NTI Paper

AUGUST 2016

The Case for a Pause in Reprocessing in East Asia: Economic Aspects

SUMMARY

In view of the proliferation and terrorism concerns raised by stockpiling and use of plutonium in nuclear power programs, countries reprocessing and using mixed oxide fuel should able to demonstrate benefits that are sufficiently compelling to compensate for these risks. In this paper, John Carlson observes that the benefits of reprocessing and using MOX fuel are questionable. The costs are so high that it is difficult to see how they can be justified relative to alternative approaches for spent fuel management, such as direct disposal or long-term storage pending further research on the viability of new recycling technologies.

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Introduction

In the context of current calls for East Asian countries to defer their plans to reprocess spent fuel from power reactors, it is instructive to compare the costs of reactor fuel for the *once-through fuel cycle*, where spent fuel is stored for eventual disposal in geological repositories, and the *closed fuel cycle*, where spent fuel is reprocessed for recovery and recycle of plutonium (Pu) and (in some cases) uranium.[1]

The currently established reprocessing technology (Purex) was originally developed to separate plutonium for weapons use. When reprocessing was adapted for civilian application, it was thought that uranium was scarce and would become increasingly expensive. Hence it was believed that the sustainability of nuclear power would depend on the development of fast neutron reactors together with reprocessing, in order to use plutonium fuels. A number of countries initiated programs to establish civilian reprocessing and fast neutron reactors. Subsequently, however, two major developments undercut the rationale both for reprocessing and for fast reactors: the rate of growth of nuclear power has been much lower than expected; and substantial new uranium resources have been discovered. It has turned out that economically recoverable uranium is not scarce after all.

These changed circumstances led to some countries discontinuing reprocessing plans. Others, however, continued with these programs, changing the rationale from supplying planned fast reactors to the recycle of plutonium through light water reactors (LWRs). Japan has a term for this, "pluthermal"; that is, the use of plutonium fuel in thermal reactors[2] as distinct from fast neutron reactors.

Reasons given for continuing with reprocessing and recycle using LWRs include:

1. Efficient use of uranium;
2. Spent fuel management;
3. Energy independence/security;
4. Broader economic considerations;
5. Maintenance of skills and research and development (R&D) to support the development of fast reactors in the future.

Each of these justifications is open to question.

1. Efficient Use of Uranium

Recycle with LWRs saves approximately 11 percent of uranium compared with the once-through cycle.[3] This is because, roughly speaking, the plutonium output of three low enriched uranium (LEU)-fuelled reactors is required to provide sufficient plutonium to refuel one MOX-fuelled[4] reactor using a one-third MOX core (a 100 percent MOX core would require the plutonium output of nine LEU-fuelled reactors). As will be discussed, the value of uranium saved is only a fraction of the cost of reprocessing.

[1] Irradiated uranium contains U-236, which reduces the performance of the uranium if it is recycled in thermal reactors. Accordingly, generally reprocessed uranium is not recycled.

[2] Thermal reactors use a moderator—light water, heavy water, or graphite—to slow neutrons to thermal speeds where fission is more likely.

[3] Assuming the uranium component of MOX fuel comprises depleted uranium tails from enrichment.

[4] MOX—mixed oxides of plutonium and uranium—is the form of plutonium fuel used in LWRs. Typically the plutonium content of MOX fuel is approximately 8 percent.

2. Spent Fuel Management

Fast reactors, if they prove viable, offer the possibility of transmuting long-lived radioactive elements to much shorter lived materials, substantially reducing the quantity of high-level waste (HLW) requiring long-term disposal. In the absence of fast reactors, a major driver for reprocessing appears to be the political desire to be seen to be "doing something" about spent fuel. Some may see reprocessing as a short-term solution because it involves removing spent fuel from reactor sites, but reprocessing is extremely expensive and only defers the disposal problem, because disposal of the resulting HLW presents issues and costs similar to those for disposal of spent fuel.

It is claimed that reprocessing substantially reduces the volume of HLW to be disposed of, compared with spent fuel. Such claims do not allow for the packaging required for HLW canisters. France's Institute for Radiation Protection and Nuclear Safety (IRSN) reports that, taking packaging into account, reprocessing results in a reduction of about 28 percent in high- and intermediate-level wastes compared with disposal of spent fuel[5]—as discussed in the Appendix to this paper, this notional saving in repository costs is substantially outweighed by reprocessing costs.

In practice, the overall reduction in volume of HLW and intermediate-level waste (ILW) will be rather less than the 28 percent figure suggests. This is because, using LWRs, the closed cycle is in reality a *twice-through cycle*[6]—the build-up of non-fissile plutonium isotopes and other transuranic elements makes it impractical to reprocess MOX fuel for use in LWRs. Looked at over two cycles, the notional reduction in volume is effectively halved (i.e., approximately 14 percent).

In fact, depending on how spent MOX fuel is managed, there could be a substantial *increase* rather than a reduction in volume. The thermal output of spent MOX fuel is much higher than for LEU fuel, and MOX cools more slowly. Accordingly, spent MOX fuel will require a much larger volume in the final repository—an MIT study suggests as much as seven times larger than for LEU fuel.[7] Alternatively, MOX fuel will require a much longer storage period before geological disposal—according to EDF 150 years, compared with 50 years for LEU fuel.[8]

3. Energy Independence/Security

Plutonium in spent fuel has been described as an indigenous energy resource, providing the potential for nuclear self-sufficiency. However, with limited exceptions,[9] nuclear self-sufficiency through reprocessing is feasible only with fast reactors, hence will not be achievable (if at all) for many decades. The goal of self-sufficiency may have made sense when uranium was thought to be scarce and before the nuclear industry became globalized, but today no country has a fully self-sufficient fuel cycle,[10] and uranium is abundant. For countries that do have a genuine concern about long-term security of supply, this can be addressed through multilateral arrangements, such as long-term fuel supply assurances and the IAEA LEU Bank.

4. Broader Economic Considerations

Reprocessing is thought to be necessary for recovery of investments, maintaining local employment, and so on. The claimed economic benefits do not appear to have been subjected to rigorous cost-benefit analysis. The figures discussed in this paper suggest that when all costs are considered it would be far cheaper to discontinue reprocessing and to use the savings to promote alternative employment opportunities.

5 IRSN says 1 tonne of spent LEU fuel would, after packaging, take up a volume of 3 m3, compared with about 2.15 m^3 of packaged HLW and ILW from reprocessing the same quantity of fuel. Mycle Schneider and Yves Marignac, *Spent Nuclear Fuel Reprocessing in France* (Princeton, NJ: IPFM, April 2008), available at http://fissilematerials.org/library/rr04.pdf.

6 MIT, *Study on the Future of the Nuclear Fuel Cycle: An Interdisciplinary MIT Study* (Cambridge, MA: MIT, 2011), available at http://energy.mit.edu/wp-content/uploads/2011/04/MITEI-The-Future-of-the-Nuclear-Fuel-Cycle-Summary-Report.pdf.

7 Ibid.

8 Schneider and Marignac, *Spent Nuclear Fuel Reprocessing in France*.

9 For example, in principle, a self-sufficient LWR breeder cycle is possible using enriched uranium fuel and a thorium blanket.

10 This is true even for Russia, which today is a uranium importer.

5. Maintenance of Skills

There are other, more cost-effective, ways than commercial-scale reprocessing operations for meeting this objective.

Other Concerns

In addition to these stated reasons for reprocessing, there may be another, unstated reason for a country to persist with reprocessing despite the high costs and doubtful benefits, namely, to establish *nuclear latency*. Because the currently used reprocessing technology enables plutonium separation, reprocessing gives a country the basic capability needed for a nuclear weapon option. Although the country may have no such intention today, other countries may regard this capability as presenting a proliferation risk in the future.

As well as concern about proliferation risk, there is also international concern that the use of separated plutonium and MOX fuel creates the risk of terrorists obtaining plutonium for use in a nuclear explosive device or a radiological device.

Costs of Reprocessing and MOX

Public information on the costs of reprocessing and use of MOX fuel for LWRs is not easy to find. One can't help thinking the reason for this may be because these costs are extremely high—well beyond any level that could be considered economically justifiable. It must be asked whether the proponents of these programs have fully informed their governments of the true costs.

Part of the difficulty in finding information on costs is that globally there are very few civilian reprocessing plants. The UK and French plants are old and the information that is available is not readily applicable to new plants. The only contemporary example is Japan's Rokkasho nuclear fuel reprocessing plant. Here, available information is limited. It is estimated that construction costs were $25 billion.[11] There is no firm information on likely product costs.

There is no established market value for plutonium nor for MOX fuel. Japanese utilities are reported as saying that MOX fuel imported from Europe costs *nine times* as much as LEU fuel.[12] A study by Japan's Atomic Energy Commission in 2011 estimated that MOX fuel produced in Japan from reprocessing at Rokkasho would cost over *12 times* as much as LEU fuel.[13]

These cost ratios of MOX fuel relative to LEU fuel are corroborated by the figures outlined in the Appendix. The major factor influencing the cost of MOX fuel is the cost of reprocessing. Typically 100 kilograms (kg) of spent fuel must be reprocessed to separate one kilogram of plutonium. If the cost of reprocessing is $2,500/kg HM,[14] then one kilogram of MOX fuel, with a typical plutonium content of 8 percent, will cost approximately *$22,550*. If the reprocessing cost is only $1,000/kg HM (very unlikely for reprocessing in East Asia), the cost of one kilogram of MOX fuel will be approximately $10,700. By comparison, the cost of LEU fuel is currently approximately *$1,928/kg*.

[11] Unless stated otherwise, all cost figures in this paper are in U.S. dollars. See Stephen Stapczynski and Emi Urabe, "Japan's $25 Billion Nuclear Recycling Quest Enters 28th Year," Bloomberg, available at www.bloomberg.com/news/articles/2016-01-04/japan-s-25-billion-nuclear-recycling-quest-enters-28th-year.

[12] "MOX Imports Have Cost at Least ¥99.4 Billion, Much Higher Than Uranium Fuel," *The Japan Times*, available at www.japantimes.co.jp/news/2015/02/22/national/mox-imports-have-cost-at-least-%C2%A599-4-billion-much-higher-than-uranium-fuel/#.

[13] Atomic Energy Commission Bureau (ed.), *Estimation of Nuclear Fuel Cycle Cost* (Technical Subcommittee on Nuclear Power, November 10, 2011), slide 28, available at www.aec.go.jp/jicst/NC/about/kettei/seimei/111110_1_e.pdf.

[14] Kilograms of heavy metal (i.e., uranium, plutonium, and other transuranics).

To put these figures into perspective, the following table shows the annual costs of fuel for a typical 1,000 MWe[15] LWR, changing one-third of the fuel core (that is, reloading 27 tonnes) every 18 months.

Annualized Reactor Fuel Cost

LEU only	$34.7 million
1/3 MOX (for reactors using MOX fuel, typically MOX comprises 1/3 of the core); i.e., 9 tonnes MOX and 18 tonnes LEU	$158.4 million
MOX only (newer reactors may be licensed for a 100% MOX core)	$405.9 million

Notes: Annualized cost for a 1,000 MWe pressurized water reactor reloading 27 tonnes of fuel every 18 months (i.e., 18 tonnes/year).

Based on cost for LEU fuel of $1,928/kg and MOX fuel $22,550/kg.

These figures take into account uranium saved by using MOX fuel—for recycle using LWRs, the overall saving in uranium requirements will be approximately 11 percent.

The table shows that use of MOX in LWRs comes at an extremely high cost premium. It is instructive to compare the costs of reprocessing and MOX fuel against direct disposal of spent fuel (the once-through fuel cycle). In its recently released report,[16] the South Australian Nuclear Fuel Cycle Royal Commission considered that a reasonable baseline price for direct disposal of spent fuel in a geological repository in South Australia would be approximately $1.30 million/tonne HM.[17] This would make the cost of direct disposal of spent fuel from a typical 1,000 MWe reactor, as in the above example, approximately $23.4 million/year. Reprocessing and MOX costs are considerably more expensive, and these costs do not include disposal of HLW from reprocessing, which as discussed above will incur costs broadly similar to those of spent fuel disposal.

Depending on the cost of reprocessing, calculations using the figures in the Appendix indicate that the price of uranium would have to increase to as much as $2,000/kg before reprocessing and MOX fuel could break even with the costs of LEU fuel. To put this in perspective, the cost of extracting uranium from seawater is currently estimated at approximately $660/kilogram and is expected to reduce with further research.[18]

[15] Megawatts electric.

[16] Nuclear Fuel Cycle Royal Commission, Government of South Australia, *Nuclear Fuel Cycle Royal Commission Report*, 2016, available at http://yoursay.sa.gov.au/system/NFCRC_Final_Report_Web.pdf.

[17] The figure cited by the Commission, A$1.75 million/tonne HM, equates to US$1.30 million at current exchange rates. Ibid, p. 96.

[18] See, e.g., Will Ferguson, "Record Haul of Uranium Harvested from Seawater," New Scientist, August 22, 2012, available at www.newscientist.com/article/dn22201-record-haul-of-uranium-harvested-from-seawater/.

Implications for Plutonium Recycle in the Future

This paper draws no conclusions on the economics of plutonium recycle other than Purex reprocessing and use of MOX in LWRs. It is possible that other approaches to recycle could be more viable; currently, there is insufficient cost information to enable this to be assessed with any certainty.

For pyroprocessing and fast reactors, the 2015 KAERI study referenced in the Appendix estimates that the cost of reprocessing and fuel fabrication could be in the range of $3,000 to $9,000 per kilogram. KAERI's mean estimate of $6,000 per kilogram is below the lowest cost for MOX fuel, and KAERI's lowest estimate, taking into account the possibility of minimizing HLW through transmutation, appears competitive with LEU fuel and direct disposal. However, these figures should be treated with caution as there is no experience with use of pyroprocessing on an industrial scale. Apart from pyroprocessing, another approach, liquid fuelled reactors, might also have the potential for recycle at a viable cost.

Conclusion

The high costs and questionable benefits of Purex reprocessing and use of MOX fuel with LWRs, together with proliferation and security concerns, make a compelling case to discontinue current reprocessing plans and instead opt for direct disposal or long-term storage pending further research on the viability of new recycling technologies.

Appendix

Costs of LEU and MOX Reactor Fuel

This Appendix details the cost figures used in the calculations in this paper.

The following table sets out fuel cycle cost figures and cost ranges for various stages of the fuel cycle for producing LEU fuel and MOX fuel for use in LWRs. All figures are in U.S. dollars.

The paper shows indicative costs and relativities, but is not intended as a comprehensive cost analysis (e.g., it does not include conditioning and packaging costs for spent fuel and HLW), and does not include cost of capital. A more comprehensive analysis only reinforces the conclusions on the high cost of reprocessing.

Fuel Production Costs (USD)

	Zheng 2012[a]	KAERI 2015[b]	Rothwell 2014[c]	Belfer 2016[d]	Current Spot Price[e]
Uranium ore concentrate (kg U)	\$110 (\$80–\$300)	\$121 (\$31–\$258)	\$90	\$80	\$80
Conversion (kg U)	\$9 (\$6–\$13)	\$10 (\$5–\$15)	\$11	\$10	\$6.75
Enrichment per (SWU)	—	\$110 (\$85–\$135)	\$100	\$120	\$62
Fabrication UO2 (kg U)	\$275 (\$200–\$350)	\$250 (\$200–\$300)	\$275	\$270	—
Reprocessing (kg HM)	\$2,107 (\$940–\$3,712)	\$1,120 (\$903–\$1,339)	\$2,500	\$3,200 (\$1,100–\$5,400)	—
Fabrication MOX (kg HM)	\$2,215 (\$838–\$2,754)	—	\$2,700	\$2,170	—

Note: Costs per kilogram uranium (U) or HM (heavy metal) unless otherwise indicated. Where the authors use a range of costs, the range is shown in parentheses.

[a] Youqi Zheng, Hongchun Wu, Liangzhi Cao, and Shizhuang Jia, "Economic Evaluation on the MOX Fuel in the Closed Fuel Cycle," *Science and Technology of Nuclear Installations* 2012, (2012): Article ID 698019.

[b] S.K. Kim, W.I. Ko, S.R. Youn, and R.X. Gao, "Nuclear Fuel Cycle Cost Estimation and Sensitivity Analysis of Unit Costs on the Basis of an Equilibrium Model," *Nuclear Engineering Technology* 47, no. 3 (April 2015): 306–314; (KAERI study).

[c] Geoffrey Rothwell, Thomas W. Wood, Don Daly, and Mark R. Weimar, "Sustainability of Light Water Reactor Fuel Cycles," *Energy Policy* 74, (2014): S16–S23.

[d] Matthew Bunn, Hui Zhang, Li Kang, *The Cost of Reprocessing in China*, Project on Managing the Atom, (Cambridge, MA: Belfer Center for Science and International Affairs, Harvard Kennedy School, January 2016). The reprocessing figure in the table, \$3,200, is from the Belfer paper for a \$20 billion plant without financing costs.

[e] Highest figures for March 2016, *Nuclear Intelligence Weekly*.

Cost of LEU Fuel

The figures used in the 2014 Rothwell paper (third column in the table above) are considered most representative of current market prices. Based on these figures, LEU fuel at typical enrichment level (4.5 percent) will cost approximately *$1,928/kilogram*, calculated as follows:

Enriching to 4.5 percent, with a tails assay of 0.3 percent, will require 10.2 kg U and 6.23 SWU.

- 10.2 kg U = $918;
- Conversion of 10.2 kg U = $112;
- Enrichment 6.23 SWU = $623;
- Fabrication = $275;
- Overall cost = *$1,928/kilogram* LEU fuel.

Taking the lowest and the highest figures from the sources summarized in the table (except for top of the range prices for UOC, which bear no relation to current figures), the possible range is (rounded) $950 to $2,580/kilogram LEU fuel.

Cost of MOX Fuel

There is no established market price for plutonium for use in MOX fuel. A practical way of estimating a value is to calculate the cost of reprocessing to recover a given quantity of plutonium, and to offset any other returns from reprocessing. In principle these are (a) the value of recovered uranium, and (b) the potential savings in disposal of HLW from reprocessing compared with the cost of disposing of spent fuel.

(a) Uranium recovered through reprocessing of LWR fuel typically has a residual enrichment level of less than 1 percent. This uranium can be re-enriched but generally this is not done because of the presence of U-236, which degrades the commercial value of the LEU product. So today uranium recovered from reprocessing is generally *not* recycled. However, Zheng suggests a value of $20/kilogram, and this is used here.

(b) Although reprocessing reduces the overall volume of HLW, compared with spent fuel, by the time the HLW is diluted in a waste matrix and packaged for disposal, as discussed earlier, the difference in storage volume is not significant.

Again based on the figures used in the Rothwell paper:

To obtain one kilogram of plutonium requires reprocessing approximately 100 kilograms of spent fuel—cost $250,000:

- Less value of recovered uranium, if recycled (approximately 100 kilograms)—approximately $2,000;
- So in net terms, it costs *$248,000* to obtain one kilogram of plutonium.

MOX typically contains 8 percent plutonium—so one tonne of MOX will cost:

- 80 kg Pu—$19,840,000;
- 920 kg DU (depleted uranium)—Zheng suggests a market value of $6/kilogram. On this basis the cost of the DU will be approximately $5,520;
- Total cost for 1 tonne MOX (rounded) = $19,850,000;
- Cost for 1 kilogram MOX = $19,850;
- Plus fabrication = $2,700;
- Overall total *$22,550/kilogram* MOX fuel.

Thus MOX fuel costs roughly *12 times* the cost of LEU fuel.

Taking the lowest and the highest figures from the table, the possible range for the cost of MOX fuel is (rounded) $8,900 to $46,000/kilogram. The number of variables in the LEU cost components complicates making a comparison between LEU and MOX fuel prices, but compared with an LEU fuel cost of $1,928/kilogram as used in this paper, MOX fuel is estimated to cost at least 4½ times and as much as 24 times the cost of LEU fuel.

Costs of HLW Management

The comparison here is between (a) the cost of direct disposal of spent fuel, and (b) the cost of reprocessing and producing MOX fuel plus the cost for conditioning and disposal of HLW. To be added to this are the costs for managing the resulting spent MOX fuel.

The figures are necessarily speculative since at present there is no experience with operating a spent fuel/HLW repository, but the figure used in the recent report of the South Australian Nuclear Fuel Cycle Royal Commission, $1,300/kg HM, is a reasonable basis for discussion.

Based on a typical 1,000 MWe LWR reloading 27 tonnes of fuel on an 18-month operating cycle (i.e., 18 tonnes of fuel on an annual basis):

(a) The repository costs for direct disposal of spent fuel, without conditioning and packaging costs, would be approximately $23.4 million/year.

(a) By comparison, the costs of reprocessing and producing MOX fuel would be approximately $158 million/year. This is without conditioning and disposal costs for the HLW from reprocessing.

On a purely volume basis, the repository cost for disposing of the HLW arising from reprocessing could be approximately 70 percent of the cost for spent fuel (i.e., $16.4 million), a notional saving of approximately $7 million/year compared with spent fuel. This notional saving would be vastly outweighed by the costs of reprocessing and producing MOX fuel.

In addition there are the costs of managing the resulting spent MOX fuel, which would be substantially higher than for spent LEU fuel.

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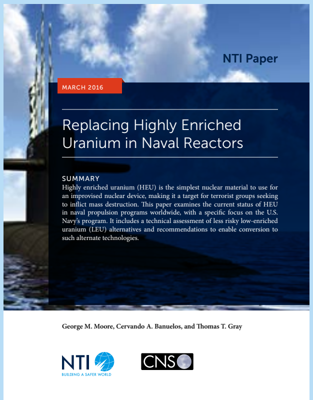

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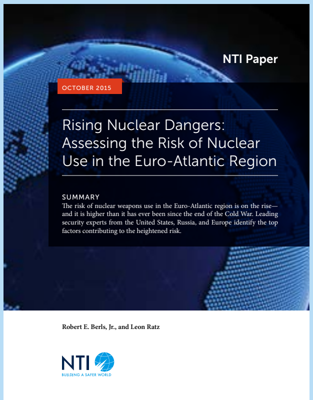

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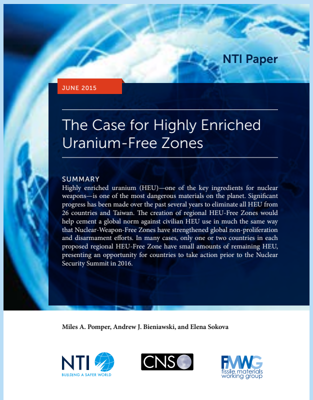

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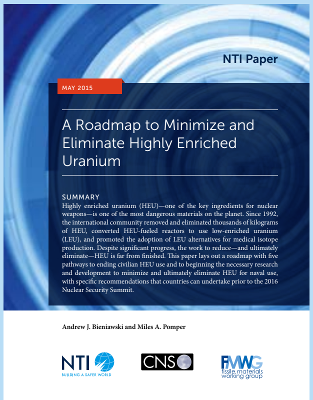

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