The Abdus Salam International Centre for Theoretical Physics

United Nations Educational, Scientific and Cultural Organization
IAEA

2055-6

Joint ICTP/IAEA School on Physics and Technology of Fast Reactors Systems

9 - 20 November 2009

Integral Fast Reactor and Associated Fuel Cycle System

Part 4. Implications on Economics and Repository

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Electricity Generation Cost

- Electricity generation cost is composed of the following:
  - Capital cost (annualized fixed charge rate)
  - Operating and maintenance (O&M) cost
  - Fuel cycle cost
  - Decommissioning cost
- Quantification of each component is not simple, and hence a consistent comparison between different reactor types is illusive.
- The goal here is to provide a broad understanding of the factors involved rather than definitive quantification.

Fast Reactor Capital Cost Expectations

- Capital costs for the first-of-a-kind and initial few reactors will be more expensive (per kWe basis) than the current commercial reactors.
- In a mature economy, there are no particular technical reasons why fast reactors cannot compete economically.
- In order to overcome the market introduction premium, the future fast reactors must employ unprescented innovations and incentives.

LWR Fuel Cycle Cost

- Discrete cost component for each step of the fuel cycle:
  - Uranium ore (U_3O_8)
  - Conversion to UF_6
  - Enrichment
  - Fabrication
  - Backend fuel cycle
    - *Storage*
    - *Reprocessing*
    - *Disposal*

Cost Assumptions

Uranium Ore, $/lbU_3O_8$	30
UF_6 Conversion, $/kg	8
Enrichment, $/SWU	100
Fabrication, $/kgHM	275
Disposal Fee, mill/kwhr	1
Reprocessing, $/kgHM	1,000
MOX Fabrication, $/kgHM	1,500

Once-Through Fuel Cycle Cost (U.S. Perspective)

	$/kgHM	mills*/kwhr
Uranium	660	1.7
Conversion	70	0.2
Enrichment	770	1.9
Fabrication	275	0.7
Disposal Fee	240-400	1.0
Total	2015-2175	5.5

*1 mill = 0.1 cent

Closed Fuel Cycle Cost (Europe/Japan Perspective)

	$/kgHM	mills/kwhr
Uranium	660	1.7
Conversion	70	0.2
Enrichment	770	1.9
Fabrication	275	0.7
Reprocessing*	610	1.5
Disposal Fee**	120	0.3
Total	2,505	6.3

*Present worth based on 5%/yr discount rate for 10 years

**Assumed to be ½ of once-through cycle, discounted as above

MOX Comparison in Closed Fuel Cycle, $/kgHM (Europe/Japan Perspective)

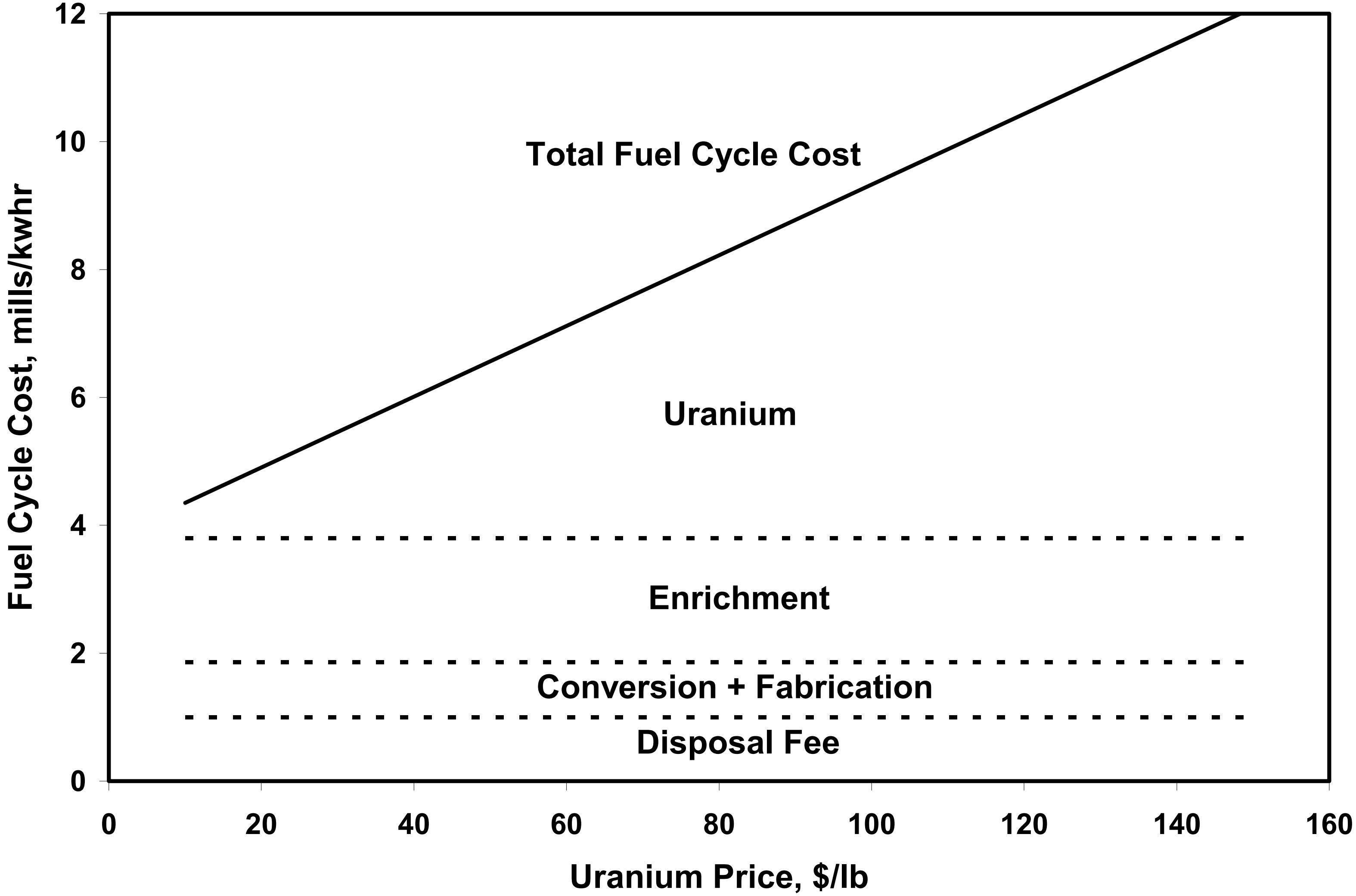
	UOX	MOX
Uranium	660	78
Conversion	70	8
Enrichment	770	0
Fabrication	275	1500
Reprocessing	610	763*
Disposal Fee	120	120
Total	2505	2469

*MOX reprocessing cost was assumed to be 25% more expensive due to higher Pu content.

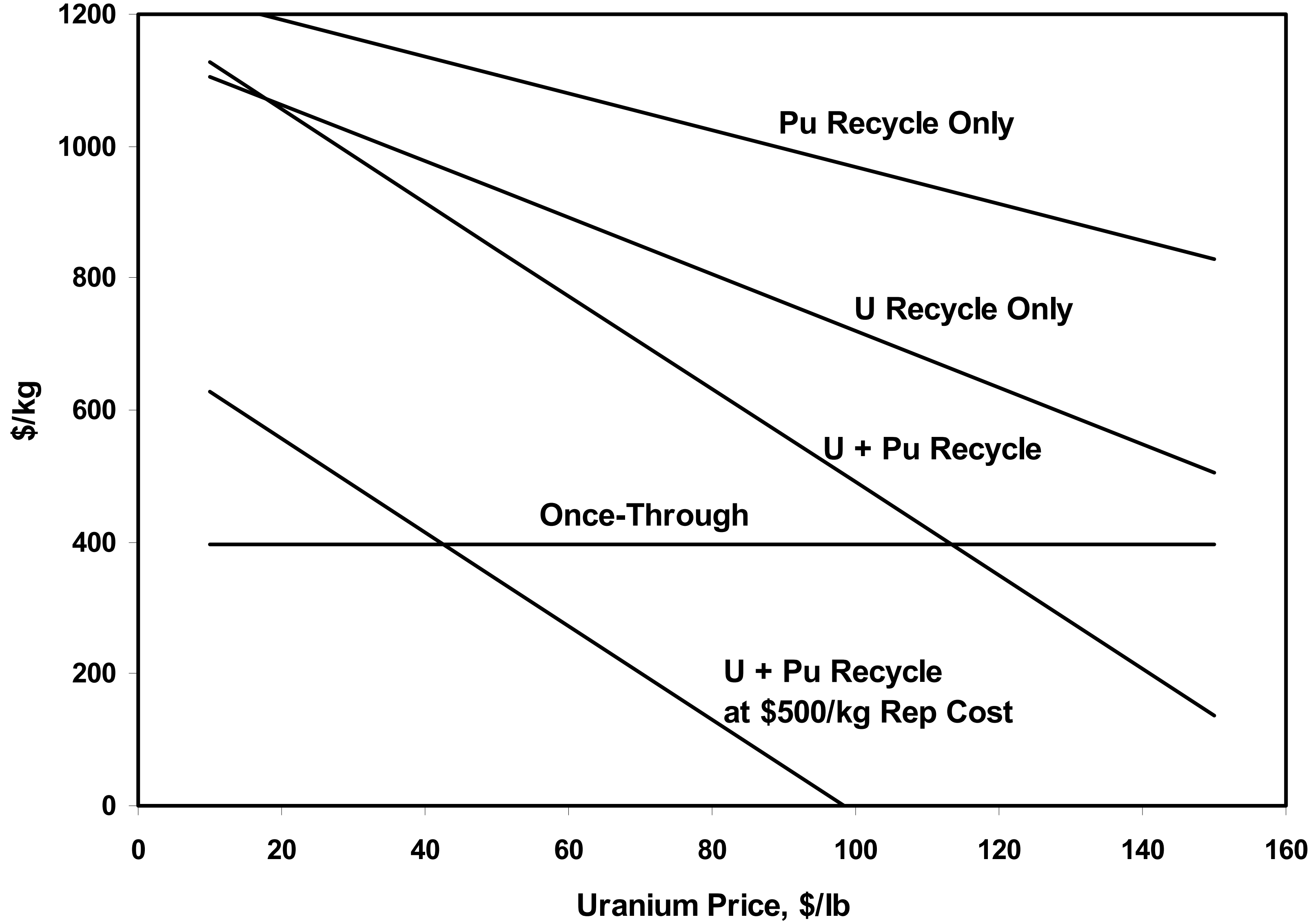
Backend Fuel Cycle Cost

- If reprocessing cost is charged to the electricity produced by the spent fuel as practiced in Europe and Japan, the fuel cycle cost penalty is affordable. Reprocessing plants have been amortized and the reprocessing cost can be heavily discounted due to 10-20 years time lag. MOX recycle is also economical.
- This situation does not apply to the U.S. industry since the entire backend fuel cycle has been assumed to be taken care of by the 1 mill/kwhr disposal fee.
- Given that fact, there is absolutely no economic incentive to reprocess and recycle in the U.S., or more broadly if the reprocessing/MOX infrastructure does not already exist.

Impact of Uranium Price on Fuel Cycle Cost



Once-Through vs. Recycle Cost



Uranium Resource Saving Incentives?

- LWR spent fuel uranium contains typically about 20% of the initial natural equivalent value and about 5% of its separative work value.
- However, recycling of the reprocessed uranium is not straightforward:
  - The U-236 buildup causes reactivity penalty and the enrichment level has to be raised by about 15% negating the recycle benefit.
  - The U-232 buildup at 0.5 to 5 parts per billion level raises contamination concerns in the enrichment and fabrication plants.
- The Pu recycle benefit is also marginal from uranium savings point of view.

Fast Reactor Fuel Cycle Cost

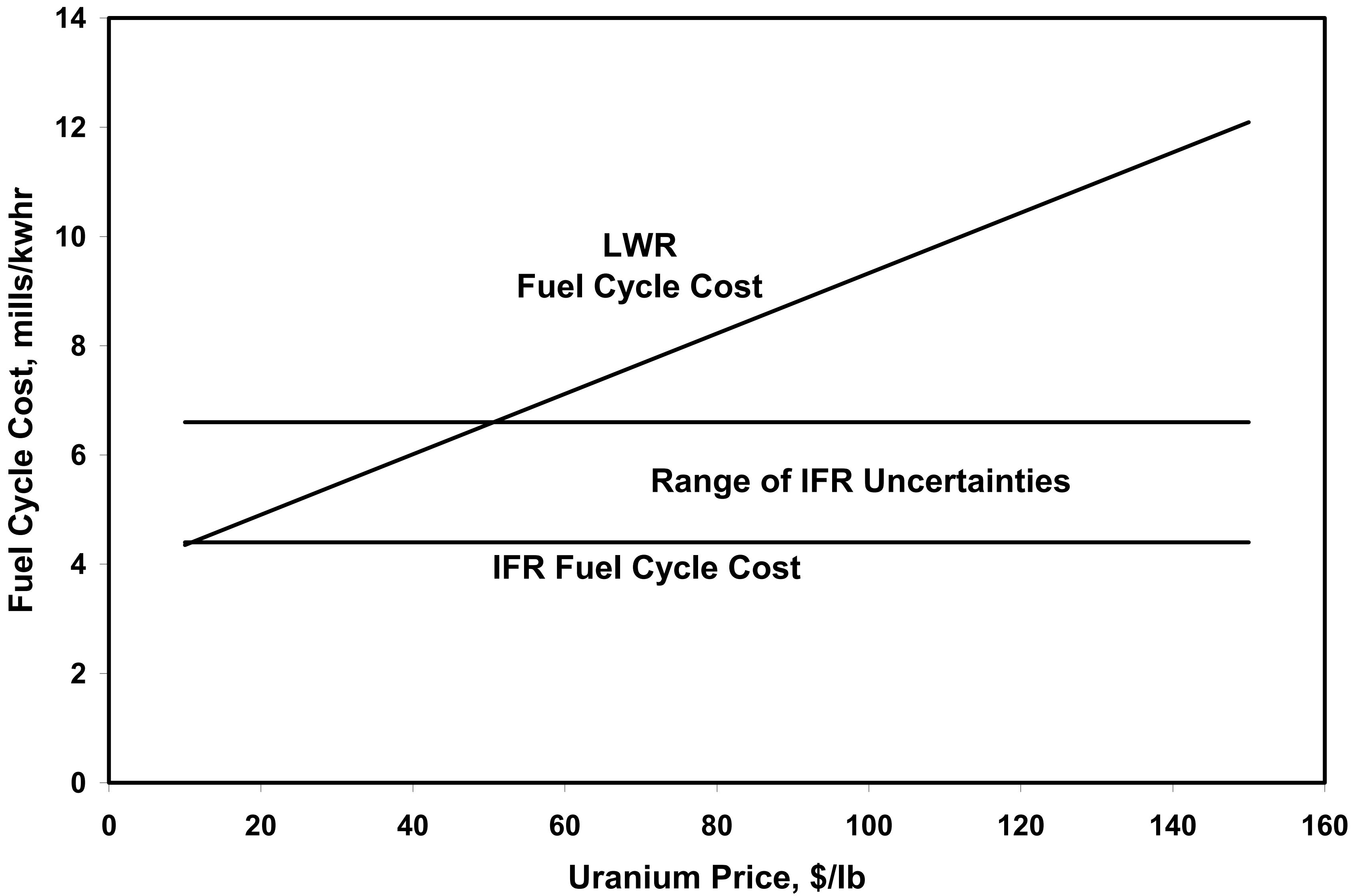
- LWR spent fuel has about 1% TRU, whereas fast reactor has about 20% TRU. Hence, conventional aqueous reprocessing cost per kgHM will be much higher (difficult to dissolve and criticality controls).
- Conventional MOX fabrication cost is also expected to be much higher, especially if remotization is required.
- These penalties can be overcome partially by higher burnup levels (10-15% in fast reactors vs. 3-5% in LWRs) and higher thermal efficiency.
- However, the net effect will be a higher fuel cycle cost for fast reactors if conventional approach is taken.

IFR fuel cycle cost is competitive with LWRs

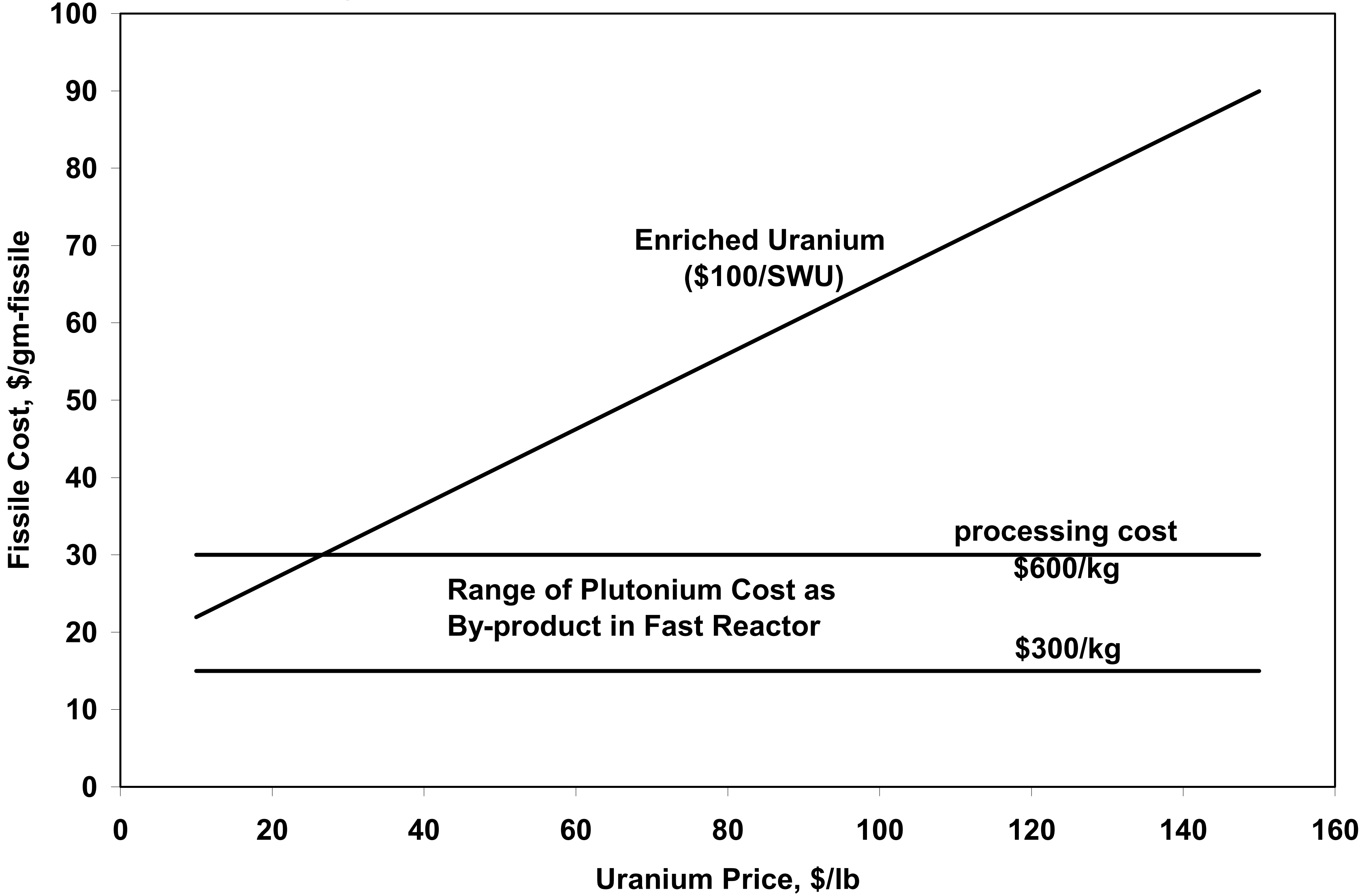
- For the on-site fuel cycle facility, the reprocessing and re-fabrication are done in the same hot cell, and the costs cannot be separated as in the LWR fuel cycle. The FCF capital fixed charge rate of 15% per year was assumed.
- Disposal fee of 0.5 mill/kwhr was assumed due to lack of long term radioactivity and decay heat.

	$million/GWe-yr	mills/kwhr
FCF capital fixed charges	15	1.90
FCF O&M	10	1.27
Assembly hardware	6	0.76
Disposal fee	4	0.50
Total	35	4.43

Comparison of IFR Fuel Cycle Cost with LWR



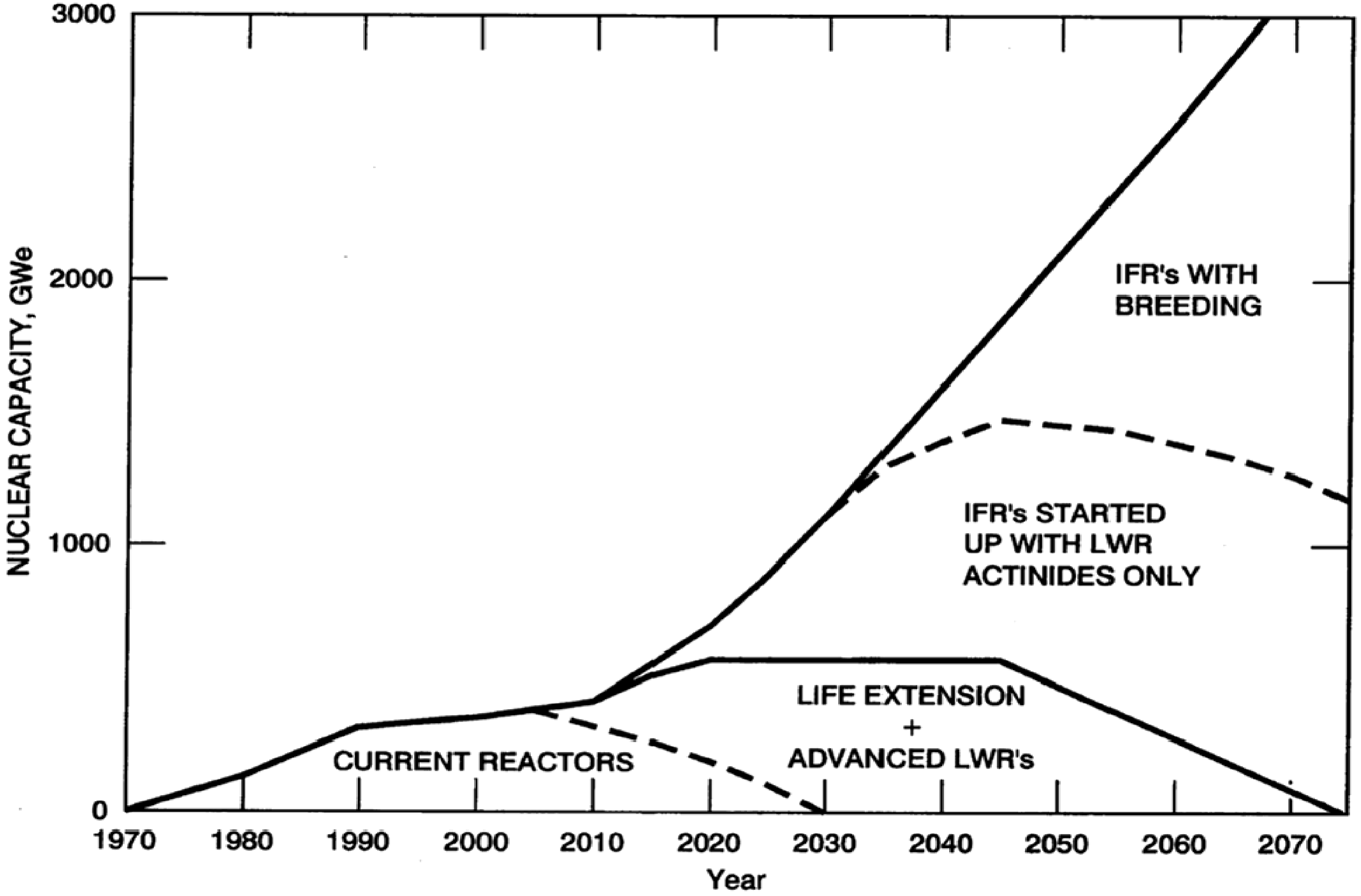
Enriched U Cost vs. Pu Cost as By-product in Fast Reactor



Total System Considerations

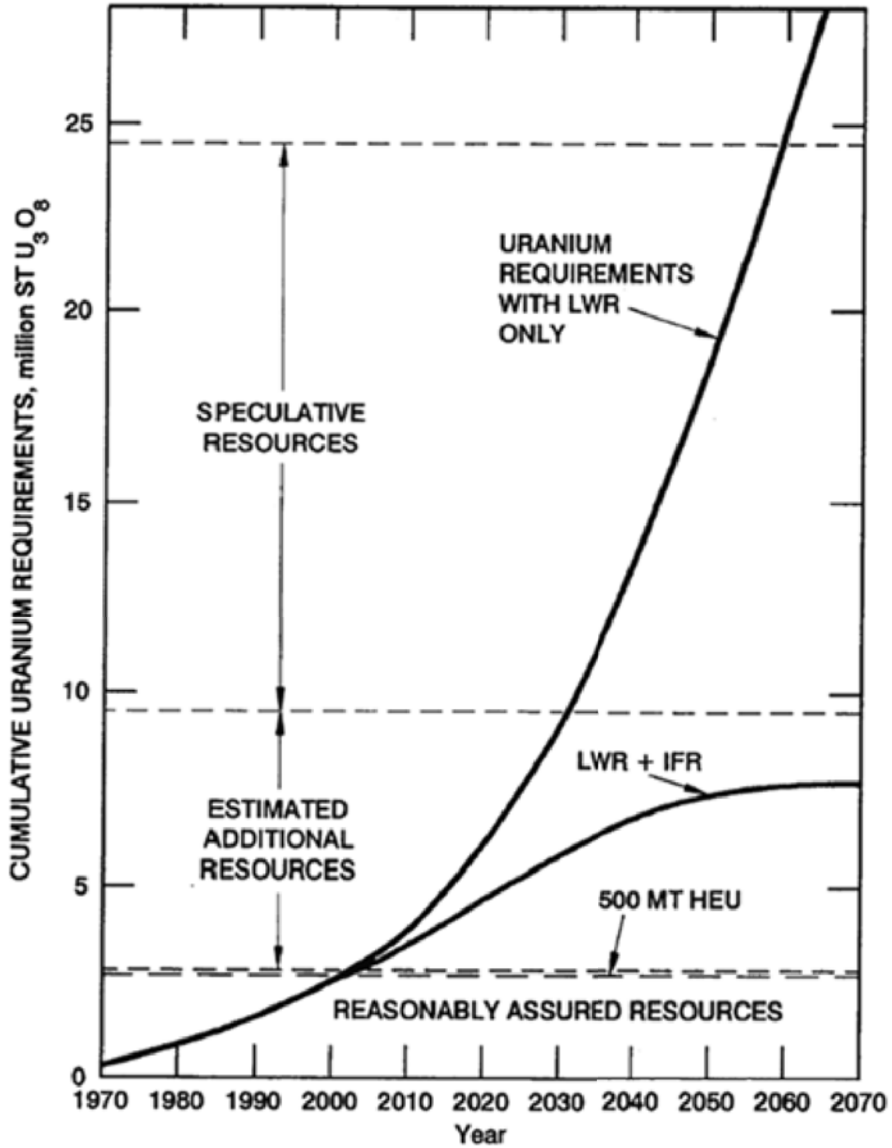
- In conventional electricity generation cost calculations, the capital cost, O&M cost, and fuel cycle cost are calculated on an individual reactor basis. This approach is used by individual utility company for next plant decision, for example.
- The system approach is needed for a national or global policy decisions, in which the impact of introducing one type vs. another in the long-term can be explicitly factored in.
  - Uranium resource requirements and associated costs
  - Repository and waste management implications
  - Environmental impacts, etc.

Plausible Scenario for Nuclear Expansion

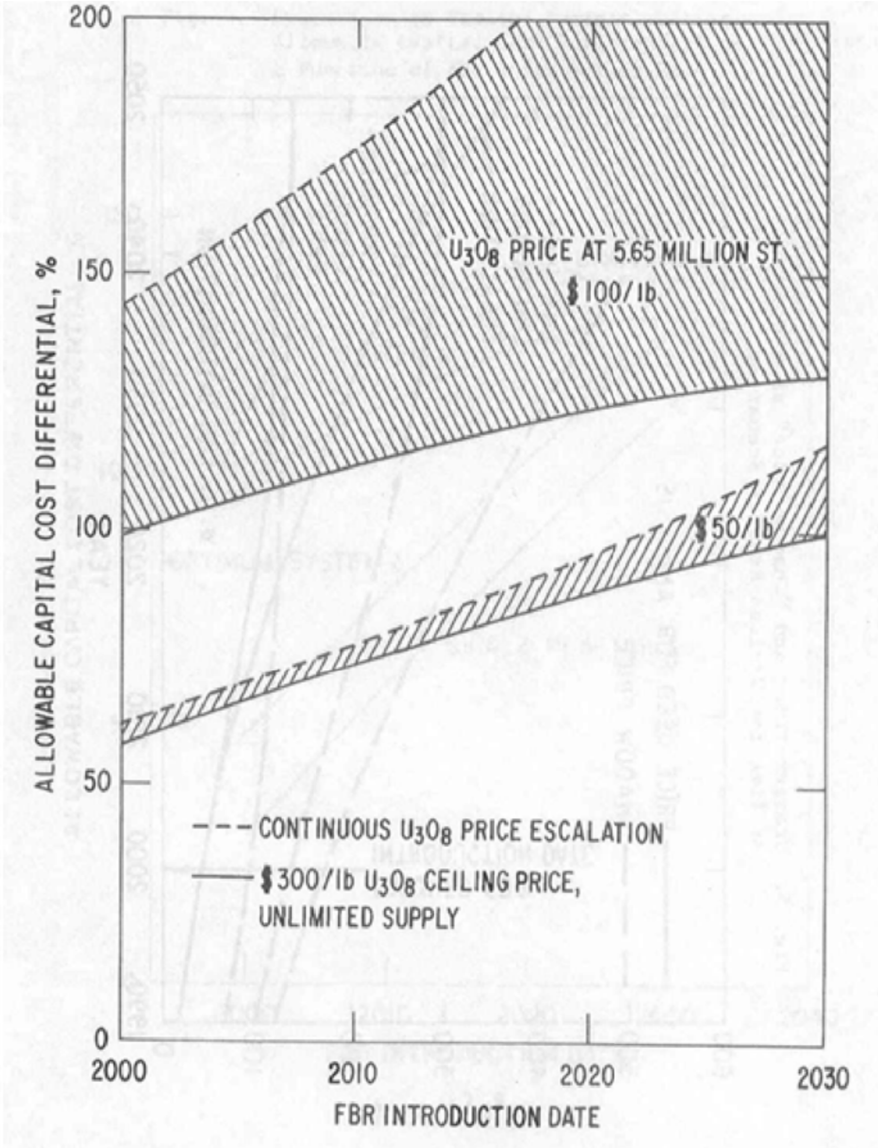


Cumulative Uranium Requirements

- With the introduction of fast reactors, the cumulative uranium requirements can be capped even for a large expansion of nuclear energy.
- The 500 metric tons of highly enriched uranium from the Russian weapons excess material are insignificant and represent only two years requirements for existing reactors.



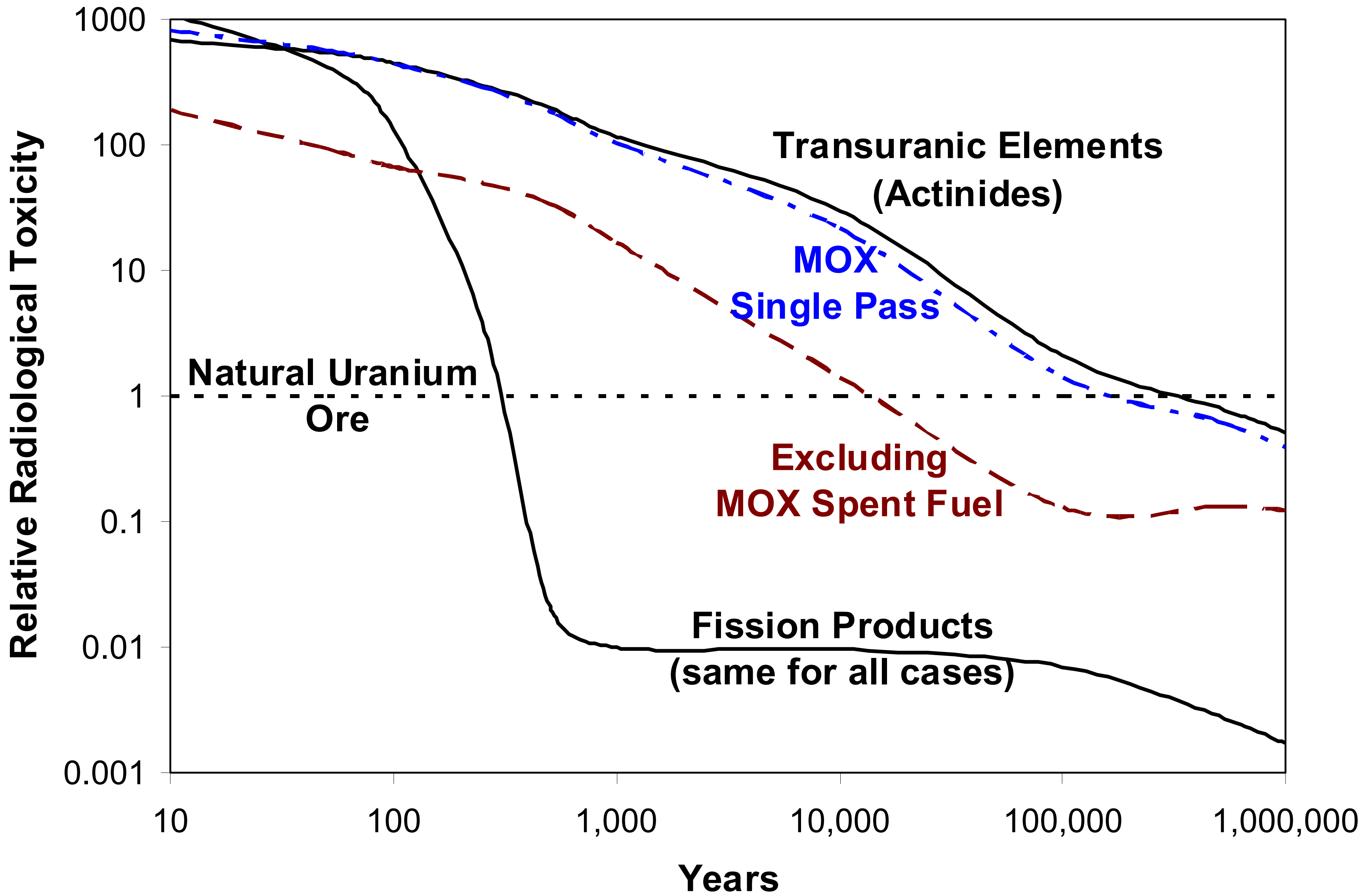
LP optimization model predicts system cost benefits even at very high capital cost premium



Repository Implications

- If actinides are removed, the waste lifetime is effectively reduced from ~100,000 years to ~300 years. Without the source term, the EPA standards and NRC regulation can be met on *a priori* basis.
  - Much simpler repository becomes viable.
- Absence of long term decay heat leads to a factor of 5 or 6 improvement in the repository space utilization.
- Actinides then have to be transmuted in the reactor. Actinides can be transmuted effectively only in fast reactors.
  - Pu recycle in LWRs burns about a third of the original Pu but higher actinide buildup results in no gain in radiological toxicity reduction.

Radiological Toxicity of LWR Spent Fuel (Single-pass MOX recycle has no effect)



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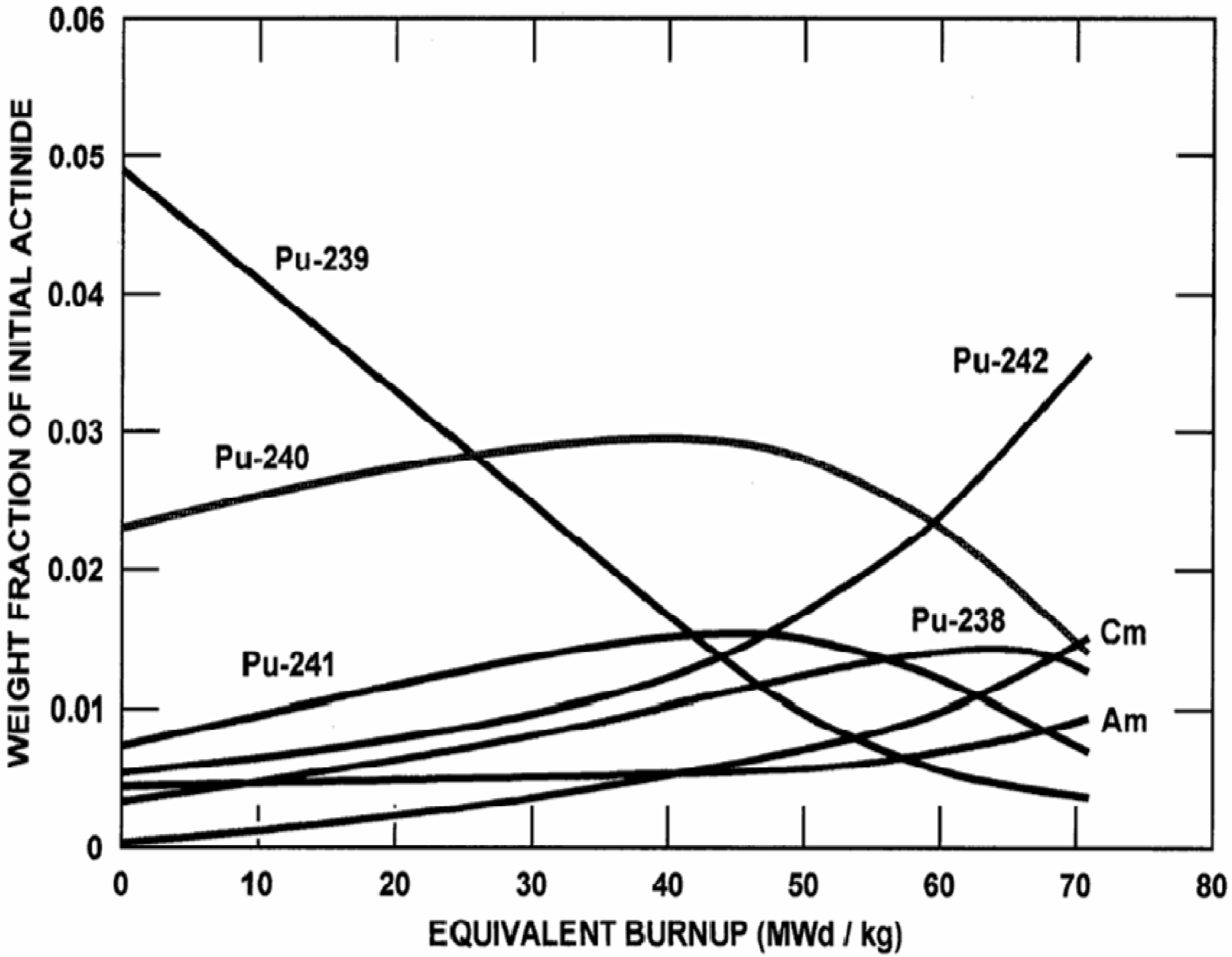
Can Actinides Be Transmuted in Thermal Reactors?

- Neutronic characteristics make the transmutation of minor actinides in thermal reactors inefficient.
- To overcome this difficulty, a reactivity compensation by increasing the enrichment of uranium fuel has been suggested. Even then, a full transmutation is not achievable.
- The fabrication cost of MOX fuel with plutonium is 5-6 times that of uranium fuel. Adding minor actinides will require a remotization of the fabrication line and economic penalty will be even greater.
- To overcome this difficulty, a heterogeneous recycling with minor actinides in targets has been proposed. This is neutronically feasible but fabrication and handling challenges make this impractical.

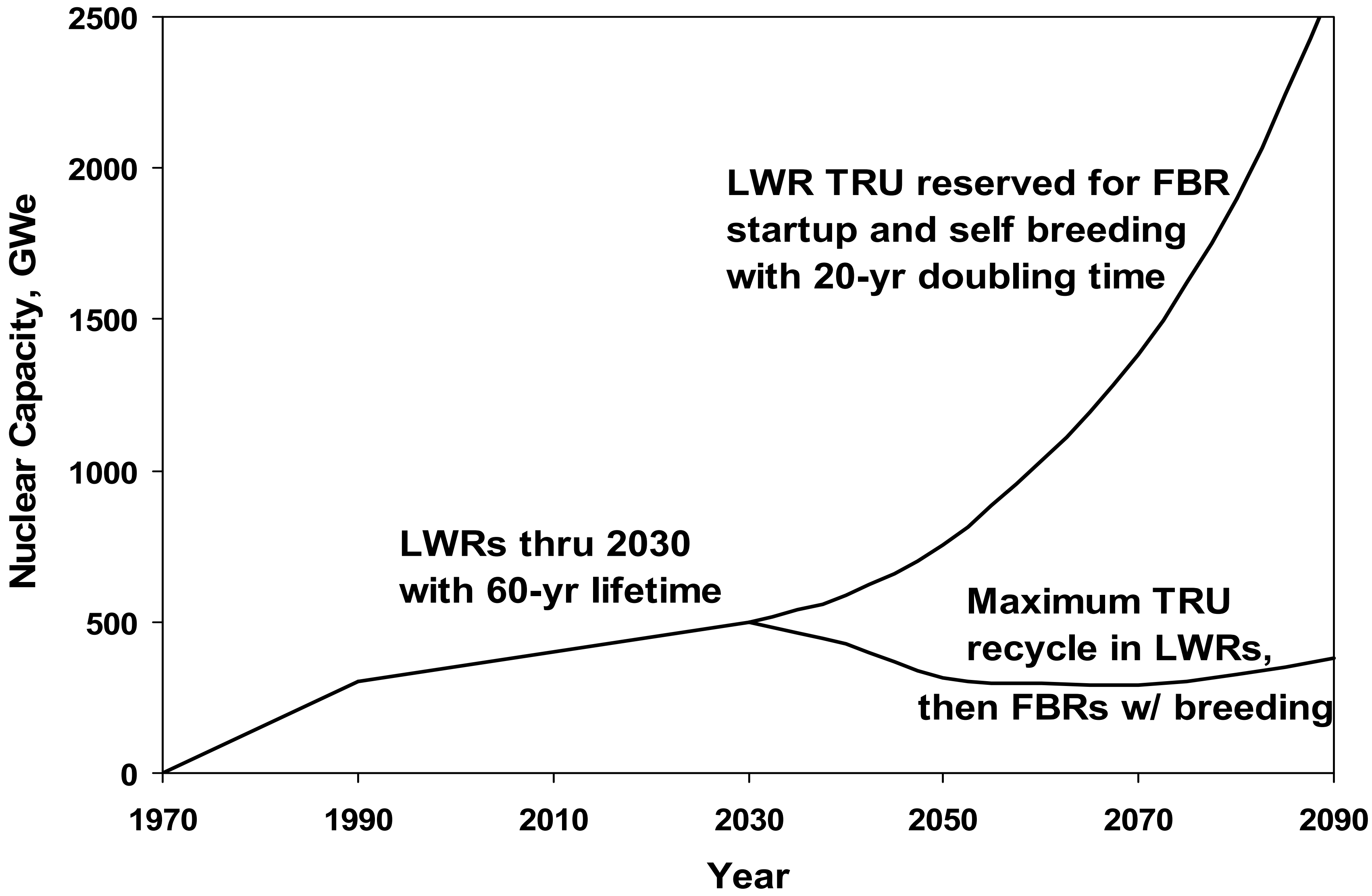
Transmutation Probabilities (in %)

Isotope	Thermal	Fast
Np-237	3	27
Pu-238	7	70
PU-239	63	85
Pu-240	1	55
Pu-241	75	87
Pu-242	1	53
Am-241	1	21
Am-242m	75	94
Am-243	1	23
Cm-242	1	10
Cm-243	78	94
Cm-244	4	33

Evolution of Actinides in Thermal Spectrum (Pu recycle is typically limited to a single pass and cannot transmute minor actinides)



Long-Term Nuclear Capacity Potential



Fuel for Initial Fast Reactors

- Today there are excess plutonium inventory from LWR reprocessing, which can be utilized as startup fuel for initial fast reactors.
- LWR produces about 250 kgPu/GWe-yr.
- The plutonium inventory requirement for a fast reactor including 2-3 reloads is of the order of 10 tons/GWe.
- Conventional burner (w/o blankets) will require annual makeup of 100-300 kgPu/GWe-yr depending on the reactor size.
- The startup of fast reactors is dictated by the availability of Pu or the reprocessing capacity.

Should Fast Reactors Be Designed as Burners?

- As long as there are plutonium inventory from LWR spent fuel reprocessing, fast reactors do not need to breed and replacing blankets with reflectors make sense technically and economically.
- But there is no reason to degrade the core performance to reach a higher transmutation rate.
  - Lower fuel volume fraction or spoiled geometry to increase leakage result in a higher Pu content core.
  - Oxide or metal fuels with up to 25-30% Pu content have been demonstrated. But much higher Pu content fuels have not been developed and may expect performance issues.
  - Increased reactivity control requirements, etc. may result in safety and economic penalties.

EPA Standard (40 CFR Part 191)

- Containment requirements in terms of allowable cumulative releases of radionuclides over 10,000 years.
- These limits are not definitive but probabilistic requirements:
  - Less than one chance in 10 of exceeding the limits
  - Less than one in 1,000 of exceeding 10 times the limits

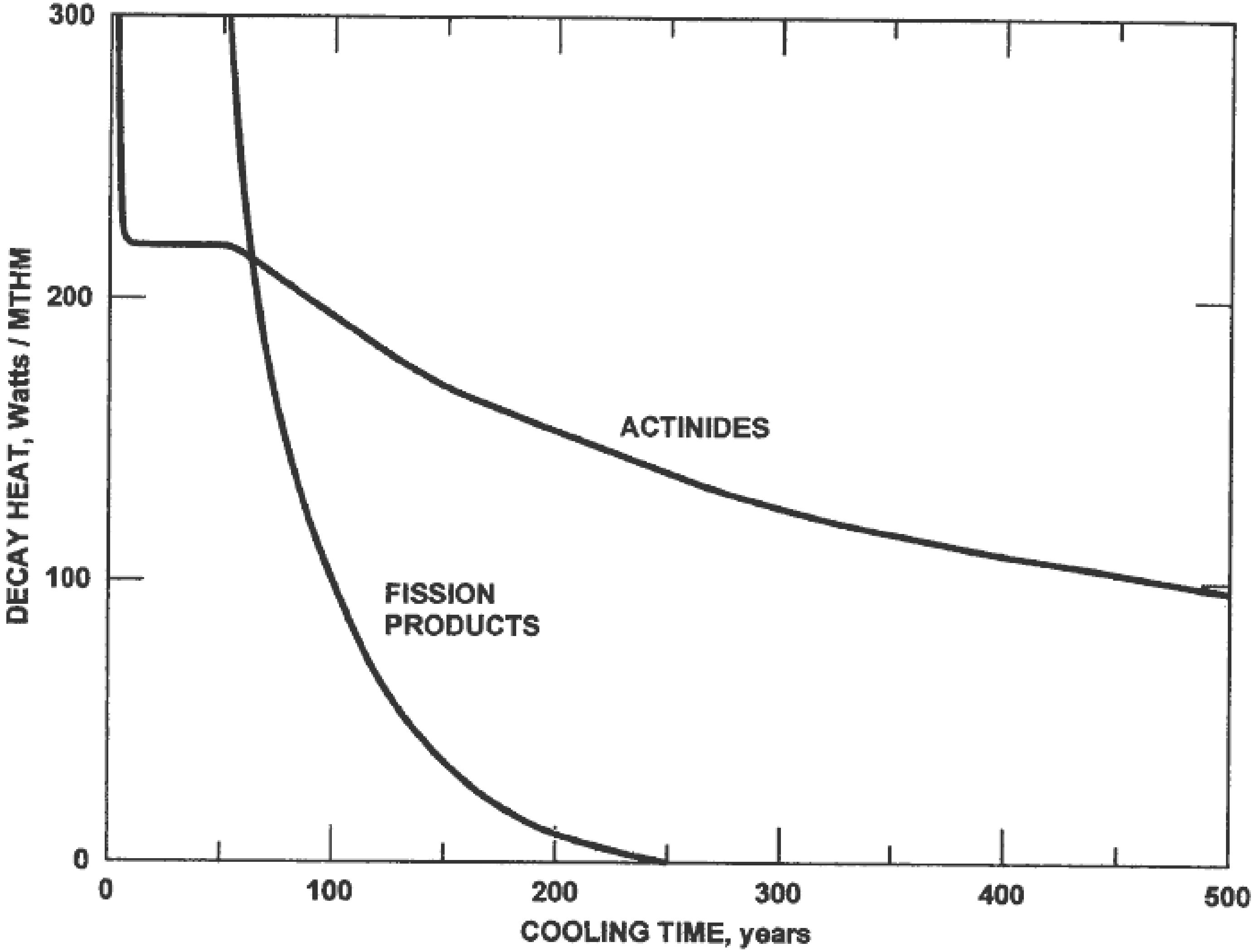
LWR spent fuel radioactivity (normalized to EPA cumulative release limits) also illustrate the importance of actinides

	Activities at 10 yrs	Activities at 1,000 yrs	Activities at 10,000 yrs
Sr-90	60,000	0.0	0.0
Cs-137	90,000	0.0	0.0
I-129	0.3	0.3	0.3
Tc-99	1.4	1.4	1.4
Other F.P.	1,050	5.1	4.4
Actinides	76,000	19,000	4,000

Can Repository Be Eliminated?

- Practical partitioning processes can recover actinides up to 99.9% at best or loss of 0.1% to waste streams.
- In addition, there are a dozen or so long-lived fission products: Tc-99, I-129, Cs-135, etc.
- The recovery of actinides and long-lived fission products to eliminate the need for repository (namely convert to low level waste) will become prohibitively expensive, even if feasible.
- We already produce much low level waste. The spent fuel should be treated to reduce the radiological toxicity (by three orders of magnitude or so) and make compact high level waste forms for disposal. This will result in less demanding repository performance requirements but would not eliminate the need itself.

Repository space utilization is improved by a factor of 5-6 if actinides are removed (99.9%)



Summary

- IFR is a next-generation reactor concept with almost limitless energy potential: implies longer term?
- However, there is a near-term imperative to deal with the LWR spent fuel management:
  - The IFR pyroprocessing can be applied to LWR spent fuel as well and can potentially reduce the cost drastically.
  - Aqueous reprocessing can be utilized in interim if the facilities exist but, if not, there is no justification for it.
  - Actinides are recovered naturally in pyroprocessing, which makes the waste disposal much easier.
  - Actinides can be transmuted effectively only in the IFR.