Economics of Plutonium Recycle

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Washington, D.C.
11 December 2009
Nuclear Fuel Cycle Options

1) Once-through cycle

2) Single-pass recycle in thermal reactors (the French/Areva option)

3) Balanced closed cycle with transmutation in fast reactors (the GNEP vision)
Historical Background

- April 26, 1944: gathering of Fermi, Szilard, Wigner, Weinberg and others at the Met Lab to discuss the possibilities for using nuclear fission to heat and light cities; they believed uranium was scarce and would need breeders.
- 1944-1969: no serious consideration given to economics of recycle or breeders.
- 1944-1974: no serious consideration given to proliferation.
- 1969-1974: AEC badly misjudged nuclear power economics; projected:
  - LWRs would cost ~ $150/kW
  - LMFBR would cost about 20% higher, i.e., $30/kW more than LWR, decreasing to $15/kW by 1990, and to zero by 2015.
  - Reprocessing would cost ~$34-50/kg (LWR); $38/kg (LMFBR).
FIGURE 4. Projected Power Plant Capital Costs Used in AEC's Cost-Benefit Analysis

Capital cost, dollars per kilowatt electric

LWR

HTGR

LMFBR (1986)

LMFBR (1984)

LWR

HTGR

LMFBR (1980)

Fossil (coal)

Coal

Gas


<table>
<thead>
<tr>
<th>Reactor</th>
<th>Fabrication cost including fuel preparation, $/kg&lt;sup&gt;a&lt;/sup&gt;</th>
<th>Reprocessing cost including conversion, $/kg&lt;sup&gt;a&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Initial</td>
<td>Year 2020</td>
</tr>
<tr>
<td>LWR (without Pu recycle)</td>
<td>$ 83</td>
<td>$ 42</td>
</tr>
<tr>
<td>LWR (with Pu recycle)</td>
<td>147</td>
<td>48</td>
</tr>
<tr>
<td>HTGR (with LMFBR)</td>
<td>243</td>
<td>89</td>
</tr>
<tr>
<td>LMFBR (intro. 1986)</td>
<td>316</td>
<td>115</td>
</tr>
</tbody>
</table>

### TABLE 9. Reactor Fuel Cycle Costs

(a) 1000-Mw LMFBR equilibrium cycle fuel cost

<table>
<thead>
<tr>
<th>Cost component</th>
<th>Cost, mill/kwh</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fabrication</td>
<td>0.334</td>
</tr>
<tr>
<td>Reprocessing and reconversion</td>
<td>0.166</td>
</tr>
<tr>
<td>Shipping</td>
<td>0.038</td>
</tr>
<tr>
<td>Plutonium carrying charge of which</td>
<td></td>
</tr>
<tr>
<td>Inpile</td>
<td>0.432</td>
</tr>
<tr>
<td>Outpile</td>
<td>0.114</td>
</tr>
<tr>
<td>Fabrication carrying charge</td>
<td>0.061</td>
</tr>
<tr>
<td>Reprocessing carrying charge</td>
<td>-0.042</td>
</tr>
<tr>
<td>Plutonium credit</td>
<td>-0.348</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>0.755</strong></td>
</tr>
</tbody>
</table>

(b) Estimated fuel cycle costs for a model
1000-Mw light-water reactor today

<table>
<thead>
<tr>
<th>Cost component</th>
<th>Cost, mill/kwh</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mining and milling</td>
<td>0.38</td>
</tr>
<tr>
<td>Conversion to UF₆</td>
<td>0.07</td>
</tr>
<tr>
<td>Enrichment</td>
<td>0.58</td>
</tr>
<tr>
<td>Reconversion and fabrication</td>
<td>0.33</td>
</tr>
<tr>
<td>Spent-fuel shipping</td>
<td>0.02</td>
</tr>
<tr>
<td>Reprocessing</td>
<td>0.12</td>
</tr>
<tr>
<td>Waste management</td>
<td>0.04</td>
</tr>
<tr>
<td>Plutonium credit</td>
<td>-0.25</td>
</tr>
<tr>
<td>Uranium credit (includes a 0.03 mill/kwh cost of reconvert to UF₆)</td>
<td>-0.12</td>
</tr>
<tr>
<td>Fuel inventory carrying charge</td>
<td>0.57</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>1.74</strong></td>
</tr>
</tbody>
</table>

Using GDP Deflator Index to convert from 1970 to 2010 dollars

- $2010 = 4.65 \times 1970$

- In $2010$ the AEC estimates of 1970:
  - LWRs would cost $\sim$ $700/kW$
  - LMFBR would cost about 20% higher, i.e., $140/kW$ more than LWR; decreasing to $70/kW$ by 1990, and zero by 2015
  - Reprocessing would cost $\sim$ $160-230/kg$ (LWR); $\sim$ $180/kg$ (LMFBR)
Current Costs Estimates

- LWRs: $4,000/kW (MIT II) to 8,000/kW (Harding-mid) (overnight) (~6-12 times greater)
- LMFBR-LWR cost difference: ~several times $1,000/kW (more than 10 times greater)
- Reprocessing: $2,000/kg to 4,000/kg (more than 10 times greater)
- LEU fuel cost: (decreased)
  - U₃O₈: ~$50/kg (no significant change)
  - Enrichment: $150/kgSWU (decreased 2.5 times)
Single-pass Recycle

- Makes reprocessing appear more attractive by storing spent MOX fuel assemblies indefinitely—delay reprocessing spent MOX assemblies until the Pu in the MOX assemblies is needed to fuel fast breeder reactors
  - Treats spent MOX as an asset, rather than a liability.
  - Avoids half the heat loading of the repository and thus reduces the perceived repository capacity requirement.
Table A-5.D.1  Once-through UOX Fuel Cycle Cost

<table>
<thead>
<tr>
<th></th>
<th>$M_i$</th>
<th>$C_i$</th>
<th>$\Delta T_i$ (yr)</th>
<th>DIRECT COST $M_i \cdot C_i$ ($)</th>
<th>CARRYING CHARGE $M_i \cdot C_i \cdot \phi \cdot \Delta T_i$ ($)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ore purchase</td>
<td>10.2 kg</td>
<td>30 $/kg</td>
<td>4.25</td>
<td>307</td>
<td>130</td>
</tr>
<tr>
<td>Conversion</td>
<td>10.2 kg</td>
<td>8 $/kg</td>
<td>4.25</td>
<td>82</td>
<td>35</td>
</tr>
<tr>
<td>Enrichment</td>
<td>6.23 kg SWU</td>
<td>100 $/kg SWU</td>
<td>3.25</td>
<td>623</td>
<td>202</td>
</tr>
<tr>
<td>Fabrication</td>
<td>1 kgIJHM</td>
<td>275 $/kg IJHM</td>
<td>2.75</td>
<td>275</td>
<td>76</td>
</tr>
<tr>
<td>Storage and disposal</td>
<td>1 kgIJHM</td>
<td>400 $/kg IJHM(^{30, a})</td>
<td>-2.25</td>
<td>400</td>
<td>-90</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Total</td>
<td>1686</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Grand Total</td>
<td>2040</td>
</tr>
</tbody>
</table>

\(^{a}\) The cost of waste storage and disposal is assumed to be paid at the end of irradiation, even though the unit cost of $400/kgIJHM is a proxy for the 1 m/kWehr paid by utilities during irradiation.
### Table A-5.D.2 Single Recycle MOX Fuel Cycle Cost

<table>
<thead>
<tr>
<th></th>
<th>$M_i$ (kgIHM)</th>
<th>$C_i$ ($/kgIHM$)</th>
<th>$\Delta T_i$ (yr)</th>
<th>DIRECT COST $M_i \cdot C_i$ ($)</th>
<th>CARRYING CHARGE $M_i \cdot C_i \cdot \phi \cdot \Delta T_i$ ($)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Credit for UOX SF</td>
<td>5.26</td>
<td>–400</td>
<td>4.25</td>
<td>–2105</td>
<td>–895</td>
</tr>
<tr>
<td>Reprocessing</td>
<td>5.26</td>
<td>1000</td>
<td>4.25</td>
<td>5263</td>
<td>2237</td>
</tr>
<tr>
<td>HLW storage and disposal</td>
<td>5.26</td>
<td>300</td>
<td>3.25</td>
<td>1579</td>
<td>513</td>
</tr>
<tr>
<td>MOX Fabrication</td>
<td>1</td>
<td>1500</td>
<td>3.25</td>
<td>1500</td>
<td>488</td>
</tr>
<tr>
<td>MOX Storage and disposal</td>
<td>1</td>
<td>400</td>
<td>–2.25</td>
<td>400</td>
<td>–90</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td></td>
<td></td>
<td><strong>6637</strong></td>
<td><strong>2253</strong></td>
</tr>
<tr>
<td><strong>Grand Total</strong></td>
<td></td>
<td></td>
<td></td>
<td><strong>8890</strong></td>
<td></td>
</tr>
</tbody>
</table>
Once-through cycle:
$2040/kg = 0.515 \text{ cents/kWh}$

Single-pass recycle:
$8890/kg = 2.24 \text{ cents/kWh}$

Increase in electricity cost (assuming 16% of fuel is MOX) is 0.791 cents/kWh

Incremental Cost to US consumer: ~$6.4 billion/y (809 billion Kwh produced by nuclear in US in 2008);
$0.25 \text{ trillion over 40 years}$

### Table A-5.D.3 Breakeven Values

<table>
<thead>
<tr>
<th>COST COMPONENT</th>
<th>ORIGINAL VALUE</th>
<th>REQUIRED VALUE</th>
<th>REQUIRED/ORIGINAL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Natural uranium</td>
<td>$30/kgU</td>
<td>$560/kgU</td>
<td>19</td>
</tr>
<tr>
<td>Reprocessing</td>
<td>$1,000/kg\text{HM}$</td>
<td>$90/kg\text{HM}$</td>
<td>0.09</td>
</tr>
<tr>
<td>MOX fabrication</td>
<td>$1,500/kg\text{HM}$</td>
<td>Impossible</td>
<td>N/A</td>
</tr>
<tr>
<td>Waste storage and disposal</td>
<td>$400/kg\text{HM (SF)}$</td>
<td>$1,130/kg\text{HM}$</td>
<td>2.8</td>
</tr>
<tr>
<td></td>
<td>$300/kg\text{HM (HLW)}$</td>
<td>$100/kg\text{HM}$</td>
<td>0.33</td>
</tr>
</tbody>
</table>
Balanced Closed Cycle with Fast Reactors

- 1.27 cents/kwh per $1,000/kW LWR-FR capital cost differential, assuming FR achieve 90% capacity factor.
- Assuming one-third of nuclear capacity from fast reactors and 1,000 billion kWh/y nuclear capacity, incremental cost to US consumer = >$10 billion/y
  - $4.2 billion/y per $1,000/kW cost differential
  - >$6.4 billion for recycle
Actinide Recycle is Doomed to Fail

About 1/3 of the deployed reactor capacity must be from fast reactors

- Fast reactors currently **cost considerably more** than thermal reactors, and seem likely to stay that way.

- **Commercial/naval fast reactor development programs failed** in the: 1) United States; 2) France; 3) United Kingdom; 4) West Germany; 5) Italy; 6) Japan; 7) Russia 8) U.S. Navy and 9) the Soviet Navy; and the program in India is showing no signs of success. The Soviet Union/Russia never closed the fuel cycle and never fueled its fast reactors with MOX. (China is starting a fast reactor development program).

- After spending tens of billions of dollars on fast reactor development there is **only one** operational commercial-size fast reactor out of about 436 operational commercial power reactors worldwide and even this one (BN-600 in Russia) is not fueled with plutonium

- Fast reactors have proven to be **less reliable** than thermal reactors
Conclusion

- No evidence that single pass or fast reactor recycle costs will break-even with once-through cycle cost.
- Like all major minerals the improving efficiency of uranium extraction outpaces depletion of the resource.

Figure A-5.E.2 Composite mineral price index for 12 selected minerals, 1900 to 1998, in constant 1997 dollars. Selected mineral commodities include 5 metals (copper, gold, iron ore, lead, and zinc) and seven industrial mineral commodities (cement, clay, crushed stone, lime, phosphate rock, salt, and sand and gravel).
Conclusion (cont.)

- Why separate the plutonium?
- USG has 34 tonnes of excess weapon-grade plutonium; it cannot give it away; separated Pu has a negative economic value for energy use
- To get Pu for one MOX assembly, one needs to reprocess 6-8 spent LEU fuel assemblies
- Even taking credit for recovery of unused uranium, a MOX assembly will cost several times (MIT estimate is 4.5 times) the cost of a fresh LEU assembly
Conclusion (cont.)

But if one advocates storing spent MOX fuel indefinitely, a better strategy is to:

- Store spent fuel indefinitely;
- Postpone reprocessing until recycle is clearly economical (which will not happen any time soon, and may never happen);
- Defer major closed cycle R&D commitments until the international control regime can provide adequate safeguards (which is clearly not the case today).
Single-pass Recycle

- Reduces uranium mining requirements ~20-25%
- But at great cost
- We could also reduce uranium requirements by operating enrichment plants at very low tails assay; also at great cost and consequently an equally dumb idea
- Better strategy is to minimize the cost of the fuel cycle
Single-Pass Recycle is the Wrong Strategy

- Proliferation risks associated with plutonium separation in non-weapon states of concern
- High costs; massive federal subsidies
- Safety risks
- High, intermediate and low-level radioactive waste
- Air, sea/groundwater pollution
- Decommissioning
- No reduction in repository requirements
Proliferation is the Biggest Concern
International Safeguards are Inadequate

“the objective of safeguards is the **timely detection of diversion of significant quantities of nuclear material** from peaceful activities to the manufacture of nuclear weapons or of other explosive devices or for purposes unknown, and deterrence of such diversion by the risk of early detection.”

IAEA, INFCIRC/153; Emphasis supplied
In Non-Weapon States
This IAEA Objective
Cannot be Met Today at:

- Nuclear Fuel Reprocessing Plants
- Mixed-Oxide Fuel Fabrication Plants
- Storage Facilities for Separated Plutonium and Highly-Enriched Uranium
- Commercial Gas Centrifuge Plants
Conclusion (cont.)

The current open fuel cycle is likely to remain less costly than closed fuel cycles indefinitely. Therefore, the US should renew the search for alternative repository sites.
Dry Cask Storage at a U.S. Power Plant
Dry Cask Storage at a Site in Germany
Reprocessing Complex in France
Areva - La Hague Complex
**La Hague Complex:**
Area: 300 hectares = 3 million square meters (m²)  
~2 million m² within the outer fence  
Processing Area: ~373,000 m²  
Capacity: 1,600 tonnes of spent fuel (t SF) per year  
(~0.0043 t of SF/year-m²)

**Ahaus Spent Fuel Facility:**
Building Area: ~7,680 m²  
Capacity: 3,960 tonnes of spent fuel  
(~0.5 t of spent fuel per m²)

**Maine Yankee Dry Cask Storage Facility:**
Pad Area for 64 casks: ~2,580 m²  
Assumption: 12 t SF/cask  
Capacity: 768 tonnes of SF  
(~0.3 t of SF per m²)
Area required for dry cask storage of 60,000 t spent fuel:
on one red square \( (60,000 \text{ t SF} / 0.5 \text{ t SF/m}^2 = 120,000 \text{ m}^2) \)
La Hague Complex – chemical processing area:
blue polygon \((\sim 373,000 \text{ m}^2)\)
Dry Cask Central Storage

- Consolidated central storage of spent fuel from shut down reactors makes sense.

- Consolidated storage of spent fuel from operating reactors does not make sense.
END
Extra Slides
President Gerald R. Ford on October 28, 1976 announced his decision that

... the reprocessing and recycling of plutonium should not proceed unless there is sound reason to conclude that the world community can effectively overcome the associated risks of proliferation ... 

that the United States should no longer regard reprocessing of used nuclear fuel to produce plutonium as a necessary and inevitable step in the nuclear fuel cycle, and that we should pursue reprocessing and recycling in the future only if they are found to be consistent with our international objectives.
If one wants to minimize:

- Fuel cycle costs
- Proliferation risks
- Waste volumes
- Safety risks
- Radioactive releases
- Occupational exposures

Don’t reprocess spent fuel