

The Future of Plutonium Disposition

In 2000 the United States and Russia signed a Plutonium Management and Disposition Agreement (PMDA),¹ in which each side agreed to dispose of at least 34 tons² of weapons plutonium made surplus by the reductions in its Cold War nuclear arsenal. President Barack Obama has described the combined 68 tons of plutonium as enough “for about 17,000 nuclear weapons.”³

In part, the PMDA was intended to demonstrate to other member states of the nuclear Nonproliferation Treaty that the large cuts in the Soviet and U.S. warhead stockpiles at the end of the Cold War were irreversible. An additional U.S. motivation was to minimize the risk that the plutonium made excess by the warhead reductions, especially in Russia, might become a target of nuclear theft.

The PMDA is in the news again today because the Obama administration announced in April in the Department of Energy budget request to Congress

for fiscal year 2014 that the “current [U.S.] plutonium disposition approach may be unaffordable...due to cost growth and fiscal pressure” and that the administration “will assess the feasibility of alternative plutonium disposition strategies.”⁴ As detailed below, there are other issues in addition to funding that have arisen in connection with the U.S. and Russian plutonium disposition programs. The administration and congressional reviews of the program should deal with as many of these issues as possible without compromising the

overall objective of reducing the global stockpile of weapons-usable separated plutonium.

Background

In the 2000 agreement, the United States committed to disposing of 75 percent of the 34 tons of plutonium by using it in mixed-oxide (MOX) fuel—so called because it is a mixture of uranium and plutonium oxides—and irradiating the MOX fuel in light-water reactors. The remaining 25 percent, which the United States judged too impure to use for MOX fuel fabrication, was to be “immobilized,” that is, it would be embedded in fission-product waste from military reprocessing plants at the Savannah River Site in South Carolina as that waste was “vitrified,” or mixed with molten glass.

Beyond the 34 tons of material covered by the PMDA, the United States also has declared excess an additional nine tons of plutonium from warhead pits and 12 tons of unirradiated plutonium that is impure, not weapons grade, or both.

Russia consented to the U.S. “dual track” plan although it had reservations about immobilization because, unlike irradiation of MOX fuel, it would not alter the isotopic mix of the plutonium from weapons grade. Yet, it is the view of

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The partially completed facility in South Carolina for turning excess U.S. weapons plutonium into mixed-oxide fuel for nuclear power reactors is shown in this March 29 photo. The U.S. government is reassessing its plans for the facility.

the U.S. nuclear weapons establishment that changing the isotopic mix of plutonium to that in power reactor spent fuel has little effect on the ability of an advanced nuclear-weapon state to utilize the plutonium for weapons.⁵

For its part, Russia was interested in using its excess weapons plutonium to fuel liquid-sodium-cooled fast-neutron reactors that had not yet been built. The United States argued that this would unduly delay disposition, and Russia reluctantly agreed to dispose of its plutonium in parallel with the United States, mostly in MOX fuel in existing water-cooled power reactors.

In 2002 the Bush administration decided to cancel one of the two U.S. tracks as a cost-saving measure. Internal Energy Department analyses found that immobilization would be less costly than irradiation of MOX fuel. In view of Russia's objection to immobilization, however, the department concluded that it had to choose the more costly MOX option. Elimination of the immobilization track reduced costs, but the need to add chemical processing lines to remove troublesome impurities from plutonium that originally had been slated for immobilization is one of many reasons for the subsequent cost escalation

of the MOX program from an estimated total cost of \$3.1 billion (\$3.9 billion in 2012 dollars)⁶ to \$18 billion for the plant and its operations during disposition of the 34 tons of plutonium.

To implement the agreement, both countries needed to construct costly facilities to fabricate MOX fuel and to adapt operating reactors to utilize it. Without full external funding, however, Russia was not willing to pursue a plan it did not fully support. As the estimated costs of both MOX plants increased, the funding that the United States and its allies were willing to commit to Russia for this purpose became insufficient.

In 2010, therefore, Russia and the United States concluded a revision of the PMDA under which Russia would be allowed to use its excess weapons plutonium to fuel its operational BN-600 and under-construction BN-800 demonstration fast-neutron reactors. In the revised PMDA, the United States committed to support and monitor the Russian plutonium-disposition program with up to \$400 million "subject to the U.S. budgetary review process and the availability of appropriated funds." At least \$100 million of this amount is reserved, however, for activities relating to verification of the disposition of

Russia's plutonium.⁷

The National Nuclear Security Administration (NNSA)—the semiautonomous arm of the Energy Department whose responsibilities include the plutonium-disposition program—has opened negotiations with Rosatom, the government-owned company that runs Russia's nuclear-energy and nuclear weapons programs, on "milestones" at which installments of the \$400 million could be disbursed.⁸ Thus far, however, Russia has been financing by itself the construction of a MOX fuel fabrication facility at Zheleznogorsk for its fast-neutron reactors.

The intention of Russia's nuclear establishment is to use its fast-neutron reactor program to launch what Glenn Seaborg, chairman of the U.S. Atomic Energy Commission during the 1960s, called a "plutonium economy" in which plutonium would be used to fuel fast-neutron "breeder" reactors that would produce more plutonium than they fissioned and in whose fuel cycle the plutonium would be separated and recycled indefinitely.⁹

Therefore, Russia does not intend the disposition of its excess weapons plutonium to be permanent. The revised

PMDA commits Russia, however, to not re-separate the plutonium covered by the agreement until all 34 tons have been irradiated. Before that time, Russia can reprocess up to 30 percent of the fuel discharged by the BN-800, provided that it was made with plutonium other

Japan, reprocesses its spent fuel.

When the Clinton administration committed to a MOX program in 1997, it tried to make clear that the U.S. MOX plant should not be seen as a justification for the separation and recycling of plutonium, the approach that France has

the preliminary cost increases and the current budget environment," the administration is conducting an assessment of alternative plutonium disposition strategies in fiscal year 2013 and identifying options for fiscal years 2014 and onward. As a result, the NNSA

All [the direct-disposal] options would avoid the costs and risks of transport, storage, and utilization of unirradiated MOX fuel.

than disposition plutonium. Russia has been separating an average of 1.4 tons of civilian plutonium per year at its Mayak reprocessing plant since 1996 and, as of the end of 2011, had 50 tons of separated civilian plutonium in addition to its excess weapons plutonium.¹⁰ At this point, the primary way in which the PMDA is affecting Russia's plutonium program is by assuring that Russia will use its excess weapons-grade plutonium in breeder reactor fuel before its civilian "reactor-grade" plutonium.

The United States began construction of its MOX fuel fabrication facility in 2007 at the Energy Department's Savannah River Site. As work progressed, however, the estimated cost of the U.S. MOX program continued to grow rapidly, and in April 2013, the Obama administration decided to look at alternatives. The British and Japanese also have encountered major problems with their MOX programs, and even France's program is not problem free (see sidebar, page 12).

Decisions about plutonium disposition have been and are being made in the context of a 40-year-old international debate over the proliferation implications of civilian spent fuel reprocessing, that is, the separation of plutonium from spent power-reactor fuel and its use in fresh fuel. That debate was triggered by India's use in its 1974 "peaceful nuclear explosion" of plutonium nominally separated for breeder reactor research and development. In part due to U.S. diplomatic efforts¹¹ and the poor economics of separating plutonium and recycling it into reactor fuel, today only one non-nuclear-weapon state,

taken.¹² Areva, the French government-owned company that designed and has been a lead contractor for the U.S. MOX plant, apparently has not accepted the U.S. policy. Areva lobbied the Bush administration to buy a reprocessing plant and has been encouraging the employees and neighbors of the Savannah River Site to think of the MOX program as a first module in a massive, commercial spent fuel reprocessing program that would guarantee the site's future.¹³

U.S. Reassessment

In April 2013, the Obama administration revealed that, as the result of a "bottom-up review" of the MOX project, the project contractor, Shaw Areva MOX Services, had found that the estimated cost for building the MOX facility had increased from \$1.1 billion in 2002 and \$4.8 billion in 2008 to \$7.7 billion in 2013. The NNSA estimates that the facility is 60 percent complete. As noted above, the estimated total cost for disposing of the 34 tons of excess U.S. plutonium covered by the PMDA, including the costs of operating the MOX facility but not the cost of extracting the plutonium from excess weapons "pits" or the cost of disposing of the spent MOX fuel, has climbed to \$18 billion.¹⁴ (Extracting the plutonium from the pits will be a very costly project in its own right. The costs may partly depend on which disposition option the United States chooses, but this article does not discuss those costs.)

In its detailed justification for its budget request for fiscal year 2014, the NNSA announced that "considering

"will slow down the MOX project and other activities associated with the current plutonium disposition strategy during the assessment period."¹⁵

The Senate delegations from South Carolina and Georgia have come to the defense of the MOX project and wrote a letter to Obama on May 13 threatening retaliation on his legislative agenda and against confirmation of his appointees if the MOX program does not move forward.¹⁶

There are at least three reasons for concern about the current direction of the program other than the cost escalation of the MOX plant. First, the Energy Department has not been able to find a utility to use the MOX fuel. Duke Energy originally agreed, but then backed out in 2008. The government-owned Tennessee Valley Authority signed a letter with Shaw Areva in July 2009 expressing "an interest in using MOX fuel as an alternate fuel." There have been some technical studies, but no progress toward an agreement has been reported since.

Second, MOX supporters have succeeded in persuading the U.S. Nuclear Regulatory Commission (NRC) to weaken its physical protection standards for MOX fuel at reactor sites and have been lobbying for reduced security requirements for transport of MOX fuel and at the MOX plant itself.¹⁷ These actions are troubling because a fresh MOX fuel assembly for a pressurized water reactor would contain enough plutonium to make more than three Nagasaki bombs.¹⁸ In addition, the NRC Atomic Safety and Licensing Board is reviewing arguments that the plant's design, based on Areva's facilities in France, makes it impossible to

maintain strict compliance with certain NRC material control and accounting regulations, for example, the requirement that items containing two kilograms or more of plutonium be inspected on a periodic basis to verify their presence and integrity.¹⁹ Such corner-cutting undermines U.S. efforts to strengthen the security of nuclear weapons-usable materials worldwide.

Third, Russia and the United States agreed in their 2000 PMDA that the International Atomic Energy Agency (IAEA) would verify their plutonium disposition once the plutonium was in unclassified form, but negotiations with the IAEA on the verification arrangements have stalled. In April, at the 2013 Carnegie International Nuclear Policy Conference, IAEA Director-General Yukiya Amano could only report that “[r]ounds of discussions have taken place. And we are continuing these efforts.”²⁰

The PMDA will have to be renegotiated again if the United States decides not to proceed with its costly MOX program and switches to direct disposal of the plutonium without irradiation in a reactor. Because it is not a treaty, it can be changed simply by mutual agreement in writing. A first meeting between U.S. and Russian negotiators to discuss the potential need for changes to the agreement took place on April 25.

Alternatives to the MOX Program

The two main alternatives to the use of reactor fuel for plutonium disposition are continued storage and direct disposal.²¹ Each of these could be the subject of an in-depth analysis with regard to cost, technical readiness, occupational risks, security from diversion, verifiability, and perceptions of irreversibility on the parts of Russia and the rest of the concerned international community. The description and analysis below are intended to serve as a brief overview and introduction to the policy discussion.

With regard to storage, most U.S. excess plutonium currently is in weapons pits stored inside insulated double containers in bunkers at the Energy Department’s Pantex warhead assembly-disassembly plant outside Amarillo, Texas. Most of the remaining plutonium covered by the PMDA is among the 13 tons stored, mostly in the form of plutonium dioxide



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Secretary of State Hillary Rodham Clinton and Russian Foreign Minister Sergey Lavrov pose for photographers after signing a protocol to the Plutonium Management and Disposition Agreement in Washington on April 13, 2010. Under the protocol, Russia can use its excess weapons plutonium as fuel in fast-neutron reactors.

powder, in double-walled containers in the K-Area Material Storage facility, located in an old reactor building at the Savannah River Site.²² These storage arrangements are relatively safe and secure and could continue for a decade or more, but they are not a permanent solution.

With regard to direct disposal, the alternatives include disposal in the Energy Department’s Waste Isolation Pilot Plant (WIPP), immobilization with high-level reprocessing waste, and immobilization in a ceramic matrix and disposal in a deep borehole.

All these options would avoid the costs and risks of transport, storage, and utilization of unirradiated MOX fuel. The immobilization options, however, would require interim storage pending geological disposal.

Disposal in WIPP. The Energy Department already is disposing of plutonium-contaminated waste in caverns mined out of a salt deposit 650 meters under southeast New Mexico. About five tons out of a projected total of 10 tons of plutonium in waste had been emplaced there as of 2009.²³

In addition, the Energy Department has approved the shipment of up to 0.585 tons of contaminated plutonium to

WIPP from the Savannah River Site after converting it into oxide powder, diluting it with a classified “inert” material, and placing it in double-walled containers for a resulting container volume of 1.4 cubic meters per kilogram of plutonium.²⁴ An official at the Savannah River Site has estimated that this disposal route costs about \$100,000 per kilogram of plutonium, about one-fifth of the current per-kilogram cost estimate for the MOX project.²⁵

The work of diluting and packaging the waste plutonium is being done in the Savannah River Site HB-line glove box facility.²⁶ Operating on a one-shift basis, the throughput of this facility would be 0.6 tons per year.²⁷ The HB line is not a “Category 1” facility with security arrangements for processing weapons quantities of plutonium. As a small facility, perched on top of the H-Canyon reprocessing building, however, it might be possible to upgrade it to Category 1.

The Energy Department could dispose of more plutonium in this manner, but as of the end of fiscal year 2013, about 85,000 cubic meters of plutonium-contaminated waste already had been emplaced in WIPP,²⁸ half of the limit of 175,600 cubic meters of transuranic waste that the Waste Isolation Pilot Plant Land Withdrawal Act of 1996 imposes. The

Plutonium Disposition: The International Context

The original reason for industrialized-country initiatives to launch large-scale civilian reprocessing in the 1970s was to obtain plutonium fuel to start up liquid-sodium-cooled plutonium “breeder” reactors that were to be deployed by the thousands by the year 2000. In fact, breeders were not deployed. They were found to be costly and unreliable, and they were a solution to a problem of costly uranium that did not materialize. Of the 31 countries with operating nuclear power plants today, only India and Russia are building new demonstration breeder reactors (one each). Due to institutional inertia, four more countries are still separating plutonium in civilian spent fuel reprocessing programs. France is reprocessing on a large scale and China on a small scale. The United Kingdom recently decided to wind down its large reprocessing program.¹ Japan, after 20 years of construction and fixing problems, has just completed a large reprocessing plant.

As a result of these civilian plutonium programs, France, Japan, and the United Kingdom, in addition to Russia and the United States, have large stockpiles of excess separated plutonium. All have encountered problems with their programs to use mixed-oxide (MOX) fuel.

France is separating about 10 tons of plutonium a year in its reprocessing facilities at La Hague. It is fabricating much of that plutonium into MOX fuel at its Melox facility in Marcoule. However, France’s stockpile of unused separated civilian plutonium has grown from one ton in 1988 to about 60 tons, plus about 23 tons of plutonium from reprocessing foreign spent fuel, as of 2011.² Recently, another cloud developed over the future of France’s MOX program when the Hollande administration committed to reducing the share of France’s electricity generated by nuclear power from 75 percent to 50 percent by 2025. The 24 French nuclear power reactors that are licensed to use MOX fuel are France’s oldest and therefore could be retired by this plan.

Japan has accumulated a stockpile of 44 tons of separated plutonium, mostly in France and the United Kingdom, to which it sent spent fuel for reprocessing in the 1990s.³ In 2001, France began shipping MOX fuel back to Japan. Due to safety concerns, however, there was considerable local opposition to loading the fuel, and only 2.5 tons of plutonium had been loaded as of the time of the March 2011 accident at the Fukushima Daiichi nuclear reactors. As Japan’s utilities seek to get permission to restart their reactors, none is known to be planning on loading fresh MOX fuel.⁴

Operating at design capacity, Japan’s new reprocessing plant in the village of Rokkasho would separate about eight tons of plutonium per year. If the reprocessing plant begins commercial operations next year as currently planned, Japan’s domestic stockpile of separated plutonium will grow very rapidly.

The United Kingdom had about 90 tons of its own civilian separated plutonium as of 2011, plus 28 tons of foreign plutonium, primarily Japanese.⁵ Starting in 2001, the United Kingdom operated a MOX plant at its Sellafield reprocessing site to fabricate MOX fuel for its foreign reprocessing customers, but the plant was able to produce at an average of only about 1 percent of its design capacity and was abandoned in 2011. The currently preferred plan of the British Department of Energy and Climate Change is to have Areva build a new MOX plant in the United Kingdom, but a final decision cannot be made until contracts to use the MOX fuel that it would produce can be signed.⁶ This process will take years because the United Kingdom currently has only one light-water power reactor, which could absorb only about half a ton of plutonium in MOX fuel per year.⁷ The British government currently is trying to provide incentives to foreign vendors to build additional light-water reactors in the United Kingdom to replace its aging gas-cooled reactors.—FRANK VON HIPPEL

ENDNOTES

1. UK Nuclear Decommissioning Authority, “Oxide Fuels: Preferred Option,” SMS/TS/C2-OF/001/Preferred Option, June 2012.
2. IAEA, “Communication Received From France Concerning Its Policies Regarding the Management of Plutonium,” INFCIRC/549/Add.5/16, 2012.
3. IAEA, “Communication Received From Japan Concerning Its Policies Regarding the Management of Plutonium,” INFCIRC/549/Add.1/15, 2012.
4. Masako Toki and Miles Pomper, “Time to Stop Reprocessing in Japan,” *Arms Control Today*, January/February 2013.
5. IAEA, “Communication Received From the United Kingdom of Great Britain and Northern Ireland Concerning Its Policies Regarding the Management of Plutonium,” INFCIRC/549/Add.8/15, 2012.
6. UK Department of Energy and Climate Change, “Management of the UK’s Plutonium Stocks: A Consultation Response on the Long-Term Management of UK-Owned Separated Civil Plutonium,” December 1, 2011, https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/42773/3694-govt-resp-mgmt-of-uk-plutonium-stocks.pdf.
7. Sizewell B, the United Kingdom’s only LWR, requires about 20 tons of uranium in its fuel per year. LWRs not specifically designed to use MOX fuel typically can replace only about one-third of their conventional fuel assemblies with MOX fuel assemblies containing about 6 to 8 percent plutonium.

Energy Department has said that WIPP has only 19,700 cubic meters of space that is not already allocated for identified waste at the department's sites.²⁹ At 1.4 cubic meters per kilogram, this space could accommodate an additional 14 tons of plutonium. It would take a 25 percent increase in the WIPP volume limit to accommodate the remaining 31 tons of plutonium that the United States has declared excess.³⁰ Yet, raising the volume limit on WIPP would be controversial in New Mexico and in Congress.

In an influential 1994 study of plutonium disposition options by the National Academy of Sciences (NAS), considerable emphasis was put on the "spent fuel standard."³¹ The idea was that disposition plutonium should be embedded in a waste form that generates a "self-protecting" gamma radiation barrier like that surrounding the plutonium in spent fuel. The waste packages in WIPP do not have such a radiation barrier.

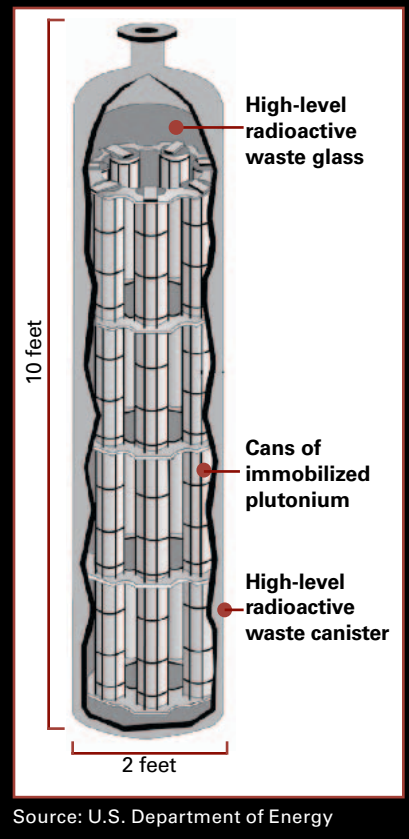
The Energy Department now argues that emplacing excess plutonium in WIPP protects plutonium "from theft, diversion, or future reuse in nuclear weapons akin to that afforded" by the spent fuel standard.³² The department should provide further justification for this assertion. In any event, until the WIPP repository is closed, the security there of the excess plutonium being processed into containers at the Savannah River Site will depend on active monitoring to assure that none of the inner canisters holding the plutonium are removed.

Another concern with the current arrangements for WIPP is the lack of IAEA verification of the amount of plutonium being entombed there. As the first country disposing of significant quantities of plutonium in an underground repository, the United States should be setting an example of international transparency. IAEA verification of the amount of plutonium being deposited in WIPP and the absence of its diversion thereafter should be added to the current plan for disposal of plutonium-contaminated waste and any plan for disposal of additional plutonium in WIPP.

Immobilization with high-level

Figure 1: The Can-in-Canister Method

In the can-in-canister method of plutonium disposal, 28 cans of ceramic or glass, each containing about one kilogram of excess weapons plutonium, would be placed in a canister. The cans would be surrounded by glass containing radioactive reprocessing waste at the Department of Energy's Savannah River Site in South Carolina.



reprocessing waste. The immobilization option proposed in the 1994 NAS study was to mix plutonium into high-level radioactive waste as the waste was being mixed into molten glass.³³ The Energy Department concluded, however, that plutonium could not simply be metered into the existing melter at the Savannah River Site. The department opted for a "can-in-canister" approach in which the plutonium first would be immobilized in cans of glass or ceramic. Those cans would be placed on a rack inside standard canisters after which molten high-level-waste glass would be poured into the canisters (see figure 1). In that conception, each canister would hold

about 28 kilograms of plutonium.³⁴

This option is still very much available. At 28 kilograms of plutonium per canister, it would take 2,000 canisters to dispose of 56 tons of plutonium. In fiscal year 2012, 275 canisters were filled at the Savannah River Site, bringing the cumulative total of canisters filled with high-level waste there to 3,526.³⁵ Yet, only a small fraction of the cesium-137 originally in the waste tanks at the Savannah River Site has been vitrified.³⁶ The cesium-137 would provide a protective gamma-radiation barrier around the canisters containing the immobilized plutonium. There is therefore still enough cesium-137 available at the Savannah River Site for a few thousand canisters of immobilized plutonium.

A facility for producing the cans of immobilized plutonium would be required. In the past, the Energy Department has identified facilities such as the K-Reactor building at the Savannah River Site that could be adapted for this purpose. This building would be convenient because it currently is the site's plutonium-storage facility. Alternatively, the department could consider repurposing the partly constructed MOX fuel fabrication facility for plutonium immobilization. It is likely that only a part of the building would be required because immobilization does not require that the plutonium feed be purified as extensively as for fabrication into MOX fuel.

Immobilization without high-level waste. Plutonium could be embedded in a ceramic matrix and then stored securely pending disposal. One option for disposal could be putting the immobilization form inside a welded-shut container with spent fuel and emplacing the container in a deep repository. Alternatively, the Energy Department could dispose of the immobilization form in boreholes, three to five kilometers deep, from which retrieval would be extremely difficult. The NAS study addressed this option two decades ago, but, at the time, considered it "less fully developed" than vitrification and MOX fuel fabrication.³⁷ There has been continuing interest in a number of countries in deep boreholes for disposal of radioactive waste, and the Energy

Department is currently examining this approach as an alternative to a mined repository for disposal of spent fuel.³⁸

Optimized immobilization forms have been developed in which the radiation damage to the crystal structure of the ceramic would be self-healing and that would release plutonium very slowly into the water that would be expected to seep into a deep geological repository or borehole.³⁹

The United Kingdom is currently constructing a facility to immobilize contaminated plutonium in ceramic using a hot isostatic pressing process that takes eight to nine hours to turn a container of powder into a smaller ceramic cylinder with a volume of five liters.⁴⁰ Such a cylinder of ceramic could easily accommodate two kilograms of plutonium. For a single cylinder per shift, operating one shift 250 days per year, it would be possible to immobilize 0.5 tons of plutonium a year.

At the moment, the United Kingdom expects to immobilize less than a ton of plutonium in this way, but the program could be expanded to immobilize all of the approximately 100 tons of separated plutonium that the United Kingdom has to dispose of.

A variant of this option would be to utilize portions of the MOX fuel fabrication facility in South Carolina to produce what a British screening study described as “low-specification” MOX fuel: sintered fuel pellets that are not chemically pure or fabricated to the rigorous quality assurance standards required for reactor fuel.⁴¹ These pellets could be put in tubes for disposal with spent fuel or embedded in a larger matrix for disposal down a deep borehole.

Conclusion

The Obama administration’s April announcement that it is “conducting an assessment of alternative plutonium disposition strategies” is welcome news. It is indeed time to look seriously at the alternatives. Given the commitment that the Energy Department’s Office of Fissile Materials Disposition and Areva have to the MOX option, the administration, Congress, or both should require an independent study of the costs and benefits of the alternatives.

Based on the analysis above and

the data on which it draws, such an independent review probably will find direct disposal much less costly and simpler to execute than the current MOX strategy. A MOX pellet must be formed from chemically pure materials and ground to very precise dimensions.⁴² Because a single pellet contains less than a gram of plutonium, more than a million must be manufactured to dispose of a single ton of plutonium. By contrast, direct disposal of a ton of plutonium would require the production of only hundreds to thousands of immobilization forms with much less stringent chemical and mechanical specifications. Furthermore, as the NNSA, Japanese utilities, and the United Kingdom’s Nuclear Decommissioning Authority are learning, even after one has fabricated MOX fuel, finding a reactor to use it can be extremely difficult.

Finally, because Japan, the United Kingdom, and the United States all have encountered difficulties in executing MOX programs, it would make sense for them to collaborate in research and development on direct disposal options. The United States and Japan could, for example, learn from the United Kingdom’s ongoing program to immobilize its impure plutonium.

ENDNOTES

1. The official title is “Agreement Between the Government of the United States of America and the Government of the Russian Federation Concerning the Management and Disposition of Plutonium Designated as No Longer Required for Defense Purposes and Related Cooperation.” See <http://www.state.gov/documents/organization/18557.pdf>.

2. As used in this article, “tons” means “metric tons.”

3. Office of the Press Secretary, The White House, “Remarks by President Obama at Hankuk University,” March 26, 2012, <http://www.whitehouse.gov/the-press-office/2012/03/26/remarks-president-obama-hankuk-university>.

4. U.S. Department of Energy, fact sheet on fiscal year 2014 budget, April 10, 2013, <http://www.whitehouse.gov/sites/default/files/omb/budget/fy2014/assets/energy.pdf>.

5. “[A]dvanced nuclear weapon states such as the United States and Russia, using modern

designs, could produce weapons from reactor-grade plutonium having explosive yields, weight, and other characteristics generally comparable to those of weapons made from weapon-grade plutonium.” U.S. Department of Energy, “Nonproliferation and Arms Control Assessment of Weapons-Usable Fissile Material Storage and Excess Plutonium Disposition Alternatives,” DOE/NN-0007, January 1997, p. 39, http://www.osti.gov/bridge/product.biblio.jsp?osti_id=425259.

6. These figures do not include estimated credits of \$0.9 billion from sale of the mixed-oxide (MOX) fuel and from recovery of highly enriched uranium from composite pits. National Nuclear Security Administration (NNSA), “Report to Congress: Disposition of Surplus Defense Plutonium at Savannah River Site,” February 15, 2002, p. 5-9, table 5-3, <http://www.nci.org/pdf/doe-pu-2152002.pdf>.

7. For a copy of the PMDA revision, see <http://fissilematerials.org/library/PMDA2010.pdf>.

8. U.S. Department of Energy, “FY 2014 Congressional Budget Request: National Nuclear Security Administration,” DOE/CF-0084, April 2013, p. DN-112 (hereinafter NNSA 2014 budget request).

9. Glenn Seaborg, “The Plutonium Economy of the Future” (paper presented at the Fourth International Conference on Plutonium and Other Actinides, Santa Fe, New Mexico, October 5, 1970).

10. International Atomic Energy Agency (IAEA), “Communication Received From the Russian Federation Concerning Its Policies Regarding the Management of Plutonium,” INFCIRC/549/Add.9/14, November 23, 2012.

11. See Kurt Campbell, Robert Einhorn, and Mitchell Reiss, eds., *The Nuclear Tipping Point* (Washington, DC: Brookings Institution Press, 2004), pp. 262-263, 298-300.

12. U.S. Department of Energy, “Record of Decision for the Storage and Disposition of Weapons-Usable Fissile Materials Final Programmatic Environmental Impact Statement,” *Federal Register*, Vol. 62, No. 13 (January 21, 1997): 3014.

13. See Paul Murray, “Backend of the Fuel Cycle,” December 2012, <http://www.energy.sc.gov/gnac/AREVA.pdf> (presentation to the South Carolina governor’s Nuclear Advisory Council).

14. Derived from \$7.7 billion construction cost for the MOX fuel facility, \$8.2 billion for

operations and security costs over 15 years, \$0.4 billion for construction of the associated Waste Solidification Building, and \$1.9 billion for its operation over 20 years. NNSA 2014 budget request, pp. DN-119, DN-147, DN-148.

15. *Ibid.*, p. DN-119.

16. Office of Senator Lindsey Graham, "Obama Administration 'Jeopardizing' Partnership Between Savannah River Site and South Carolina, Georgia Over Plutonium Disposition," May 15, 2013, http://www.lgraham.senate.gov/public/index.cfm?FuseAction=PressRoom.PressReleases&ContentRecord_id=a8f99c66-ad7f-9e32-9326-c600d025ecac.

17. Edwin Lyman, "Is Dilution the Solution to the Plutonium Threat?" (paper for the Institute of Nuclear Materials Management 52nd Annual Meeting, Palm Desert, California, July 17-21, 2011), <http://allthingsnuclear.org/wp-content/uploads/2012/11/INMM2011paper-lyman1.pdf>.

18. A fuel assembly for a pressurized water reactor contains about 450 kilograms of heavy metal. MOX fuel made with weapons-grade plutonium would contain about 5 percent plutonium, which translates into about 20 kilograms of weapons-grade plutonium per fuel assembly. The Nagasaki bomb contained 6.1 kilograms of plutonium.

19. Edwin Lyman, "Material Control and Accounting Issues at the MOX Fuel Fabrication Facility," (paper for the Institute of Nuclear Materials Management 53rd Annual Meeting, Orlando, Florida, July 15-19, 2012).

20. In September 2010, Russia and the United States wrote to the IAEA "with the goal of preparing the necessary legally-binding verification agreements in 2011." IAEA, "Communication From the Permanent Missions of the Russian Federation and the United States of America Regarding a Joint Letter Regarding the Agreement Concerning the Management and Disposition of Plutonium Designated as No Longer Required for Defense Purposes and Related Cooperation," INF/CIRC/806, September 16, 2010. For Amano's statement, see <http://carnegieendowment.org/files/0410carnegie-opening-remarks-and-morning-keynote.pdf>.

21. The National Academy of Sciences (NAS) 1994-1995 study on plutonium disposition had an entire volume on the use of different reactor types as alternatives to the use of MOX fuel in existing light-water reactors (LWRs), but concluded that these alternatives had

no important advantages and that choosing reactors that did not yet exist would delay the program and make it more costly. NAS Committee on International Security and Arms Control, "Management and Disposition of Excess Weapons Plutonium: Reactor-Related Options," 1995, http://www.nap.edu/openbook.php?record_id=4754&page=R1.

22. Bill Bates, "Plutonium Storage and Consolidation" (presentation to the Citizen's Advisory Board Nuclear Materials Subcommittee, September 27, 2011), http://www.srs.gov/general/outreach/srs-cab/library/meetings/2011/fb/201109_pu.pdf.

23. NNSA, "The United States Plutonium Balance, 1944-2009," June 2012, pp. 8, 17 <http://fissilematerials.org/library/doi12.pdf>.

24. There are 150 grams of plutonium per 55-gallon container. Mike Swain, "Citizens Advisory Board: Update on H Area Operations," August 28, 2012, http://www.srs.gov/general/outreach/srs-cab/library/meetings/2012/nm/20120828_hcanyon.pdf.

25. Savannah River Site official, personal communication to Tom Clements, Augusta, Georgia, March 26, 2013.

26. A glove box is a sealed box within which workers can process dangerous materials, such as plutonium oxide powder, with their hands in gloves that cover holes in the walls. The air in the box is at less than ambient pressure so that any air leakage is into the box. Air leaking into the box is pumped out through high-efficiency particulate filters.

27. Allen Gunter, "Plutonium Ship to WIPP HB-Line Mission" (presentation to the Citizen's Advisory Board Nuclear Materials Subcommittee, September 30, 2011), http://www.srs.gov/general/outreach/srs-cab/library/meetings/2011/nm/20110830_putowipp.pdf.

28. U.S. Department of Energy, "FY 2014 Congressional Budget Request: Environmental Management," DOE/CF-0088, April 2013, p. EM-52.

29. NNSA, "Draft Surplus Plutonium Disposition Supplementary Environmental Impact Statement," DOE/EIS-0283-S2, July 2012, p. 2-25.

30. The U.S. stockpile in 1994 was 99.5 tons. Of that amount, 61.5 tons has been declared excess, including 9.6 tons already committed to WIPP and 7 tons in spent fuel, leaving 44.9 tons for disposal.

31. NAS Committee on International Security and Arms Control, "Management and Disposition of Excess Weapons Plutonium," 1994, p. 34, http://www.nap.edu/openbook.php?record_id=2345&page=R1 (hereinafter NAS 1994 plutonium disposition report).

32. NNSA, "Draft Surplus Plutonium Disposition Supplementary Environmental Impact Statement," p. S-14.

33. NAS 1994 plutonium disposition report, p. 187.

34. U.S. Department of Energy, "Surplus Plutonium Disposition: Final Environmental Impact Statement," DOE/EIS-0283, November 1999, p. 2-29.

35. U.S. Department of Energy, "FY 2014 Congressional Budget Request: Environmental Management," pp. EM-12, EM-227. The document's figure of 3,801 canisters filled by the Energy Department through 2012 includes 275 canisters from the cleanup of a small commercial reprocessing plant near West Valley, New York.

36. Steve Thomas, e-mail communication with Tom Clements, March 22, 2013.

37. NAS 1994 plutonium disposition report, pp. 196-199. See also William G. Halsey, "Disposition of Plutonium in Deep Boreholes," UCRL-JC-120995, 1995.

38. U.S. Department of Energy, "FY 2014 Congressional Budget Request," DOE/CF-0086, April 2013, p. NE-45.

39. W.J. Weber and R.C. Ewing, "Ceramic Waste Forms for Uranium and Transuranium Elements," in *Uranium: Cradle to Grave*, ed. Peter C. Burns and Ginger E. Sigmon (Quebec: Mineralogical Association of Canada, 2013).

40. J.W. Hobbs et al., "A Programme to Immobilise Plutonium Residues at Sellafield" (paper for the Institute of Nuclear Materials Management 53rd Annual Meeting, Orlando, Florida, July 15-19, 2012).

41. UK Nuclear Decommissioning Authority, "Plutonium: Credible Options Analysis (Gate A)," SMS/TS/B1-PLUT/002/A, 2010.

42. Office for Nuclear Regulation, UK Health and Safety Executive, "An Investigation Into the Falsification of Pellet Diameter Data in the MOX Demonstration Facility at the BNFL Sellafield Site and the Effect of This on the Safety of MOX Fuel in Use," February 18, 2000, paras. 84, 85, <http://www.hse.gov.uk/nuclear/mox/mox3.htm>.