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Storage MOX: A Third Way for Plutonium Disposal?*

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By 2010, the UK could have 110 tons of separated civilian plutonium and Russia up to 150 tons of excess weapons and civil plutonium. Neither country has enough LWR capacity for disposal in MOX fuel. Plutonium disposal via MOX fuel is also difficult for some other countries. Combined disposal with HLW may be infeasible after reprocessing ends because the reprocessing enterprises are under pressure to rapidly solidify their stocks of liquid HLW. In a third approach, low-cost MOX pins would be mixed directly with spent fuel in final-disposal casks. We have analyzed the economics and proliferation resistance of this "storage MOX" option and conclude that it should be considered seriously.

INTRODUCTION

There are few physical barriers to the quick use of separated plutonium for nuclear weapons. This is why a U.S. National Academy of Sciences (NAS) report has described the United States and Russian stockpiles of excess weapons plutonium as "a clear and present danger to national and international security."[1]

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∗ Previous articles on this subject by the authors have appeared in *The Bulletin of the Atomic Scientists*, May/June 2001, p. 53; and in the *Proceedings of the Global 2001 International Conference on the Back End of the Fuel Cycle*, Paris, Sept. 10–13, 2001.

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Similarly, a Royal Society report on the United Kingdom's very large stockpile of separated civilian but weapons-usable plutonium concluded that, even in stable Britain, "the chance that the stocks of plutonium might, at some stage, be accessed for illicit weapons production is of extreme concern."[2] There is, consequently, a developing consensus that plutonium cannot be left indefinitely in separated form. It must be made less accessible for weapons use.

The U.S. and Russia have proposed programs to dispose of at least 34 tons each of excess weapons plutonium in mixed-oxide (MOX) uranium-plutonium fuel for light-water reactors (LWRs). Prior to 2002, the U.S. planned to "immobilize" a fraction of its separated plutonium in metal-clad ceramic cylinders embedded in canisters of high-level-waste (HLW) glass.[3] If the two countries were to reduce their stockpiles of weapon-grade plutonium to about 20 tons each—equivalent to perhaps 5,000 warheads[4]—the U.S. could declare an additional 27 tons of plutonium excess and Russia on the order of 80.[5]

In part, the emphasis on MOX fuel in both Russia and the U.S. reflects the fact that MOX-fuel fabrication and utilization are well-developed technologies in Western Europe. It also reflects the preference of Russia's Ministry of Atomic Energy (MinAtom). Regardless of current economics, MinAtom insists that the fuel value of its separated plutonium must be utilized. It also insists that the isotopics of U.S. excess weapon-grade plutonium should be degraded to reactor grade by neutron irradiation.

There are also large stockpiles of separated civilian plutonium, totaling about 200 tons, mostly stored at civilian reprocessing plants in Britain, France, and Russia (see Table 1). Because of limited LWR capacity, MOX disposal will be straightforward for less than half of this separated civilian plutonium. The U.K. is projected to have a stockpile of about 115 tons and only one LWR by 2010.[6] Russia has an LWR capacity that is sufficient at most to deal with the weapon-grade plutonium that it has declared excess. Some other countries that have sufficient LWR capacity may have problems licensing the reactors to use MOX. Virtually all countries have thus far been reluctant to use MOX fuel fabricated from other countries' plutonium.[7]

Disposal of plutonium with high-level waste would, in principal, be possible for reprocessing establishments in Britain, France, and Russia. They are reluctant to pursue such an "antireprocessing" option, however, as long they still have hopes for additional reprocessing contracts. They are also required to minimize their backlogs of liquid high-level waste and may therefore no longer have sufficient stocks for this disposal approach when they cease reprocessing.[8]

A third option for plutonium disposal, "storage MOX," was proposed by a group of German analysts in 1999.[9] According to this concept, MOX pins would be produced but not used as fuel. Instead, they would be mixed directly

Table 1: Stocks of civilian unirradiated plutonium.[a] (End of year in metric tons)

Country	Total Pu in-country	Foreign-owned Pu in-country	Pu in foreign countries
Belgium (1999)[b]	3.9	?	0.9
Britain (2000)	78.1	16.6	0.9
France (2000)	82.7	38.5	0
Germany (1999)[c]	7.2	0	~17
Italy	0	0	0.5
Japan (2000)	5.3	0	32.1
Netherlands	0	0	1.2
Russia (2000)[d]	33.4	0	0.0006
Sweden	0	0	0.8
Switzerland (2000)[e]	0.6	0	<5
Totals	~200	~55	~50

[a]For countries reporting, based on national declarations to the International Atomic Energy Agency (see Infcircs549 at http://www.iaea.org/worldatom/Documents/Infcircs). For countries not reporting (Italy, Netherlands, and Sweden), 1998 estimates by the Institute for Science and International Security, <http://www.isis-online.org>.
[b]Belgium does not provide a breakdown of its in-country plutonium by domestic and foreign ownership.
[c]Germany does not report the amount of separated plutonium that it has stored at foreign reprocessing plants. Our estimate assumes that all plutonium in foreign countries not accounted for by other countries is German, neglecting foreign plutonium in Belgium and Swiss plutonium in other countries.
[d]Although Russia reprocesses foreign spent fuel, it assumes ownership of the recovered plutonium.
[e]Switzerland only declares the total amount of plutonium in fuel that it has sent abroad to be reprocessed.

with spent fuel in final-disposal casks. We have carried out additional cost, criticality, and nonproliferation analyses of this approach and find that it is worthy of serious consideration.

Figure 1 shows flow diagrams for the disposition of plutonium in fuel and storage MOX.

COST

Since storage MOX would not be designed for reactor use, it could be designed to less exacting standards and with higher plutonium content than used in LWRs. Given the current high cost of conventional MOX-fuel production, this could substantially offset the savings in LEU fuel costs associated with MOX fuel use.

According to a study done in 1999 for an anonymous German utility, "first-generation" storage MOX containing 9.2 percent plutonium could be fabricated at an existing European MOX fuel-fabrication facility for about 1850 Euros ($1665 per kg heavy metal or HM, i.e. uranium plus plutonium)

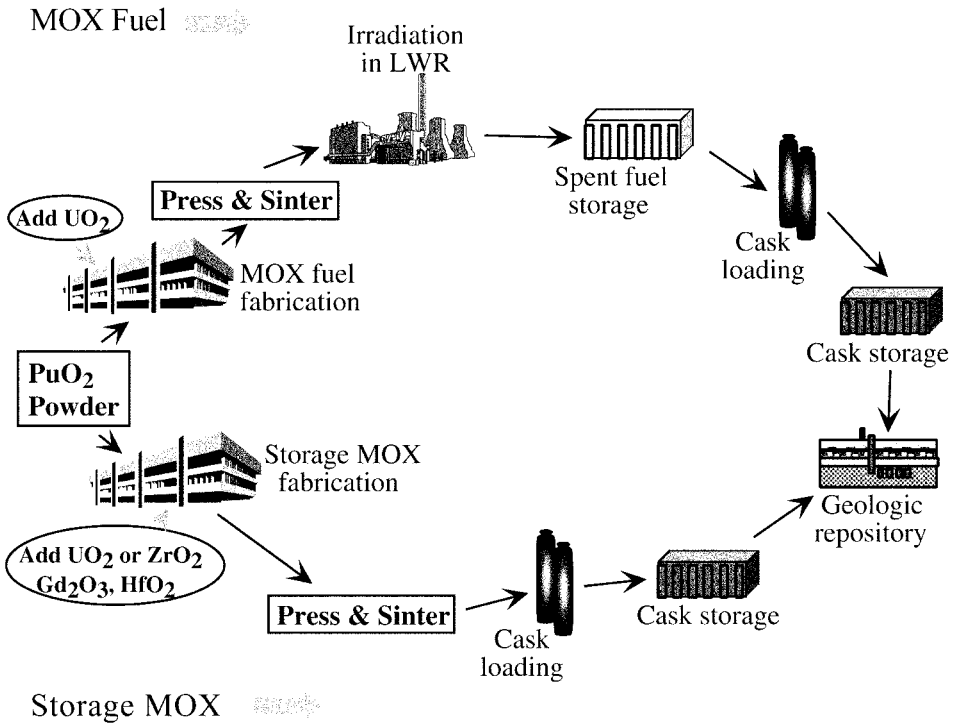

Figure 1: Steps in the disposition of plutonium in fuel and storage MOX.

with the current production arrangements for fuel MOX.[10] This corresponds to $18,000 per kilogram of contained plutonium. If the design and quality control requirements imposed by reactor use were relaxed and less costly zirconium were used[11] and fissile plutonium loadings were raised to 10 percent of heavy-metal content (15 percent total plutonium), the cost per rod was estimated to increase by about 10 percent because of increased criticality concerns with the higher plutonium concentrations. However, because of the higher loadings, the cost per kilogram of contained plutonium could be reduced by one third to about $12,000/kgPu for "second generation" storage MOX.

There would be other additional costs for storage MOX, however, since the storage MOX would not replace LEU fuel. One cost would originate from the need for additional storage/disposal containers for the storage MOX and the associated emplacement costs. We estimate these additional costs at about $1000/kgPu.[12]

For comparison, for a fabrication cost of $1800/kgHM for MOX fuel[13] containing 6.1–8.5 percent plutonium/kg and displacing LEU fuel worth

$800–1200/kgU, the cost of using fuel MOX for plutonium disposition would be $7,100–16,400/kgPu. The cost within this range depends upon the plutonium content of the MOX fuel and the enrichment of the LEU fuel that is being displaced, that is, upon the design burnup of the MOX and LEU fuel. Higher burnup requires higher plutonium content or enrichment. We consider a burnup range of 43–53 MWd/kgHM here. The plutonium content also depends upon the fissile content of the plutonium—which decreases with increasing burnup of the spent fuel from which it was recovered. We have assumed a range of 33–43 MWd/kgHM for this burnup.[14] The high end of the plutonium-disposition cost range reflects current practice and the lower end what is expected within the decade.

Based on these numbers, in a future with high-burnup plutonium used in high-burnup MOX, plutonium disposition in fuel MOX would be less costly than in storage MOX. It can also be seen however that, for countries that do not have an adequate MOX fuel option, the cost of plutonium disposition via storage MOX would be comparable to the current costs for subsidizing disposition via fuel MOX. The cost comparison is summarized in Table 2.

Cost estimates for MOX fuel fabrication vary widely, however. For example, the U.S. government's most recent cost estimate for the cost of disposing of 34 tons of excess weapon plutonium in fuel MOX comes to about $70,000/kgPu.[15] The current estimate of the cost of disposing in MOX of 34 tons of Russian excess weapon plutonium is about $44,000/kgPu.[16] For such high fuel-fabrication costs, the cost savings in the fabrication of storage MOX would be approximately equal to or win out over the LEU-fuel cost savings associated with fuel MOX. To illustrate this, we show in Table 2 estimates of the cost of storage MOX

Table 2: Comparison of disposal costs via fuel MOX and storage MOX. (Dollars per kg plutonium)

	Fuel MOX (Design burnup/burnup of spent LEU fuel from which plutonium is derived, MWd/kgHM)		**Storage MOX (10% Pu_f)**
	53/43	43/33	
Fabrication	$21,200	$29,500	$12,000
Fuel credit	$14,100	$13,100	
Additional storage cask and emplacement costs	—	—	$1000
Net cost	**$7,100**	**$16,400**	**$13,000**
Cost of disposing of 34 tons US WgPu in fuel MOX	$70,000 (including	$22,000 fuel credit)	$73,000
Cost of disposing of 34 tons Russian WgPu in fuel MOX	$44,000 (including	$10,000 fuel credit)	$27,000

containing 10% fissile plutonium, assuming that the percentage of weapon-grade plutonium in the U.S. and Russian fuel MOX will be 5.3 percent and 4.4 percent respectively, and that the fissile isotopic content of this weapons plutonium is 94 percent. We assume that the costs of the MOX fuel-fabrication facility are fixed and that the other costs per kg HM are 10% more for storage MOX than for fuel MOX.

CRITICALITY

For specificity, we have assumed that the mixture of storage MOX and spent fuel pins are disposed of in the Pollux cask developed for the disposal of German spent fuel. These casks contain neutron-absorbing borated steel plates between the fuel compartments (see Figure 2). With these plates, the casks can hold even fresh mixed-oxide fuel rods containing up to 5.3 percent of fissile plutonium (Pu-239 + Pu-241) and be flooded with water without going critical.[17]

The borated steel plates may not guarantee long-term subcriticality in a final repository because the boron is expected to leach away from the waste package much faster than plutonium.[18] Even without the boron, however, our calculations show that a Pollux cask would be subcritical when filled with storage MOX pins containing 10 percent fissile plutonium oxide by weight mixed with spent LEU fuel pins in a ratio of 1 to 2 (see Table 3). Even an infinite hexagonal array of storage MOX rods mixed with spent LEU rods in the same ratio (see Figure 3) would be subcritical ($k_{eff} < 1$).[19]

It would be possible to add neutron absorbers to storage MOX. Both gadolinium and hafnium make excellent neutron absorbers, and both form oxides (HfO_2 and Gd_2O_3) that are compatible with the crystalline structure of PuO_2 and resistant to chemical leaching. For this reason, the U.S. design for immobilizing plutonium in high-level waste proposed to mix both gadolinium and hafnium in approximately one-to-one atomic ratios with weapon-grade plutonium in a ceramic storage form that would then be imbedded in high-level-waste glass.[20] These neutron absorbers would cost less than $1000/kgPu at this concentration.[21] However, the savings in the fabrication process from not having to worry about criticality should more than offset this cost.[22] Table 3 shows the effect of adding such neutron absorbers on the criticality of a mix of 1/3 storage MOX rods with 2/3 spent LEU fuel rods. The effect of the neutron poisons is less in the dry cask because the poisons are most effective for thermalized neutrons. With the neutron poisons, it would be possible to load a Pollux cask with 100% storage MOX and still stay comfortably subcritical.[23] This

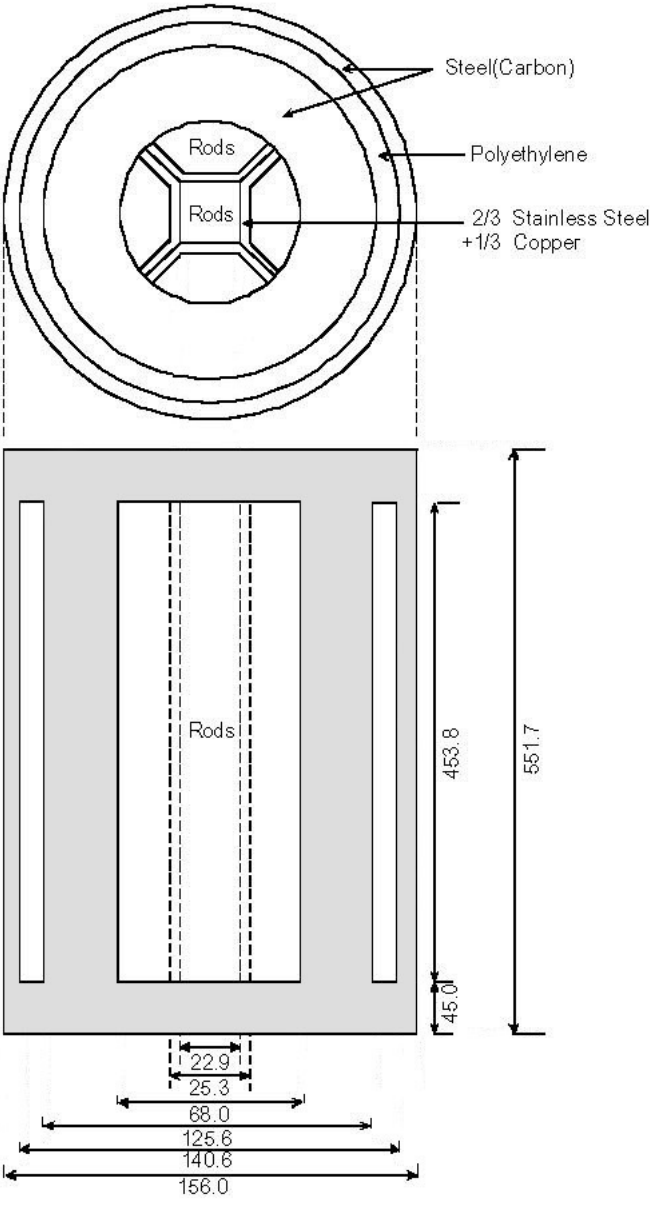

Figure 2: POLLUX cask design specifications. (a) shows a horizontal cross-section of the cask, (b) shows the outer and inner casks with moderator rods in the walls of the outer cask and spent fuel inside the inner cask compartments, and the dimensions of the cask, after Janberg (1998), (c) model used in criticality calculations. *(Continued)*

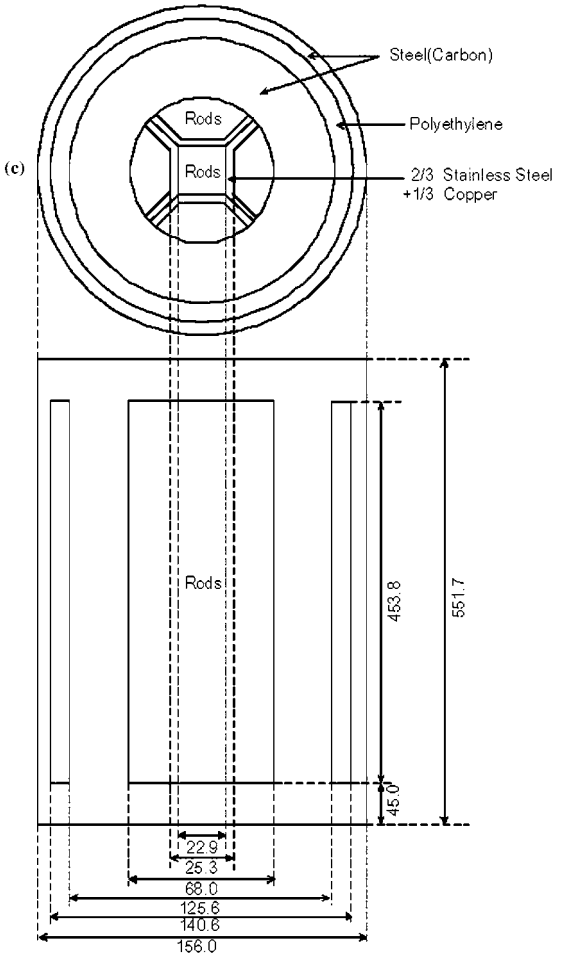

Figure 2: (Continued)

provides assurance that a mistake in loading would not result in a criticality accident.

IMPLICATIONS FOR GEOLOGICAL DISPOSAL

As already noted, more casks would be required to dispose of plutonium via the storage-MOX route than via the fuel-MOX route. The spent MOX fuel displaces spent LEU fuel. Storage MOX does not displace spent fuel. However, the capacity of a geological repository is determined more by radioactive decay heat than by the volume of the waste form and, for 500 years after discharge,

Table 3: Neutron multiplication (k_{eff}) of 1/3 storage MOX, 2/3 spent LEU fuel.

	Infinite array		2360 rods in a Pollux cask w.o. boron	
	Flooded	**Dry**	**Flooded**	**Dry**
Without neutron poisons	0.89	0.75	0.73	0.49
With neutron poisons	0.63	0.71	0.53	0.47

the rate of heat output from the spent MOX fuel is greater than the combined heat outputs from the equivalent amount of storage MOX plus spent LEU fuel (see Figure 4). This is because the fuel MOX contains much larger quantities of heat-generating Pu-238 (half-life = 88 years) and Am-241 (432 years) than the equivalent amount of storage MOX plus spent LEU fuel.[24]

Not having the constraint that the storage MOX be a good fuel makes it possible to design it to be a better plutonium storage medium. We have already mentioned the possibility of adding neutron absorbers. It would also be possible to make the waste form out of a more chemically durable base material than UO_2. Uranium dioxide oxidizes readily to higher oxides and therefore is expected to degrade relatively rapidly in a repository with oxidizing

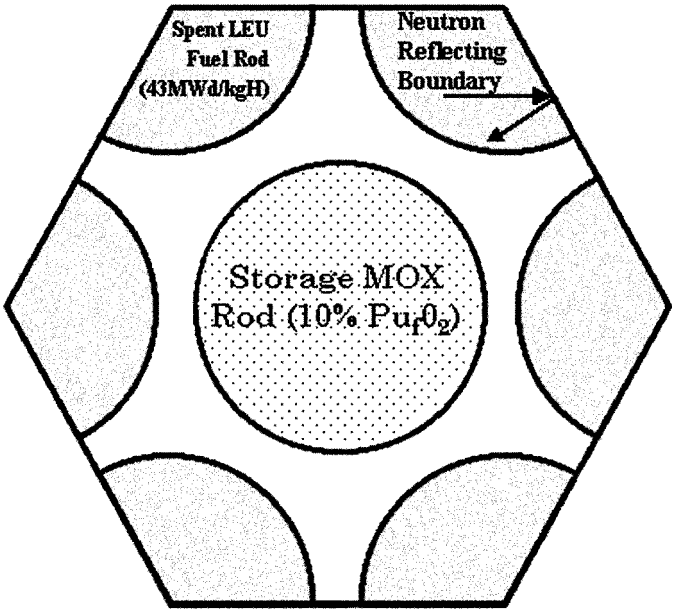

Figure 3: Hexagonal cell with neutron reflecting walls used in calculating the criticality of an infinite horizontal array of 2/3 spent LEU fuel and 1/3 storage MOX rods.

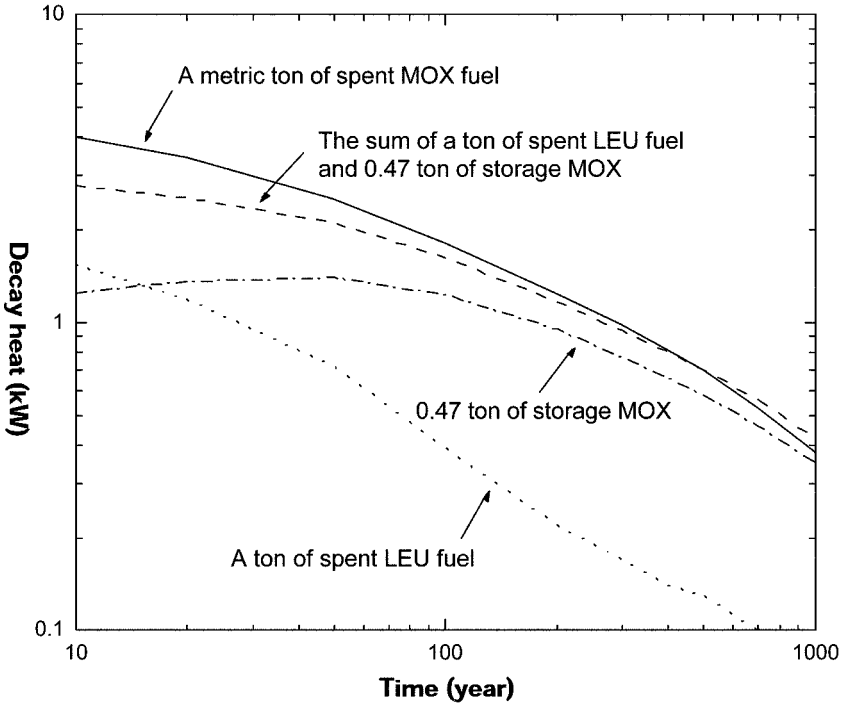

Figure 4: Comparison of the decay heat of a ton of spent MOX fuel (43 MWd/kgHM) with that from a ton of spent LEU fuel (also 43 MWd/kgHM) plus 0.47 tons of storage MOX containing the same amount of plutonium as the fresh MOX fuel.

conditions such as the U.S. repository being developed within Yucca Mountain, Nevada.[25]

One chemically durable, radiation resistant alternative to storage UO_2 is zirconia (ZrO_2). If storage MOX is seriously considered, this variant would be well worth investigating. It should be possible to adapt existing MOX fabrication facilities to fabricate a zirconia-based storage form. The principal necessary change would be higher-pressure presses for forming the ceramic into pellets. One tradeoff for the greater durability of the zirconia form would be that, in the absence of an admixture of depleted uranium, the U-235 decay product to which plutonium-239 decays with a 24,000-year half-life, will be highly enriched. However, it is not clear that the plutonium in the less chemically durable UO_2-based form would remain associated with the uranium long enough for the uranium to be an effective isotopic denaturant. Of course, making storage MOX more chemically durable would not solve the durability problem of the UO_2 based spent LEU fuel.

PROLIFERATION RESISTANCE

Could a final-disposal cask be opened, the storage MOX rods separated from the contained spent-fuel rods, and the plutonium recovered much more quickly than an equal amount of plutonium could be separated out of spent fuel? A very similar question was examined in 2000 by a U.S. National Academy of Sciences (NAS) panel with respect to the then-proposed U.S. plutonium immobilization form.[26]

The NAS report asked whether a subnational group could use explosives to quickly separate the plutonium-carrying ceramic cylinders from the surrounding high-level waste glass. In the case of storage MOX, the problem of physical separation of the storage MOX could be relatively easy but, if the pins appeared externally identical to spent fuel, separation would require radiation measurements to determine the presence or absence of highly-radioactive fission products.[27]

The separation process could be carried out remotely in a large hot cell or under water in a spent-fuel storage pool. If final-disposal casks containing storage MOX and spent fuel are blocked from ready access to such facilities by distance or other barriers, however, it is implausible that a subnational group could separate out the storage MOX and escape in the time likely to be available.

The first task of plutonium thieves, once they had penetrated site security and reached a disposal cask would be to open it. In the case of the Pollux cask, the outer lid, weighing about 2.7 tons, would be bolted on. The middle lid, weighing one quarter of a ton, would be welded on. Finally, the inner lid, weighing almost 1 ton, would be screwed on. It would ordinarily take at least several hours to open the cask.

The NAS study asserts that the lid of a spent-fuel shipping cask "can be removed by cutting or blasting in a matter of a few minutes." However, removing the top would also remove the radiation shielding that it provides. The thieves would then be faced with having to pull out the storage MOX in a radiation field that, if unshielded, would be high enough to give a lethal dose within tens of minutes.[28]

Recovery of the storage MOX could be made more time consuming if the final-disposal cask were filled with a material that would "glue" it to the spent fuel. A plausible material would be a low-melting-point metal such as lead. The filler material—or a mesh imbedded in it—would have to grip the pins strongly enough to assure that their ends would break off before they could be withdrawn.

Even with such additional measures, however, a host nation could recover the storage MOX relatively quickly. For example, it might take only a day or

so to heat up the cask to the melting point of the filler material and drain the material out. Nevertheless, storage MOX in a massive container mixed with highly-radioactive spent fuel would be preferable to the indefinite storage of separated plutonium with its associated security risks.

Some object to the immobilization of weapon-grade plutonium because, unlike irradiation, it would leave the plutonium weapon grade. This objection is sometimes overstated since reactor-grade plutonium is weapon useable.[29] In any case, for most of the cases discussed here, the plutonium is already reactor-grade and the objection is therefore inapplicable. Even in the case of weapon-grade plutonium, the isotopic mix could be degraded by mixing with reactor-grade plutonium.

A complete proliferation analysis would take into account the possibility of diversion during fabrication, transport, and loading of the storage MOX. However, these risks would be essentially the same as at the corresponding stages for fresh MOX fuel. The stage of loading storage MOX into the storage cask would be the counterpart of the stage of loading the fresh MOX fuel into a reactor core. Similar monitoring and security arrangements would be required.

FABRICATION

The obvious place to make storage MOX is in existing MOX fuel-fabrication facilities after they are no longer occupied with the production of fuel MOX. Table 4 shows the existing and planned MOX fuel-fabrication facilities. The

Table 4: Storage-MOX production capacities of existing and planned MOX fuel-fabrication facilities.[1]

	Capacity (Tons/year)	
Facilities (status)	**Heavy metal in fuel**	**Reactor grade plutonium (15% HM)**
OLD		
Belgium: Dessel (1973-)	35	5
France: Cadarache (1970-)	40	6
NEW		
France: Melox (1995-)	115→195?	18–29?
UK: Sellafield (2002-)	120	18
PLANNED		
US: Savannah R. (2007?)	~50	7.5
Russia: MOX FFF (2007?)	~90	13
Japan: Rokkasho (2008?)	130	20

[1] *Plutonium and Highly Enriched Uranium 1996*, p. 197 except for more recent information referenced in the text.

older facilities, Belgium's Dessel plant and France's Cadarache ATPu plant, are approaching the end of their lives and the Cadarache facility must be shut down in any case because of seismic hazards. Cogema is seeking a license to expand the capacity of its relatively new Melox plant to offset the shutdown of the two older plants. Britain's SMP plant recently received its operating license.[30] Japan is planning to build a MOX plan to dispose of the plutonium separated at its Rokkasho reprocessing plant.[31]

At full capacity, the U.K. SMP plant could in seven years fabricate into storage MOX the 115 tons of civilian plutonium that Britain is projected to have accumulated by 2010. However, the radiation barrier would have to be provided by Advanced Gas Reactor spent fuel, which would be distinguishable from the LWR fuel that the SMP is designed to produce. This could facilitate the task of a group trying to steal the storage MOX rods and would therefore put a greater premium on "gluing" together the storage MOX and spent-fuel rods. The proposed Russian MOX plant could similarly immobilize 50 tons of Russian civilian plutonium in about four years. If the stalemate over the loading of MOX fuel into Japan's power reactors continues, its utilities too may become more interested in storage MOX.

CONCLUSION

Given the fact that few foreign utilities are signing new contracts with the British and French reprocessing companies and it is unlikely that their domestic utilities will long be willing to carry the burden of supporting their national reprocessing industries by themselves, the flood of newly separated plutonium will soon begin to abate. Then it will become more possible to focus world attention on the importance of eliminating the existing stockpiles of separated plutonium. In this context, storage MOX appears a viable option for countries with large stocks of separated plutonium for which a fuel-MOX disposal option is not readily available. The relatively small number of existing and planned MOX fuel fabrication facilities could deal with these "orphan" stocks of plutonium relatively quickly.

NOTES AND REFERENCES

1. Committee on International Security and Arms Control, *Management and Disposition of Excess Weapons Plutonium* (Washington, DC: National Academy Press, 1994), p. 1.

2. *Management of Separated Plutonium*, (London, The Royal Society, 1998) Summary.

3. *Report to Congress on the Projected Life-Cycle Costs of the U.S. and Russian Fissile Materials Disposition Programs*, National Nuclear Security Administration (Distribution Draft) March 30, 2001, Fig. 2.2. In the most recent U.S. plan, immobilization has been dropped ("Revised plutonium disposition strategy," Office of Fissile Materials Disposition, National Nuclear Security Administration, U.S. Department of Energy, January 2002).

4. The average amount of plutonium per warhead is classified. The U.S. National Academy of Sciences study used 4 kg as a "planning figure," *Management and Disposition of Excess Weapons Plutonium*, p. 40.

5. The U.S. has declared its total stockpile of separated plutonium, *Plutonium: The First 50 Years* (U.S. Department of Energy report DOE/DP-0137, 1996). Only estimates are available for Russia's stockpile of weapon-grade plutonium. These estimates are summarized as 131 ± 25 tons in *Plutonium and Highly Enriched Uranium 1996*, David Albright, Frans Berkhout, William Walker (Oxford University Press, 1997), p. 58.

6. *Radioactive Waste Management Advisory Committee's Advice to Ministers on the Radioactive Waste Implications of Reprocessing*; November 14, 2000, <http://www.open.gov.uk/rwmac/reprocess/index.htm>.

7. The Nuclear Disarmament Forum AG of Zug, Switzerland has, however, developed a proposal, *Russian Weapons Plutonium and the Western Option* (2002), under which Russian MOX would be shipped to Belgium, Germany and Switzerland, countries that have decided to end reprocessing of their spent fuel and therefore would have available MOX-licensed reactor capacity.

8. An excellent preliminary analysis of the United Kingdom's immobilization options, with and without radiation barriers provided by vitrified high-level waste and spent fuel, may be found in Fred Barker and Mike Sadnicki, *The Disposition of Civil Plutonium in the UK*, April 2001, available from the authors (fbarker@pop.gn.apc.org and sadnicki@aol.com).

9. C. Küppers, W. Liebert, M. Sailer, *Realisierbarkeit der Verglasung von Plutonium zusammen mit hochradioaktiven Abfällen sowie der Fertigung von MOX-Lagerstäben zur Direkten Endlagerung als Alternativen zum Einsatz von MOX-Brennelementen* (Darmstadt, Germany: Öko Institute, 1999). An English summary is available in Christian Küppers, "Feasibility of vitrification of plutonium together with high-active waste concentrate and fabrication of MOX storage rods for direct final disposal instead of a use of MOX fuel for further handling of separated plutonium," paper delivered to the IAEA technical committee meeting on "Factors Determining a Long Term Back End Nuclear Fuel Cycle Strategy and Future Nuclear Systems," Vienna, November 8–10, 1999. A brief earlier discussion of this idea also may be found in G. A. Armantrout, L. J. Jardine, "Disposition of excess plutonium using "off-spec" MOX pellets as a sintered ceramic waste form" paper submitted to Waste Management '96 Symposia Working Towards a Cleaner Environment, Tucson, AZ, Feb 25–29, 1996; UCRL-JC-121830 Preprint.

10. 1700 Euros for fabrication plus 150 Euros for the cost of the zircalloy tubes, end caps, springs, etc.

11. Much of the cost of reactor-grade zirconium is associated with the need to remove the neutron poison, hafnium.

12. A Pollux disposal cask could hold 2360 PWR fuel rods (Klaus Janberg, Harry Spilker, "Status of the Development of Final Disposal Casks and Prospects in Germany," *Nuclear Technology* 121 (February 1998), pp. 136–147). Although the storage MOX would be

mixed with spent LWR fuel, an extra cask would be required for each 2360 rods of storage MOX. At 15 percent plutonium in the heavy metal by weight this number of storage MOX rods would contain about 800 kg of plutonium total. We assume a cost per cask of $0.5 million and a cost of emplacement of $0.4 million per cask, based on the estimated $4.94 billion cost in year 2000 dollars for emplacing 14,768 casks in the proposed Yucca Mountain geological repository (U.S. Department of Energy, Office of Civilian Radioactive Waste Management, Department of Energy, May, 2001, DOE/RW-0533.) and an estimated cost of $1.16 billion to construct 180 km of emplacement drifts *(Report to Update Total System Life Cycle Cost Estimates for Site Recommendation/License Application*, TRW Environmental Safety Systems Inc. Department of Energy, TDR-CRW-SE-000001 REV 1,1999); *Analysis of the Total System Life Cycle Cost of the Civilian Radioactive Waste Management Program*, Office of Civilian Radioactive Waste Management, Department of Energy. DOE/RW-0510, 1998).

13. We assume that the cost would be 10 percent higher than that quoted for the "first generation" storage MOX.

14. For the isotopic content of uranium and plutonium in fresh and spent fuel at these burnups, see *Plutonium Fuel: An Expert Assessment* (Nuclear Energy Agency of the Organization for Economic Cooperation and Development, 1989). The enrichment of LEU fuel for 43 MWd/kg burnup is given there as 3.7 percent. For enrichment tails of 0.3%, the corresponding amount of natural uranium feed required is 8.3 and 10.0 kg, respectively, and the enrichment work required is 4.7 and 6.1 SWU, respectively. The fissile content of the plutonium also depends upon the period of storage of the spent fuel from which it was recovered because of the short half-life (14.4 years) of Pu^{241}. We have assumed 10 years of storage before reprocessing.

15. About 34 tons of U.S. weapons plutonium is to be made into MOX fuel for an estimated net cost of about $2.4 billion in constant 2001 dollars or about $70 million per ton, even after taking into account an estimated savings of $733 million in low-enriched uranium fuel ($22,000/kgPu). This cost includes $1.4 billion for R& D and "pre-capital" and construction costs for the MOX-fuel fabrication facility, $1.2 billion for 12 years of operation, and 0.5 billion for "contingencies," which we assume is divided equally between the capital and operations costs. Not included here is an additional estimated cost of about $1.7 billion for extracting the plutonium metal from weapon "pits" and converting it into oxide suitable for making into MOX. We have also excluded an "HEU credit" of $231 million assigned in the report to the MOX facility from the disposition of HEU recovered during pit dismantlement ("Revised plutonium disposition strategy").

16. The most recent estimate of the net cost is $1.5 billion, where the main costs are $1.4 billion for MOX fuel fabrication, storage and transport ($0.46 billion for R&D and construction, $0.66 billion for operation for 17 years, $0.19 billion for storage, and $0.12 billion for transport) and $0.3 billion for adaptation of seven Russian reactors so that they can use MOX fuel. These costs are partially offset by estimated savings of $345 million from displacement of low-enriched uranium fuel ($10,000/kgPu). Not included here is an additional estimated cost of $310 million for conversion of plutonium metal into oxide. *Cost Estimates for the Disposition of Weapon-grade Plutonium Withdrawn from Russia's Nuclear Military Program*, Joint U.S.-Russia Working Group, March 2001, p. 7.

17. Janberg, Spilker, "Status of the Development of Final Disposal Casks and Prospects in Germany." For 5.3% fissile plutonium in fresh MOX, the authors get $k_{eff} = 0.84$ when the cask is flooded. To check our model of the cask, we did the same calculation and got 0.85.

18. See, e.g., the discussion developed for the Yucca Mountain Project, *Disposal Criticality Analysis Methodology Topical Report* document YMP/TR-004Q, Revision 0, November 1998, <http://www.ymp.gov/documents>.

19. The criticality calculations were done with MCNP4 (Los Alamos National Laboratory, *Monte Carlo N-Particle Transport Code System*, Radiation Safety Information Computational Center, document CCC-660 MCNP4B2, 1998). The fuel was assumed to be in a hexagonal array with a center-to-center spacing of 1.17 cm, have an active length of 3.9 meters, a gas plenum of 0.64 m and a density of 10.4 and 10.5 grams/cc for the LEU and storage MOX, respectively (95% theoretical density). The cask top and bottom were assumed to be of steel 45 and 53 cm thick, respectively. The fuel pellet diameter was taken as 0.91 cm, and the inner and outer diameters of the zircalloy-4 as 0.93 cm and 1.076 cm, respectively. The storage MOX was assumed to be a mixture of 15 percent plutonium and 85 percent depleted uranium (0.2 percent U-235) dioxide with the plutonium having isotopics associated with spent LEU fuel with 43 MWd/kgHM burnup after 10 years storage. The spent LEU fuel mixed with the storage MOX was taken to have an initial enrichment of 3.7 percent and a burnup of 43 MWd/kg.

20. Lawrence Livermore National Laboratory, Westinghouse Savannah River Company, Argonne National Lab, Pacific Northwest National Lab, *Integrated Development and Testing Plan for the Plutonium Immobilization Project* [LLNL, UCRL-ID-131608, Rev. 3, PIP-00-035, March 2000, <http://library.llnl.gov>], Table 2.1.

21. For one atom of each poison per atom of fissile plutonium or 0.66 gm Gd and 0.75 gm Hf per gm of fissile plutonium. We assume Gd and Hf would cost about $0.5 and $0.2 dollars per gram, respectively, <http://minerals.usgs.gov/minerals/pubs/metal_prices>.

22. Recall that the estimated cost of storage MOX increased by 10% per rod as the fissile content increased from about 6% to 10%.

23. For 100% storage MOX, k_{eff} for the cask flooded and dry was calculated to be 0.68 and 0.78, respectively. Without the neutron poisons, the k_{eff}s rose to 1.02 and 0.85, respectively.

24. MOX fuel designed for a burnup of 43 MWd/kgHM contains about 4.6 percent fissile plutonium. The isotopic percentages assumed for the plutonium in spent LEU fuel, spent MOX fuel (both with burnups of 43 MWd/kgHM), and storage MOX made out of plutonium separated from 10-year-old spent LEU fuel with a burnup of 43 MWd/kgHM are (see also *Plutonium Fuel: An Assessment*):

	Pu-238	Pu-239	Pu-240	Pu/Am-241	Pu-242
Spent LEU fuel	2.0	52.5	24.1	15.2	6.2
Spent MOX fuel	2.8	37.4	32.6	18.2	9.0
Storage MOX	2.1	55.8	25.6	9.9	6.6

In the longer term, the combined thermal outputs from the greater quantities of long-lived isotopes in the storage MOX and spent LEU fuel is greater than that from the spent MOX fuel. The ratio is 1.1 at 1000 years, 1.5 at 5000 years, 1.8 at 20,000 years, and 1.3 at 100,000 years. However, between 1000 and 100,000 years, the thermal output of a ton of spent MOX fuel declines from 380 to 5 Watts/tHM.

25. Even for reducing repository environments, such as that produced by salt, localized oxidizing conditions may be produced by hydrolysis of pore water near the waste package. Thus, oxidation of MOX is a concern for all repository environments. L. H. Johnson, L. O. Werme, "Materials characteristics and dissolution behavior of spent nuclear fuel,"

Bull. Materials Research Soc., December 1994, pp. 24–27; A. Loida, B. Grambow, H. Geckeis, "Anoxic corrosion of various high burnup spent fuel samples," *Jour. Nuclear Materials*, 238, (1996), pp. 11–22; B. Grambow, A. Loida, E. Smailos, J. Kim, B. Grambow, "Geochemical assessment of actinide isolation in a German salt repository environment," *Eng. Geology*, 52 (1999), pp. 221–230.

26. *Spent-Fuel Standard for Disposition of Excess Weapon Plutonium: Applications to Current DOE Options* (National Academy Press, 2000, <http://www.nap.edu/catalog/9999.html>), p. 10.

27. One reviewer suggested that the storage MOX rods and spent LEU rods might be distinguished by their heat output. The heat output of spent LEU fuel with 43 MWd/kgHM burnup 10 years after discharge is about 1.5 Watts/kgHM and that of storage MOX is about 2.7 Watts/kgHM. For a fuel-rod diameter of 1.076 cm, the fuel-rod surface area per kg would be 380 cm^2/kg and the heat outputs of the spent LEU fuel and storage MOX would be 0.0039 and 0.0071 Watts/cm^2, respectively. For a black body in equilibrium in a 20°C environment, that would correspond to temperatures of about 26°C and 32°C for the spent LEU fuel and storage MOX, respectively. Measuring these few degrees difference in a complex thermal environment would probably be more difficult than distinguishing the rods by their gamma emissions.

28. The dose rate 1 meter from the bottom end of a single PWR LEU spent fuel assembly with 30 MWd/kgHM burnup at 10 years was calculated as 630 rem/hr, including the shielding effect (reduction factor of about 2) of the 1.5-cm thick stainless steel bottom plate. W. R. Lloyd, M. K. Sheaffer, W. G. Sutcliffe, *Dose Rate Estimates from Irradiated Light-Water-Reactor Fuel Assemblies in Air*, (Lawrence Livermore National Laboratory, UCRL-ID-115199, 1994). A Pollux cask containing 2/3 LEU spent fuel would hold the equivalent of 6.7 fuel assemblies of spent fuel. A dose above 650 rads is almost always lethal, even with hospitalization and heroic medical treatment. *Sources and Effects of Ionizing Radiation, Vol. II: Effects*, Annex J, "Exposures and Effects of the Chernobyl Accident" (New York: United Nations, 2000) Table 11.

29. J. Carson Mark, "Explosive properties of reactor-grade plutonium," *Science & Global Security* 4, (1994), p. 111; *Management and Disposition of Excess Weapons Plutonium* (Washington, DC: National Academy Press, 1994), p. 32; *Nonproliferation and Arms Control Assessment of Weapons-usable Fissile Material Storage and Excess Plutonium Disposition Alternatives* (U.S. Department of Energy, 1997), p. 37.

30. "Cogema aims to close Cadarache soon, move MOX fuel fabrication to Melox, "*Nuclear Fuel*, April 2, 2001; Cogema hopes to increase throughput at Melox MOX fuel fabrication plant," *Nuclear Fuel*, April 30, 2001; "U.K. decision to allow SMP to operate prompts Irish, Norwegian objections, *Nuclear Fuel*, Oct. 15, 2001.

31. "MOX Plant Construction Plan," *Nuke Info Tokyo*, Jan./Feb. 2001.