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Future Prospects for Backend Fuel Cycle

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Outline of Presentation

1. Historical Background
2. Fuel Cycle Economics
3. Rationale for Closed Fuel Cycle
4. Long Term Technology Options
   - Reactor
   - Reprocessing
5. Conclusions

Early Commercial Reprocessing Plants in U.S.

- West Valley (300 T/yr) was operated by Nuclear Fuel Services from 1966-72.
- Midwest Fuel Recovery Plant (300 T/yr) was built by General Electric at Morris, Illinois but not commissioned.
- Barnwell Reprocessing Plant (1500 T/yr) was being built by Allied Gulf Nuclear Services when President Carter announced indefinite deferral of reprocessing/recycling in 1977.
- At the time of Carter policy announcement, Exxon Nuclear was also planning another commercial reprocessing plant and already built a MOX fabrication plant.

Commercial Reprocessing Around the World

- France:
  - UP1 (400 T/yr) at Marcoule started operation in late 50’s.
  - UP2 (400 T/yr) at La Hague started in the 60’s.
  - UP3 (800 T/yr) at La Hague started operation in 1990.
  - UP2 was upgraded to 800 T/yr in 1992.
- UK:
  - Magnox fuel reprocessing plant (1500 T/yr) at Sellafield started operation in the 60’s.
  - THORP (designed at 1200 T/yr but operated at 800 T/yr) started operation in 1993.
- Japan:
  - Tokai Plant (90 T/yr) started operation in 1981.
  - Rokkasho (800 T/yr) to start commercial operation in 2008.

Nuclear Waste Policy Act of 1982

- NWPA was introduced to the Congress by the Administration in 1978, enacted in 1982, and amended in 1987.
- With waste disposal fee of 1 mill/kwhr (=0.1 cent/kwhr), the title to spent fuel was to be transferred to Federal Government for the long-term storage and permanent disposal.
- Contracts ... shall provide that:
  - (A) following commencement of operation of a repository, the Secretary shall take title to ... spent nuclear fuel involved as expeditiously as practical ...
  - (B) in return for the payment of fees ... ,the Secretary, beginning not later than January 31,1998, will dispose of ... spent nuclear fuel involved ...

Current Status of Lawsuits

- Utility industry filed lawsuits (about 60 pending) against DOE over its failure to begin accepting spent fuel in January 1998.
- Exelon was the first utility to drop the breach-of-contract litigation against DOE in 2004, settling for reimbursement of spent fuel storage costs it has incurred and will incur as a result.
- The settlements are not paid out of the nuclear waste fund collected from the utility, but from the Judgment Fund overseen by the Justice Department.

Adequacy of Disposal Fee of 1 mill/kwhr

- The NWPA of 1982 mandates periodic review of the adequacy of the fee, and that the Secretary shall propose an adjustment to the fee to ensure full cost recovery.
- Assessment in 2001: The life cycle cost of Yucca Mountain over 100 years was estimated at $57.5 billion, which will be financed by:
  - $25 billion (100 GWe x 40 years x 75% CF)
  - $15 billion investment income in treasury notes
  - $17 billion DOE share for defense high level waste

Reprocessing Cost

- Current reprocessing cost of $1,000/kg is equivalent to:
  - 4.2 mills/kwhr at 30,000 MWD/T burnup
  - 2.5 mills/kwhr at 50,000 MWD/T burnup
- Therefore, the 1 mill/kwhr disposal fee is a great bargain and hence the U.S. utility industry welcomed and supported the Nuclear Waste Policy Act of 1982 enthusiastically.

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	400*	1.0
Total	2175	5.5

*Conversion of 1 mill/kwhr at 50 MWD/kg burnup.
($240/kg at 30 MWD/kg)

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

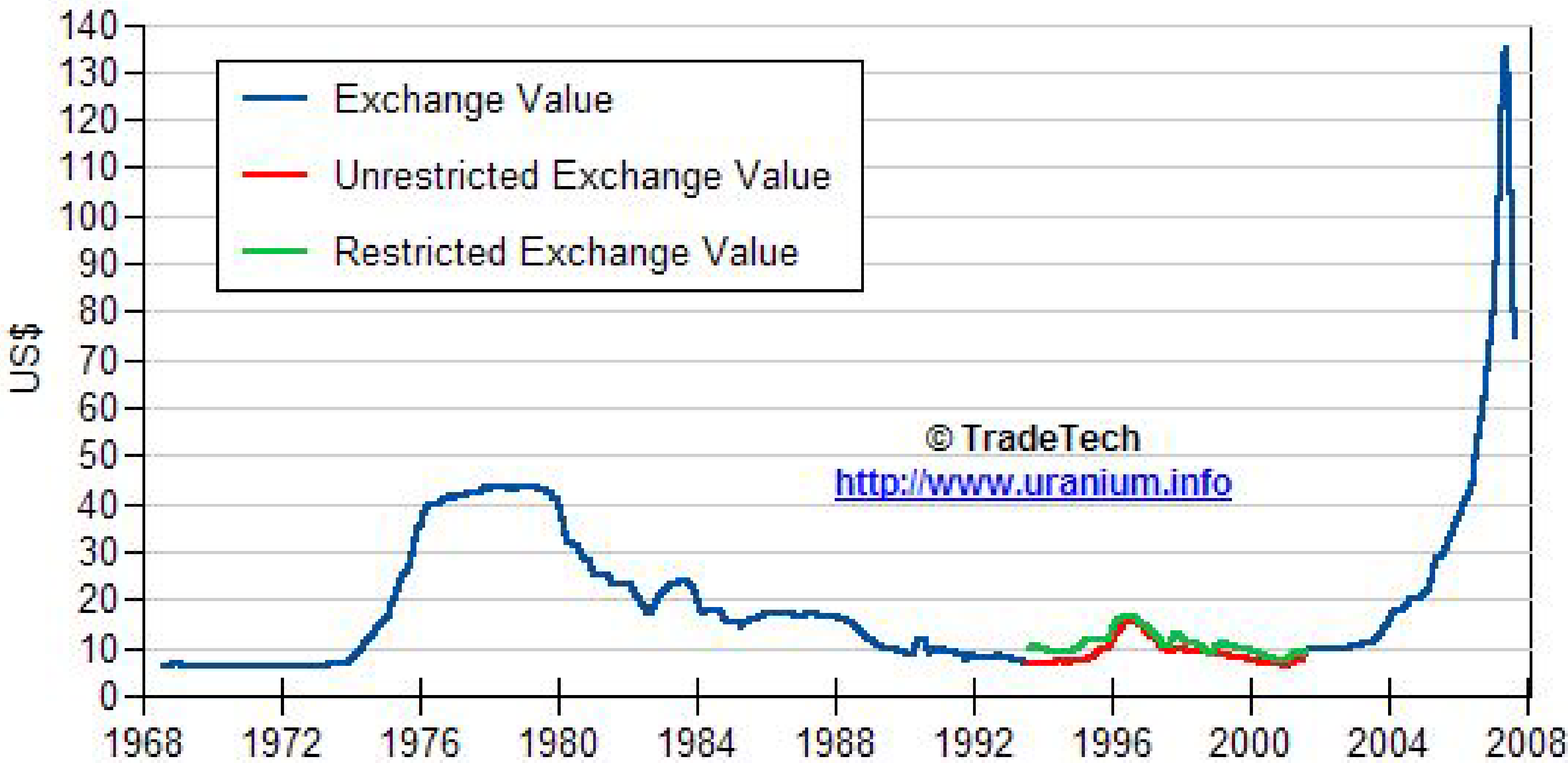
MOX Comparison in Closed Fuel Cycle, $/kgHM (Europe/Japan Perspective)

	UOX	MOX
Uranium	660	78
Conversion	70	8
Enrichment	770	0
Fabrication	275	1500
Reprocessing	610	610
Disposal Fee	120	120
Total	2505	2316

Backend Fuel Cycle Cost

- If reprocessing and MOX fabrication facilities have been constructed and their capital costs are amortized, then a closed fuel cycle is affordable although there are some economic penalty.
- On the other hand, if such infrastructure is not available, then there is absolutely no economic incentives to reprocess and recycle in LWRs.
- Other incentives?
  – Uranium resource savings
  – Waste management solutions

Uranium Spot Market Price Trend



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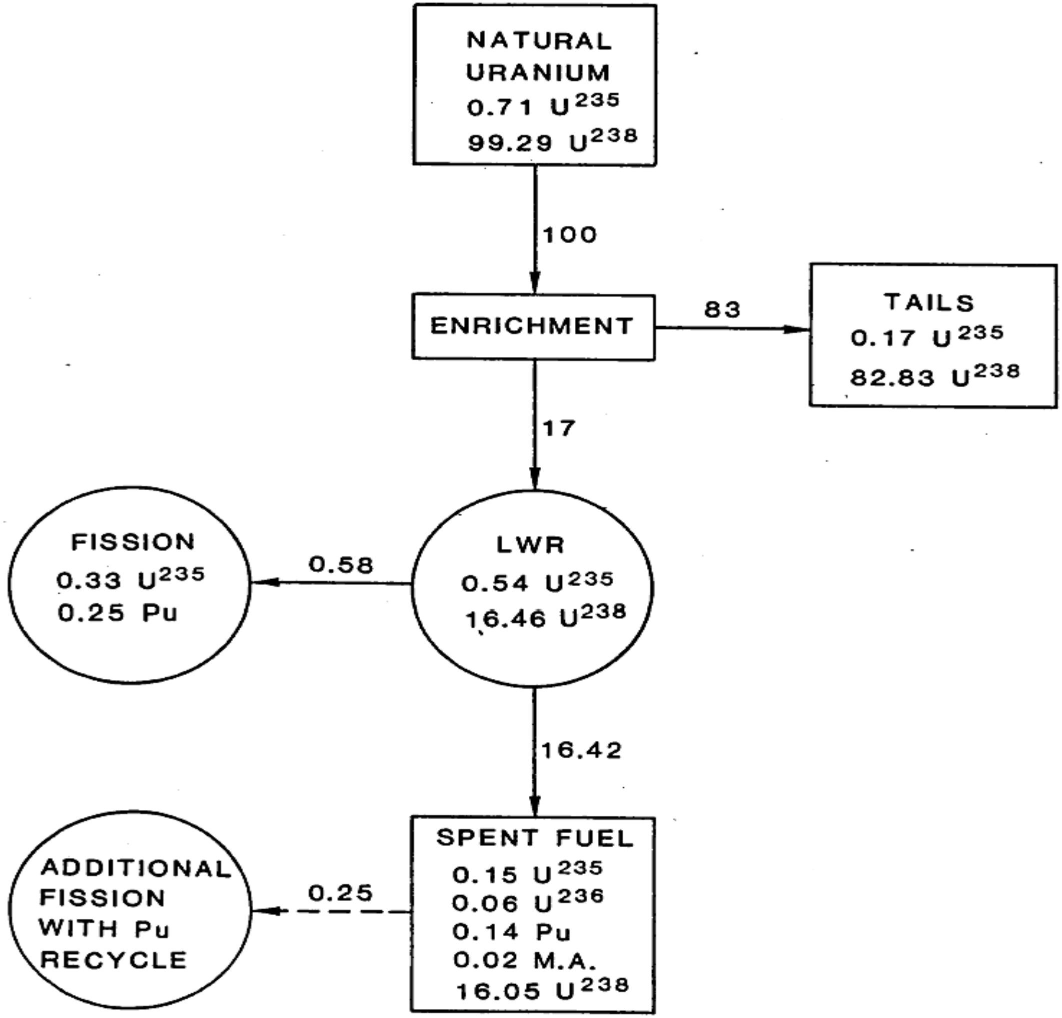
Uranium Resource Saving Incentives?

- 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.

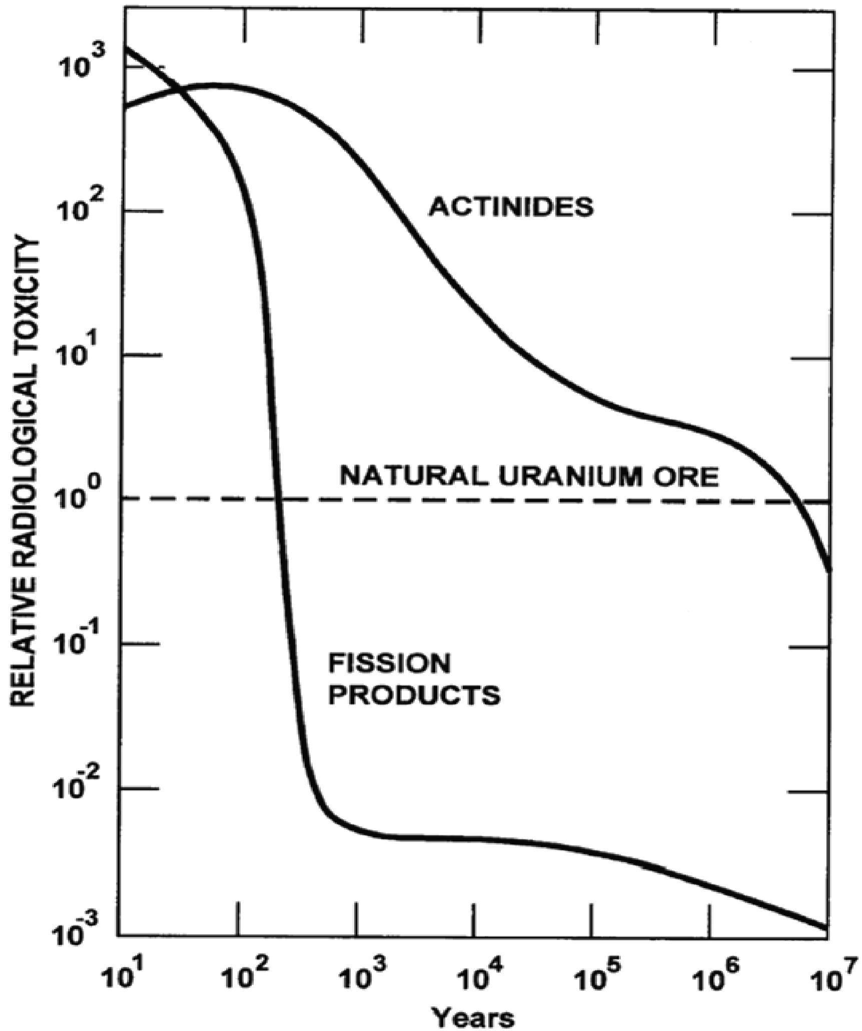
Uranium Resource Utilization in LWRs



Waste Management Implications?

- Actinides (transuranics) are the primary source of radiological toxicity in the long-term, millions of years.
- Actinides are not effectively transmuted in thermal neutron spectrum.
- Therefore, waste management benefits are also marginal with actinide recycle in thermal spectrum.

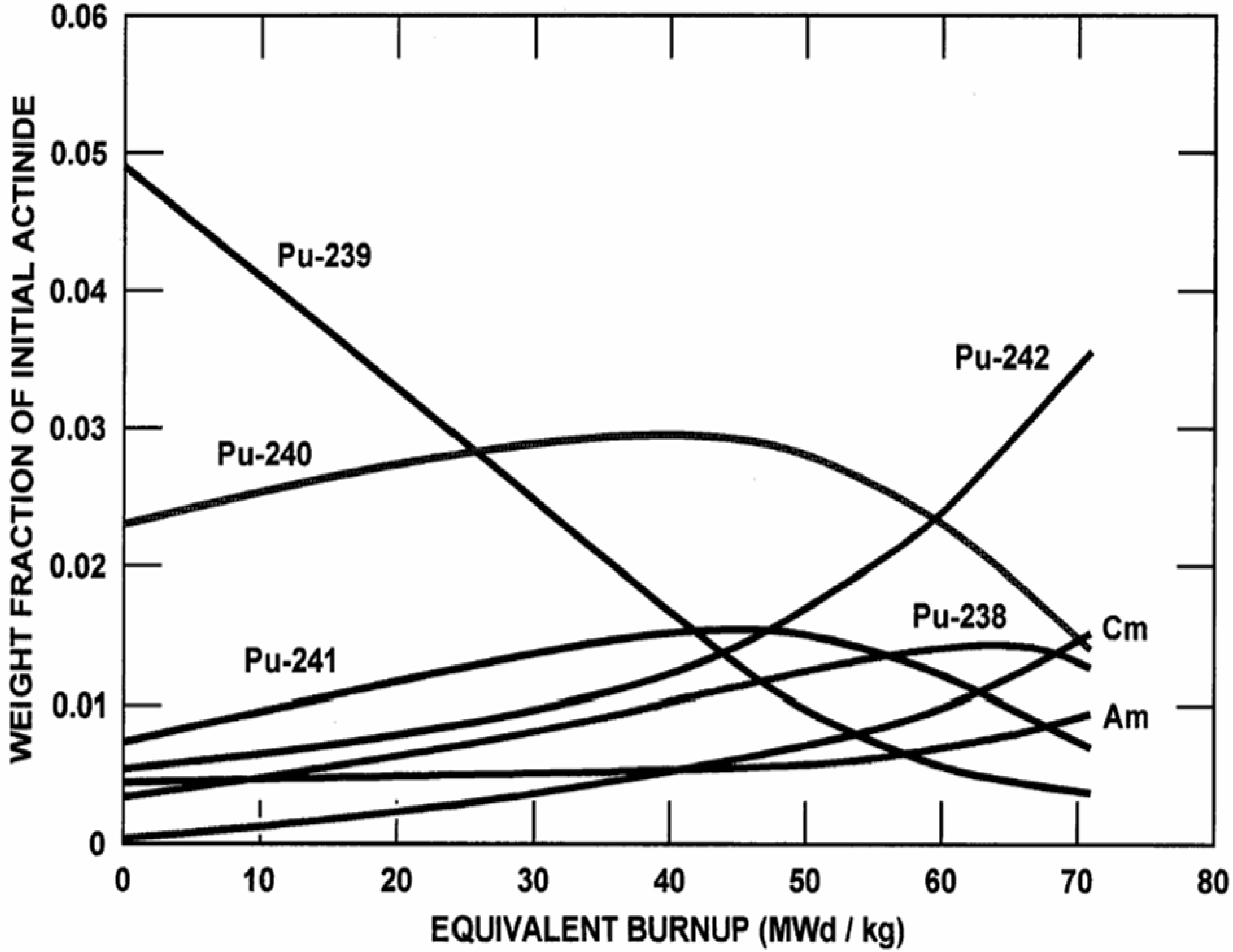
Radiological Toxicity of Spent Fuel



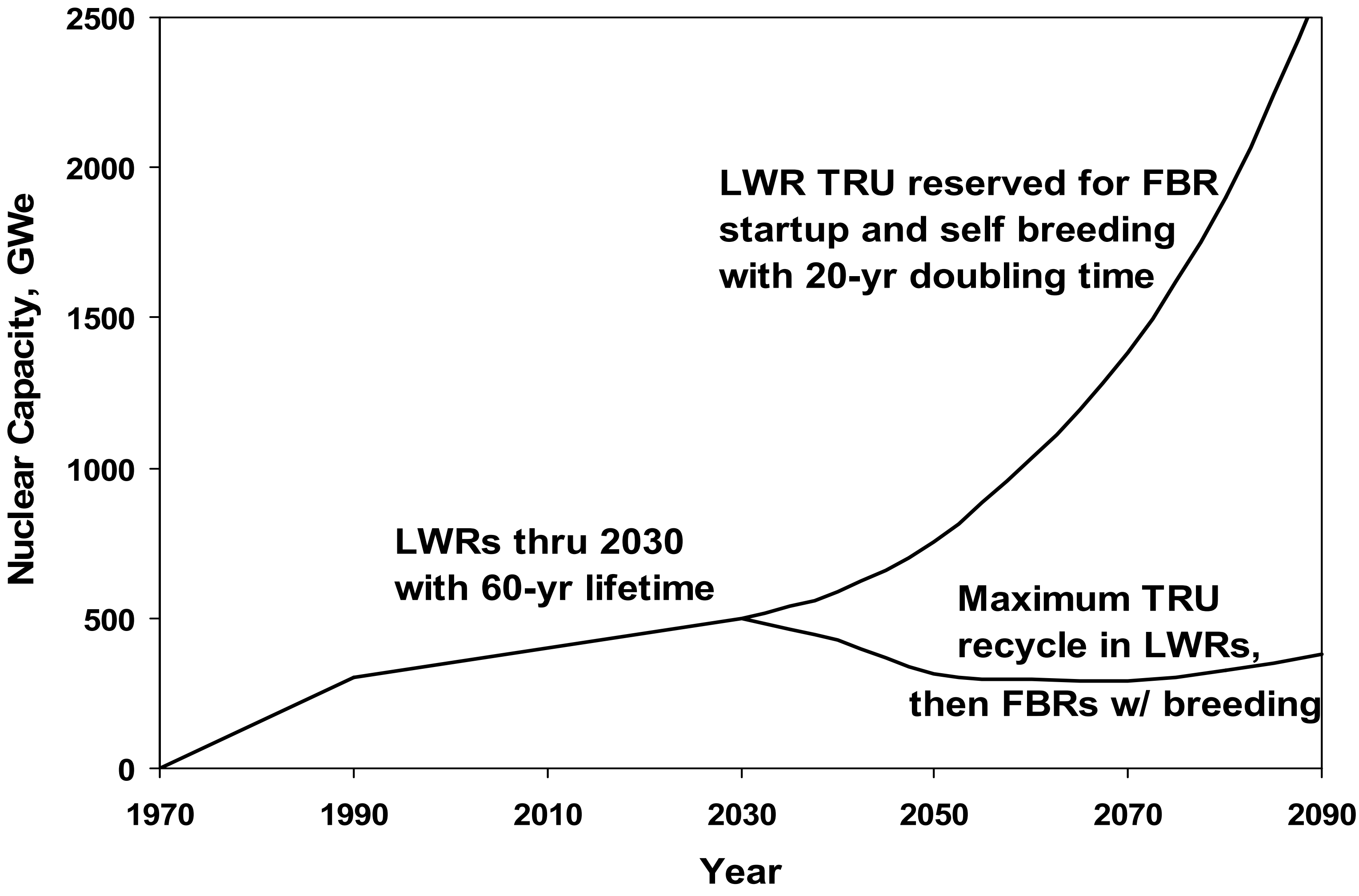
Transmutation Probabilities (in %)

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



Long-Term Nuclear Capacity Potential



Rationale for Fuel Cycle Closure

- The fuel cycle closure in LWRs cannot be justified based on:
  - Economics of recycle
  - Uranium resource savings
  - Waste management solution
- The fuel cycle closure can be justified only based on broader, longer-term perspectives:
  - Longer-term uranium resource utilization, namely fast reactors to realize the full energy potential.

Fast Reactor Imperative: Resource Extension

- Current commercial reactors utilize less than one percent of uranium resources.
- Fast reactors can utilize essentially all through recycling, except for small losses in processing.
- Intrinsic nuclear characteristics make this distinction.
- Therefore, if nuclear is to contribute a significant portion of future energy demand growth, then fast reactors will have to play a key role.

Waste Management Benefit is a Bonus

- Long-lived actinides are the long term radiological risks.
- Actinides can be burned only in fast reactors (in fact, generating energy at the same time).
- Actinides also contribute to long term decay heat, which limits the disposal per unit area. Hence, actinide burning in fast reactors can increase the repository space utilization in the long term.

Technical Rationale for the IFR

- Revolutionary improvements for the next generation nuclear concept:
  - Inexhaustible Energy Supply
  - Inherent Passive Safety
  - Long-term Waste Management Solution
  - Proliferation-Resistance
  - Economic Fuel Cycle Closure
- Metal fuel and pyroprocessing are key to achieving these revolutionary improvements

Key Attributes of Pyroprocessing

- Compact equipment systems based on electrorefining.
- All actinides are recovered together, and hence there is no need to develop additional partitioning processes.
- Direct waste processing and no liquid low level waste streams.
- Intrinsic proliferation-resistance characteristics.
- All of the above characteristics combine to a potentially drastic improvement in economics.

Pyroprocessing for LWR Spent Fuel

- Electrorefining has been demonstrated for fast reactor metal spent fuels.
- For LWR spent fuel application, oxide-to-metal reduction front-end step is required:
  - Electrolytic reduction process
- For economic viability, the electrorefining batch size and throughput rate has to be increased: this should be straightforward with planar electrode concept.

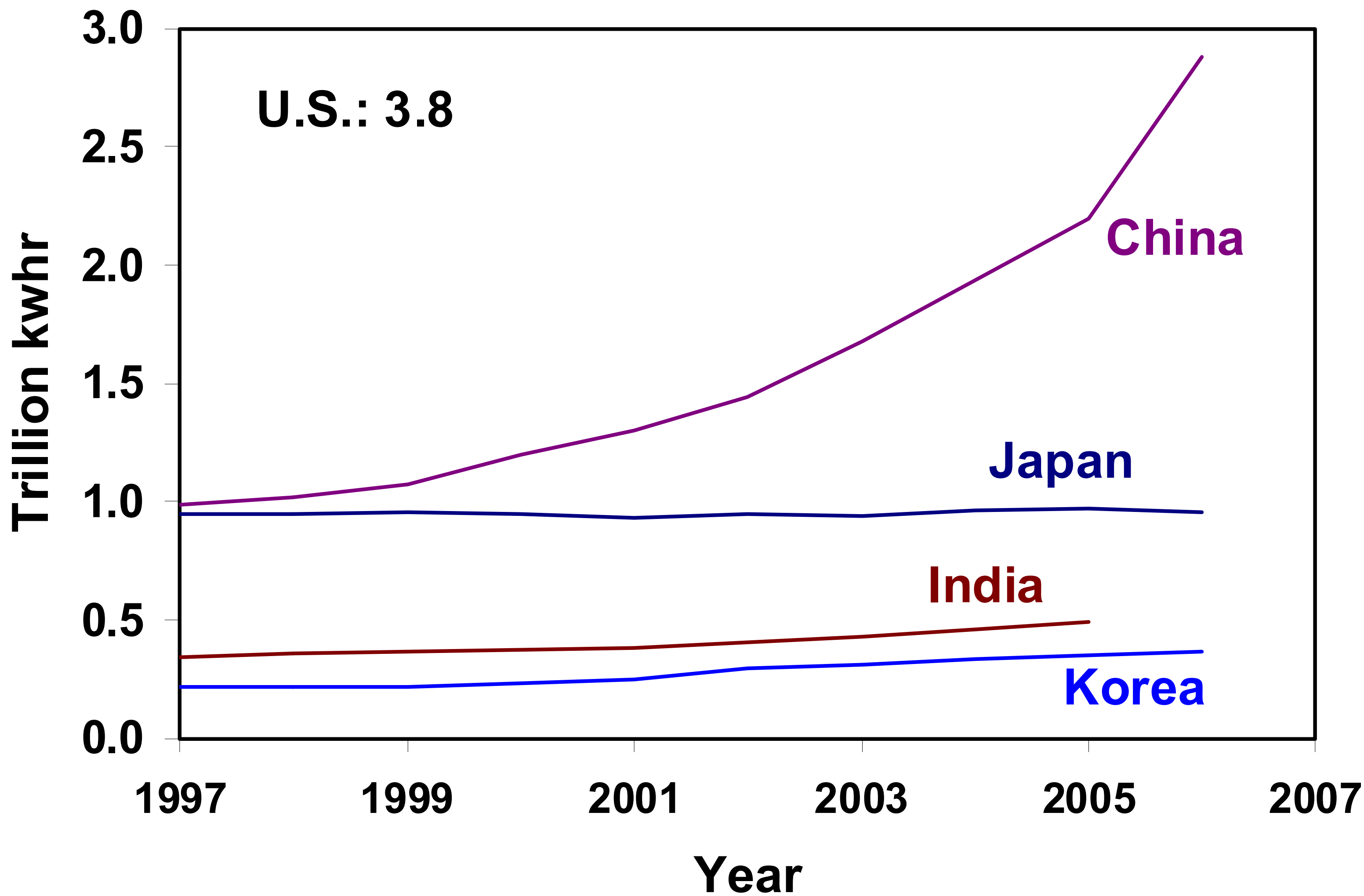
Common Perception on Timing Dilemma

- The current nuclear renaissance will be based on advanced LWR's (AP-1000, EPR, ABWR, ESBWR, APWR, etc.) through 2020's and 30's.
- Commercial fast reactors could start around 40's at the earliest. Hence, no urgency for a fast reactor project now.
- How to balance the near term priorities and the long term vision?

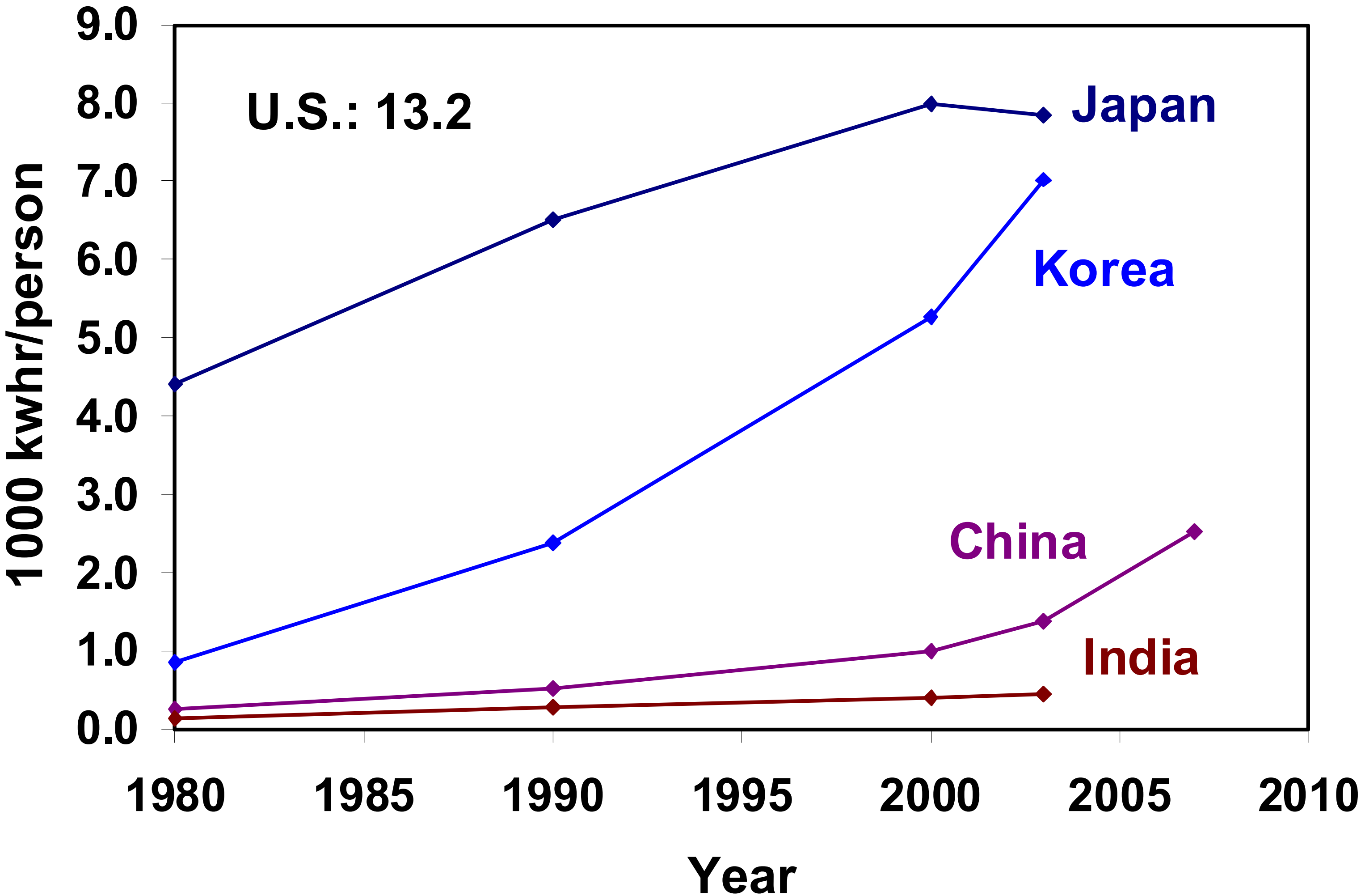
Need for Long-term Roadmap for Nuclear Energy Development

- Long-term (~50 years) vision and goals need to be established:
  – Technical consensus of nuclear community is essential.
- Once long-term vision and goals are established, then the mid-term (~25 years) roadmap naturally follows.
  – Commitment of resources is essential.
- Then, the near-term (~5 years) priorities become obvious.

Electricity Consumption per Year



Per Capita Electricity Consumption



Current Status of Nuclear Energy in China

- Annual growth rate of electricity has been over 14% in recent years. In 2007 alone, 100 GWe generating capacity has been added.
- Rapidly growing electricity demand has been met mostly by coal (76%) and hydro (23%), nuclear contributing only 1.3%.
- Currently 11 reactors (9 GWe) in operation and 16 reactors under construction.
- The current capacity has been built under a past policy of "moderate development". In 2006, the Chinese government committed to an "actively promoted" nuclear power program: 40 GWe by 2020, with another 18 units under construction at that time. Recently, the target was raised to 50-60 GWe.
- 120-160 GWe nuclear capacity is planned by 2030.

CEFR Reactor Building Completion Ceremony (8/15/02)

Current Status of Nuclear Energy in India

- Currently 16 reactors (3.9 GWe) in operation, contributing to about 3% of electricity generation.
- Seven reactors (3.4 GWe) under construction:
  - 4 x 220 MWe Heavy water reactors
  - 2 x 1000 MWe Russian reactors
  - 1 x 500 MWe Prototype Fast Breeder Reactor (PFBR)
- Four more units of 500 MWe FBRs are planned by 2020.

PFBR Architectural View

PFBR to be commissioned by 2010

Conclusions

- Nuclear has emerged as a major clean energy option for the future. Nuclear renaissance in the U.S. and around world will be based on advanced LWRs in the near-term, which should be given priority. At the same time, however, establishment of a longer-term vision for fast reactors is also crucial.
- Then, the fuel cycle closure in fast reactors is mandatory in the long-term and the fuel cycle closure in LWRs is an interim measure only if infrastructure already exists.
- Fast reactor technology has been well established and a demonstration project is not so urgent, maybe ~2025.
- However, an innovative reprocessing technology, e.g. pyroprocessing should be given a near-term priority for development and demonstration.