The Economics of Reprocessing and MOX Recycle

April 5, 2004

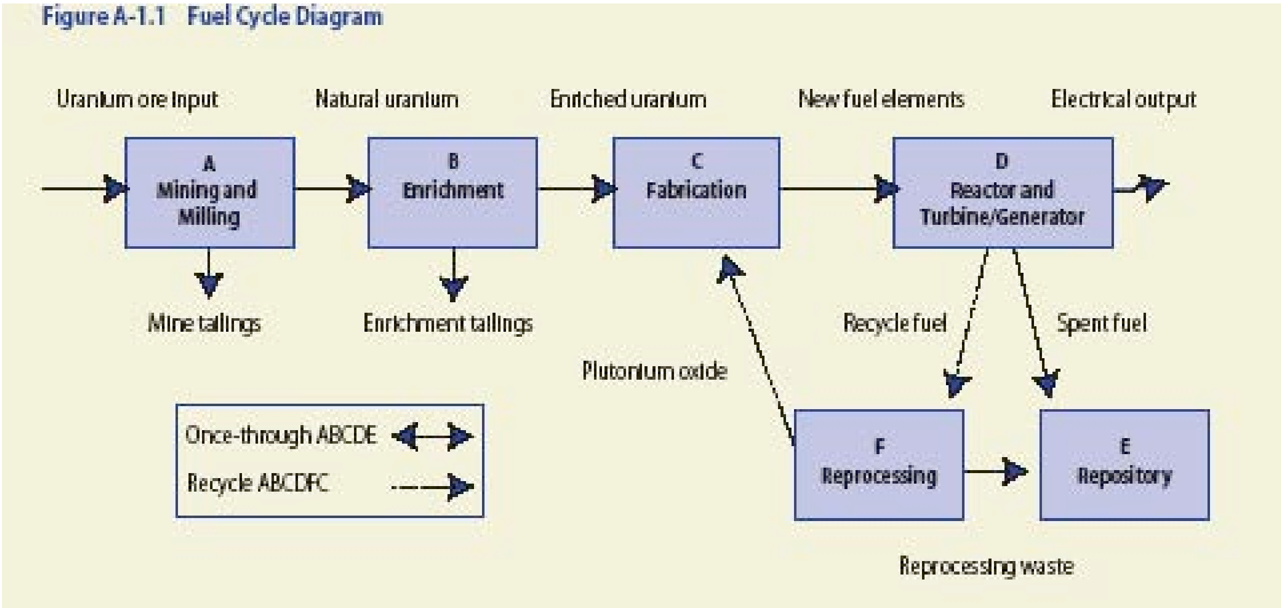
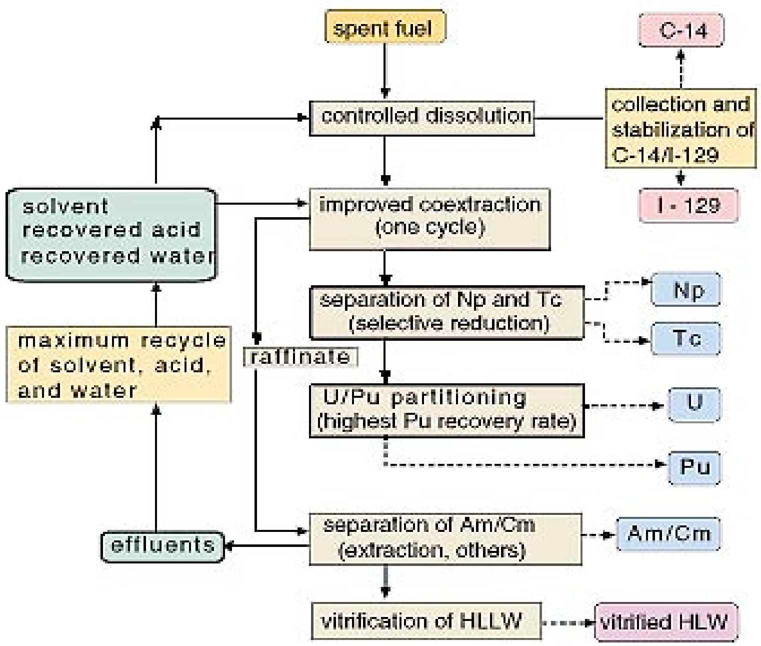


Figure A-1.1 Fuel Cycle Diagram
Uranium ore input
Natural uranium
Enriched uranium
New fuel elements
Electrical output
A
Mining and
Milling
B
Enrichment
C
Fabrication
D
Reactor and
Turbine/Generator
Mine tailings
Enrichment tailings
Recycle fuel
Spent fuel
Plutonium oxide
Once-through ABCDE
Recycle ABCDFC
F
Reprocessing
E
Repository
Reprocessing waste

Reprocessing



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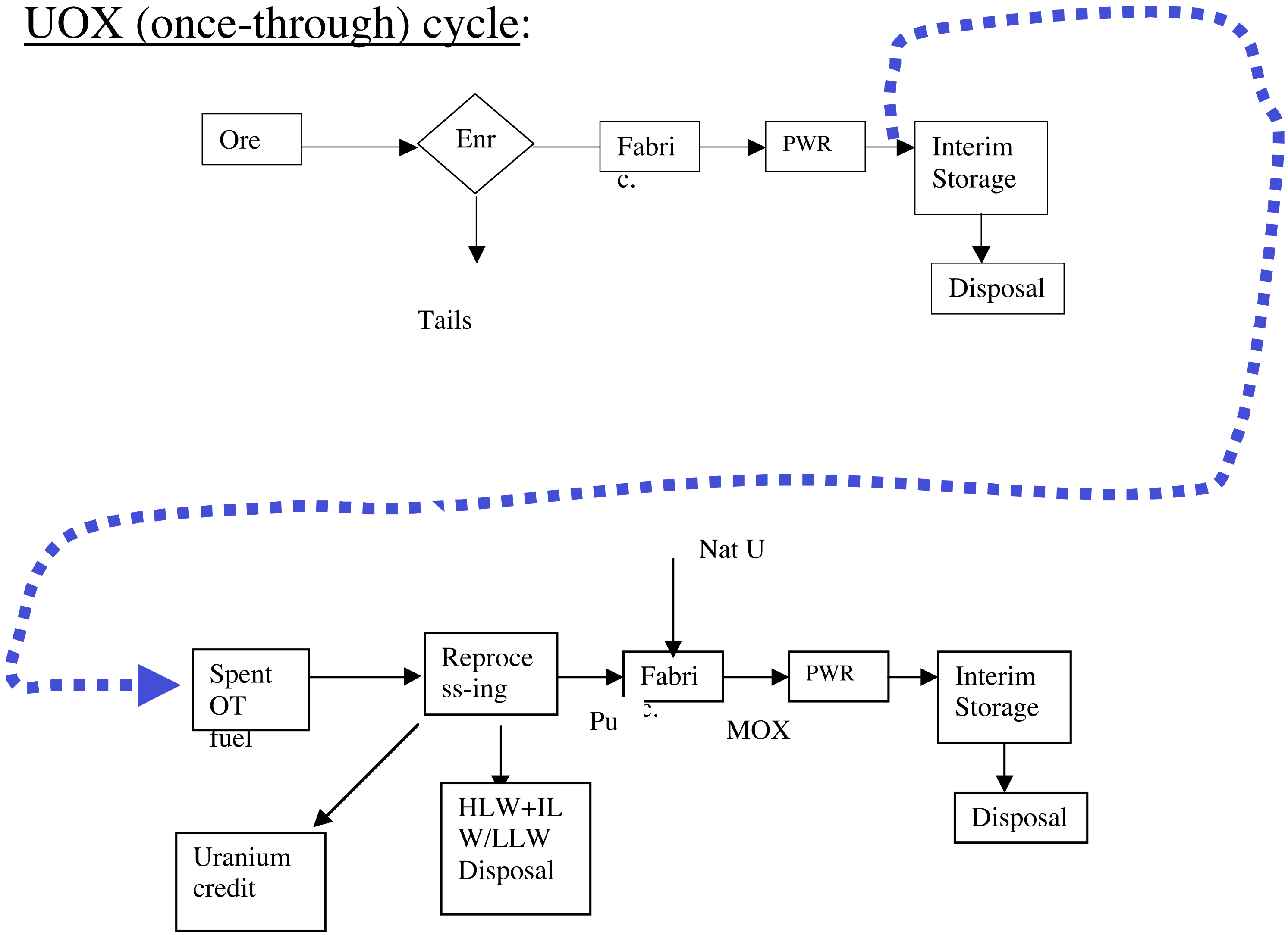
Estimated Separated Plutonium Holdings

Country	Separated civilian Pu (kg)	Declared military Pu (kg)*
Japan	4,900	0
Germany	6,600	0
Belgium	3,800	0
Switzerland	<50	0
France	29,100	0
United States	4,650	47,500
China	0	0
United Kingdom	69,100	4,400
Russia	32,000	50,000

*Declared to be in excess of national security requirements

UOX (once-through) cycle:



Assumptions

1. The contents of the spent fuel discharged from reactors operating on the UOX once-through cycle with a burnup of 50,000 MWDth/MTIHM are as follows:

   Uranium: 93.4 w/o (U^{235} enrichment: 1.1 w/o)
   Plutonium: 1.33 w/o (total fissile enrichment (Pu^{239}+Pu^{241}) = 0.93 w/o)
   Fission products: 5.15 w/o
   Minor actinides: 0.12 w/o

2. Fissile plutonium (Pu^{239}+Pu^{241}) is approximately equivalent to U-235 on a gram for gram basis; that is, equal weight percent enrichments of U-235 and fissile plutonium in U-238 are needed to drive a fuel assembly to the same cycle and discharge burnups. (In practice, MOX fuel has a lower initial reactivity for the same weight percent fissile enrichment, but undergoes a slower loss of reactivity with burnup.)

3. Value of uranium recovered from reprocessing spent PWR fuel is zero. (The recovered uranium is still slightly enriched in U-235, but other U isotopes make it less attractive, and under current market conditions, with low natural uranium prices, it is not economic to reuse it.)

MOX Fuel Cycle Cost Parameters

Transaction	Unit Cost	Lead Time (to start of MOX fuel loading)
Credit for elimination of SF interim storage and disposal cost	$500/kg HM	2 years
Reprocessing	$400 - $1600/kg HM	2 years
Uranium credit	0	--
HLW/ILW/LLW storage and final disposal cost	$200-400/kg HM in SF	1 year
Natural uranium ore purchase and yellowcake conversion	$40/kg HM	1 year
Blending + MOX fuel fabrication	$1500/kg HM	1 year
Interim storage of spent MOX fuel	$100/kg HM	At discharge
Final disposal of spent MOX fuel	$400/kg HM	At discharge

Note: Duration of irradiation = 4.5 years.

Material balance

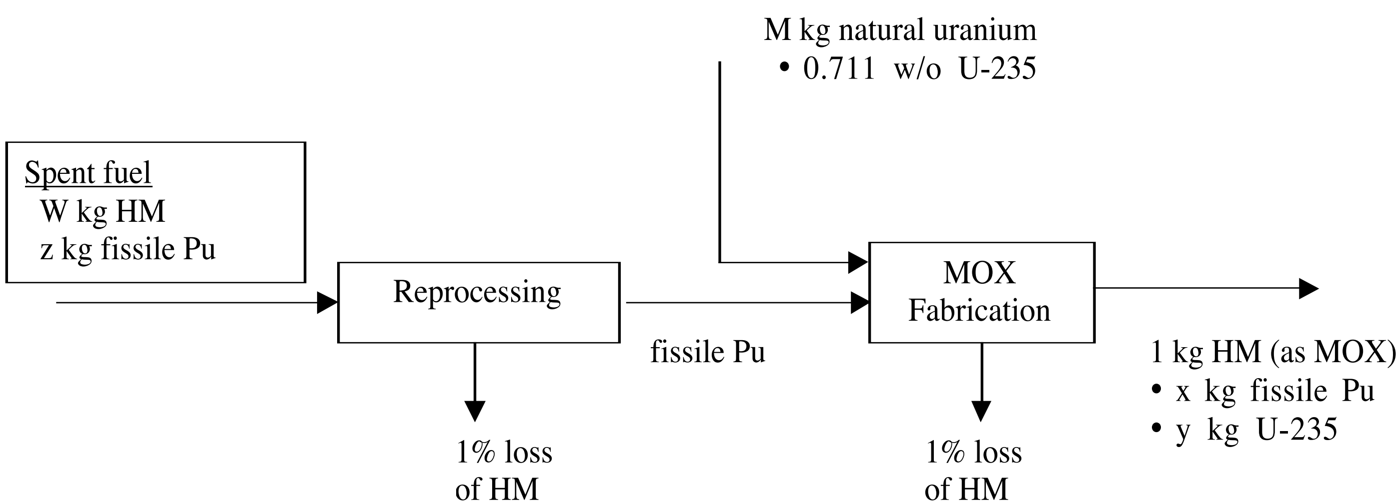
Q: How many kilograms of spent PWR fuel must be reprocessed and natural U purchased to produce 1 kg of MOX fuel at 4.51% fissile enrichment?

Let W be the mass of spent fuel (in kg/kg of MOX fuel)

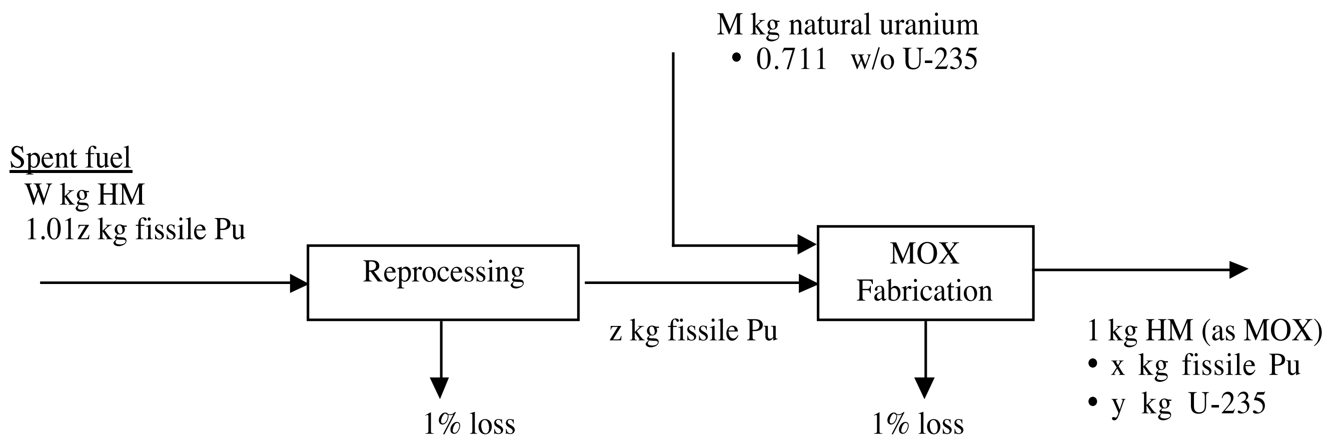
Let M be the mass of natural uranium (in kg/kg of MOX fuel)

Let x be the enrichment of fissile Pu in the MOX fuel

Let y be the enrichment of U-235 in the MOX fuel



Material Balance: Front-end of MOX cycle



Calculation of MOX Fuel Cycle Cost

Total batch cost $= \sum_i M_i C_i + \sum_i \left[M_i C_i \right] \phi \cdot \Delta T_i$

<u>Transaction</u>	Unit Cost, C_i ($/kg)	Mass Flow, M_i (kg)	ΔT_i (years)	Direct Cost, $M_i C_i$ ($/kg)	Carrying Charge, $M_i C_i \phi \cdot \Delta T_i$ (ϕ - 0.1/yr)
SF Storage Disposal Credit	400	4.2	4.25	-2100	-893
Reprocessing	1000	4.2	4.25	4200	1785
HL/IL/LL Waste Disposal	300	4.2	3.25	1260	410
U purchase + conversion	40	0.97	3.25	39	11.7
MOX fab	1500	1.01	3.25	1515	492
Interim storage and disposal of MOX fuel	500	1.0	-2.25	500	-113
TOTAL				5414	1692.7
GRAND TOTAL				**$7107/kg HM MOX fuel**	

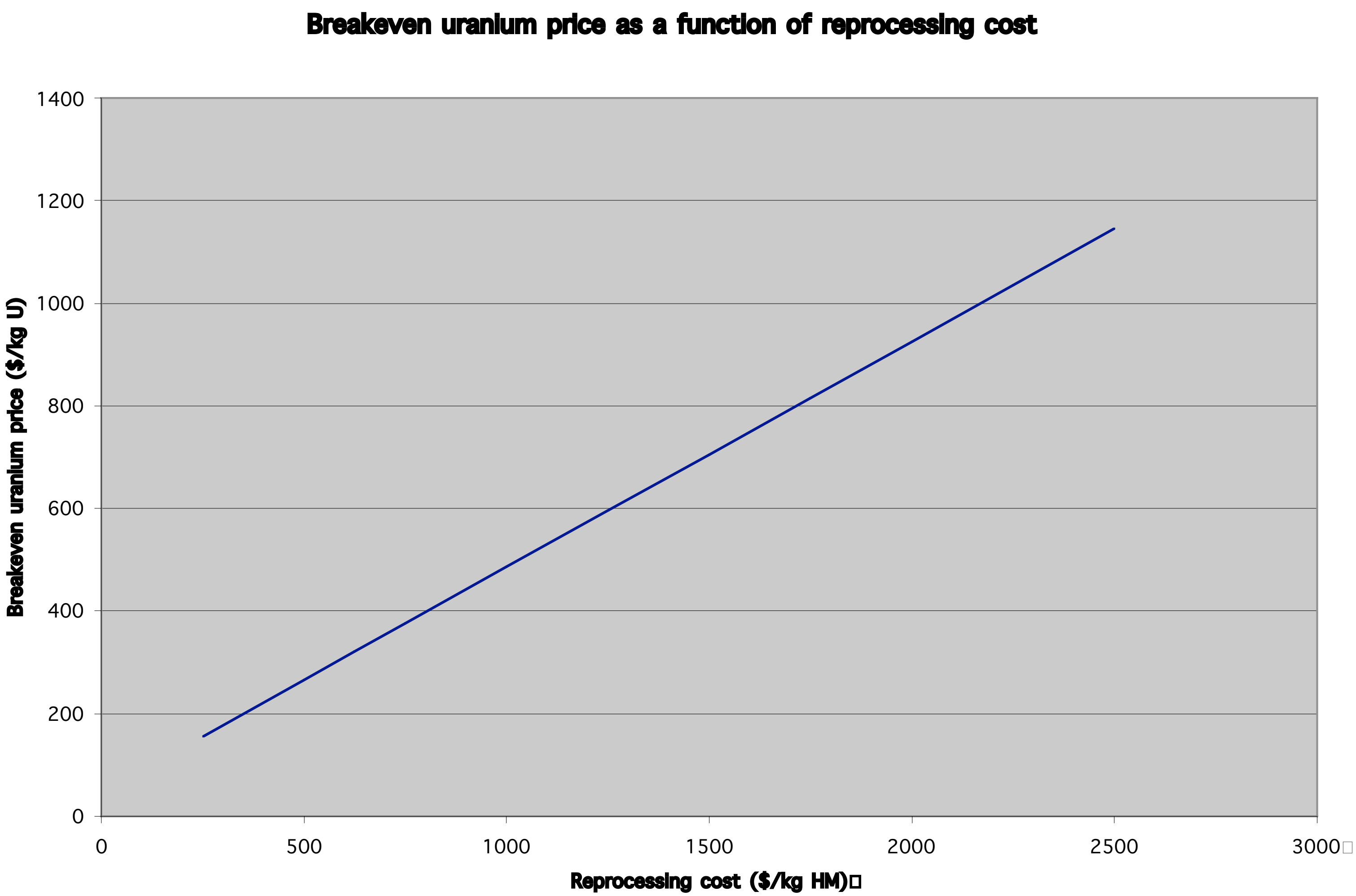
i.e., MOX fuel cycle cost ~ 3 x once through cycle cost

Questions

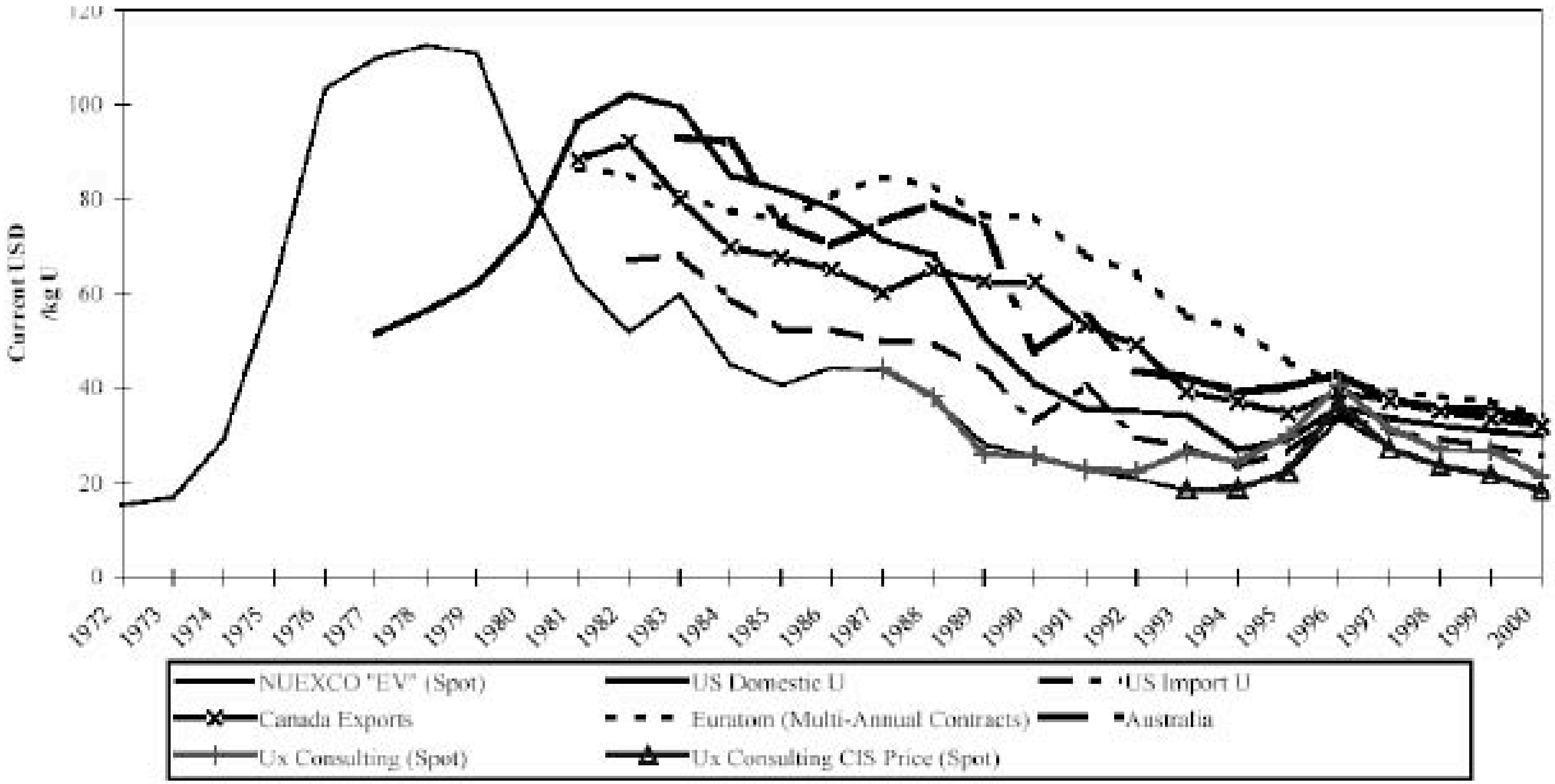
1. What is the minimum price of natural uranium ore at which MOX recycle would be economic?
2.

3. What is the maximum cost of reprocessing at which MOX recycle would be economic?
4.

5. Why are countries such as France and Japan pursuing MOX recycle?


Breakeven uranium price as a function of reprocessing cost
Breakeven uranium price ($/kg U)
0
200
400
600
800
1000
1200
1400
0
500
1000
1500
2000
2500
3000
Reprocessing cost ($/kg HM)

Natural Uranium Price Trends



Notes:

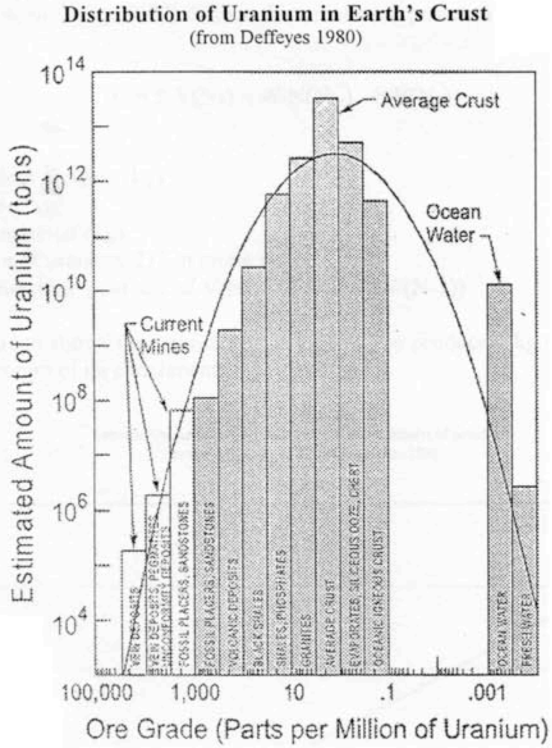
1) NUEXCO Prices refer to the "Exchange Value". The values for 1992-1998 refer to the unrestricted market.

2) Euratom prices refer to deliveries during that year under multiannual contracts.

Sources: Australia, Canada, Euratom, United States, NUEXCO (TradeTech), Nukem, Ux Consulting Company, LLC.

Source: OECD Nuclear Energy Agency and IAEA, *Uranium 2001: Resources, Production and Demand,* 2002, p. 68.

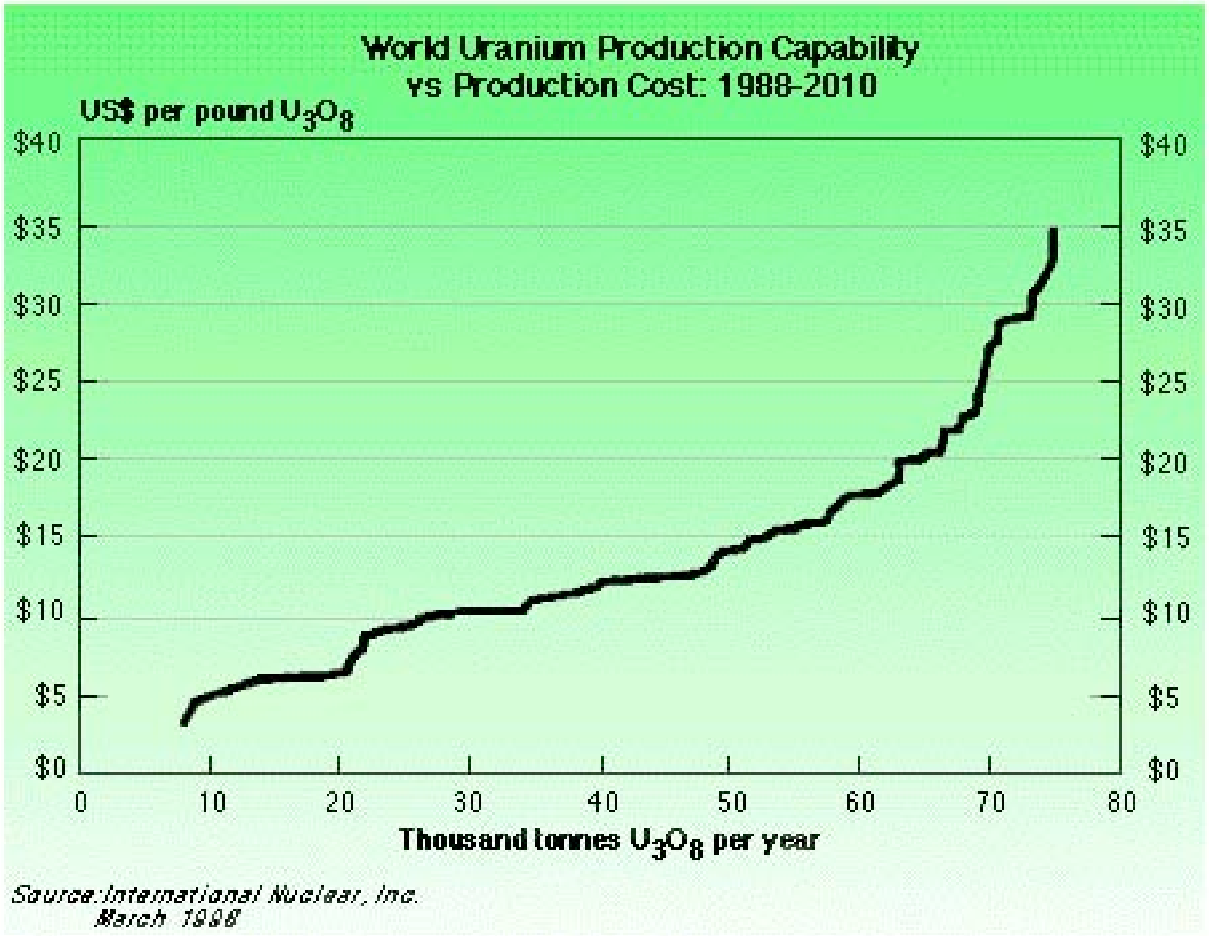
Natural Uranium Availability

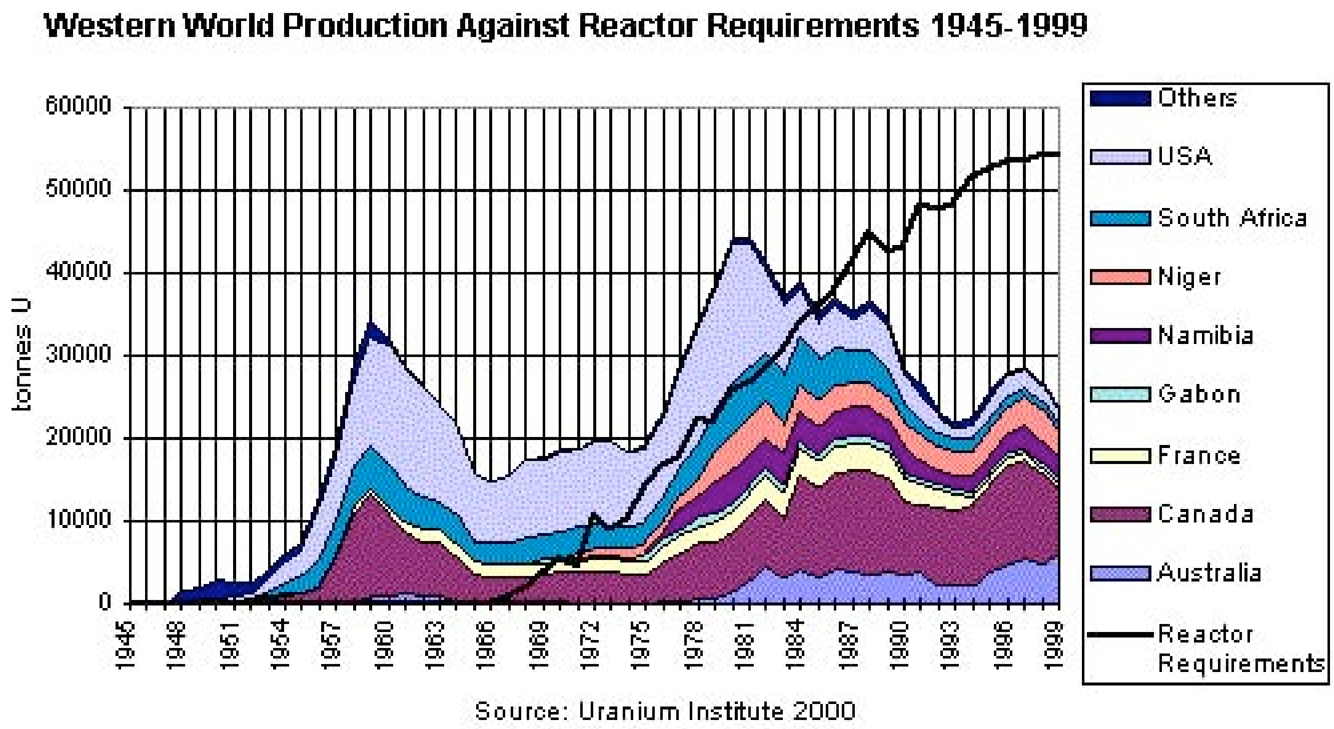


Overview of uranium resources (from NEA "Red Book" 1999)

Resources (1000 tU) reported in 1999			Number of years of present nuclear electricity production[1]
Uranium stocks		200	4
HEU and Pu		600	12
Known Conventional Resources	< 40 $ / kgU	> 1254	
	< 80 $ / kgU	3002	
	< 130 $ / kgU	3954	80
Undiscovered Conventional Resources	< 80 $ / kgU	1460	
	< 130 $ / kgU	5338	
	Total	11459	230
Uranium in phosphates		22 000	440
Uranium in seawater		4 200 000	80000

[1] The number of years of present nuclear electricity production (in 2000: 2540.5 TWhe [Nucleonics Week, February 8, 2001]), is calculated using a thermal efficiency of 33%, average load factor of 85%, and a ratio of natural to enriched uranium of 8 kgUnat / kgUenr (3.7%).


World Uranium Production Capability
vs Production Cost: 1988-2010
US$ per pound U3O8
$40
$35
$30
$25
$20
$15
$10
$5
$0
0
10
20
30
40
50
60
70
80
Thousand tonnes U3O8 per year
Source: International Nuclear, Inc.
March 1998



Western World Production Against Reactor Requirements 1945-1999
tonnes U
60000
50000
40000
30000
20000
10000
0
1945
1948
1951
1954
1957
1960
1963
1966
1969
1972
1975
1978
1981
1984
1987
1990
1993
1996
1999
Others
USA
South Africa
Niger
Namibia
Gabon
France
Canada
Australia
Reactor Requirements
Source: Uranium Institute 2000