposed and a few have been thoroughly considered:

- LWR, most widely deployed reactors
- Gas cooled HTRs
- Heavy water cooled CANDU reactors
- Fast reactors (with various conversion ratios)
- Accelerator Driven Systems

☆ Choices include uranium, thorium, or inert material as a host of the actinide. Only uranium has a wide industrial base.

☆Choices also involve the higher actinide content besides Pu (Np, Am, Cm, etc)

☆ Metallic, Oxide, nitride or carbide forms , Oxide and metal have some industrial base.

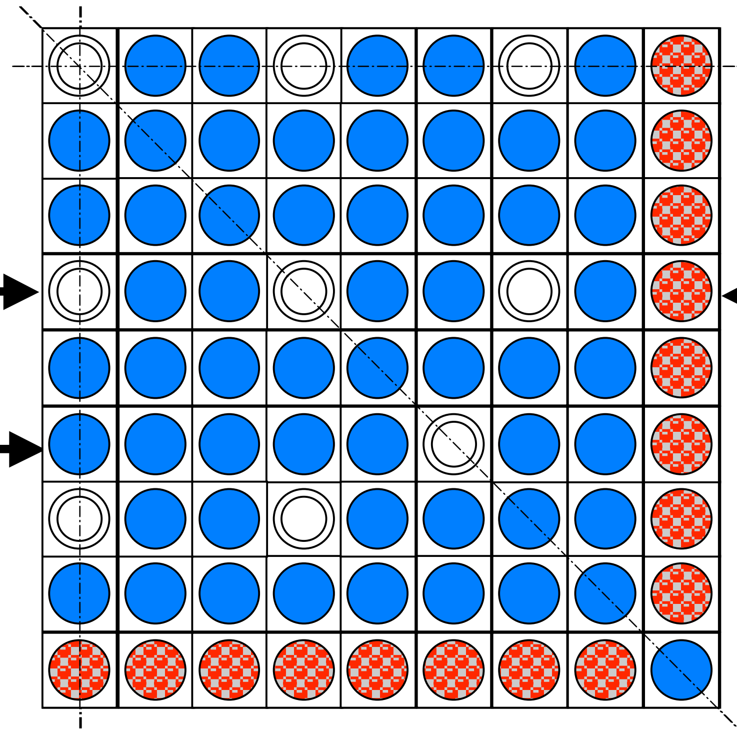
LWRs as Actinide Burners

It is possible to recycle TRUs in LWRs such that there would be net TRU reduction. Designs include CORAIL and CONFU

- **A CONFU fuel assembly composed of 80% of U fuel pins and 20% TRU in non-fertile host pins would preserve power peaking and safety characteristics of current reactors.**
- **CONFU approach is superior to MOX recycling (limiting Pu and MA production), and limiting the heavy metal throughput in recycling plants.**
- **This approach is better than thorium based TRU burning since it avoids U232/U233 issues.**
- **Handling of high content of Am and Cm is an issue that needs further evaluation. Longer cooling time after discharge should limit the neutron sources to only a few times the level of MOX recycling.**

The CONFU Assembly Concept

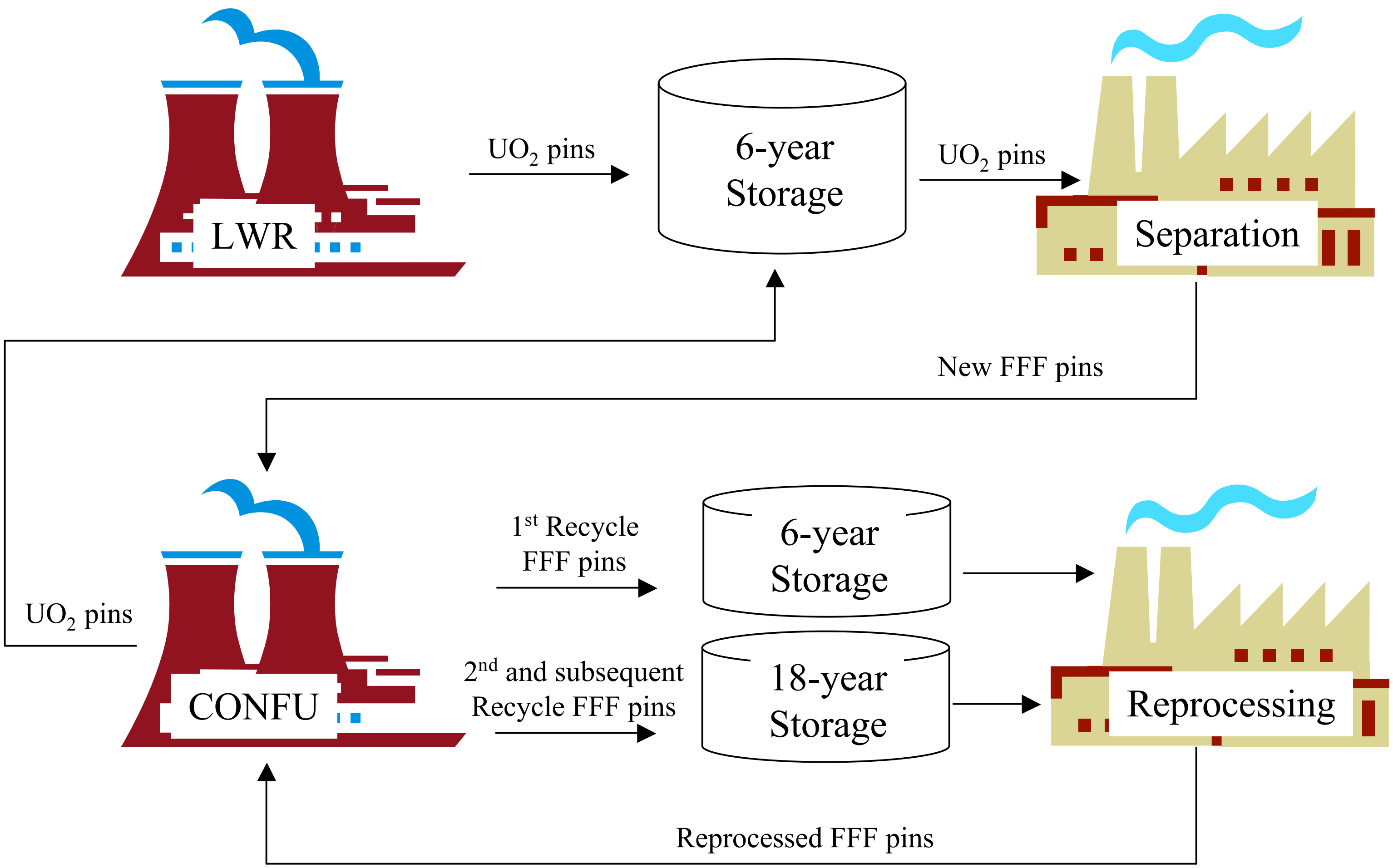
Combined Non-Fertile and UO_2 Assembly



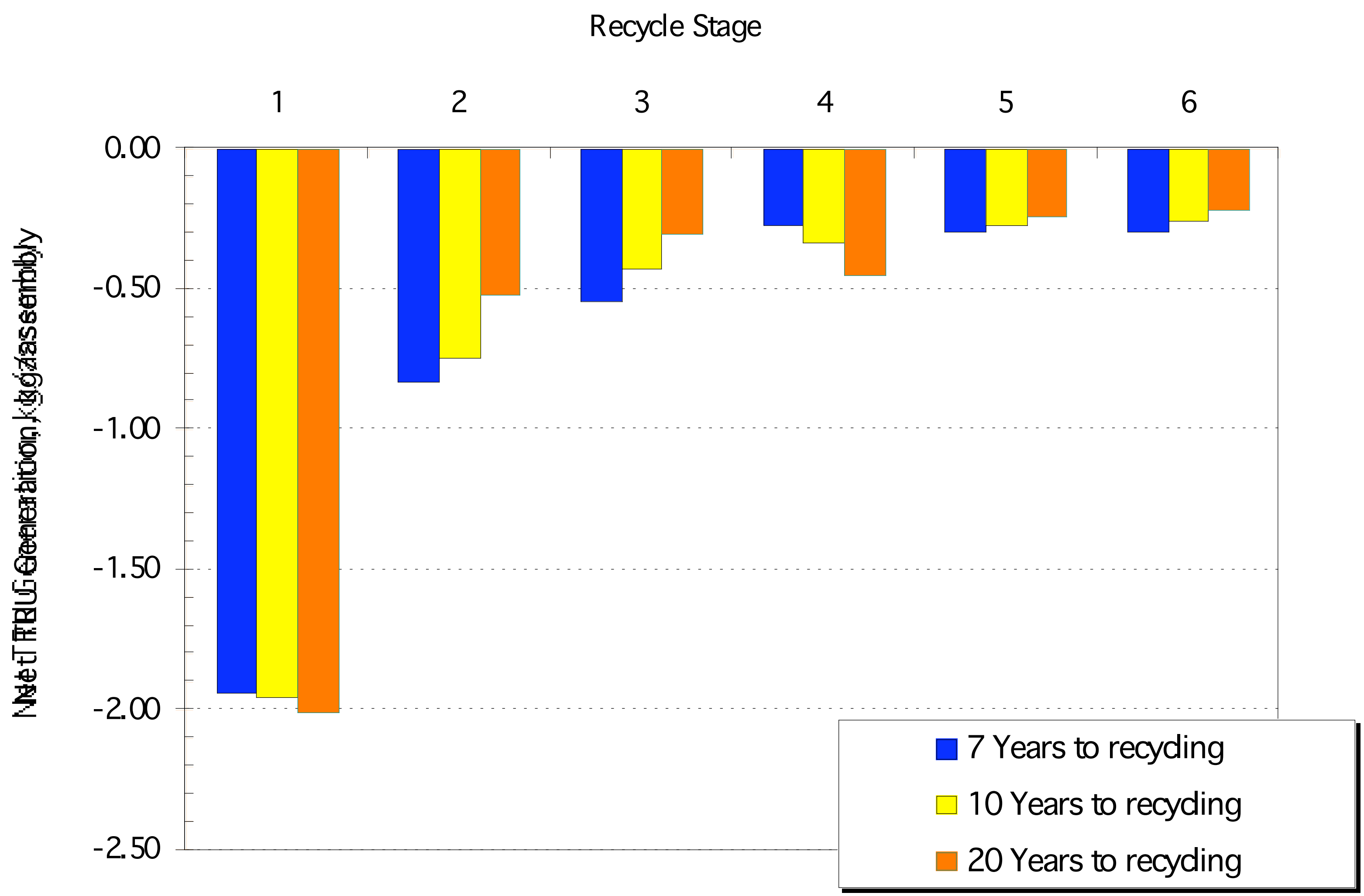
- *Multi-recycling of all transuranics (TRU) in fertile free pins leads to zero net TRU generation*
- *Preserves the cycle length, neutronic control and safety features of all uranium cores*

Shwageraus, Hejzlar and Kazimi, Nuclear Technology, 2005

CONFU Strategy



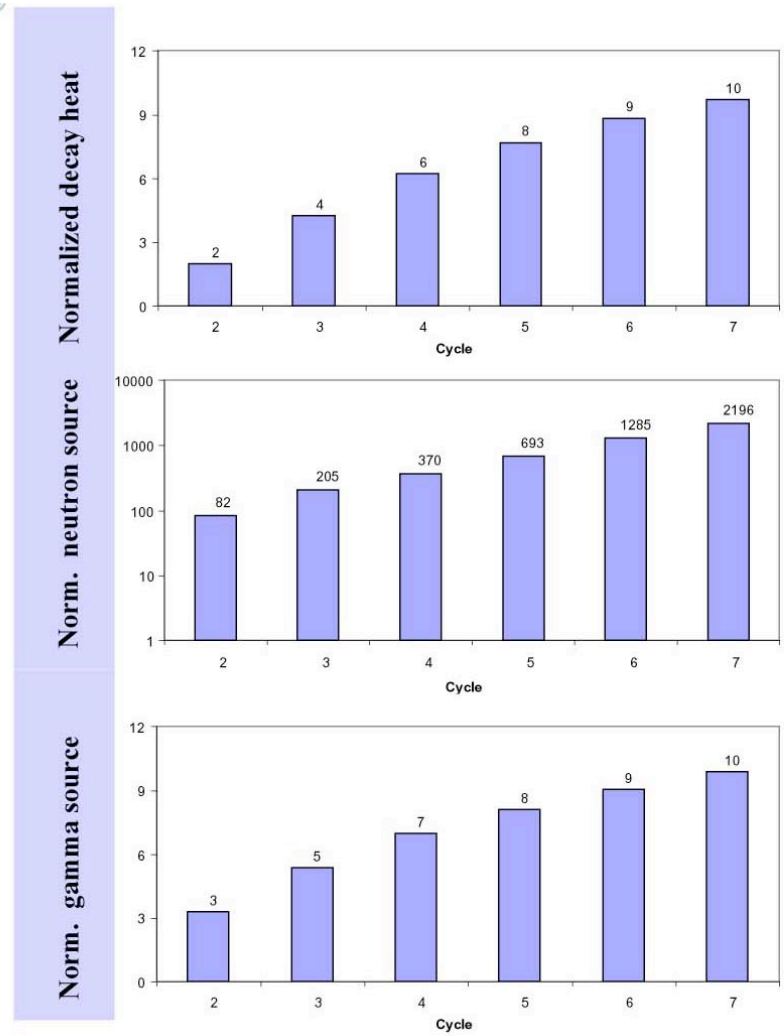
CONFU: TRU net generation rate



Shwageraus, Hejzlar and Kazimi, Nuclear Technology, 2005

Practical Issues for Repeated TRU Recycle

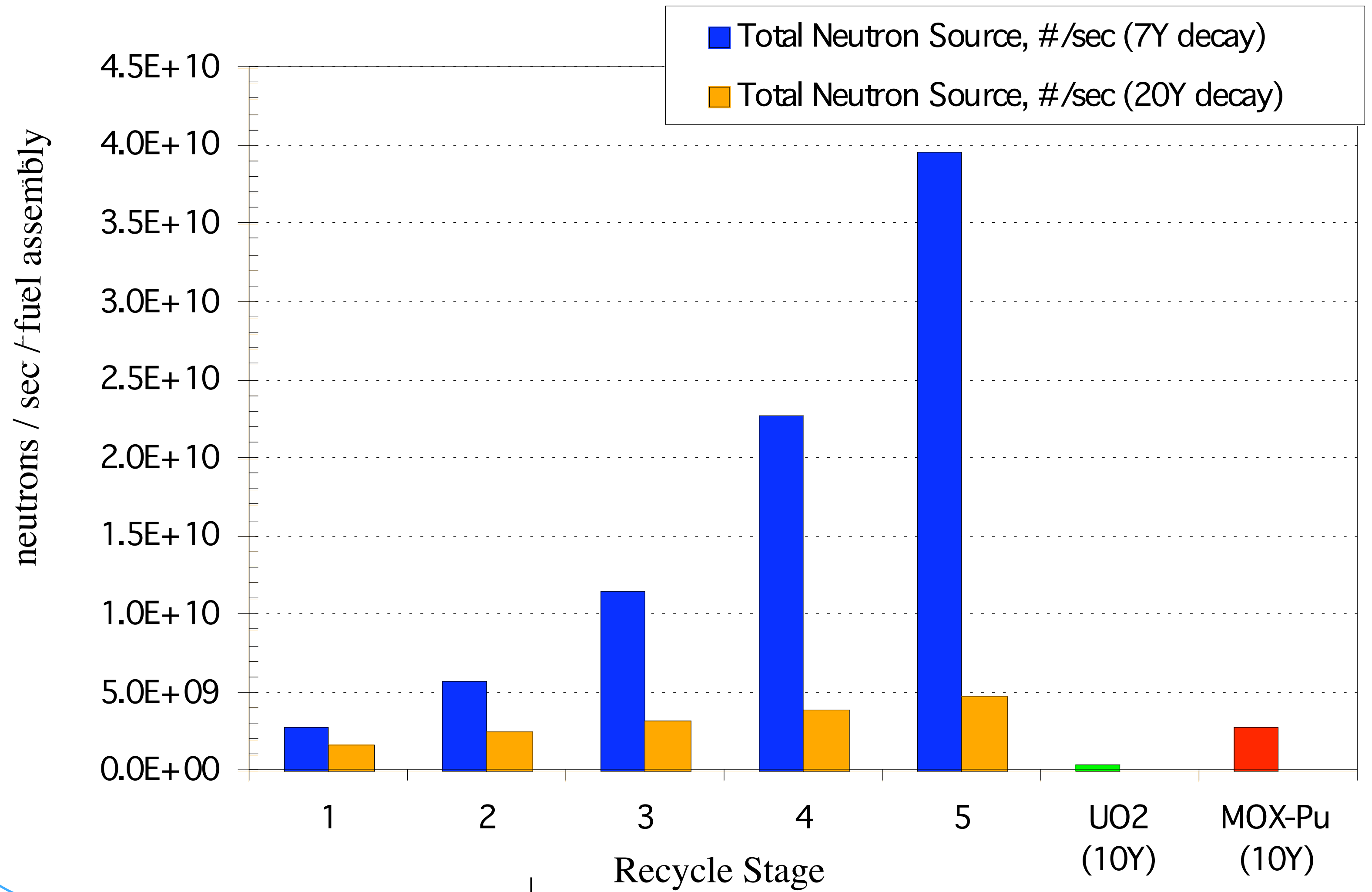
- Repeated recycle can be achieved
  - Based on physical considerations (reactivity balance and coefficients)
- Repository goals are met
- TRU content gradually increase with recycle
- High minor actinide content complicates fuel handling and usage
  - Number of recycles may be limited in practice - 2 to 3



Fuel Handling Indices at Fabrication Stage Compared to CORAIL-Pu Cycle 7

From AFCI presentation to Blue Ribbon committee by Philip Finck, 2004

CONFU: Spent fuel SFS After Multiple Cycles



Advanced Fuel Cycles Assessment

CAFCA is a nuclear fuel cycle systems model :

- ✓ Tracks nuclear fuel materials in the various components of a fuel cycle.
- ✓ Estimates the cost of various fuel cycle strategy and technology choices.
- ✓ Simulates deployment of advanced technology in the context of a growing nuclear energy demand.
- ✓ Helps study impact of choices of fuel cycle strategies on: TRU inventories, demand for recycling facilities and advanced reactors, and fuel cycle cost.

Actinide Fueled Reactor Choices

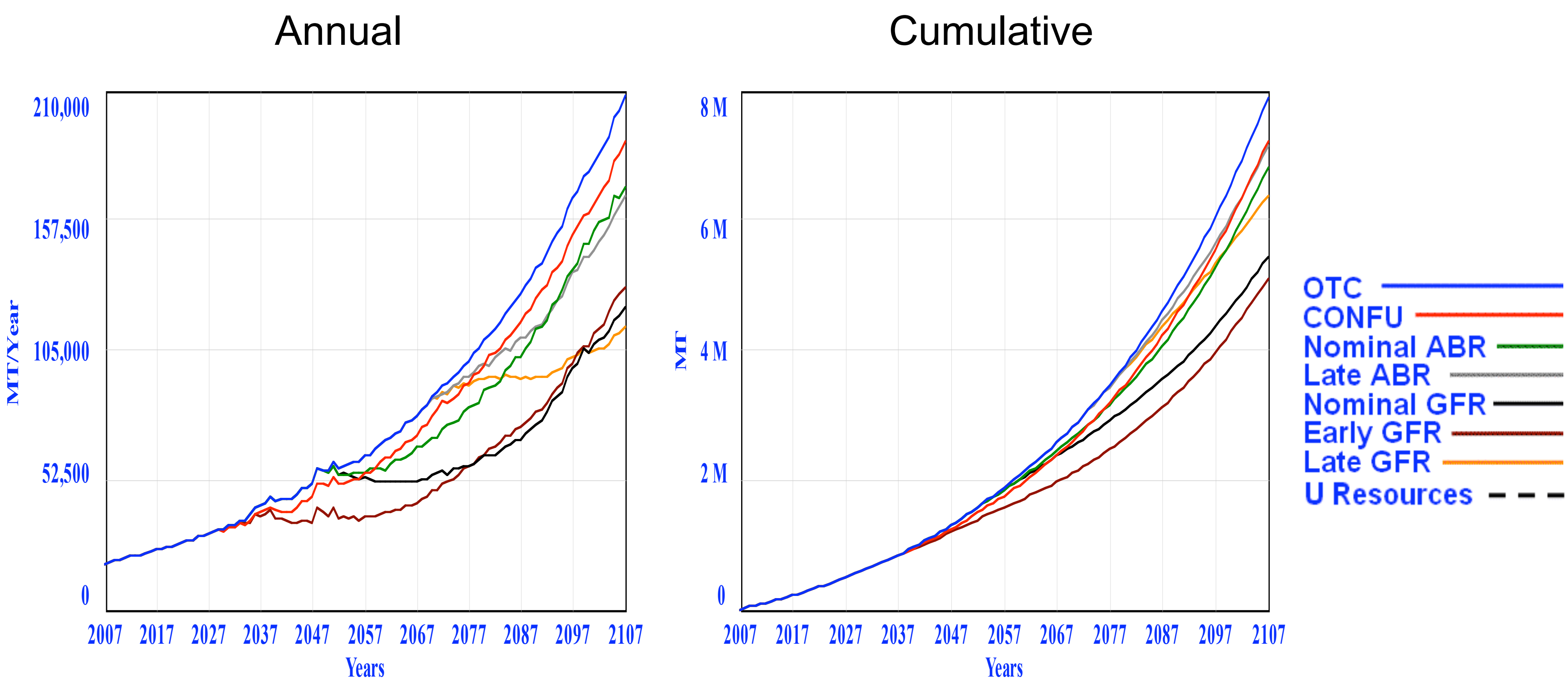
- **CONFU: Recycling of TRU LWRs, using COmbined Non-Fertile and UO2 fuel assemblies technology starting 2027**
- **ABR: Recycling TRU in fast spectrum cores of Actinide Burner Reactors (TRU in Fertile Free Fuel); starting either early in 2047 or late in 2067**
- **GFR: Recycling TRU and U in self-sustaining (conversion ratio of one) Gas-cooled Fast Reactors, starting either early in 2047 or late in 2067**

Simulation Parameters & Recycling Industrial Capacity

LWRs lifetime	**60 Years**
Fast reactors lifetime	**60 Years**
Fuel facilities lifetime	**40 Years**
Initial LWR fleet	**The U.S. fleet**
Industrial capacity doubling date	**2047 year**
The U.S. spent fuel "legacy"	**50,000 MT**

Simulation period	100 Years
Annual growth rate	2.4 %
UO2 separation plant nominal capacity	1,000 MT/Yr
FFF reprocessing plant nominal capacity	50 MT/Yr
U/TRU RP nominal capacity	1,000 MT/Yr
UO2 separation plant industrial capacity	500 MT/Yr/Yr
FFF reprocessing plant industrial capacity	50 MT/Yr/Yr

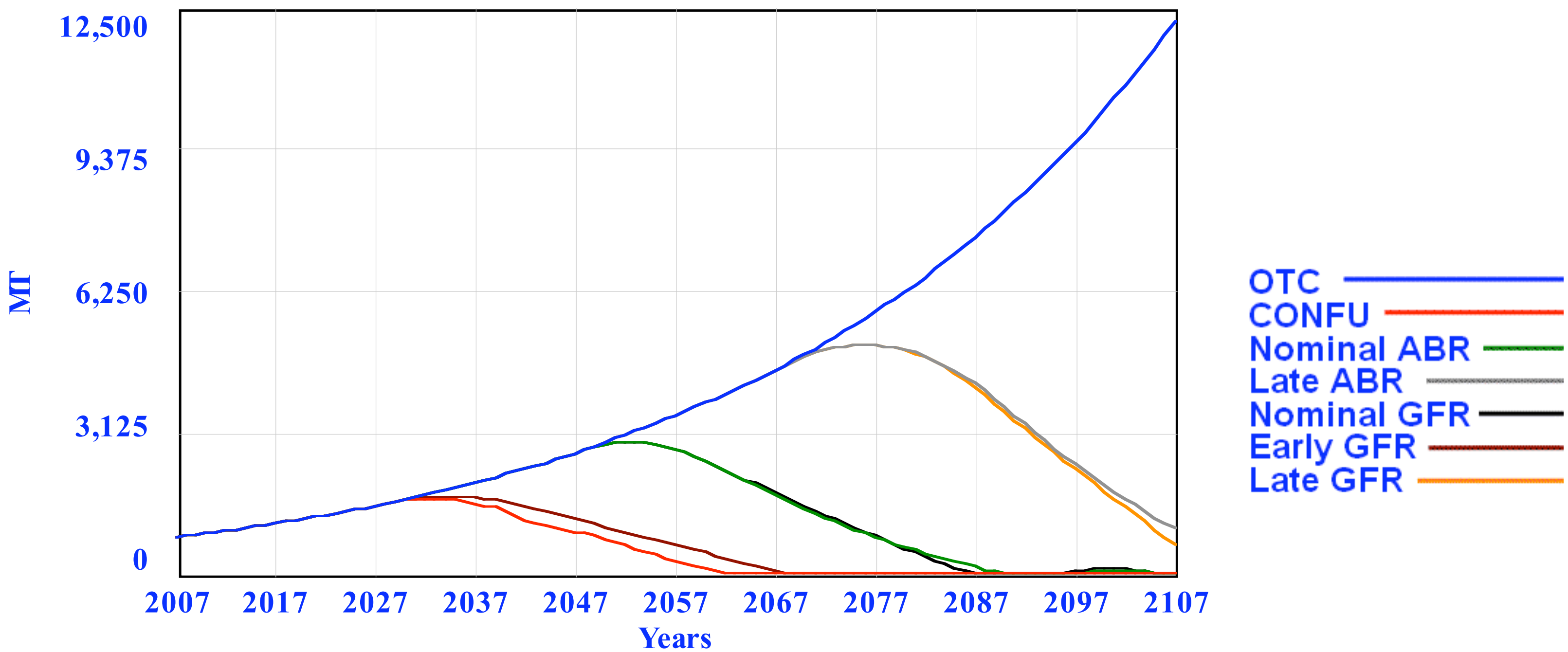
Uranium Demand for Various Options



- **Little difference in U consumption will result from TRU burning in low conversion ratio reactors.**
- **GFR technology requires less uranium resources due to U recycling and near unity conversion ratio.**
- **In a non-breeding fuel system (CR=1), there is Increased consumption of U after 75 years due to lack of TRU.**

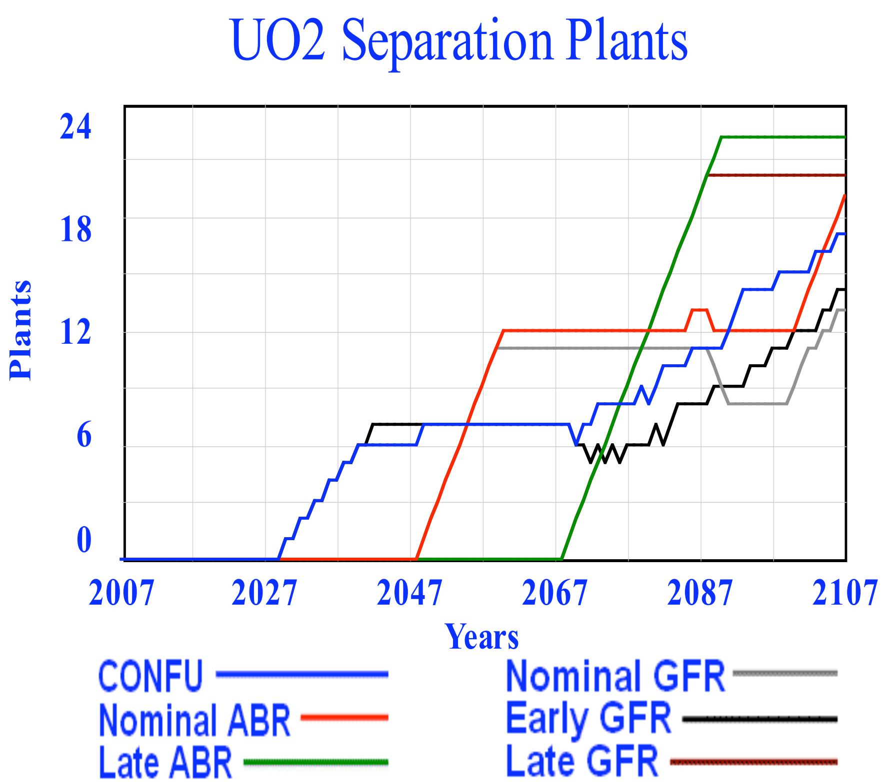
From R. Busquim eSilva, P. Hejzlar and M. Kazimi, ANS, Boston, 2007

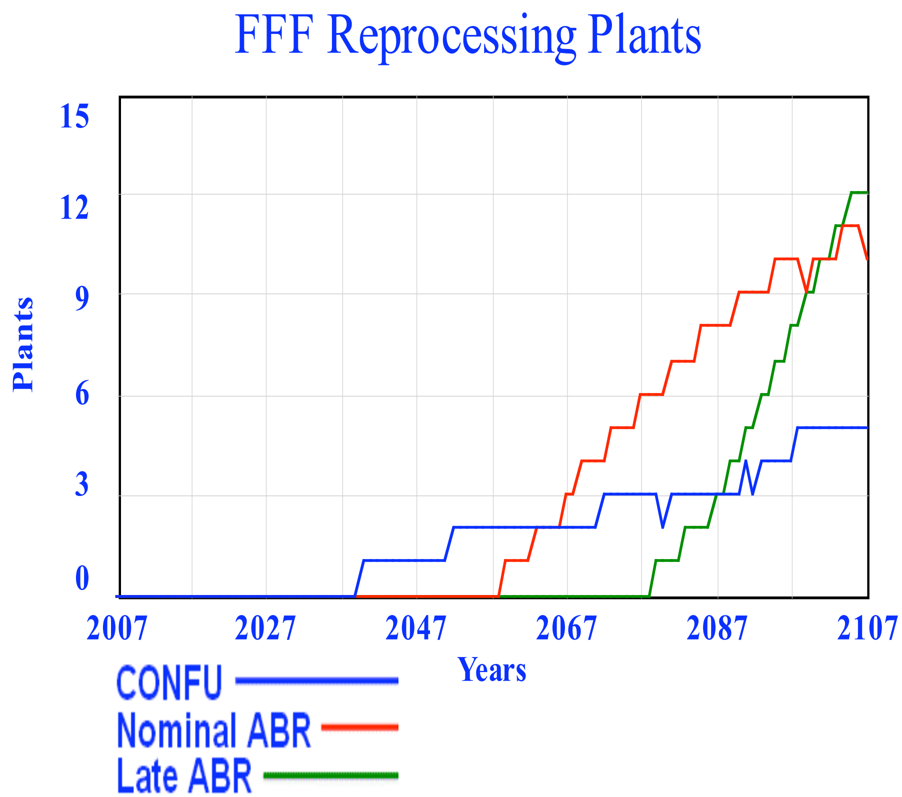
TRU Inventory in Interim Storage



- **CONFU is the best option to deplete the current TRU inventory, and to consume the TRU generated from LWRs fleet every year.**
- **Earlier introduction of ABRs or GFRs will have a small impact on TRU inventory in interim storage.**
- **The time for depletion of TRU in interim storage is little affected by the burner vs breeder reactor choice.**

Fuel Recycling Facilities



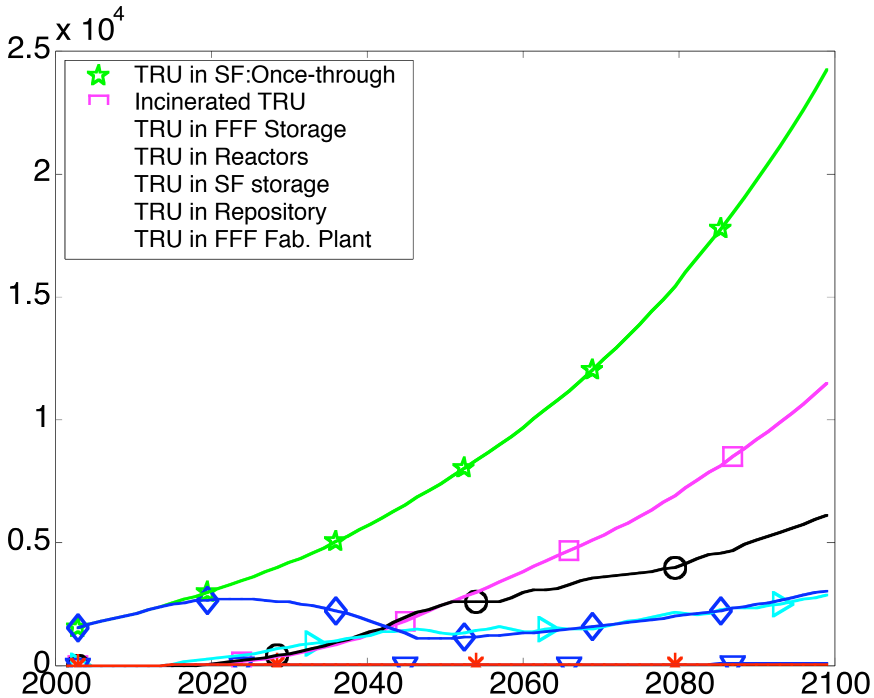


- **Earlier recycling in LWRs will require fewer separation plants for the first half of this century to minimize TRU in interim storage.**

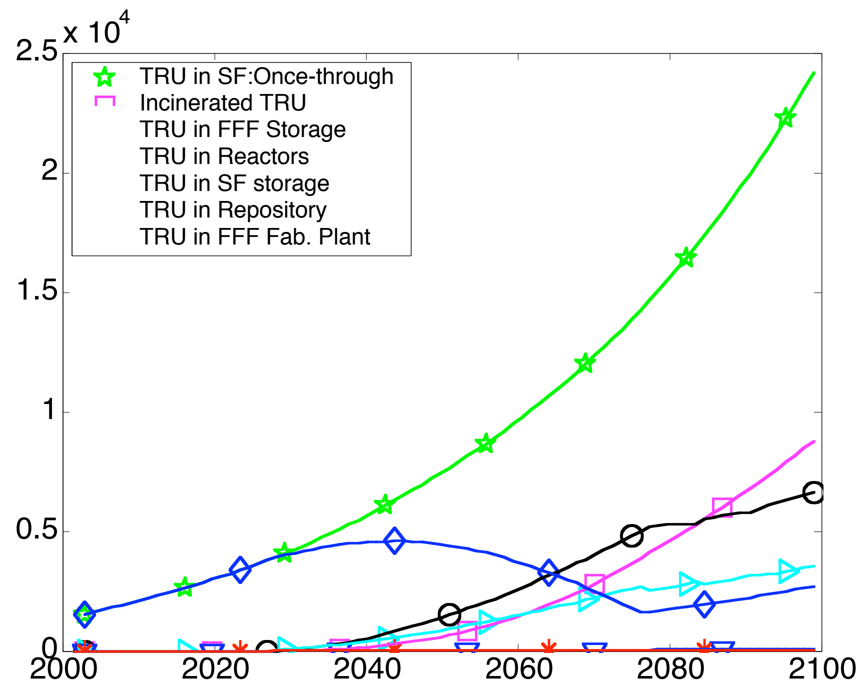
- **Delayed introduction of advanced actinide burning technology will end up requiring a faster buildup of these facilities to burn down the interim TRU inventory.**

TRU Mass Balances until 2100
(Scenario C: continued growth at 2.1%)

CONFU



ABR

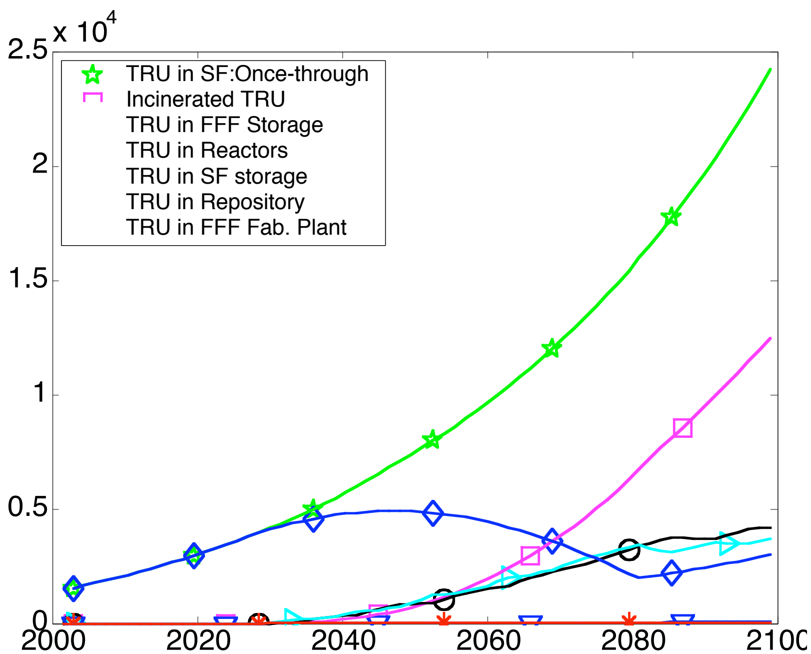


Note: CONFU incinerates more TRU than fertile-free ABR

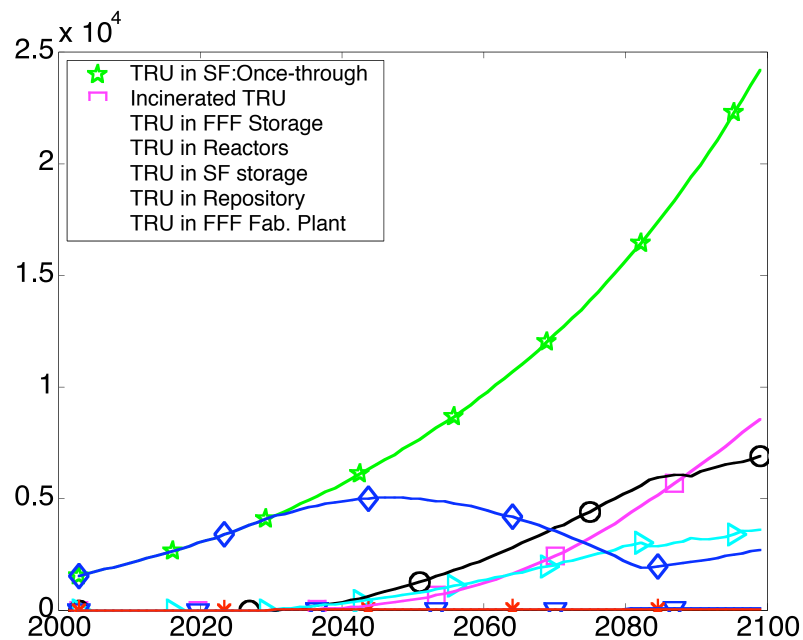
Sourcel MIT paper by Boscher et al, Nuclear Technology, September issue, 2006

TRU inventories : CONFU vs ABR (same year of deployment)

CONFU



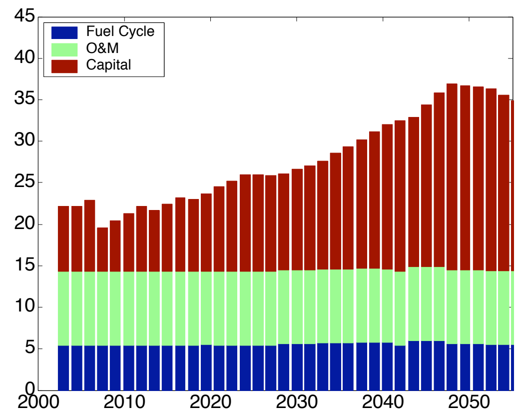
ABR



- CONFU still incinerates more TRU
  - Limited by TRU availability from reprocessing plants
  - ABR has higher thermal efficiency than CONFU (45% vs 33%)

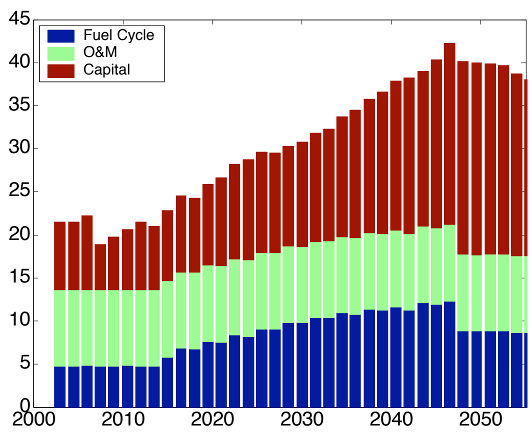
Nuclear Electricity Cost $/MWhr

Once Through

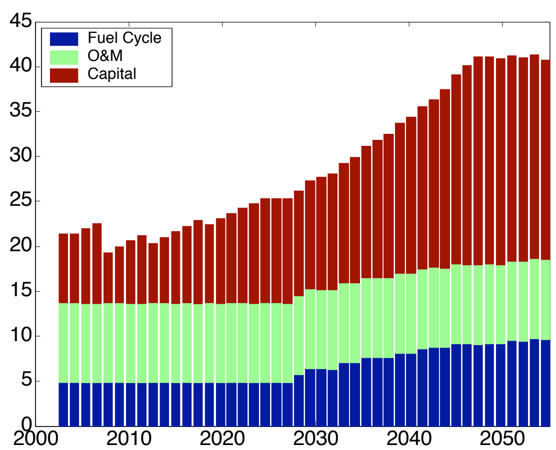


All strategies mean building new units which will increase cost:
OT : CONF: ABR
Peak: 37 : 40 : 41 in 2048

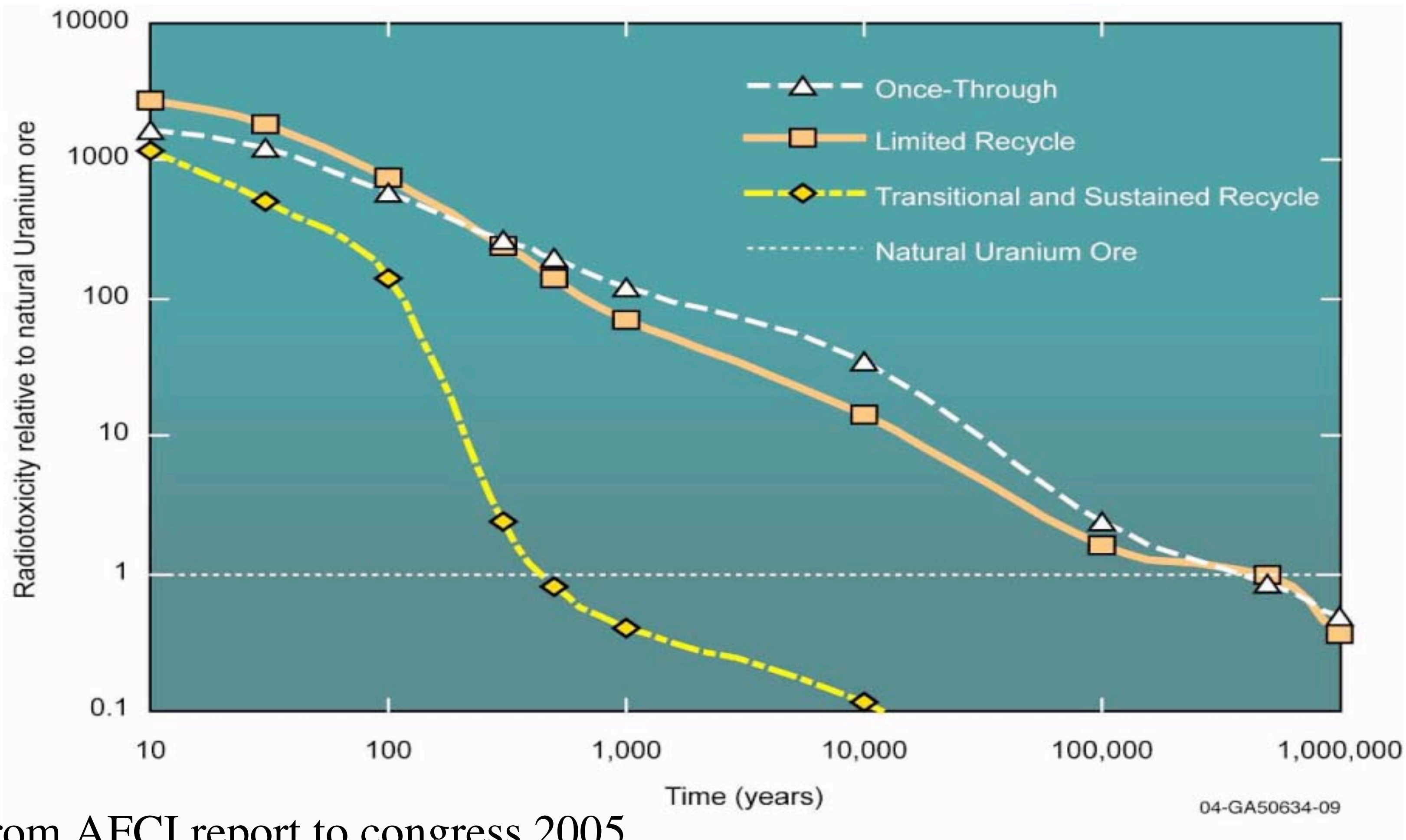
CONFU



ABR

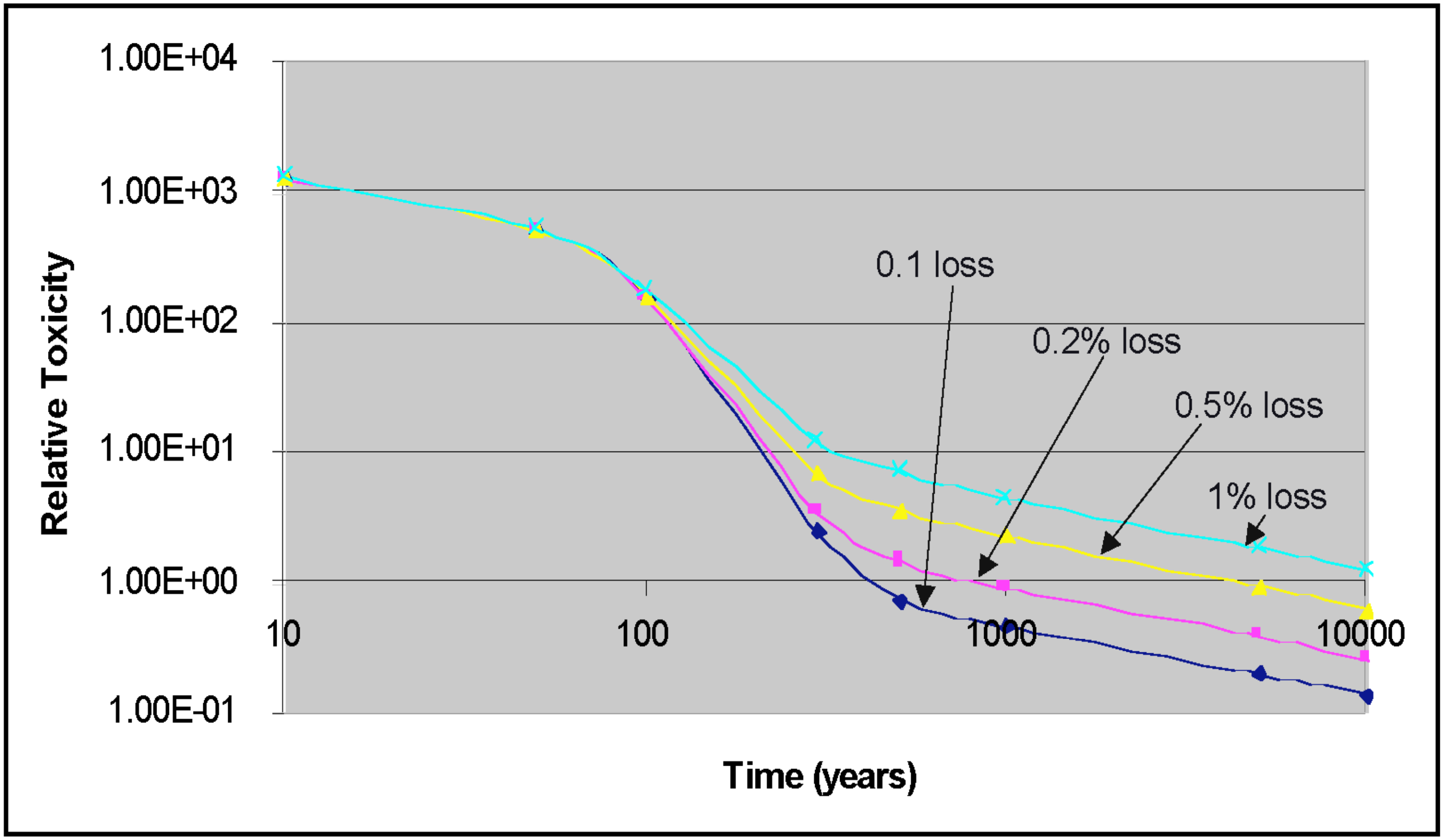


Radiotoxicity of wastes from Once-Through and Recycle (transmutation) Options



From AFCI report to congress 2005

Importance of Processing Loss Fraction



Radiotoxicity of process high-level waste decreases to less than that of natural uranium ore from which the original fuel was derived in less than 1,000 years if the loss fraction can be held below 0.2%

From Jim Laidler's talk at MIT Symposium "Rethinking The Nuclear Fuel Cycle", October 2006

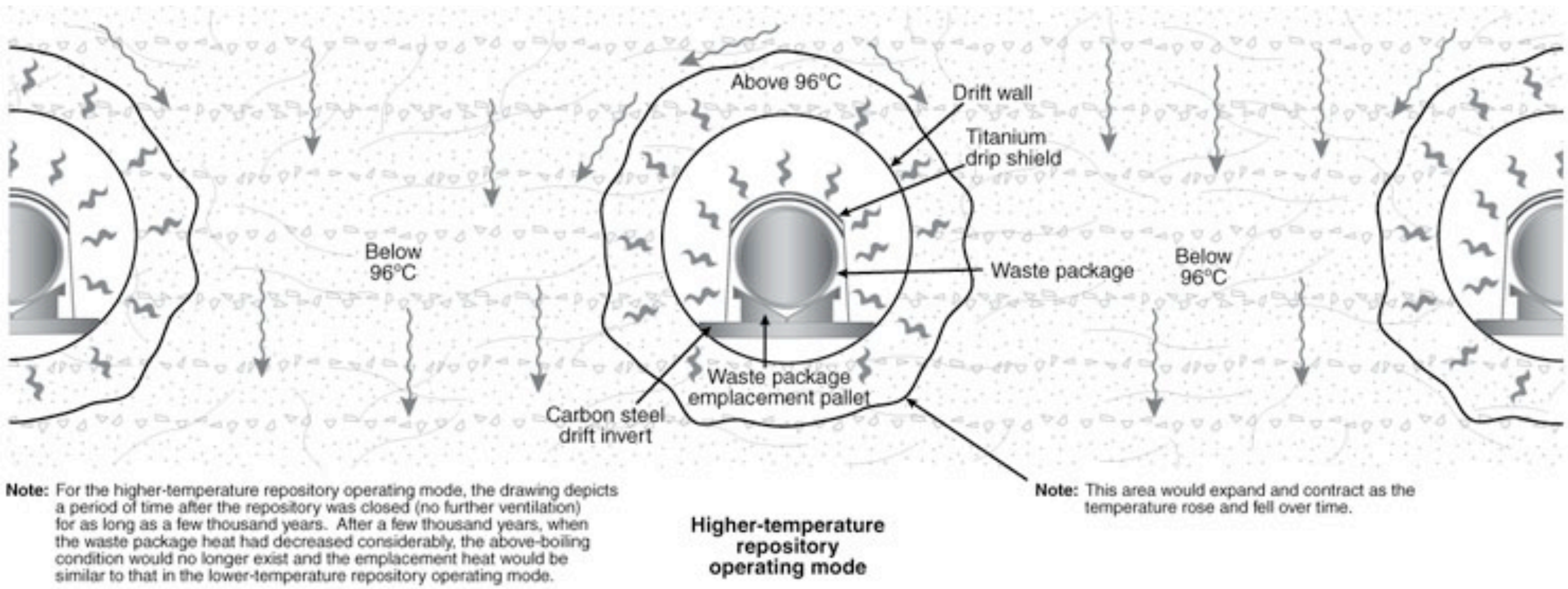
Geologic Disposal of Hazardous Nuclear Waste

- In the United States, geologic disposal of spent nuclear fuel and high-level waste is planned for at the Yucca Mountain repository
- Disposal of nuclear wastes at a single location may be constrained by at least three major factors
  - Peak dose rate for repository releases to satisfy regulatory limits
  - Temperature limits for parts of the repository system to provide greater assurance of long-term performance predictions
  - Volume of the waste materials
- For direct spent fuel disposal, the loading of the Yucca Mountain repository is constrained by the temperature limits due to the high decay heat
  - Estimates of peak dose rate have been calculated, and they meet EPA guidelines. But there are no regulations (from NRC) in place at this time for acceptability of the planned waste disposal
  - Space between the waste packages is applied to limit the linear heat load in the emplacement drifts (tunnels), so waste package volume is not an issue

From Roald Wigeland talk at MIT Symposium “Rethinking the Nuclear Fuel Cycle”, October 2006

Current Yucca Mountain Thermal Limitations

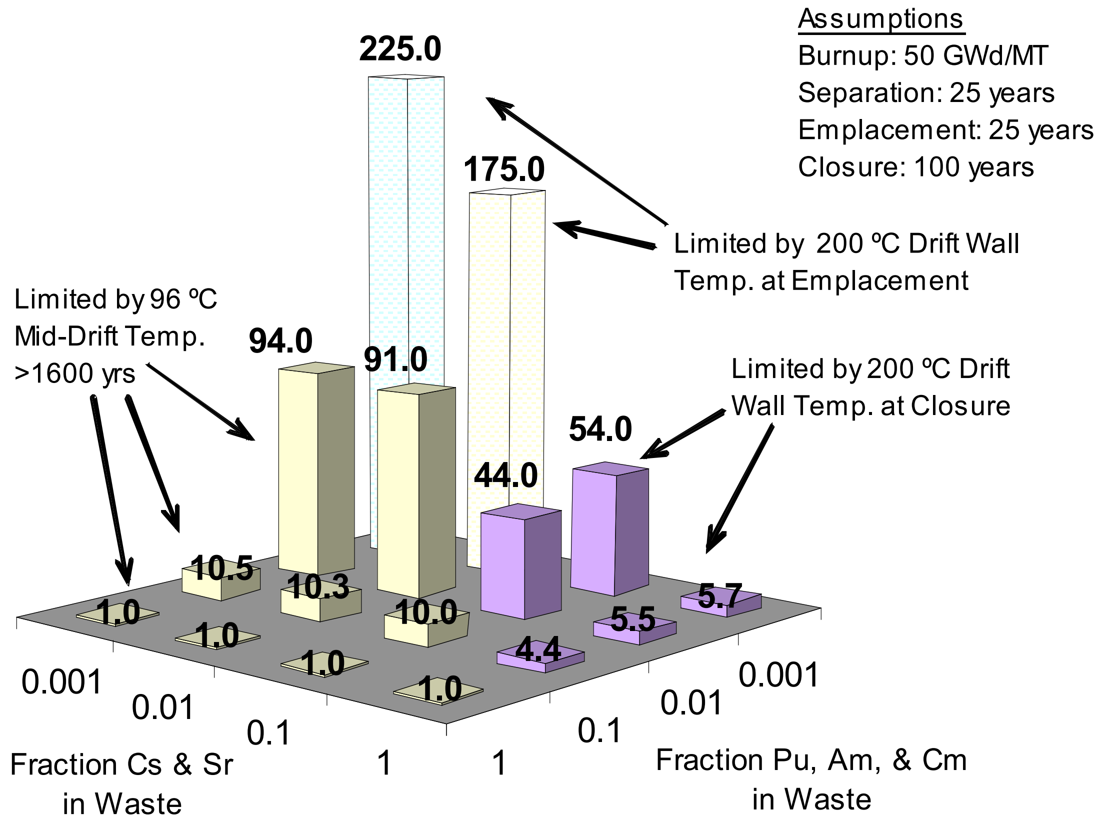
- Current temperature limits for the repository design include:
  - Peak temperature below the local boiling point (96 ºC) at all times midway between adjacent drifts
    - To ensure adequate drainage of water at all times
  - Peak temperature of the drift wall below 200 ºC at all time
    - Structural integrity of the repository
  - Limits are still evolving, in response to concerns related to the long-term performance of the repository



Potential Increase in Utilization of Repository Space

- With the processing of spent PWR fuel to remove the elements responsible for the decay heat that cause temperature limits to be reached, large gains in utilization of repository space are possible
  - The amount of gain is related to separation efficiency
  - Only considering thermal performance, not dose rate

- Pu, Am, Cs, Sr, & Cm are the dominant elements
  - The recovered elements must be treated
  - separate storage of Cs & Sr for 200-300 years
- Recycling of Pu, Am, & Cm for transmutation and fission
  - Irradiation in reactors
- No direct disposal of any spent fuel



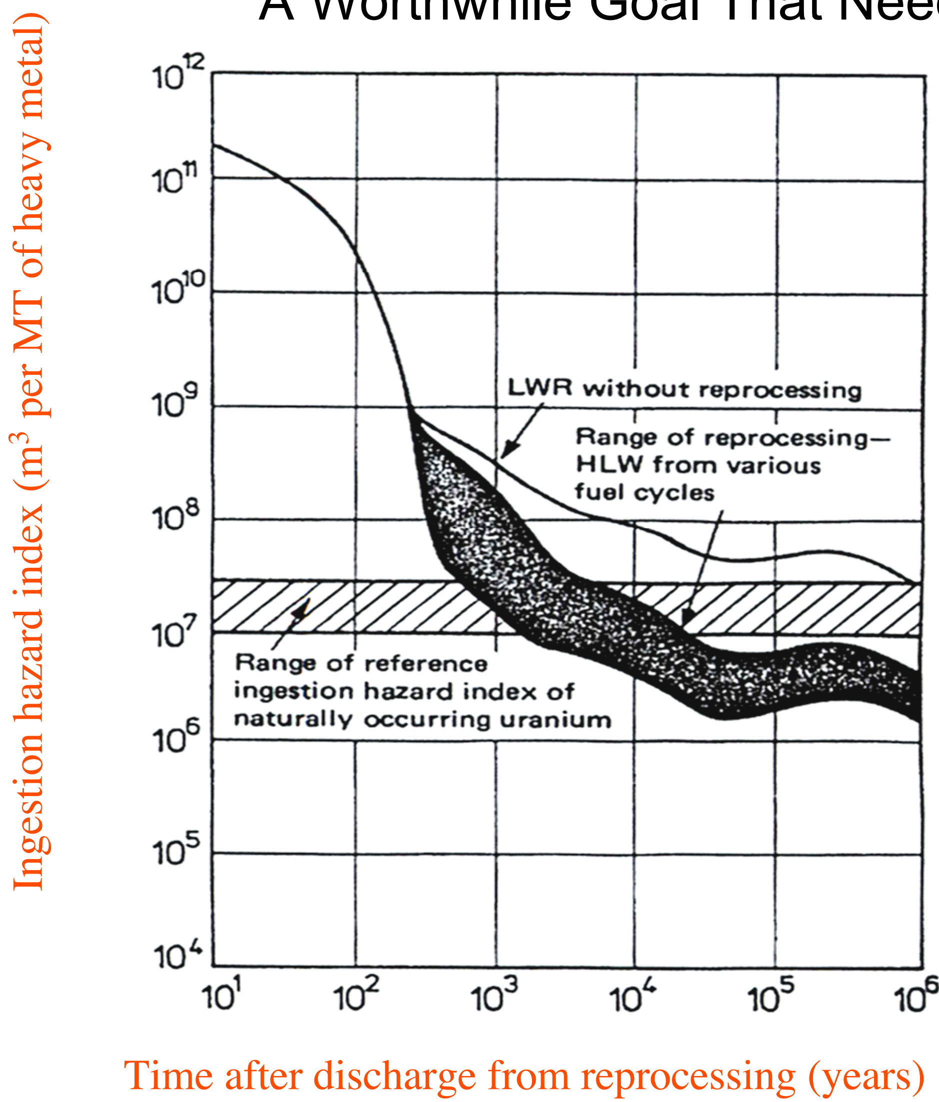
From Jim Laidler's talk at MIT Symposium "Rethinking the Nuclear Fuel Cycle", October 2006

Can we afford recycling?

- The closed fuel cycle is beneficial to waste handling, but at a higher cost than the open cycle unless U prices stay high. The French Pu recycling technology, after much learning, is estimated to be economic when the U price is above $300/kg.
- Cost of new processes is not certain, since the engineering scale tests have yet to be performed.
- If the waste fee fund is allowed to cover reprocessing cost, our studies show economic parity with direct fuel disposal after 25 years of cooling period in which the fee is accumulating interest.
- Other cost reduction routes:
  - High plant capacity factor
  - Increased plant throughput capacity - after learning at a smaller scale - will bring cost down
  - Innovative process and process equipment design
    - Voloxidation head-end step for tritium removal and capture
    - Use of centrifugal contactors to minimize floor space and overhead clearance requirements for chemical separations segments
    - Minimization of liquid wastes

Reducing the Waste Burden:

A Worthwhile Goal That Need Not be Hurried



Sensible Fuel Cycle Steps:

Once-Through

- High burnup fuel
- Central storage facility
- Repository that allows retrievability for a long time

Closed Cycle

- Advanced separation research
- Develop Non-fertile fuel for actinide burning
- System simulation to assess impact of the multiple options