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INTERNATIONAL PANEL
ON FISSILE MATERIALS

# Global Fissile Material Report 2007

## Second report of the International Panel on Fissile Materials

Developing the technical basis for policy initiatives to secure and
irreversibly reduce stocks of nuclear weapons and fissile materials

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# Developing the Technical Basis for Policy Initiatives to Secure and Irreversibly Reduce Stocks of Nuclear Weapons and Fissile Materials

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**On the cover:** the map shows existing and planned uranium enrichment and plutonium separation (reprocessing) facilities around the world. *See Figure 6.1 of this report for more details.*

# 3 Disposition of Excess Plutonium

During the Cold War, the Soviet Union and United States produced huge quantities of plutonium for weapons. In the early 1990s, following substantial cuts in their nuclear arsenals, Russia and the United States began discussing what to do with their excess weapon materials and, in 2000, concluded a Plutonium Management and Disposition Agreement (PMDA), committing each to eliminate 34 tons of excess weapon plutonium.[103]

The most urgent steps to be taken with this excess plutonium—and with all other separated plutonium worldwide—are to ensure that it is secure and under international monitoring to increase confidence that these stocks will not be used in weapons. In the longer term, however, these excess stocks should be physically transformed into forms from which it would be expensive and difficult to recover for use in weapons.

Applying disposition only to the 34 tons of plutonium in each country currently covered by the U.S.-Russian agreements would have little benefit for international security, however, unless it was a first step toward disposition of much larger quantities of excess plutonium. For Russia, 34 tons of plutonium represents about a quarter of its total stockpile of 120-170 tons of weapon-grade plutonium. For the United States, it is just over a third of its *total* stockpile of 92 tons of separated plutonium—including plutonium that is not weapon-grade (see Chapter 1). If the United States and Russia disposed of larger fractions of their plutonium stockpiles, it would make deep nuclear arms reductions more difficult to reverse and constitute a step toward fulfilling their Nonproliferation Treaty commitments. This would help build political support for strengthening the nonproliferation regime.

Disposition also could facilitate consolidation of excess plutonium into smaller numbers of secure sites.[104] It is not likely, however, that disposition of the 34 tons of excess weapon plutonium by each country will substantially reduce the risk of nuclear theft. This plutonium is some of the most secure in either country and some of the buildings where it resides are likely to still contain tons of plutonium when its disposition is complete. If the highest practicable standards of security and accounting are not maintained during processing and transport, in terms of the danger of theft, the disposition cure could be worse than the disease of excess stockpiles.

Unfortunately, disposition of the U.S. and Russian excess weapon plutonium has yet to begin. The original schedules on both sides have slipped by more than seven years and the estimated costs have more than doubled.

This chapter describes disposition options and assesses the Russian and U.S. programs. The discussion is also relevant to the problem of disposing of the world's growing stocks of separated civil plutonium—especially in the United Kingdom, which currently has no disposition plan.

**Plutonium Disposition Options**

Unlike highly enriched uranium (HEU), weapon-grade plutonium cannot simply be eliminated as a potential weapon material by dilution with a non-fissile isotope. All plutonium isotopes can support an explosive chain reaction and only plutonium-238, which is available in only relatively small quantities, is considered unusable for weapons. Nuclear weapon designers prefer to use weapon-grade plutonium, containing typically more than 90 percent Pu-239 because other isotopes generate far more heat and spontaneous neutrons. Nevertheless, even a simple Nagasaki-type design made from power reactor plutonium, which contains only 50-60 percent Pu-239, would have an assured yield in the kiloton range. Advanced nuclear weapon states can make nuclear weapons with reactor-grade plutonium that have yield, reliability, and weight comparable to those made from weapon-grade plutonium.[105] Table 3.1 lists the isotopics of typical plutonium compositions. Additional properties of plutonium are summarized in the Appendix to this report.

| | Pu-238 | Pu-239 | Pu-240 | Pu-241 | Pu-242 | Am-241 |
|---|---|---|---|---|---|---|
| Super-grade | – | 98.0% | 2.0% | – | – | – |
| Weapon-grade | 0.01% | 93.8% | 5.8% | 0.13% | 0.02% | 0.22% |
| Fuel-grade | 1.2% | 70.9% | 15.4% | 6.4% | 1.9% | 4.2% |
| Reactor-grade (33 GWd/t) | 1.3% | 60.3% | 24.3% | 5.6% | 5.0% | 3.5% |
| Reactor-grade (50 GWd/t) | 2.7% | 47.0% | 26.0% | 9.0% | 9.0% | 6.0% |
| MOX-grade | 1.9% | 40.4% | 32.1% | 10.7% | 7.8% | 7.1% |
| Fast breeder reactor blanket | – | 96.0% | 4.0% | – | – | – |

**Table 3.1. Isotopic contents of different plutonium grades.[106]**

An extensive two-volume study from the U.S. National Academy of Sciences (NAS), published in the mid-1990s, laid out potential plutonium-disposition options.[107]

One option would be to store excess inventories of separated plutonium indefinitely in high-security facilities, such as that built with U.S. assistance near the Mayak reprocessing facility in Russia[108] and its U.S. counterparts such as the Device Assembly Facility in Nevada (see Figure 4.2). The security of the plutonium would depend on the ceaseless vigilance of the responsible institutions, however, and it would remain available for remanufacture into nuclear weapons quickly and at low cost.

Beyond storage, the NAS, U.S.-Russian and G-8 studies all concluded that the two least problematic approaches would be:

- Mixing the plutonium with uranium, fabricating it into mixed oxide (MOX) fuel and irradiating the material in existing reactors, or

- Immobilizing the plutonium with high-level wastes (HLW).[109]

Both of these approaches would result in most of the plutonium being embedded in large, intensely radioactive waste forms from which it would be difficult and costly to recover. The NAS judged that, in these forms, the plutonium could be made roughly as inaccessible for weapon use as the much larger and growing quantity of plutonium in spent nuclear fuel, an objective they called the "spent fuel standard."[110]

Disposition begins with the weapon components that contain plutonium metal being cut up and the plutonium being separated from other materials and converted to an oxide (see Figure 3.1). A variety of mechanical or chemical processes can be used for doing this.

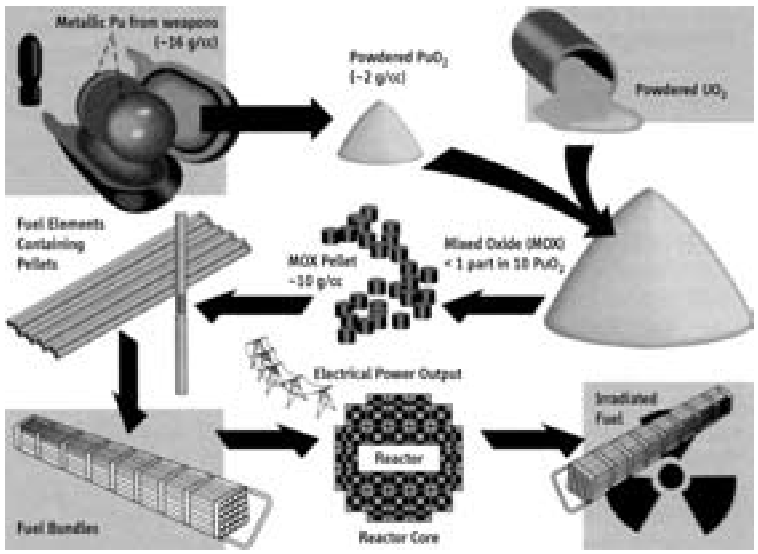


**Figure 3.1. Diagram of plutonium pit being cut up, the plutonium made into MOX fuel and the fuel being irradiated in a nuclear-power reactor.[111]**

The U.S. DOE is planning to build a large and expensive Pit Disassembly and Conversion Facility (PDCF) for this purpose at its Savannah River Site. It appears likely that Russia will do this work at existing facilities that have been used for manufacturing plutonium weapon components, primarily at the Mayak plutonium facility in the Urals. Plutonium from excess Russian pits is currently being moved into the Mayak storage facility after conversion into 2-kg metal balls. It would be turned into oxide just before fabrication into MOX.[112]

The plutonium declared excess by the United States also includes a variety of non-metallic forms ranging from oxide powders to fabricated fuel elements. Some may be too contaminated to be used as MOX fuel, and could be immobilized with radioactive waste.[113]

***MOX fuel.*** In the MOX fuel approach, the plutonium oxide would be mixed with uranium oxide, pressed, baked and ground into cylindrical ceramic pellets, and loaded into long metal tubes to make fuel rods. The fresh MOX fuel would contain 4-5 percent plutonium. After irradiation in a reactor, the spent MOX fuel would still contain about two thirds as much plutonium, but in large, intensely radioactive fuel assemblies that would require remotely-handled chemical processing to recover the plutonium.

MOX fuels are much more hazardous and expensive to fabricate than standard uranium. Also, handling a weapon-usable material like plutonium requires much more stringent safeguards and security than are required at a facility fabricating low-enriched uranium-fuel.[114]

How many reactors might be required for plutonium disposition? For a one-GWe light-water reactor (LWR) able to take a full core of MOX fuel, roughly one ton of plutonium would be loaded every year.[115] For safety reasons, however, almost all LWRs are limited to using MOX for only one-third of their cores, which reduces the amount of plutonium loaded per GWe-year by a factor of three. Fast-neutron reactors designed for full MOX cores can use fuel with much higher plutonium concentrations. They also fission a smaller fraction of the plutonium. As a result, Russia's demonstration 0.8 GWe BN-800 fast-neutron reactor, currently under construction, is expected to be able to irradiate some 1.6 tons of plutonium in MOX each year—as much as five 1-GWe LWRs operating with one-third cores.

***Immobilization.*** In the immobilization approach, the plutonium would be immobilized in either a glass (often called "vitrification") or a ceramic form.[116] The glass form would typically contain less than 10 percent plutonium by weight. Some ceramics might hold more. In most variants of the immobilization approach, fission products would also be included in the immobilized form.

Mixing plutonium and high-level waste (HLW) together into a homogeneous glass or ceramic poses challenges ranging from the need to avoid criticality to the difficulty of finding waste forms and production processes that can handle substantial concentrations of *both* plutonium and fission products. In recent years, the U.S. DOE therefore has focused on a "can-in-canister" approach, in which the plutonium is immobilized in cylinders of glass or ceramic. These cylinders fit into metal cans that are placed on a rack inside a large canister into which molten HLW glass is poured (see Figure 3.2). Thus, the immobilized plutonium would end up embedded in a large, intensely radioactive waste form that would be stored pending ultimate disposal in a geologic repository.

Another immobilization approach that has been proposed is referred to as "storage-MOX." In this option, MOX plants would fabricate MOX pellets without the stringent quality requirements required for reactor fuel, and tubes containing these pellets would be interspersed with spent fuel rods in disposal casks for storage and eventual disposal. The spent fuel would provide a radiation barrier that would make it more difficult to access the storage MOX.[117]

### Disposition of Russia's Excess Weapon Plutonium

Russia's nuclear-energy establishment has always seen its excess plutonium as an asset that should be used to produce energy. It has taken the view that, if other countries want Russia to burn weapon plutonium before it becomes an economic fuel for future fast-neutron reactors, then they should pay the full costs of doing so, including the design, construction and operation of facilities to produce MOX fuel, and the reactor modifications required to adapt existing Russian reactors to use it. The Russian-U.S. plutonium-disposition agreement of 2000 therefore committed the parties to seek international funding for Russia's disposition program. It was also agreed that each country could blend the 34 tons of weapon-grade plutonium with up to four tons of reactor-grade plutonium, for a total of 38 tons of plutonium. This provision was inserted at Russian insistence to keep the isotopics of the weapon-grade plutonium secret.

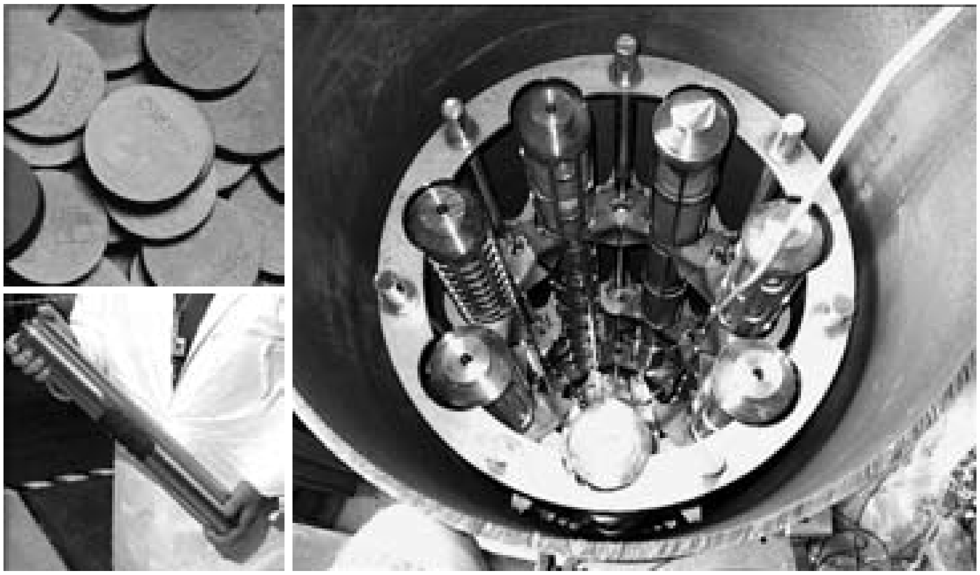

**Figure 3.2. Plutonium immobilization with the can-in-canister approach.** Left top: plutonium immobilized in ceramic pucks. Left bottom: pucks stacked in a can. Right: cans emplaced in a canister before molten glass containing radioactive waste is poured around them to provide the radiation barrier. [Source: U.S. DOE]

In 2001, a joint U.S.-Russian study envisioned that 14.5 tons of Russia's excess plutonium would be used in the BN-600 fast-neutron reactor and the rest in VVER-1000 LWRs.[118]

It also has been suggested that Russian plutonium could be disposed of in West European reactors that have already been licensed for MOX fuel.[119] Reactors in Canada and the Ukraine have also been proposed. None of these proposals have, however, found constituencies in Russia, the United States, or the proposed third countries.

Although it was originally envisioned that a full-scale MOX plant would be operating in Russia by 2007, a December 2006 joint U.S.-Russian report projected that this facility would not begin operations until 2017 or 2018, a delay of at least ten years.[120] One reason for the delay was an extended dispute over the liability of U.S. contractors for any damages due to their contributions to Russia's plutonium disposition program. The Bush administration demanded for a time that Russia should accept liability even in the event of intentional sabotage by U.S. personnel. This was only resolved, without such a provision, in a U.S.-Russian protocol signed on September 15, 2006.[121]

Funding also has been a problem. To date, Western contributors have only pledged about $850 million (including $400 million from the U.S. Government).[122] The estimated cost for the Russian disposition program increased from about $1.8 billion in 2000 ($2.1 billion in 2006 dollars) to $4.1 billion, with roughly half of the total being for up-front capital and licensing costs, and the other half for operations costs over the program lifetime.[123] These cost estimates are substantially higher than international experience would suggest and the differences have not been publicly explained.[124]

Another complication stemmed from the fact that, while the year-2000 Russian-U.S. plutonium disposition agreement called for using most of the excess plutonium as MOX in Russian LWRs, there continued to be a strong faction within the Russian nuclear establishment that believed that the plutonium should be saved for starting up a fleet of fast-neutron breeder reactors. The position of this group has been strengthened by the Bush Administration's recent Global Nuclear Energy Partnership (GNEP) initiative, which proposes international cooperation on fast-neutron reactors.[125] Another group in the Russian nuclear establishment has favored the use of high-temperature gas reactors, such as the gas-turbine modular helium reactor, which is being developed in a joint Russian-U.S. program.

By early 2007, it appeared that the fast-neutron-reactor advocates had won and the Russian Government had decided to use most of the excess plutonium covered by the year-2000 agreement to fuel the BN-800 fast-neutron reactor, now under construction at Beloyarsk.[126] Russian officials have publicly indicated that Russia will pay the cost of building the BN-800 itself.[127] The U.S. Government has reported that it has told the Russian Government that "it does not plan to provide assistance beyond the $400 million already pledged, and does not expect any significant increase in any other donors' pledges."[128] Nevertheless, the international funds already pledged may well be sufficient to pay the costs of converting the weapon plutonium metal into oxide and of storing the resulting spent fuel to assure that it is not reprocessed until after the disposition program is complete.

Some argue that proceeding with disposition in the BN-800 may be worse than not proceeding with disposition at all, as the BN-800 is designed to produce more plutonium than it consumes, and the spent fuel will be reprocessed and the plutonium recycled. DOE is seeking a commitment from the Russian Government that it will modify the BN-800 to operate as a net burner of plutonium (although likely changes would only change the breeding ratio from slightly above to slightly below 1.0). It is also seeking a commitment that any future reprocessing of the spent fuel would be done in a way that does not separate pure, weapon-grade plutonium. Russia always planned to reprocess the spent MOX fuel in any case but the Plutonium Management and Disposition Agreement prohibits it from recovering the plutonium until all the original plutonium has been irradiated. The plutonium therefore would stay in the spent fuel for a period of some decades at least.[129]

#### Disposition of U.S. Excess Weapon Plutonium

The U.S. program for disposition of its own excess weapon plutonium has also suffered years of delay and rapidly escalating costs. Today, its future, like that of the Russian disposition program, is very much in question.

In the mid-1990s, the U.S. Government conducted extensive studies of the technical feasibility, cost, safety, environmental impacts, and nonproliferation implications of a wide range of different plutonium disposition options.[130] In January 1997, it was decided to pursue a "dual-track" strategy to convert relatively uncontaminated plutonium metal and oxide into MOX and immobilize materials too difficult to clean up for MOX use—though the option of immobilizing the entire excess stock remained open. At that time, implementing such a hybrid strategy was estimated to cost $3.1 billion ($3.8 billion in 2006 dollars).[131] The U.S. DOE envisioned that an immobilization plant would begin operating by the end of 2003 and a MOX plant by the end of 2006.[132]

Today, DOE does not expect its MOX plant to open until 2016.[133] It hopes that an immobilization plant might open by 2013.[134] The capital and operating costs for disposition of U.S. excess plutonium using these facilities are now estimated at more than $10 billion (in 2006 dollars).[135] The delays and cost over-runs have been attributed, in part, to lax DOE oversight of the contractors, along with delays and limits on funds projected to be available, which have stretched out the planned construction period and increased costs.[136] The liability dispute also delayed the U.S. program, as Congress had linked U.S. disposition to progress on Russian disposition.

As in the Russian case, current cost estimates are dramatically higher than those for comparable European facilities, for reasons that have not been publicly explained.[137] Congress, observing the delays and mounting costs, has become increasingly skeptical, and several key members have sought to cut the program's budget or redirect its course.[138]

As of mid-2007, DOE's "baseline" approach was to dispose of at least 34 tons of U.S. excess weapon-grade plutonium in MOX fuel. If less than 34 tons usable in MOX is available from the plutonium stocks already declared excess, DOE expects to make up the difference from additional declarations of excess plutonium in the future. This would leave up to 13 tons of contaminated separated plutonium, which is not covered by the Russian-U.S. deal to be disposed of (see Figure 3.3).[139]

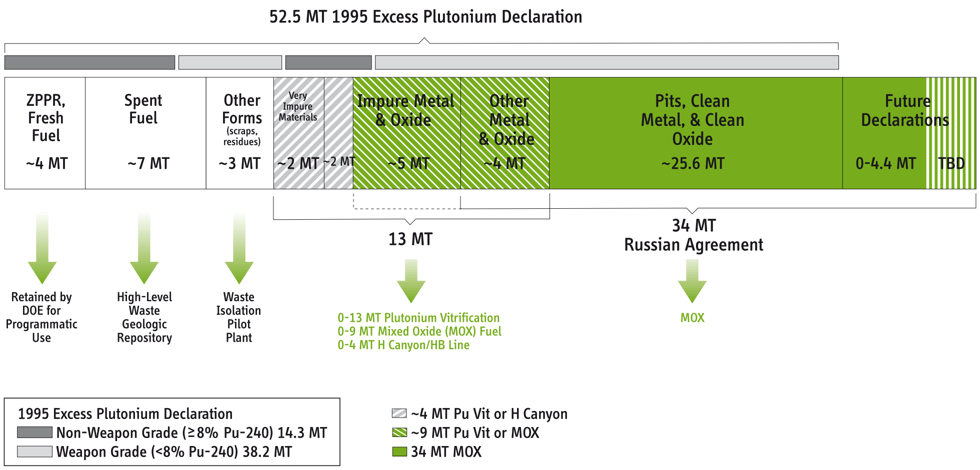


**Figure 3.3. Planned disposition pathways for different categories of U.S. excess plutonium.** The 52.5 tons of plutonium the United States declared excess in 1995 contains many different categories of material. Seven tons are already in spent fuel and, according to current plans, will be disposed of in a geologic repository. Three tons are in various low-concentration scraps and residues and are being disposed of in the deep underground transuranic waste repository known as the Waste Isolation Pilot Plant. Four tons are in the form of fresh fuel for a fast critical assembly that DOE decided to decommission in 2007 but may be used elsewhere. That leaves 38.5 tons requiring some form of further processing for disposition. [Source: DOE, April 2007]

In addition to the MOX plant, DOE's baseline approach therefore includes a small-scale plutonium vitrification plant to prepare up to 13 tons of impure plutonium for can-in-canister disposition with U.S. high-level waste. If any of the plutonium is too contaminated for immobilization, it would be dissolved in the H-canyon at the Savannah River Site, which was formerly used for reprocessing HEU fuel from plutonium and tritium production reactors. The plutonium solution would then be mixed directly with high-level waste being vitrified in a large melter at the Savannah River Site.[140]

***MOX or not?*** The fundamental question being debated in the U.S. Government in 2007 is whether to go ahead and build the extraordinarily expensive proposed MOX plant or not. Construction began on August 1, 2007 but the fate of the facility is by no means assured.

One option would be to abandon the effort and continue to store the U.S. excess plutonium indefinitely. This would mean abandoning the Russian-U.S. year-2000 agreement, which would presumably lead to no disposition of Russian excess weapon plutonium. In addition, DOE argues that this approach would be very expensive, continuing the costs of storage effectively forever.[141]

Alternatively all the plutonium could be immobilized. This too, however, might result in no Russian plutonium disposition. Russian negotiators have objected to the immobilization of U.S. plutonium on the grounds that, unlike the MOX approach, the plutonium isotopics would remain weapon-grade. It appears unlikely that Russia would give up this objection except perhaps in the context of a larger bargain on nuclear trade.

The passion of the internal U.S. debate on MOX versus immobilization reflects, in part, the concern on the part of the critics that pursuing the MOX route will make easier and more likely the establishment of a closed fuel cycle in the U.S. With the DOE's recent embrace of reprocessing, this concern has become more plausible. Unless the design of the proposed MOX plant were substantially changed, however, it would not be capable of handling reactor-grade plutonium without unacceptable radiation doses to the workers. In any case, having a MOX plant already paid would mitigate only slightly the poor economics of plutonium recycling.

DOE has brought forward a constellation of technical and economic arguments against immobilization of all of its excess plutonium, arguing that plutonium immobilization is not as technically mature as MOX, which has been used commercially in Western Europe for years;[142] that the cost for immobilization would be almost as high as for MOX;[143] and that the radioactive waste at Savannah River will be disposed of before immobilization could be completed, leaving no source of a radiation barrier for the plutonium-bearing waste forms.[144]

Immobilization advocates point to DOE's baseline plan to design, build, and begin operating a plutonium vitrification plant at Savannah River by 2013 as evidence that the technical challenges with immobilization are manageable. There are serious technical concerns, however, over the viability of DOE's current plans for this plant.[145] With regard to costs, immobilization advocates argue that much of the $4.8 billion capital cost of the projected MOX plant could be saved by canceling it and using DOE's proposed small immobilization plant and operating it at a somewhat higher throughput for a longer time. DOE's belief, however, is that a larger facility using ceramic rather than glass would have to be built, requiring years of additional research and development. Finally, it seems unlikely that the high-level waste at Savannah River would be all disposed of before immobilization could be carried out.[146] If this were to happen, however—or if more plutonium were declared excess, canisters containing immobilized plutonium could be shipped from Savannah River to Hanford, where vitrification of HLW will last much longer.

There is a real possibility that an all-immobilization approach could be implemented relatively quickly at a lower cost than the MOX approach. Too little is known at present, however, to be confident of this—partly because of DOE's refusal to pursue immobilization seriously. An independent review of the issues would be valuable.

For any approach, the year-2000 Russian-U.S. plutonium-disposition agreement specifies that disposition covered by the agreement cannot proceed until the two sides have agreed on bilateral monitoring provisions. No such agreement is yet in sight. Moreover, the year-2000 agreement calls for consultations with the IAEA "at an early date" on IAEA monitoring of the plutonium disposition process starting by the time the material arrived at a fuel fabrication or immobilization facility. Although construction on the U.S. MOX plant has begun, no consultations have yet occurred with the IAEA on the design features that would affect its ability to monitor the process.[147]

#### Disposition of Civil Plutonium

In addition to the stockpiles of excess weapon plutonium, there are also over 250 tons of separated plutonium in civilian stores—mostly in France, Russia and the United Kingdom—but increasingly in Japan as well. This plutonium is also weapon-usable.

Most countries with separated civil plutonium plan eventually to use this material as fuel—either in LWRs or in future fast-neutron reactors. Currently, however, the use of plutonium as fuel is not keeping up with its continued separation, leading to ever-growing stockpiles (see Chapter 1).

Russia has some 40 tons of civilian separated plutonium. Its current plan appears to be to continue to store this material for fast-neutron reactors that the leaders of its nuclear-energy establishment believe will become economic around 2030 (see Chapter 8).

While Japan has an official policy not to build up stockpiles of separated plutonium, it is in the process of doing so, starting up its Rokkasho reprocessing plant while use of its plutonium as MOX fuel continues to be delayed.[148]

The United Kingdom, which has no plutonium recycle program in place, has the world's largest civil stock of separated plutonium, with over 100 tons of separated plutonium on its soil, of which it owns over 75 tons. The U.K. Government has examined both immobilization and MOX options, but has not yet made a disposition decision, and its plutonium will continue to build up in storage until the United Kingdom ends its reprocessing program in 2012. A number of analysts have proposed options for immobilizing this plutonium for disposal.[149]

#### Conclusion

Disposition of excess separated plutonium has proven to be difficult for both Russia and the United States. Schedules on both sides have slipped by a decade over the past seven years, and estimated costs have more than doubled. Neither country has the technical infrastructure for carrying out plutonium disposition today. The implementation of their commitments to reduce their stockpiles of plutonium therefore remains very much in question.

Pending physical disposition, the United States and Russia should move aggressively to consolidate their stocks of excess plutonium in a smaller number of highly secure locations and open this material to international monitoring, including monitoring from outside its containers while it is still in classified form.[150] The United States and Russia also should agree on and implement bilateral and international monitoring measures on their eventual plutonium disposition, as called for in their agreement of 2000.

Given the decisions that they have made to further reduce their weapon stockpiles since 2000, the United States and Russia should also each substantially increase the amounts that they have declared excess. They should declare excess and available for disposition all of their separated plutonium except for that needed to maintain a small remaining nuclear warhead stockpile, pending nuclear disarmament.

States that have excess stocks of separated civilian plutonium also should reduce these stockpiles to the minimum required to support ongoing nuclear energy programs. If they cannot use these materials expeditiously as fuel, they should consider the option of immobilization for disposal with radioactive waste.