Classnote

The Economics of the Nuclear Fuel Cycle: (2) MOX Recycle in LWRs

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We can use the same fuel cycle cost model to investigate the economics of recycling plutonium in mixed-oxide fuel for LWRs.

The original expectation with regard to the plutonium in spent LWR fuel is that it would be extracted in reprocessing and then fabricated into mixed oxide fuel for fast breeder reactors. For a variety of reasons (mainly economic), the deployment of breeder reactors is not now expected to occur for many decades, at the earliest.

The only practical alternative use of plutonium in the short run is in MOX fuel for LWRs. Utilities in several countries are currently engaged in LWR MOX recycle.

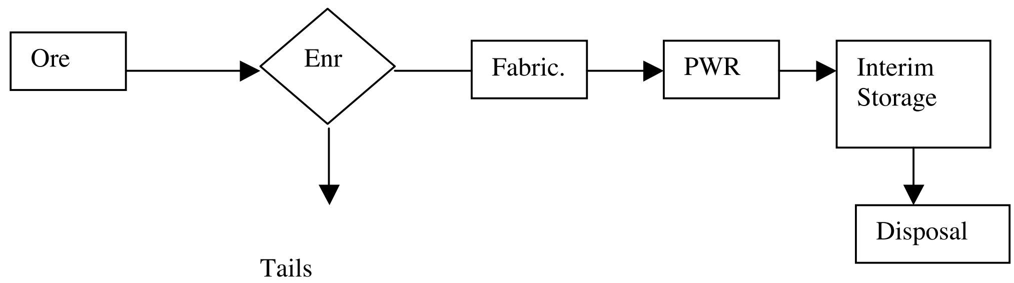
But MOX recycle has been strongly opposed by environmental and non-proliferation advocates.

The question we will analyze is an economic one: Under what circumstances would it be economically attractive for a utility to use MOX fuel as an alternative to low enriched uranium (LEU) in LWRs?

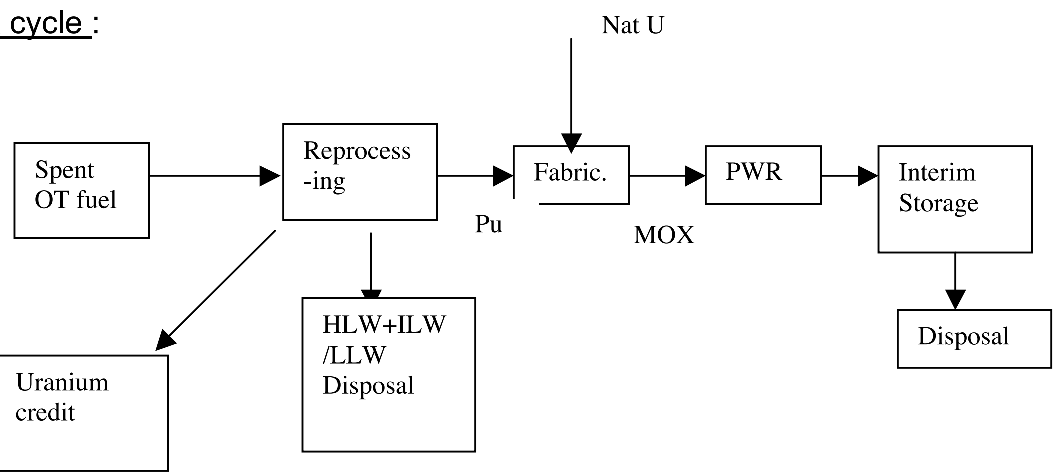
To determine this, consider two utilities: Utility C – the 'conventional' utility operating its PWR on the standard once-through fuel cycle, and utility E – the 'entrepreneurial' utility contemplating a switch to the MOX cycle.

The two alternative fuel cycles are as follows:

UOX fuel cycle (conventional once-through)



MOX cycle :



Utility C would be indifferent to either:

(a) arranging for storage and disposal of spent fuel or,
(b) surrendering the fuel to Utility E along with a payment that it would otherwise make for SF storage and disposal

In the latter case, Utility E could credit its operation with this payment, which would partly offset its costs of reprocessing, waste disposal, MOX fabrication, etc.

Utility E would be interested in proceeding with the MOX option if the total fuel cycle cost for the MOX fuel was competitive with the once-through fuel cycle cost.

Make the following 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

   (From Mcode results presented in Zhiwen Xu thesis)

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.)

4. 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.

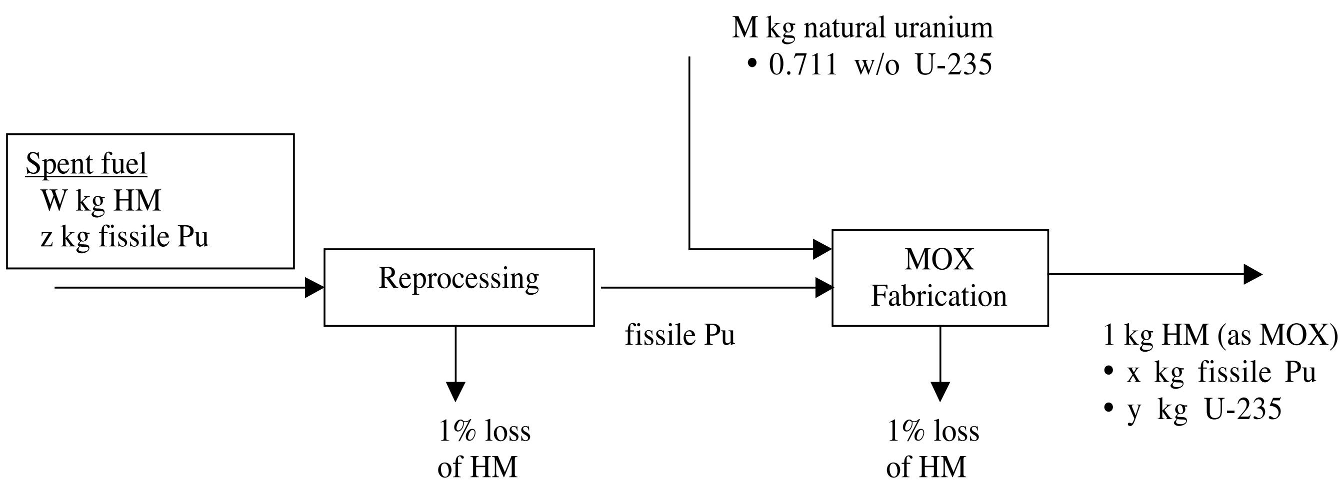
Q: How many kilograms of spent PWR fuel must be reprocessed and natural U purchased to produce 1 kg of MOX fuel at 4.51% fissile enrichment?

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



For fissile enrichment of 4.5%, we require

$$x + y = 0.0451 \qquad (1)$$

A material balance on the MOX fabrication stage for U-238 gives:

$$M \times 0.9929 \times 0.99 = 1 - 0.0451 = 0.9549$$

Thus,

M = <u>0.971 kg nat U</u>

Material balance on the MOX fabrication stage for U-235 gives

$M \times 0.00711 \times 0.99 = y$

Thus,

$x = 0.00683$ kg

Hence, from (1), $y = 0.0383$

Then, an overall material balance on fissile Pu gives

$z \times 0.99 \times 0.99 = 0.0383$

Thus $z = 0.0391$ kg

And since the enrichment of fissile Pu in the spent PWR fuel is 0.93 w/o, we have that

$W = 0.0391/0.0093 =$ <u>4.2 kg</u>

Thus, to produce 1 kg HM of MOX fuel we need to reprocess 4.2 kg HM of UOX SF and also purchase 0.97 kg of natural U.

<u>Calculation of MOX Fuel Cycle Cost</u> (Basis: 1kg MOX Fuel)

We use the approximate fuel cycle cost model for a single batch derived previously:

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

Transaction	Unit Cost, C_i (\$/kg)	Mass Flow, M_l (kg)	ΔT_l (years)	Direct Cost, M_lC_l (\$/kg)	Carrying Charge, $M_lC_l\phi\Delta T_l$ (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

= 7107 (\$/kg U) x 1000 (kg/MT) x 1/50,000 (MTHM/MWD) x 1/24 (days/hr) x 1/ 1000 (MW/kw) x 1/0.33 (kwh(th)/kwh(e))

= <u>1.8 cents/kwh(e)</u>

If, in spite of this increased cost, all PWR UOX fuel was reprocessed and the Pu recycled, the incremental MOX fuel cost would contribute to an increase in the cost of electricity in proportion to the ratio of MOX to UOX fuel in the entire fleet. Accordingly, the incremental electricity cost for the fleet would be:

0.58 x (4.2/5.2) + 1.8 x (1/5.2) = <u>0.81 cents per kwh(e)</u>

<u>Questions</u>

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

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

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

Question 1

How high would the cost of uranium ore have to rise for MOX recycle to be economical?

1. Once through fuel cycle cost = $1691 + (10.45\ c_u + 10.45 \times 4.25 \times 0.1 \times c_u)$
   $= 1691 + 14.9\ c_u$

2. MOX cycle cost = $7056 + (0.97\ c_u + 0.97 \times 0.1 \times 3.25 \times c_u) = 7056 + 1.29\ c_u$

Equating the two:

$$13.6\ c_u = 5365$$

$$c_u = \sim 395\ \$/\text{kg}$$

(i.e., 10 x the current price of uranium!)

Question 2

How low would the cost of reprocessing go in order for MOX recycle to be economical?

1. Once-through fuel cycle cost = \$2287/kg
2. MOX recycle cost = $\$1122 + 5.99\ c_R$

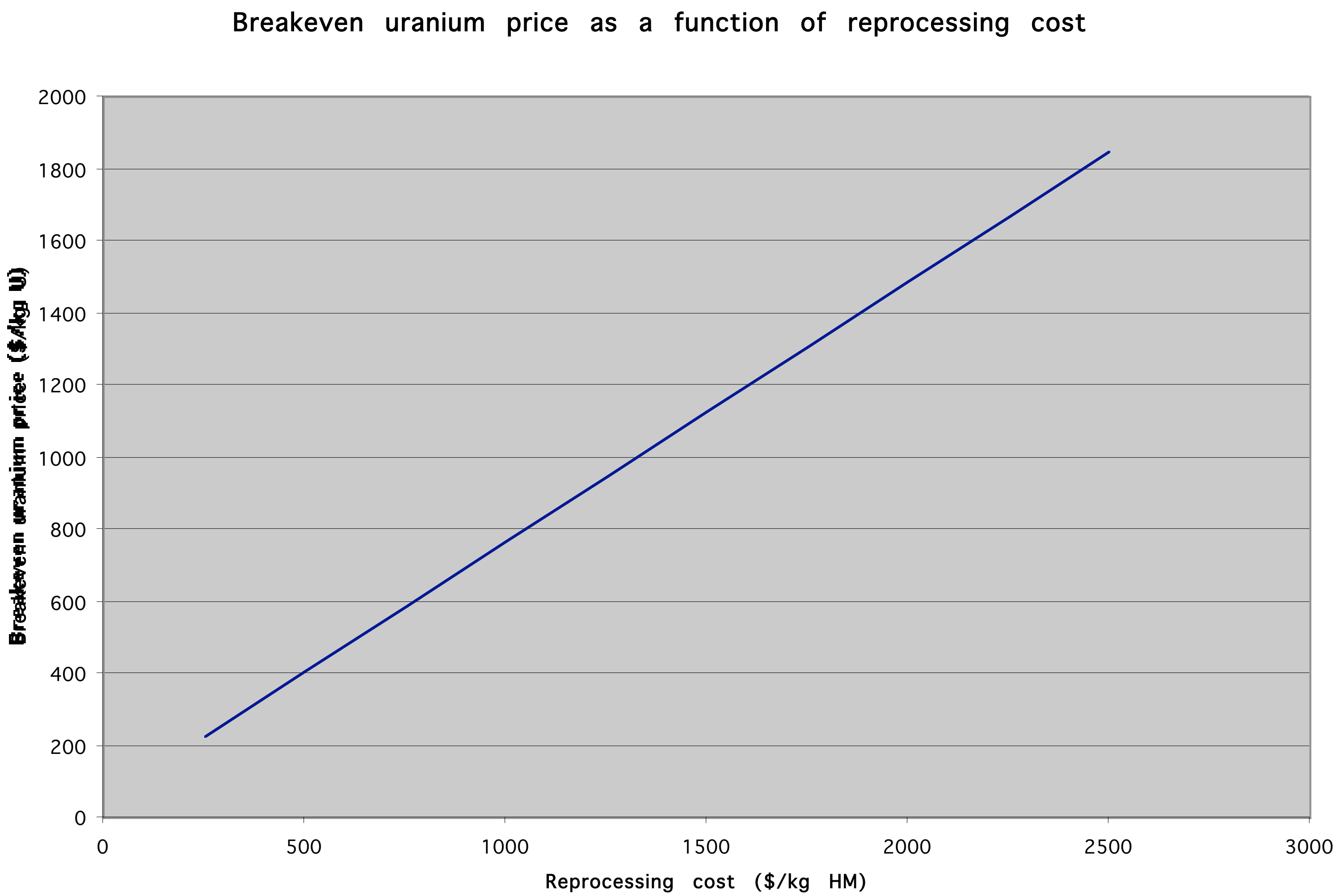
Hence, even if reprocessing were free, the MOX cycle would not be economical!

A different way to look at it:

Equating the once through and MOX cycle cost per kg:

$$1691 + 14.9\ c_u = 1071 + 5.99c_R + 1.29c_u$$

$$c_u = 0.44\ c_R + 45.6$$


Breakeven uranium price as a function of reprocessing cost
Breakeven uranium price ($/kg U)
2000
1800
1600
1400
1200
1000
800
600
400
200
0
0
500
1000
1500
2000
2500
3000
Reprocessing cost ($/kg HM)

Question 3 – why reprocess?

There are several reasons for this:

- the lack of storage space for spent fuel
- other environmental concerns
- the belief that MOX recycle can contribute to energy security
- the inertia associated with plans and contracts for reprocessing made decades ago.

NOTE: For a very detailed analysis of the issues discussed in this note, see Matthew Bunn et al, "The Economics of Reprocessing vs. the Direct Disposal of Spent Fuel", Project on Managing the Atom, Kennedy School of Government, Harvard University, December 2003.