Nuclear Energy Systems Economic Evaluations: **Uranium Resource Availability Fuel Cycle Cost**

Course 22.39, Lecture 19

11/15/06

Professor Neil Todreas

Scope of Presentation

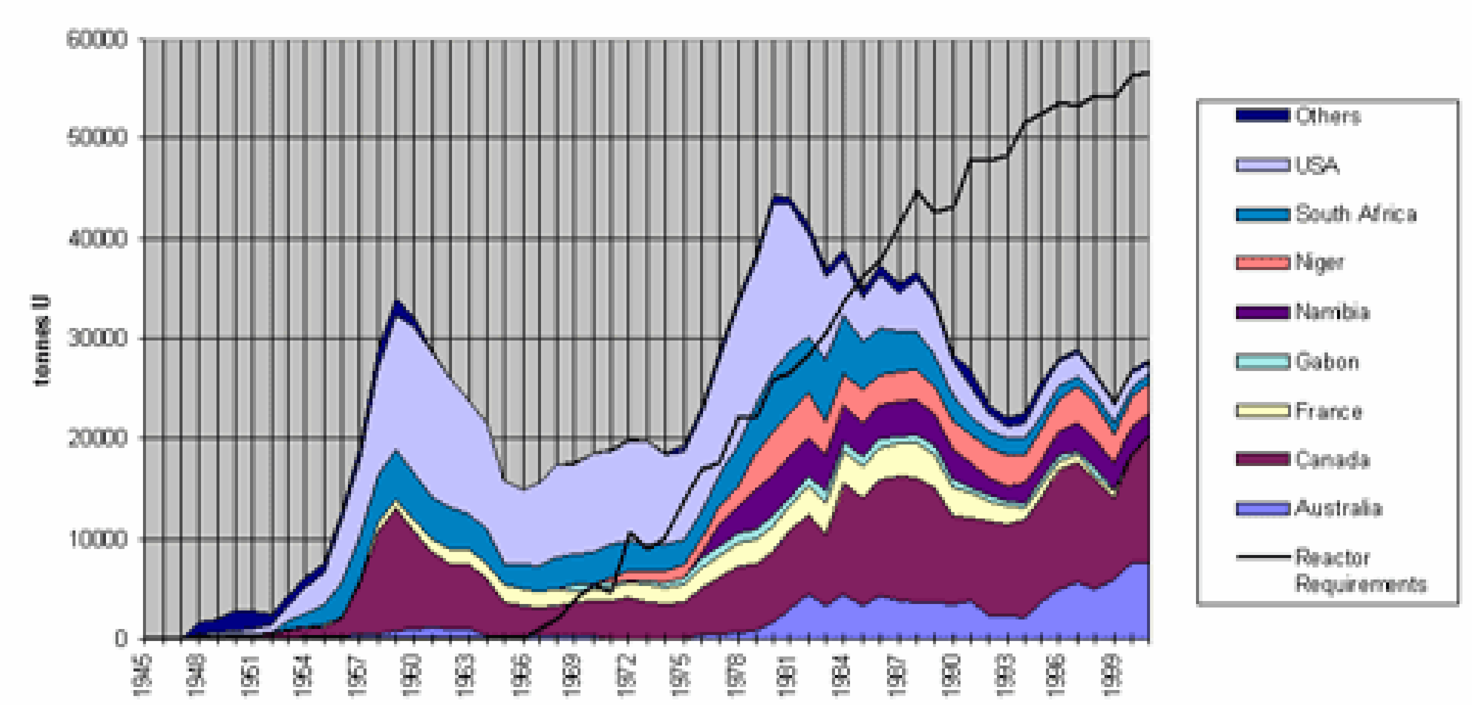
- Uranium Resource Availability
- Fuel Cycle Costs

Background

- Early thinking: Reprocessing followed by recycling of plutonium in breeder reactors
- The 70’s: Reprocessing followed by recycling of mixed oxide fuel in LWRs
  - Generic Environmental Impact Statement on Mixed Oxide Fuel (GESMO)
  - Commercial US reprocessing facilities
  - Carter Administration’s Decision (1977)
- The 80’s: Nuclear industry growth does not materialize
  - Any economic incentives vanish as uranium prices fall sharply
- The 90’s: U ores are cheap
  - Supply constraints appear to be far in the future

A. Machiels, Presentation at Internat. Symp.: Rethinking the Nucl. Fuel Cycle, Cambridge, Mass., Oct. 30-31, 2006, Slide 3

Western World Production against Reactor Requirements 1945-2001



Nuclear Issues Briefing Paper 36, "Uranium Markets" May 2006. Uranium Information Center, Ltd., Melbourne, Australia.

Background (continued) - Uranium Prices Historical Trends

Graph removed due to copyright restrictions.

From: Economic Assessment of Used Nuclear Fuel Management in the United States (BCG, 2006)

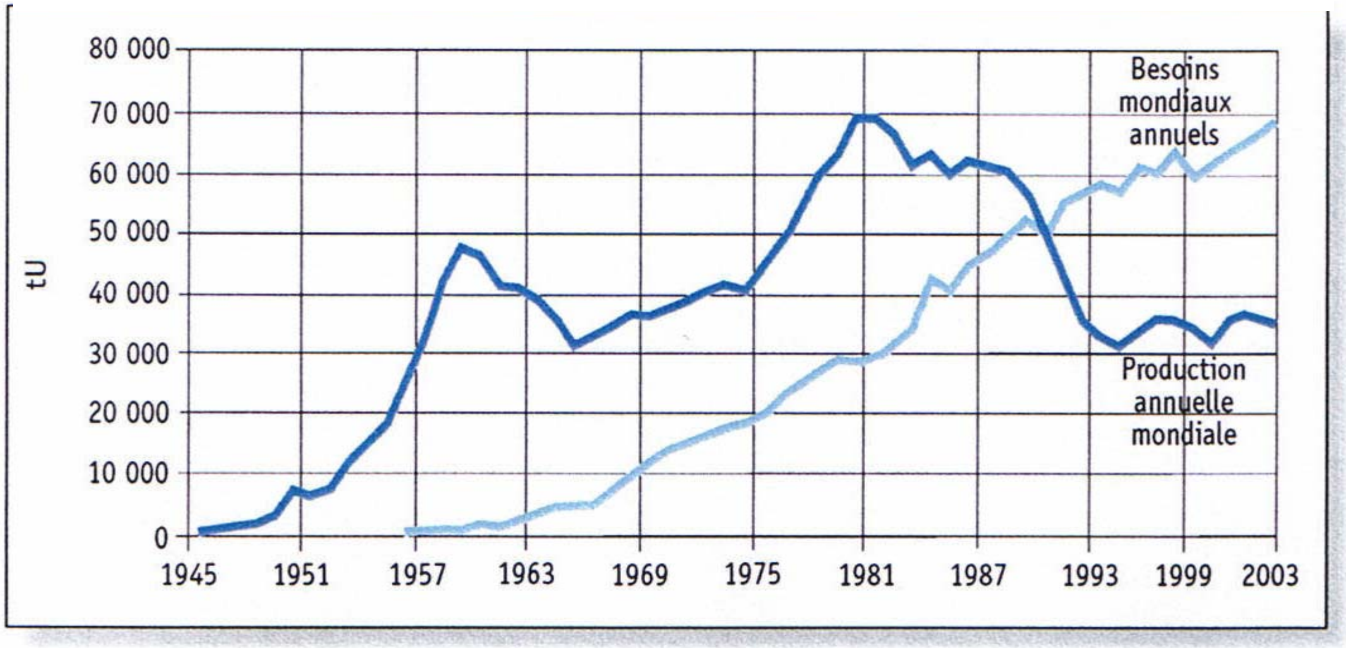
A. Machiels, Presentation at Internat. Symp.: Rethinking the Nucl. Fuel Cycle, Cambridge, Mass., Oct. 30-31, 2006, Slide 4

Uranium

Demand > Supply

→ ***Additional resources** (WPu, U_{rep}, MOX) **used so far***

Annual demand and supply of Uranium (1945 → 2003)



Courtesy of F. Carre, CEA. Used with permission.

NEA Source 2006

F. Carre et al, Presentation at Internat. Symp.: Rethinking the Nucl. Fuel Cycle, Cambridge, Mass., Oct. 30-31, 2006, Slide 4

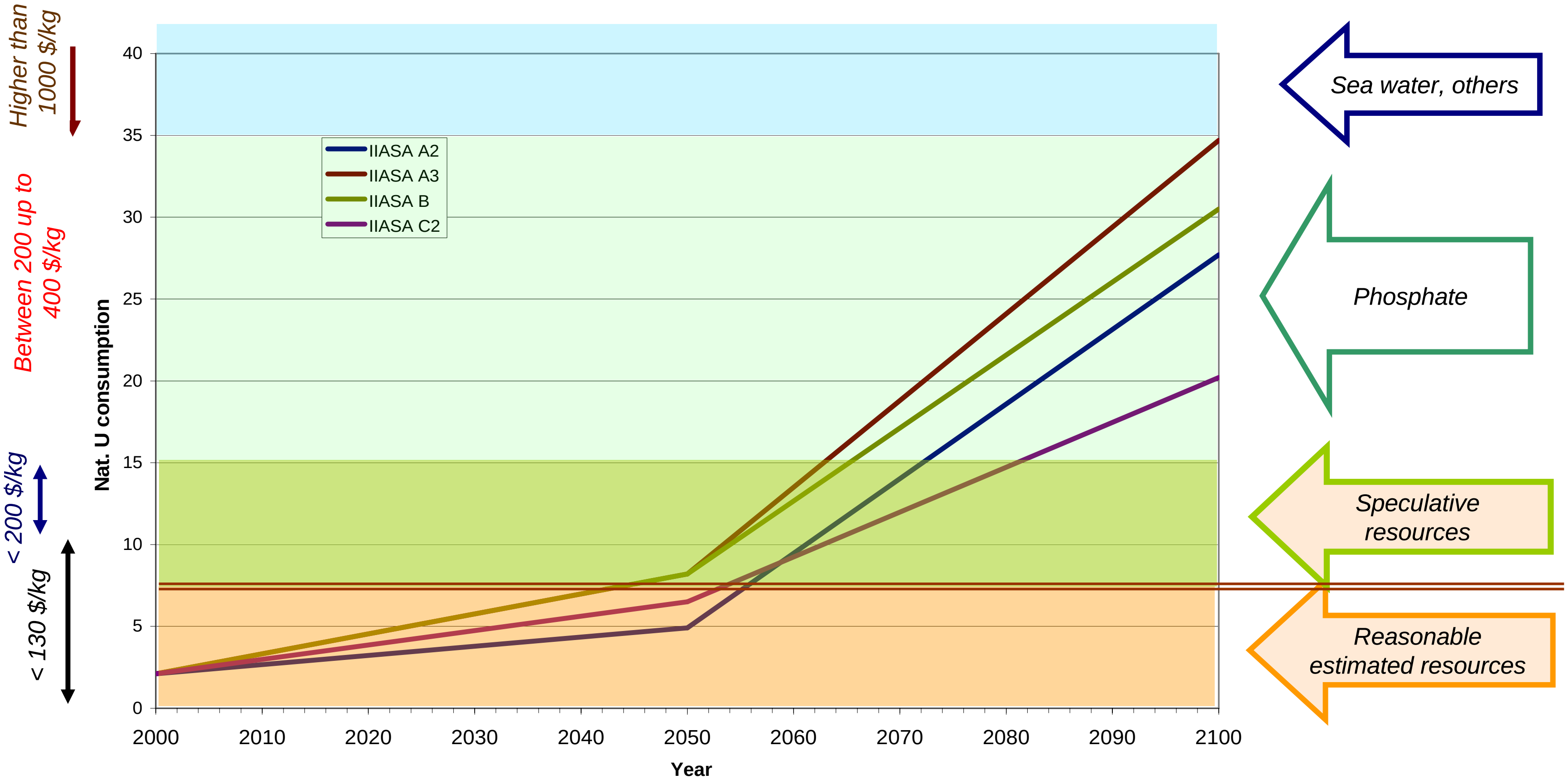
Uranium Resource Availability

- 4.7 Million MTU (conventional resources mined < US $130/kgU)
  - 3.3 Million MTU reasonably assured
  - 1.4 Million MTU inferred resources
- Enough to feed current world requirements for 80-90 years
- Additional 22 Million MTU could be recovered from phosphate deposits
- About 600,000 MTU equivalent stored in depleted uranium inventories
- Currently identified resources are sufficient to support growth of 20-40% in nuclear capacity over next two decades

Source: "Uranium 2005: Resource, Production and Demand," OECD/NEA and IAEA

A. Hanson, Presentation at Internat. Symp.: Rethinking the Nucl. Fuel Cycle, Cambridge, Mass., Oct. 30-31, 2006, Slide 15

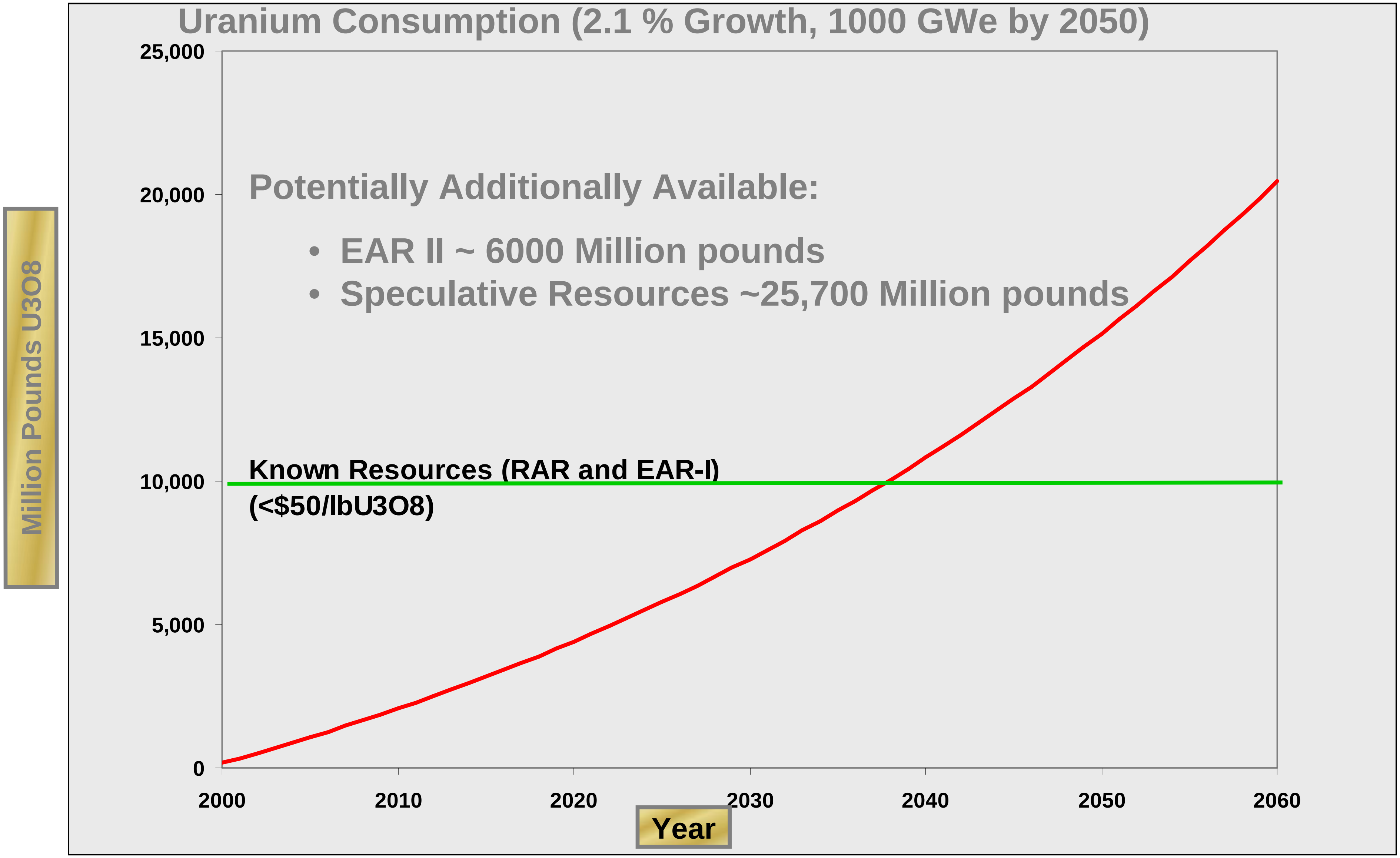
Uranium consumption (whithout engaged uranium in installed reactors) : IIASA



<u>U consumption in 2050 :</u> ***from 5 to 8 Mtons, up to 17 Mtons, including the Uranium engaged in installed reactors (extraction cost > 130 $/kg)***

<u>2100 : minimum 20 Mtons</u> up to 50/60 Mtons including engaged uranium (IIASA scenarios : high, medium, low)

Uranium Resource vs. Needs



N.E. Todreas, MIT Study on the Future of Nuclear Power, Seabrook Station, American Nucl. Soc., 18 Dec. 2003, Slide 15

Useful Conversion Factors

	Nat U*	U_3O_8
Metric Tons	1	1.18
Kilograms	1000	1180
Pounds	2205	2601

*Taken as 100% U-238

Example:

Reasonably assured (< 130 $/kg extraction cost)

Bouchard 20×10^6 MT nat U

Hanson 3.3×10^6 MT nat U

Todreas* 10 to $16 \times 10^3 \times 10^6$ lbs U_3O_8 ⇨ 3.8 to 6.5×10^6 MT nat U

*Including EAR II Potentially Available Reserves

Fallacy of the Traditional Economic Resource Model*

Classical economic theory suggests that the price of non-renewable resources should rise over time, as the fixed available stock grows scarcer and more and more costly resources have to be used.[218] Forecasters relying on this model have routinely predicted that the uranium price would imminently begin a steady rise as resources began to become scarce, and these forecasters have just as routinely been proved wrong.

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[218] For a useful discussion of the logical flaws of this classical model – still amazingly widely used, especially in projections of future uranium prices – see M.A. Adelman, "My Education in Mineral (Especially Oil) Economics," *Annual Review of Energy and Environment*, Vol. 22, 1997, pp. 13-46. Another excellent critique of the standard model (drawing on examples related to uranium resources) is Thomas L. Neff, "Are Energy Resources Inexhaustible?" presentation to the "Global Energy Prospects: Supply-Side Issues," London School of Economics and Political Science, November 11, 1985. Neff's basic answer is close to "yes," and with respect to uranium, he concludes "we were not so much captive of nature's limits as of our own in thinking about uranium reserves and resources."

*M. Bunn, S. Fetter, J.P. Holdren, B. van der Zwaan, "The Economics of Reprocessing vs. Direct Disposal of Spent Nuclear Fuel," J.F. Kennedy School of Government, Harvard University, Dec. 2003, p. 107

Sustainability: uranium resources

- U resources recoverable at prices below those at which recycling would be justified are likely to be sufficient to fuel an expanding nuclear energy enterprise for many decades
- "Red Book" estimates of U resources rose significantly in last decade, even with little uranium exploration – more will be found now that high prices are motivating exploration
- Current price run-up has nothing to do with lack of U in the ground, everything to do with constraints on rapidly bringing additional production on-line; but over time, profits to be made will motivate additional production
- Reliance on recycling is *not* a path to energy security – as unforeseen events across the globe (or at home) can play havoc with a country's plutonium programs

M. Bunn, Presentation at Internat. Symp.: Rethinking the Nucl. Fuel Cycle, Cambridge, Mass., Oct. 30-31, 2006, Slide 29

Fuel Cycle Cost Calculation

$$\left[\frac{1}{24}\ \frac{F_o}{\eta\ Bu_d}\right]\left[1+\frac{yT_{plant}}{2}\right]$$

		Typical LWR Value[1]
y	*annual rate of monetary inflation (or price escalation,, if different)*	*0.03/yr*
T_{plant}	*prescribed useful life of plant, years*	*40 yrs*
η	*plant thermodynamic efficiency, net kilowatts electricity produced per kilowatt of thermal energy consumed,*	*0.33*
F_o	*net unit cost of nuclear fuel,, first steady-state reload batch,, dollars per kilogram of uranium; including financing and waste disposal charges,, as of start of plant operation,*	*$2,000/kg*
Bu_d	*burnup of discharged nuclear fuel, megawatt days per kilogram of heavy metal*	*45 Mwd/kg*
	Sum for Fuel Cycle Cost for Existing LWR Plant	*5-6 mills/kWe-hr*

Driscoll, M.J., Chapter 5 from "**Sustainable Energy - Choosing Among Options**" by Jefferson W. Tester, Elisabeth M. Drake, Michael W. Golay, Michael J. Driscoll, and William A. Peters. MIT Press, June 2005

Economic Assessment of Open vs. Closed Fuel Cycles

1) Are the options being compared comparable in requirements and experience to date?
2) Who is asking the question?
3) How is the question being asked?
4) What should you listen for in the answer?

Economic comparison: Recycling vs Once-Through

- Characteristics of the options (E. Proust, CEA)
  - the two options do not provide the same overall services: recycling responds to more extended requirements than bare spent fuel management
  - for the power companies, the cost of R&R is well established (commercial practice and prices), while spent fuel conditioning for direct disposal is still under development and associated costs are forecasted with more uncertainty

E. Proust, Presentation at Internat. Symp.: Rethinking the Nucl. Fuel Cycle, Cambridge, Mass., Oct. 30-31, 2006, Slide 7

2) Who is Asking the Question?

COST ELEMENT	COST/PRICE	% DUE TO BACK END CHARGES	AFFECTED PARTY
Back end cost	1 mil/kwh	100%	Nuclear fuel manager
Fuel cycle cost	4-5 mil/kwh	20-25%	Nuclear utility
Production cost	17 mil/kwh	6%	Nuclear utility
Busbar cost	22-23 mil/kwh*	4%	Electricity wholesaler
Retail electricity price	50-84 mil/kwh*	1-2%	Retail consumer (or his government)

The retail price for electricity varies widely by region and by season.
Number above is range for the national average.

Source: A. Hanson, AREVA, personal communication with N. Todreas, 11/3/06
*Courtesy of Nuclear Energy Institute

2) Who is Asking the Question? (cont.)

Recycling is Cost Effective if:

Cost of recycling (treatment and fabrication) < **Value of recovered products (U + Pu)**

Cost of recycling (treatment and fabrication) < **Value of recovered products (U + Pu)** + **Value of cost savings to the repository due to recycling**

Cost of recycling (treatment and fabrication) < **Value of recovered products (U + Pu)** + **Value of cost savings to the repository due to recycling** + **Avoided costs of utility settlements due to early receipt of used fuel**

A. Hanson, Presentation at Internat. Symp.: Rethinking the Nucl. Fuel Cycle, Cambridge, Mass., Oct. 30-31, 2006, Slide 16

Economic Assessment of Open vs. Closed Fuel Cycles
3) “How is the question being asked?”

- Harvard: What is the cost of disposing of a kg of spent fuel? (closed cycle cost is >80% of open cycle cost)
- MIT (2003): What is the cost of producing a kg of fresh fuel? (4.5x for the closed cycle versus the open cycle)
- OECD/NEA (1994):
- French: Charpin Dessus Pellat Report (2000): “a study concerning the economic data of the entire nuclear industry and in particular the later stages of the nuclear fuel cycle, including reprocessing.”

4) What should you listen for in the Answer? Once-Through vs Single MOX Recycle

1. Single Owner Cost [MIT 7/03]

   Once Through (UOX) 0.515¢/kWh(e) [0.643 OECD/NEA (1994)]

   Single MOX Recycle 2.24¢/kWh(e) [0.680 OECD/NEA (1994)]

   ΔFCC% = 335% MIT [5% OECD/NEA]

   ΔCOE% = 43% MIT [0.9% OECD/NEA]

   where $COE_{UOX} \equiv$ 4¢/kWh(e)

2. World (Entire Fleet) Cost [MIT 7/03]

   $FCC_{FLEET} = FCC_{UOX}$ [% Fleet UOX] + FCC_{MOX} [% Fleet MOX]

FLEET	1500 MWe
UOX	1260 MWe
MOX	240 MWe

   0.791 ¢/kWh(e) $\Leftarrow$ 0.515 [0.84] + 2.24 [0.16]

   ΔFCC% = 53%

   ΔCOE% = 6.9%

N.E. Todreas, “Perspectives on the Economics of Nuclear Power from the MIT Study,” NE ANS Symposium, Troy, NY 3/30/2006, p.16

4) What should you listen for in the Answer? (cont.)
Fuel Cycle Cost [MIT 7/03]

	SINGLE OWNER	WORLD (FLEET)
ΔFCC%	+335%	+53%
ΔCOE%	+43%	+6.9%

Assume: COE_{UOX} 4¢/kWh(e)
FLEET 1500 MWe (operating on single MOX recycle)
UOX 1260 MWe
MOX 240 MWe

N.E. Todreas, "Perspectives on the Economics of Nuclear Power from the MIT Study," NE ANS Symposium, Troy, NY 3/30/2006, p.17

The MIT Cost Comparison

See Appendix Chapter 5.D, pp. 145-148 of MIT Study

Comparison of Cost for Once-Through and Recycle Process Steps (MIT 7/03)

Cost Component	Unit	Estimated Cost (lower bound – nominal – upper bound)			
		OECD/NEA[1] (2002)	DOE GEN-IV[2]	Fetter, Bunn, Holdren[3]	Our Best Guess
Ore Purchase	$/kg	20-30-40	20-30-80	33	30
Conversion	$/kg	3-5-7	3-5-8	4-6-8	8
Enrichment	$/kg SWU	50-80-110	50-80-120	50-100-150	100
UOX fabrication	$/kgIHM	200-250-300	200-250-350	150-250-350	275
SF storage and disposal	$/kgIHM	410-530-650	210-410-640	0-150-300 more than HLW	400
UOX reprocessing	$/kgIHM	700-800-900	500-800-1100	500-1000-1600	1000
MOX reprocessing	$/kgIHM	700-800-900	500-800-1100	-	-
HLW storage and disposal	$/kgIHM	63-72-81	80-200-310	0-150-300 less than SF	300
MOX fabrication	$/kgIHM	900-1100-1300	600-1100-1750	700-1500-2300	1500

[1] OECD/NEA, "Accelerator-driven Systems and Fast Reactors in Advanced Nuclear Fuel Cycles", 2002
[2] DOE, "Generation 4 Roadmap - Report of the Fuel Cycle Crosscut Group", 2001
[3] Fetter, Bunn, Holdren, "The Economics of Reprocessing vs. Direct Disposal of Spent Nuclear Fuel", 1999

N.E. Todreas, "Perspectives on the Economics of Nuclear Power from the MIT Study," NE ANS Symposium, Troy, NY 3/30/2006, p.18

Converting YM costs to $/kg HM

$50B/70,000 MT HM = $300/kg HM

Reprocessing costs: The impact of financing

Assume: Capital, operating costs = reported costs for THORP, (similar to UP3), continuous operation for 30 years at 800 tHM/yr. What is revenue requirement?

- Government-financed (4% real): $1350/kgHM
- Utility-financed: >$2000/kgHM
- Private venture financed: >$3100/kgHM

- Hence, achieving our $1000/kgHM illustrative figure would already require government financing, dramatic technological improvement, or a combination of both

M. Bunn, Presentation at Internat. Symp.: Rethinking the Nucl. Fuel Cycle, Cambridge, Mass., Oct. 30-31, 2006, Slide 4

Conditions for Competitiveness of the MOX Option

Table A-5.D.3 Breakeven Values

COST COMPONENT	ORIGINAL VALUE	REQUIRED VALUE	REQUIRED/ORIGINAL
Natural uranium	$30/kgU	$560/kgU	19
Reprocessing	$1,000/kgIHM	$90/kgIHM	0.09
MOX fabrication	$1,500/kgIHM	Impossible	N/A
Waste storage and disposal	$400/kgIHM (SF)	$1,130/kgIHM	2.8
	$300/kgIHM (HLW)	$100/kgIHM	0.33

Table A-5.D.4 Breakeven Values (components adjusted simultaneously)

COST COMPONENT	UNIT	ORIGINAL VALUE	REQUIRED VALUE
Ore purchase	$/kg	30	50
Reprocessing	$/kgIHM	1,000	600
MOX fabrication	$/kgIHM	1,500	1,100
Storage and disposal:			
Spent Fuel	$/kgIHM	400	600
HLW	$/kgIHM	300	100
Fuel cycle cost (both options)		6.3 mills/kWh	

The Future of Nuclear Power: An Interdisciplinary MIT Study. MIT, 2003, pp. 148-149

COST OF RECYCLING AND ONCE-THROUGH STRATEGIES COMPARABLE IN A GREENFIELD APPROACH (BCG)

Especially Given Uncertainty on Yucca Mountain Costs and Future Uranium Price

Graph removed due to copyright restrictions.

Boston Consulting Group, "Economic Assessment of Used Nuclear Fuel Management in the United States," July 25, 2006, p. 18

Problems with the BCG study

- Estimates unit cost of $620/kgHM for *both* reprocessing and MOX fab – much less than real plants have achieved for either process
- Achieves this by:
  - Using low 3% government rate (OMB insists on 7% for such projects)
  - Assuming large increase in capacity at minor additional cost
  - Assuming never has any contract or technical delays, so dramatic increase in throughput – unrealistic
- Variety of other unrealistic assumptions
- By contrast, real experience of using Areva technology in U.S. (SRS MOX plant) has resulted in costs many times *higher* than in France – unmentioned by BCG

M. Bunn, Presentation at Internat. Symp.: Rethinking the Nucl. Fuel Cycle, Cambridge, Mass., Oct. 30-31, 2006, Slide 8

References

- Harvard Study: http://www.publicpolicy.umd.edu/Fetter/publications.htm
- EPRI: Report NP-7261 (March 1991) "An Evaluation of the Concept of Transuranic Burning Using Liquid Metal Reactors"
- "The U.S. Advanced Reactor Development Program: A Report by The U.S. Electric Utility Industry's Advanced Reactor Corporation" (1995)
- The National Academy of Sciences: "Nuclear Wastes: Technologies for Separations and Transmutation" (1996)
- Boston Consulting Group, Economic Assessment of Used Nuclear Fuel Management in the United States, July 25, 2006

Intentionally conservative

- These estimates of breakeven U price and ΔCOE are low, because of assumptions favorable to reprocessing:
  - Central reprocessing cost estimate far below cost that would pertain in privately financed facilities with costs comparable to those demonstrated at existing plants
  - MOX fuel fabrication estimate well below many recent prices
  - No charge for Pu storage, Am removal, licensing or security for MOX use
  - High cost dry cask storage required for all fuel for direct disposal option – though most new plants designed with lifetime pools
  - HLW disposal cost advantage higher than most current estimates
  - Equal disposal costs for spent MOX and LEU, despite much higher MOX heat

M. Bunn, Presentation at Internat. Symp.: Rethinking the Nucl. Fuel Cycle, Cambridge, Mass., Oct. 30-31, 2006, Slide 7