

IPFM
INTERNATIONAL PANEL
ON FISSILE MATERIALS

Alternatives to MOX

Direct-disposal options for stockpiles of separated plutonium

Frank von Hippel and Gordon MacKerron
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On the cover: the map shows the states with large plutonium stockpiles covered in this report.

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About the IPFM

The International Panel on Fissile Materials (IPFM) was founded in January 2006. It is an independent group of arms-control and nonproliferation experts from eighteen countries, including both nuclear weapon and non-nuclear weapon states.

The mission of the IPFM is to analyze the technical basis for practical and achievable policy initiatives to secure, consolidate, and reduce stockpiles of highly enriched uranium and plutonium. These fissile materials are the key ingredients in nuclear weapons, and their control is critical to nuclear disarmament, halting the proliferation of nuclear weapons, and ensuring that terrorists do not acquire nuclear weapons.

Both military and civilian stocks of fissile materials have to be addressed. The nuclear weapon states still have enough fissile materials in their weapon and naval fuel stockpiles for tens of thousands of nuclear weapons. On the civilian side, enough plutonium has been separated to make a similarly large number of weapons. Highly enriched uranium is used in civilian reactor fuel in more than one hundred locations. The total amount used for this purpose is sufficient to make hundreds of Hiroshima-type bombs, a design potentially within the capabilities of terrorist groups.

The panel is co-chaired by Alexander Glaser and Zia Mian of Princeton University and Tatsujiro Suzuki of Nagasaki University, Japan. Its 29 members include nuclear experts from Brazil, Canada, China, France, Germany, India, Iran, Japan, South Korea, Mexico, the Netherlands, Norway, Pakistan, Russia, South Africa, Sweden, the United Kingdom, and the United States. Short biographies of the panel members can be found on the IPFM website, www.fissilematerials.org.

IPFM research and reports are shared with international organizations, national governments and nongovernmental groups. The reports are available on the IPFM website and through the IPFM blog, www.fissilematerials.org/blog.

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Summary

One dangerous legacy of the Cold War is about 220 tons of weapon-grade plutonium, 95 percent of it owned by Russia and United States. The U.S. and Russia have drastically downsized their nuclear arsenals since the end of the Cold War and much of this plutonium has become excess.

In 1994, the U.S. Department of Energy declared excess about half its stock of weapon-grade plutonium, 38 tons – later increased to about 50 tons including non-weapon-grade plutonium. That same year, a high-level committee, organized under the auspices of the U.S. National Academy of Sciences, declared stored separated plutonium “a clear and present danger” because of the potential for theft and urged that disposal not be delayed.

In 2000, Russia and the United States agreed to each dispose 34 tons of excess weapon-grade plutonium – mostly in uranium-plutonium mixed oxide (MOX) fuel to be used in light water reactors (LWRs). To encourage Russia to join in this effort, the United States offered to pay most of Russia’s costs. Disposal was to begin by the end of 2007.

The schedules of the MOX fuel programs slipped, however, and their projected costs grew. The United States decided that it could not continue to increase its funding commitment to Russia’s program and, in 2010, accepted Russia’s preference to use its excess weapons plutonium to fuel Russia’s demonstration plutonium-breeder reactors. Unfortunately, Russia plans to separate and recycle this plutonium after it has been irradiated. The danger of plutonium theft in Russia therefore will not be reduced.

The projected cost of the U.S. MOX program has continued to grow rapidly – more than ten-fold to date. In 2013, the Obama Administration declared that it “may be unaffordable” and decided to search for alternative less costly approaches.

In parallel, a problem of excess separated *civilian* plutonium has developed in France, Japan, Russia and the UK. All launched spent fuel “reprocessing” (plutonium separation) programs in the 1960s and 1970s – originally to provide startup plutonium for a new generation of breeder reactors that would produce more plutonium than they consumed. Civilian plutonium is not “weapon-grade”, but it is weapon-useable and therefore constitutes as much a “clear and present danger” as does excess weapons plutonium.

By the end of 2013, the global stock of separated *civilian* plutonium had grown to 260 tons – enough to make more than 30,000 Nagasaki-type nuclear bombs. But the commercialization of breeder reactors had faded into the uncertain future.

Starting in 1987, France’s COGEMA (now AREVA) therefore began to fabricate its own and its foreign reprocessing customers’ separated civilian plutonium into MOX fuel for use in the LWRs that had produced it. The UK too built a MOX fuel plant for its foreign customers, but abandoned it in 2011 because of irremediable design defects. Japan is building a MOX fuel plant fabrication plant whose completion has been long delayed.

Leaving aside the huge costs of plutonium separation from spent fuel, the cost of fabricating it into MOX fuel is more than the value of the low-enriched uranium fuel that it displaces – about twenty times more in the case of the United States. The use of plutonium in MOX fuel must therefore be regarded as a waste-disposal program and there is every reason to ask whether alternative approaches could achieve as good a result at less cost.

It is also important to understand that fabricating plutonium into MOX fuel and irradiating it does not eliminate it. Some is fissioned but spent LWR MOX fuel contains 75 percent as much plutonium as fresh MOX fuel. Repeated recycle to further reduce the plutonium is not practical because the changing isotopic composition of the plutonium makes it increasingly difficult to fission in LWRs.

The alternative to disposal of separated plutonium in reactor fuel is processing it into a stable form and deep burial.

In the United States, the Department of Energy's Plutonium Disposition Working Group concluded in 2014 that the lowest-cost option would be disposal in DOE's New Mexico Waste Isolation Pilot Plant (WIPP), a repository in a 650-meter-deep salt bed in New Mexico where plutonium-contaminated waste from the U.S. nuclear-weapons program already is being buried. Whether or not it will be politically possible to expand WIPP's mission to accommodate all U.S. excess plutonium remains to be seen.

The U.S. plutonium disposal plan originally had a second track in which plutonium was to be embedded in the high level radioactive waste being immobilized in glass at the DOE's Savannah River Site in South Carolina. DOE's Plutonium Disposition Working Group believes it is now too late to resurrect this option, but it may not be for at least a significant portion of the U.S. excess plutonium. Another option that the DOE has under development for some of its other radioactive waste is boreholes several kilometers deep. Finally, it might be possible to include some immobilized plutonium in the spent fuel containers in which spent power reactor fuel is to be disposed deep underground. Two or more these strategies might be combined depending upon the time windows during which they could be implemented.

Alternatives to MOX for plutonium disposal are being debated most openly in the United States, but the future of the MOX programs in France and Japan are very uncertain. Local safety concerns delayed Japan's MOX program for a decade before the Fukushima accident. France's MOX program is the focus of a struggle between the national utility, Électricité de France, which wants to reduce costs, and AREVA, which operates France's plutonium recycle complex. Also, the reactors France uses to irradiate its MOX fuel are growing old and AREVA is storing a growing stock of unusable MOX fuel.

Whatever the method of plutonium disposal, it is critical to the future of verified nuclear disarmament that plutonium disposal in the nuclear-weapon states be verified by the International Atomic Energy Agency (IAEA) as it already must be in the non-weapon states.

Introduction

The global stock of separated plutonium has increased continually since the beginning of the Cold War. With the end of the Cold War, the United States, Russia, UK, France and China all ended their production of plutonium for weapons and the United States and Russia have made deep cuts in their nuclear weapon stockpiles and have declared excess 40 percent of their combined stock of weapon-grade plutonium (Figure 1).

Beginning in the 1960s and 1970s, separation of plutonium from spent power-reactor fuel for *civilian* purposes began on a large scale in France, Russia and the UK.¹ Figure 1 shows that the global stock of civilian plutonium has continued to grow during the past two decades despite an agreement in 1997 by countries with civilian reprocessing programs on the need to balance plutonium separation with use.²

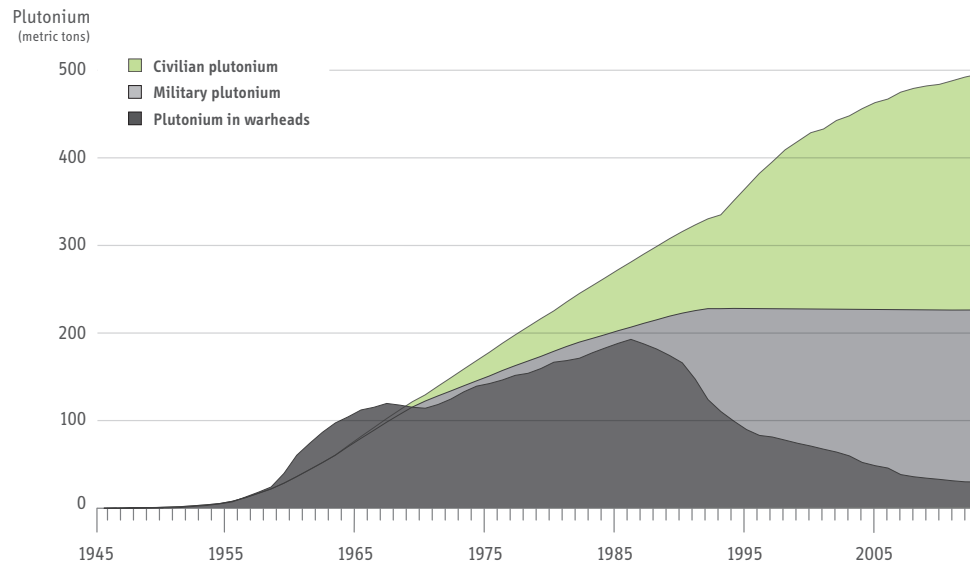


Figure 1 Growth of the global stockpile of separated plutonium and growth and decline of the global stockpile of operational nuclear warheads from 1945 to the end of 2013. The stock of military plutonium has plateaued because the Russian and U.S. disposal programs have been delayed. The civilian stock continues to grow because the rate of plutonium separation from spent power reactor fuel greatly exceeds the use of plutonium in fresh fuel. To put the estimated size of the global stock of active nuclear warheads on the same scale, the warheads were assumed to have contained an average of 3 kilograms of plutonium each. That appears to be an overestimate for U.S. warheads in the 1960s. *Sources.* Military plutonium: IPFM, *Global Fissile Material Report 2010, Balancing the Books: Production and Stocks and Global Fissile Material Report 2013*. Civilian plutonium: David Albright, Frans Berkhout and William Walker, *Plutonium and Highly Enriched Uranium 1996* (Oxford University Press, 1997) through 1996 and *Global Fissile Material Report 2013*, Appendix 1.3 thereafter. Nuclear warheads: Hans Kristensen and Robert Norris, “Global nuclear weapons inventories, 1945–2013” *Bulletin of the Atomic Scientists* Vol. 69, No. 5 (2013) pp. 75–81.

The world therefore has a huge stock of excess plutonium. Given that civilian plutonium is weapon-useable,³ this excess – sufficient for about 100,000 nuclear warheads⁴ – is a major challenge to global security.

Thus far, all the countries with excess weapon plutonium and/or separated civilian plutonium either are using or plan to use this plutonium in reactor fuel. Those plans

have suffered long delays and large cost increases. This report reviews the histories of these programs and considers alternative direct disposal options.

Table 1 shows the global stock of separated plutonium by country, broken down into four categories: in weapons or in associated reserves, weapons plutonium declared excess, civilian, and “other” for plutonium whose origin or purpose requires additional explanation.

Countries	Stocks of unirradiated plutonium (metric tons)			
	In weapons or reserves	Declared excess for weapons ⁵	Civilian	Other ⁶
United States	38.3	43.4	–	6.6
Russia	88 *	34	50	~6
United Kingdom	3.2	0.3	99.6	4.1
France	6 *	0	60.2	–
China	1.8 *	0	0.014	–
India	0.54 *	0	~0.5	~4.7
Israel, Pakistan, North Korea	1.0 *	0	0	–
Japan	0	0	47.1	–
Other non-weapon states	0	0	5 ⁷	–
Totals	138.8	77.7	262.4	21.4

Table 1 Global stocks of separated plutonium as of the end of 2013. Sources: *Global Fissile Material Report 2013* (indicated by *) and national declarations to the IAEA in annual INFCIRC/549 updates.

The original purpose for launching civilian plutonium separation on a large scale in the 1970s was to provide startup fuel for sodium-cooled plutonium breeder reactors. Programs intended to commercialize breeder reactors were abandoned in the 1980s and 1990s in France, Germany, Japan, the UK and the United States, and have been delayed for decades in India and Russia. Currently Russia plans to use its 34 tons of excess weapons plutonium as well as its 50 tons of separated civilian plutonium to fuel its two prototype breeder reactors, the BN-600, which has been operating since 1980, and the new BN-800 (~800 MWe).⁸ India intends to use virtually all of its separated reactor-grade plutonium (shown as “other” in Table 1) to start up its 500-MWe Prototype Fast Breeder Reactor.

After the abandonment of their breeder reactor commercialization programs, France and Japan decided to continue to separate plutonium from the spent fuel of their LWRs and use it in mixed-oxide (MOX) uranium-plutonium fuel as a supplementary fuel for those same LWRs. However, France has used only about two thirds of the light water reactor plutonium it has separated from its own spent fuel starting in 1976. As a result, it has a large and growing stockpile of separated civilian plutonium. Japan has only used about 5 percent of the plutonium that it has separated at home and abroad.

The UK, which has not had a plutonium disposition plan since its breeder reactor program was abandoned 1994, is only just now considering how to dispose of its huge stock of separated civilian plutonium – the world’s largest. It has offered to dispose of as well over 20 tons of plutonium that it has separated for Japan and other countries. The original plan was to fabricate their plutonium into MOX fuel and send it back to them, but the Sellafield MOX Plant was a technical failure and was shut down in 2011.

In 2010, the United States committed in its Plutonium Management and Disposition Agreement with Russia to dispose of in MOX fuel all the 34 tons of weapon-grade plutonium covered by that agreement.⁹ By the end of 2014, the U.S. Department of Energy (DOE) had spent about \$5 billion on the construction of a MOX fuel fabrication plant, four times the amount originally estimated, but the plant was less than half complete. Furthermore projected annual operating costs after completion had climbed to about \$0.7 billion per year.¹⁰ In 2013, therefore, the Obama Administration decided that the MOX plutonium disposal route “may be unaffordable” and launched a review of alternative plutonium disposal options.¹¹ Later in this report, these options are examined. This should be of interest to other countries with struggling MOX programs.

In the remainder of this introduction, we review the fading rationales for the separation of civilian plutonium and lay out some basic principles that should govern national policies for plutonium disposal, whether of civilian or military origin. Subsequent chapters examine the status of the plutonium disposal programs of France, Japan, the UK and the US; alternative approaches to the direct disposal of plutonium underground; and the need for IAEA monitoring of the weapon-state as well as the non-weapon state plutonium disposal programs.

Fading rationales for the separation of civilian plutonium

The IPFM has written reports on the history of breeder reactor programs; on spent fuel management programs worldwide; and on the reprocessing programs of France, Japan, the UK, and the U.S. reprocessing program proposed by the G.W. Bush Administration; and will publish in 2015 a new review of the global situation with regard to reprocessing. For these reports, the reader is referred to the IPFM website, www.fissilematerials.org. What follows is an overview.

There has been a succession of three major rationales for separating plutonium from spent power reactor fuel:

- To provide startup plutonium for breeder reactors;
- To provide supplementary MOX fuel for LWRs; and
- Spent fuel management.

Plutonium breeder reactors. The separation of civilian plutonium was originally undertaken in the belief that high-grade deposits of uranium were scarce and that much more uranium-efficient reactors would soon be required. Liquid-sodium-cooled fast-neutron plutonium breeder reactors would be much more uranium efficient because their ultimate fuel would be U-238 (99.3% of natural uranium) rather than the only naturally occurring chain-reacting isotope U-235 (0.7%). They would be fueled by reactor-produced chain-reacting plutonium while producing more plutonium than they consumed by transmutation of U-238¹².

In 1975, it was projected that 200 GWe of breeder reactor capacity would have to be built by the year 2000 – mostly during the 1990s – at an average rate equivalent to about 20 1,000-Megawatt (MWe) reactors per year.¹³ About 9 tons of startup plutonium would be required for each 1,000-MWe reactor. This would provide for the initial cores and for a first half-core refueling until reprocessing of the breeder core and its surrounding uranium “blanket” could begin to provide additional plutonium.¹⁴ Spent fuel from conventional LWRs contains about one percent plutonium. About 18,000 tons of LWR fuel – the amount that would be discharged in the spent fuel from nine hundred 1,000-MWe reactors, more than twice today’s global nuclear capacity – would have had to be reprocessed annually to provide the startup plutonium for the new breeder capacity.

Breeder reactors were not commercialized, however, because of their poor economics. The capital cost of sodium-cooled reactors has always exceeded that of water-cooled reactors by a substantial margin and capital cost dominates the overall cost of nuclear power. Because sodium burns on contact with air or water, sodium-cooled reactors are also accident-prone and difficult to maintain, which reduces their availability and further increases the cost per kilowatt-hour (kWh) generated. The reprocessing of spent fuel and fabrication of fuel containing plutonium also are very costly. It would require very large increases in uranium prices to offset all these extra costs.

During the past fifty years, the price of natural uranium in constant dollars has gone up and down due to temporary imbalances between supply and demand. The trend has not been upward, however (Figure 2). Also, at \$100/kg, the cost of uranium contributes only 0.2 cents/kWh – about 2% of the cost of power from a new water-cooled reactor.¹⁵

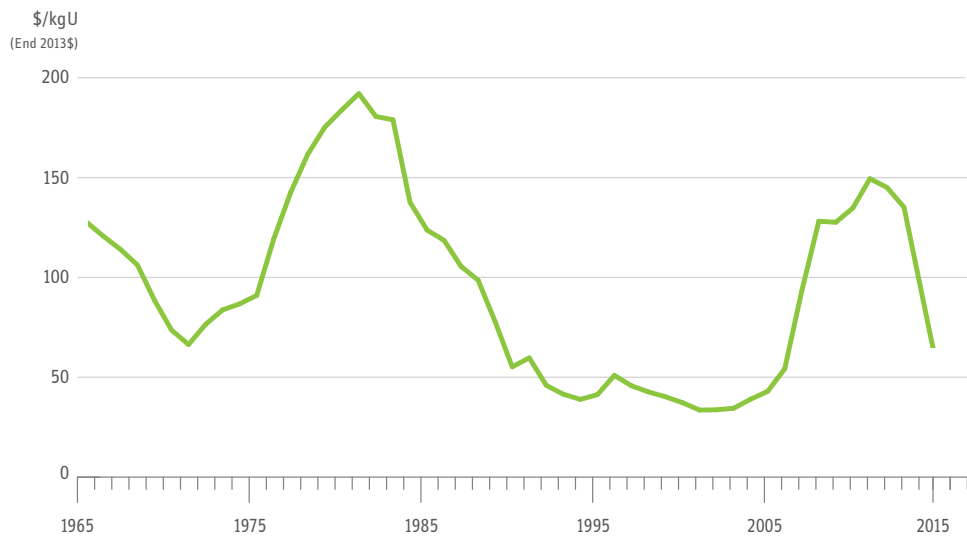


Figure 2 Average uranium prices paid by U.S. nuclear utilities during 1965–2013, in constant dollars. The value shown for 2014 is the spot-market price. Sources: For 1965 and 1968–1971, *Statistical Abstract of the United States 1975*, Table 905; for 1975 and 1980, *Statistical Abstract of the United States 1991*, Table 981; for 1981–1993 from the U.S. Energy Information Agency's (US EIA's) *Annual Energy Review* (2012), Table 9.3; 1994–2012 from US EIA *Uranium Marketing Annual Report* (2012); and, for 2014 spot price, *Nuclear Intelligence Weekly*, 4 July 2014. GDP inflators from U.S. Bureau of Economic Analysis.

According to *Uranium 2014*, published jointly by the IAEA and the OECD Nuclear Energy Agency

“If estimates of current rates of uranium consumption in power reactors are used, the identified resource base would be sufficient for over 150 years of reactor supply. Exploitation of the entire conventional resource base would increase this to well over 300 years.”¹⁶

This resource base is expected to increase rapidly with increasing price.¹⁷

During the 1980s and 1990s, the US, Germany, UK, and France all abandoned their efforts to commercialize breeder reactors.¹⁸ Russia and India continued. Russia brought a new 800-MWe prototype breeder reactor to criticality in 2014¹⁹ and India hopes to bring its 500-MWe prototype to criticality in 2015.²⁰

China has a small 20-MWe experimental fast-neutron reactor (CEFR) that it connected briefly to the grid in 2011. The CEFR only generated the equivalent of one hour of full-power output, and was not operated again until three years later when it operated for three days.²¹ There is currently great uncertainty about the future of China's breeder-development program.

Use in LWR MOX fuel. Plutonium use in LWRs has been found to be *much* more costly than the value of the relatively small fraction – about one eighth – of low-enriched uranium fuel it saves. As will be detailed in the chapter on the French and Japanese reprocessing programs, those countries have found it politically difficult to cancel their reprocessing programs.

Spent fuel management. Reprocessing advocates insist that it dramatically reduces the volume and longevity of the radioactive waste that must be placed into a deep repository. The simplest version of the argument is that uranium oxide constitutes about 95% of the mass of LWR spent fuel but, if separated, would not require deep disposal.

This argument is misleading for at least three reasons:

1. The mass of the radioactive waste from reprocessing is increased several-fold when it is immobilized in glass for disposal. Furthermore, new radioactive waste streams that also require deep burial are created during reprocessing and MOX fuel fabrication. When these facts are taken into account, reprocessing and plutonium use in LWR MOX fuel do not significantly reduce the volume of the radioactive waste that requires deep burial.²²
2. Radioactive waste volume does not determine the volume or area of a repository. In Sweden's repository design, which has been adopted by Finland and most other countries that are seriously planning repositories, the canister containing the spent fuel or solidified reprocessing waste is surrounded by bentonite clay that has to be kept below boiling temperature to retain its water-blocking properties. This limits the amount of heat-generating waste that can be put in a canister and requires spacing between canisters so that they will not significantly increase the temperatures of each other's bentonite overpacks. Calculations for Finland's repository find that an area of about 100 square meters will be required per ton of spent fuel – much larger than would be dictated by volume considerations.²³ The total decay heat generated by the radioactive waste therefore determines the area of a repository. The combined heat of the reprocessing waste and spent MOX fuel produced as a result of recycling plutonium is no less than that of the original low-enriched uranium spent fuel that would be disposed directly in the absence of reprocessing.²⁴
3. When a spent fuel assembly is cut up, it releases into the atmosphere some of the radioactive gases in the fuel – notably krypton-85 (11-year half-life) and carbon-14 (5,700-year half-life). The UN Scientific Committee on the Effects of Atomic Radiation estimated that the releases of carbon-14 to the atmosphere from reprocessing through 1997 will result in an additional global population dose of 58,000 person-Sievert over the next 10,000 years.²⁵ This is a tiny increment relative to the expected doses due to natural and medical radiation over that period but, on that scale, the doses from repository leakage that it is claimed reprocessing could reduce would be similarly insignificant.

With regard to the drastic reduction of the lifetime and hence the hazard of radioactive waste that is claimed to be a benefit by reprocessing advocates, this cannot be achieved by a single passage of plutonium in MOX through an LWR. Repeated use of plutonium in LWR MOX fuel to reduce the plutonium further becomes increasingly difficult, because some of the long-lived isotopes of plutonium and the heavier transuranic ele-

ments into which plutonium is converted in MOX cannot be effectively fissioned by the slow neutrons of water-cooled reactors.

This provides a new argument for costly fast-neutron reactors,²⁶ but simulations of leakage from Sweden's spent fuel repository find that plutonium and other long-lived transuranic elements do not dominate the long-term hazard from buried spent fuel. This is because the transuranics are relatively insoluble in deep ground water and they do not travel with it to the surface. As a result, they do not dominate the dose to the surface population.²⁷

In 2013, France's nuclear safety regulator, Autorité de Sûreté Nucléaire (ASN), arrived at a similar conclusion for France's repository

“transmutation of minor actinides should not significantly alter the radiological impact of deep geological disposal as it is mainly due to fission and activation [products] ... Therefore, ASN considers that the expected gains in safety, radiation protection and waste management from the transmutation of actinides [plutonium and other transuranics] to be minor.”²⁸

The lead advisor on radioactive waste management to Japan's Ministry of Economics, Trade and Industry (METI) recently announced a similar conclusion

“If our aim isn't to utilize resources [i.e. extract further energy out of the uranium and plutonium in spent fuel], then it would be better to dispose of the waste [spent fuel] directly without re-processing it.”²⁹

Principles for Plutonium Disposal

Separated plutonium, military or civilian, can be used to make nuclear weapons. This is why spent fuel reprocessing has been so controversial— especially since India demonstrated in 1974 that a “peaceful” reprocessing program can be used as the basis for a nuclear-weapon program.³⁰ In recent years, concerns about the possibility of nuclear terrorism by sub-national groups have been added to those about national proliferation. It would not be easy for a subnational group to make a nuclear bomb with plutonium, but it also would not be impossible.³¹ Also, if dispersed into the air in an urban area, a few kilograms of plutonium oxide, the chemical form in which separated civilian plutonium is stored, could cause mass panic and hundreds of deaths over the lifetimes of the exposed population.³²

This is why separated plutonium must be securely stored. The 1994 U.S. National Academy of Sciences (NAS) study on plutonium disposition options called for a “stored weapons standard,” i.e. that the security arrangements for separated plutonium during storage and processing should be as strong as those for nuclear weapons.³³

The NAS study group also recommended that, after disposal, the plutonium should be no more accessible than plutonium in spent fuel, i.e. a “spent-fuel standard.”³⁴ In spent LWR fuel, the plutonium is both dilute (about 1 percent by weight) and mixed with fission products that generate a gamma field around a fuel assembly that is greater than 1 Sv/hr at a distance of a meter for about a century. Such a gamma field offers a significant degree of protection.³⁵ Disposal in MOX fuel would meet the spent-fuel standard. So would mixing the excess plutonium with reprocessing waste from which it had been separated. The spent fuel standard might also be met if the plutonium were immobilized and emplaced in a borehole kilometers deep.

Because of their linkage, there were two additional requirements for the U.S. and Russian plutonium-disposal programs:

1. That the programs are acceptable to the other country. In 2000, Russia would only accept a U.S. disposal program that involved the irradiation of most of the plutonium to convert its isotopic mix from weapon-grade to non-weapon-grade – even though non-weapon-grade plutonium is still weapon-usable.³⁶ Russia’s position on this matter forced the U.S. to adopt MOX as its disposal method for at least 25 of the 34 tons of plutonium covered by their agreement.
2. The two countries also agreed that each party had the right to verify the other’s plutonium disposal, as bilateral nuclear arms limitation and reduction agreements between the two countries have traditionally been verified. But they also agreed that their plutonium reduction agreement would be taken more seriously by other countries as a step toward nuclear disarmament if the verification were carried out by the IAEA, which monitors nuclear materials in the non-weapon states. Their plutonium disposition agreement therefore commits that

“Each Party, in cooperation with the other Party, shall begin consultations with the International Atomic Energy Agency (IAEA) at an early date and undertake all other necessary steps to conclude appropriate agreements with the IAEA to allow it to implement verification measures with respect to each Party’s disposition program.”³⁷

As of the end of 2014, Russian and the U.S. had not yet agreed with the IAEA on how their plutonium disposition would be verified, including on how long spent fuel containing irradiated disposed plutonium would be subject to IAEA safeguards.

Russia’s plan to continue to separate plutonium and reuse it indefinitely defeats one of the purposes in negotiating the Plutonium Management and Disposition Agreement, which was to reduce the risk of theft of separated plutonium by subnational groups.³⁸

France and Japan

Despite the indefinite postponement of their breeder reactor programs, the governments of France and Japan have maintained their commitments to spent-fuel reprocessing and have decided to dispose of the resulting separated plutonium in MOX fuel for light water power reactors (LWRs).

In France, the reprocessing of spent low-enriched uranium fuel and use of the recovered plutonium in MOX fuel has been working relatively well – technically if not economically. Disposal of separated plutonium in MOX also has worked relatively well for France’s European reprocessing customers, Belgium, Germany and Switzerland. These customers, which did not renew their reprocessing contracts, had, as of the end of 2013, almost succeeded in disposing of all the plutonium AREVA had separated for them.³⁹

In Japan, plutonium use has largely failed thus far. Japan’s ¥2.2 trillion⁴⁰ (~\$22 billion) domestic Rokkasho Reprocessing Plant (RRP) has been delayed for almost two decades with operation currently projected for March 2016.⁴¹ Japan already has about 50 tons of separated plutonium, however. Some was separated in Japan by its pilot Tokai reprocessing plant, which operated from 1977 till 2006,⁴² and during the “hot testing” of the RRP in 2006–2008. Most, however, was separated in Europe: in the UK by the reprocessing of 2,683 tons of Japanese spent LWR fuel and 1,510 tons of Japanese gas-cooled reactor fuel in the Sellafield reprocessing complex; and in France by the reprocessing of 2,945 tons of Japanese LWR fuel in the La Hague UP3 reprocessing complex.⁴³

The plutonium in France and the UK was supposed to be returned to Japan in the form of MOX fuel from both countries starting in 1999, but the UK’s Demonstration MOX Plant was shut down after a scandal over fabricated quality-control measurement results and its Sellafield MOX fuel fabrication plant was abandoned in 2011 after having produced on average only about one percent of its design output for a decade. Between 1999 and 2014, France sent Japan in MOX fuel containing 4.4 tons of Japanese plutonium separated in France, but Japan has managed to irradiate only 1.9 tons – delayed by public safety concerns at the regional level and, since 2011, by the temporary shutdown of all of its nuclear power plants following the Fukushima accident.

Below, we discuss the uncertain futures of the French and Japanese national MOX programs.

France

France is implementing its MOX fuel program relatively smoothly, annually separating about ten tons of plutonium from its spent LWR fuel and using most of it in MOX fuel in a subset of those reactors. Supply has outpaced use, however. Since 1996, when France started publicly reporting, its stock of unirradiated civilian plutonium has increased by an average of 1.5 tons per year and, as of the end of 2013, stood at about 60 tons (Figure 3). There are multiple reasons for this growth, including a growing stock of unusable MOX fuel. More specific information about this situation is given in the chapter, *Direct disposal options*.

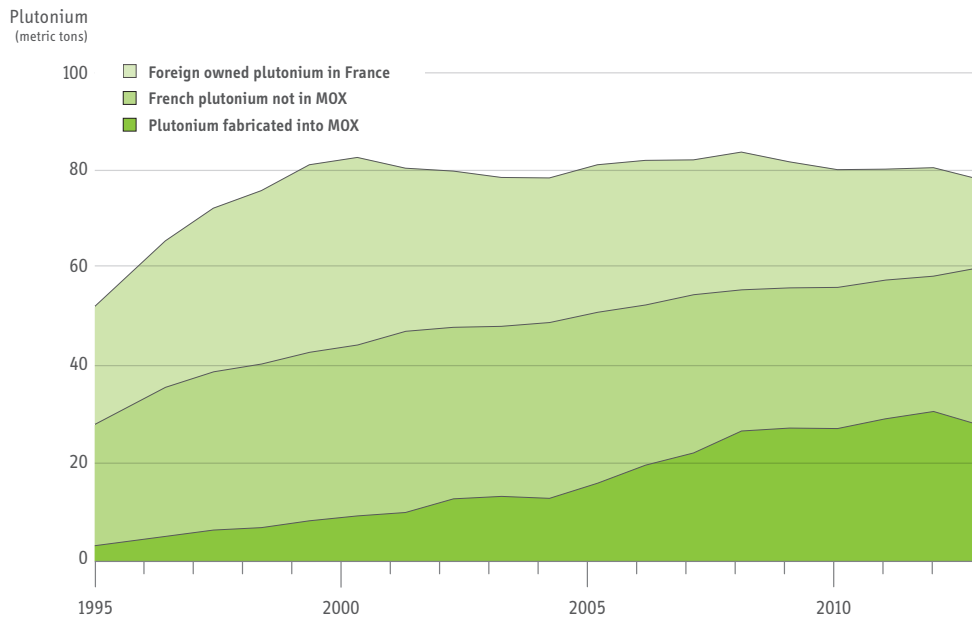


Figure 3 Growth of France's stock of unirradiated civilian plutonium due to the growth of its stock of unusable fabricated MOX fuel. The amount of French plutonium not fabricated into MOX has stayed at about 30 tons. The growth of France's stock has been offset by the decline of foreign-customer-owned separated plutonium in France. Almost all the remainder belongs to Japan. Source: IAEA, *Communication Received from France Concerning its Policies Regarding the Management of Plutonium*, INFCIRC/549/Add5/18, 2014 and previous annual reports.

The cost of France's MOX fuel program far exceeds the value of the resulting savings in low-enriched uranium fuel. France's national utility, Électricité de France (EDF) has been pressing AREVA to bring the cost down. Recently, a National Assembly Commission of Enquiry recommended that France's Court of Auditors, its equivalent of the U.S. Government Accountability Office, carry out a cost-benefit analysis of France's MOX fuel program.⁴⁴

Another source of uncertainty regarding the future of France's MOX program stems from the fact that its twenty-four 900-MWe reactors licensed to use MOX fuel could soon be retired. By 2028, all thirty-four of France's 900-MWe reactors will have operated for 40 years.⁴⁵

EDF would like to extend the operational lives of these reactors to 50 or even 60 years. The head of the ASN, France's nuclear safety regulatory agency, has warned, that clearance for an additional 10 or 20 years of operation "is not a given".⁴⁶ Also, after the Fukushima accident, France's Lower House voted (first reading) to reduce France's dependence on nuclear power from 75 to 50 percent by 2025.⁴⁷ If the oldest reactors were shut down first, this would require the shutdown of most of the 900-MWe reactors.

France's newer 1300-MWe reactors could be modified to use MOX, but this would involve lengthy relicensing and possibly costly reactor modifications. EDF likely would prefer on cost grounds to phase out plutonium separation and use instead. In 2013, it provided ASN with a scenario showing that, if all France's 900-MWe reactors were shut down at age 40, reprocessing would need to stop in 2019 to ensure that all France's separated plutonium could be used in MOX before the last of the 900-MWe reactors licensed for MOX use was shut down.⁴⁸ In the UK, where EDF owns all but one of the operating nuclear power reactors,⁴⁹ the utility refused to renew its reprocessing contracts with the UK Nuclear Decommissioning Authority. Given the absence of any new foreign orders, this will force the end of the UK's reprocessing program when the current reprocessing contracts have been fulfilled (circa 2020).

Japan

Japan's development of MOX fuel technology dates back 50 years.⁵⁰ As of 31 March 2014, it had fabricated MOX fuel containing a total of 7 tons of plutonium at a succession of R&D facilities – mostly for its two shutdown experimental fast breeder reactors and its decommissioned Fugen experimental heavy water reactor.⁵¹ About 1.6 tons of this plutonium remains in unirradiated MOX fuel.⁵² For the future, as its breeder commercialization program is indefinitely postponed, Japan plans to follow France's example and use its separated plutonium in MOX fuel for LWRs.

Thus far, Japan's only large-scale source of LWR MOX fuel has been France's Melox plant, but Japan has under construction a MOX fuel fabrication facility (J-MOX) adjacent to the Rokkasho Reprocessing Plant (RPP). Like the reprocessing plant, J-MOX has suffered repeated to delays and, as of late 2014, was scheduled for completion in October 2017.⁵³

The use of French MOX in Japan has encountered safety concerns and resistance at the prefectural level and within the general public. The opposition was fueled initially by the revelation that quality-control documentation had been falsified on the UK portion of the first shipment of MOX fuel from Europe to Japan in 1999. This led to the return to the UK of this MOX fuel in 2002.⁵⁴ The fuel had been produced at the MOX Demonstration Facility in Sellafield, which was shut down in 2001. That same year, the commercial-scale Sellafield MOX Plant was completed with a design production capacity of 120 tons per year. But, because of design defects, that plant was able to produce a total of only 14 tons of MOX fuel for European reactors over the next ten years before it too was abandoned in 2011.⁵⁵ No further MOX fuel can be expected from the UK for the foreseeable future.

France has shipped to Japan MOX fuel containing 4.4 tons of Japanese plutonium, but permission from the governors of the host prefectures to load MOX was mostly withheld. As a result, Japan's MOX fuel usage plans have been delayed by more than a decade.

In 1997, Japan's nuclear utilities committed to be using MOX fuel in 16 to 18 nuclear power reactors by 2010.⁵⁶ Specific reactor-by-reactor plans published by Japan's Federa-

tion of Electric Power Companies (FEPCo) translated this into a plan to be annually loading MOX fuel containing about 9 tons of plutonium.⁵⁷ By the time of the Fukushima accident in March 2011, the utilities had succeeded in irradiating in four reactors MOX fuel containing only 1.9 tons of the Japanese plutonium separated and fabricated into MOX fuel in France.⁵⁸ Japan's total stockpile of unirradiated plutonium is 50 tons and will grow further if the RPP is brought into operation (Figure 4).

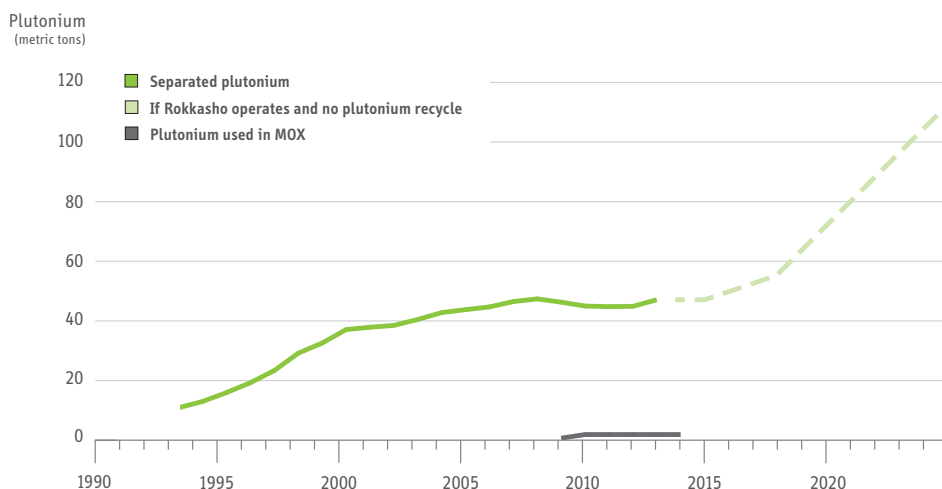


Figure 4 Growth of Japan's stock of unirradiated plutonium. Dashed line: The projected growth, if the Rokkasho Reprocessing Plant begins operations in the spring of 2016 at one-third capacity for three years and thereafter at design capacity (8 tons per year) and Japan's plutonium use in MOX continues to be delayed. Lower line: Japan's cumulative use of plutonium in LWR MOX. Sources: Past growth of Japan's stockpile of separated plutonium from its annual declarations to the IAEA under the Plutonium Management Guidelines. Quantities of plutonium loaded in MOX into Japan's LWRs from Japan Atomic Energy Commission, "The Current Situation of Plutonium Management in Japan" (in Japanese) 16 September 2014.

As of the end of February 2015, all of Japan's nuclear power reactors were still shut down pending decisions on their restart, first by Japan's new Nuclear Regulation Authority, and then by the host prefectures and local governments. A survey of expert opinion by Reuters published in April 2014 concluded that, of Japan's forty-eight remaining nuclear power reactors, "14 will probably restart at some point, a further 17 are uncertain and 17 will probably never be switched back on."⁵⁹ Nevertheless, as of mid-February 2015, the website of the Federation of Electric Power Companies of Japan (FEPCo) continued to declare that "Japan's electric power companies aim to utilize MOX fuel in 16 to 18 nuclear reactors by fiscal 2015 at the latest."⁶⁰ Japan's fiscal year 2015 begins on 1 April 2015 and ends on 31 March 2016.

As of the end of 2013, Japan had 3.6 tons of separated plutonium stored at the RRP awaiting the completion of the Rokkasho J-MOX plant. Nevertheless, the plan of Japan Nuclear Fuel Limited, which is building and will operate both plants, was to start up

RRP as soon as it received its safety license. As of the end of 2014, this was projected for March 2016.⁶¹ Japan also still had in France and the UK respectively 16.3 and 20 tons of plutonium awaiting contracts to be fabricated into MOX fuel and returned to Japan.⁶² Since the UK's 2011 decision to scrap the Sellafield MOX plant, the UK has had no ability to implement MOX contracts and has offered to take title of Japan's plutonium and dispose of it with its own, conditioned on Japan's willingness to pay enough to make such an arrangement commercially attractive. As of the end of 2014, Japan had not accepted this offer. The idea that Japan would pay another country to take its plutonium conflicts with the position of Japan's government that its separated plutonium is an asset.

Since Japan has no near-term use for more separated plutonium, the claimed reason for launching operations at its reprocessing plant is to create space in the almost-full 3,000-ton RRP intake pool to receive additional shipments of spent fuel from nuclear power plants around Japan.⁶³ Also, Aomori Prefecture, which hosts the RRP, has stated that it will not allow storage of spent fuel in the completed 3,000-ton-capacity Mutsu dry-cask spent-fuel storage facility, which it also hosts, until the RRP begins commercial operations. With the recent rescheduling of the planned opening of the RRP from October 2014 to March 2016, the planned opening of the Mutsu storage facility was postponed from March 2015 to October 2016.⁶⁴

The United Kingdom

The UK is seeking a long-term management strategy for a stockpile of separated civilian plutonium that is expected to amount to about 140 tons by the time reprocessing ends in the UK (Figure 5).⁶⁵ This includes more than 20 tons of foreign (mostly Japanese)-owned plutonium that the UK has offered to take ownership of “subject to conclusion of acceptable commercial arrangements.”⁶⁶

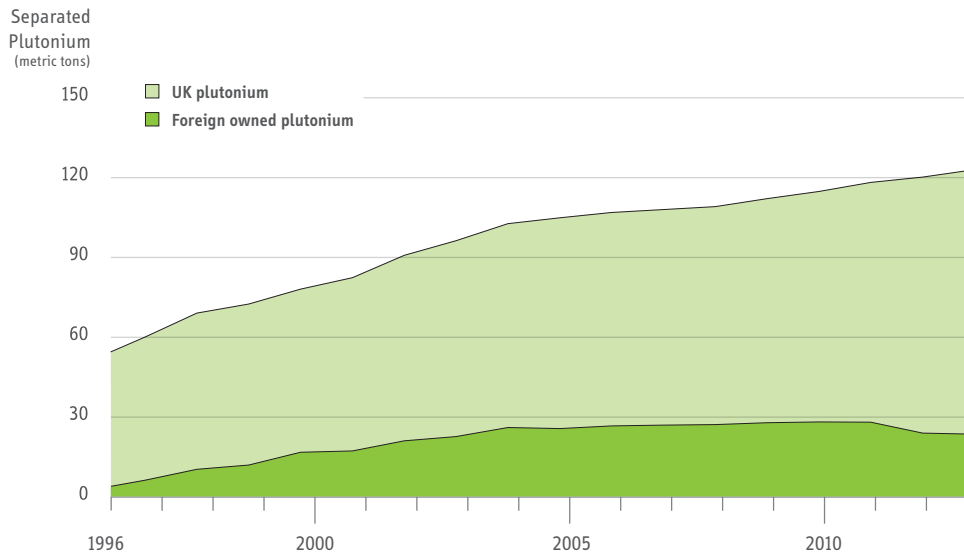


Figure 5 Growth of the UK's stock of separated civilian plutonium since the UK began to report these numbers for publication by the IAEA. Sources: IAEA, *Communication Received from the United Kingdom of Great Britain and Northern Ireland Concerning its Policies Regarding the Management of Plutonium*, INFCIRC/549/Add8/17, 15 August 2014 and previous annual reports.

The UK has had no plan for its own separated plutonium since the demise of its breeder reactor program in 1994. The plan for managing its foreign plutonium was to fabricate it into MOX fuel and return it to the countries from which it had come, but this plan became inoperative in 2011 when the Sellafield MOX plant, which was specifically built to deal with foreign plutonium, was abandoned after producing only one percent of its design output over a decade.⁶⁷ This plant could not, in any case, be used to dispose of the UK's own separated plutonium because the UK has only one LWR owned by Électricité de France, which has made clear that it is not interested in using MOX fuel. The current *de facto* UK policy for its separated plutonium is therefore secure storage at its Sellafield reprocessing site (Figure 6).

Storage for future use

The history of the development of the UK's thinking about its plutonium-disposal options since the end of its breeder reactor development program is long and meandering. British Nuclear Fuel Limited (BNFL), a government-owned company, was responsible for this problem until 2005. As of 1998, its plan was to store the UK's separated plutonium “for future use in thermal [slow] or fast[-neutron] reactors.”⁶⁸ The first challenge to this passive view came that same year from a study sponsored by the Royal Society,

the UK's national academy of science, perhaps stimulated by the U.S. National Academy of Sciences' 1994 study on the U.S. excess weapons plutonium problem.⁶⁹ The 1998 report of the Royal Society study declared it to be “disturbing” that there was no strategy under development for dealing with the UK's civil plutonium stock⁷⁰ and urged the Government to consider both MOX, and immobilization and burial.



Figure 6 UK Sellafield Product and Residue Store, which became operational in 2011. Cans of plutonium are stored in separate lockers to protect against criticality accidents. *Source:* Sellafield Ltd.

The following year, BNFL established a Plutonium Working Group within its Stakeholder Dialogues to “develop and recommend principles for BNFL's management and reduction of separated plutonium stocks.”⁷¹ The Working Group report, published in 2002, suggested that MOX fuel could be used in the UK's two newest advanced gas-cooled reactors (AGRs) plus its single LWR, the French-owned Sizewell B. It also urged serious work on a range of immobilization options. These included using the Sellafield MOX Plant, which had been completed in 2001, to produce “low-spec MOX” after it finished its commercial contracts to fabricate MOX fuel for the UK's foreign reprocessing customers.⁷² The low-spec MOX – perhaps just fuel pellets sealed in cans – would be produced to looser specifications than required for actual fuel use and would be disposed of directly in a deep repository. In parallel, two independent analysts produced the first UK estimates of the costs of the main disposal options and concluded that low-spec MOX with direct disposal would have the lowest-cost.⁷³

A preference for MOX

The UK Nuclear Decommissioning Authority (NDA) replaced BNFL in 2005. It began addressing its plutonium disposal responsibility by commissioning a study by a group of consultants – mostly ex-BNFL staff – on the “macro-economics” of future uranium and plutonium management. Cost estimates were made for three options: indefinite storage, disposal as waste, and use as fuel in fast breeder reactors. The consultants argued, without providing a reviewable basis, that the last option would yield a profit.⁷⁴

In 2007, the Royal Society returned to the subject with a new report that opposed any further plutonium separation beyond existing contracts. It strongly advocated MOX as “the optimal option” for disposing of both UK plutonium and foreign-owned plutonium stored in the UK but acknowledged that, unless new reactors were built, not all of the stockpile could be disposed in MOX. It therefore proposed that the remainder be stored as MOX pellets. In case of a terrorist attack on the storage facility, this would reduce the danger of dispersal of plutonium powder in inhalable form and, in the long term, the pellets could be disposed directly when a deep repository became available.⁷⁵

In 2008, the NDA declared that indefinite storage of plutonium was unacceptable. It also rejected the conclusion of its 2007 consultants’ study that disposal in MOX fuel could yield a profit.⁷⁶ The following year, it published the conclusions of a “credible options” report on the alternatives available to manage UK separated plutonium. It did not include the possibility of using MOX in UK reactors, because Électricité de France (EDF), which was in the process of acquiring them, was opposed.⁷⁷

The plutonium management options found to be least costly were indefinite storage and “selling” – in practice, paying another country, presumably France – to take it. Other options considered were mixing the plutonium into cement or molten glass, immobilization in ceramic or glass via Hot Isostatic Pressing (HIP), fabrication into low-spec MOX pellets using the existing Sellafield MOX Plant or a new facility, and production of MOX fuel for Canadian heavy-water reactors or European LWRs. All cost data were redacted in the published report, however. Only a summary graph showing the relative costs of the options was shown.⁷⁸

When NDA published a revised version of its Credible Options report in 2010, it added back the option of using MOX in future UK-based LWRs.⁷⁹ The NDA also revealed that it had awarded “low value” contracts to the Atomic Energy of Canada Ltd and AREVA to advise it on the MOX options.⁸⁰ It reported that AREVA advised that, after cleanup, up to 99.8 percent of the UK’s plutonium could be disposed in MOX⁸¹ and concluded that MOX fuel use in UK-based LWRs had “very few disadvantages,” listing none.⁸²

Considering alternatives

The first UK Government policy response came in a Department of Energy and Climate Change (DECC) consultation paper in 2011 that put forward a “preliminary policy view” in favor of MOX use, either in the UK or overseas, based primarily on the idea that MOX represented “proven mature technology” and that all other disposal technologies were less mature.⁸³ Although EDF had publicly stated its opposition to MOX use in the UK, the UK Government was encouraging other foreign utilities to build LWRs in the UK. DECC pointed out that just two large new LWRs operating with 40% MOX fuel could irradiate the UK’s stock of separated plutonium in 60 years.⁸⁴

With regard to immobilization, it was pointed out that, because of the surrounding gamma field from the fission products it contains, spent MOX fuel provides a higher degree of intrinsic security than unirradiated immobilized plutonium. DECC argued that it therefore would be “unwise” to build an immobilization plant before a geological disposal facility was available, because new secure stores would have to be built for

the immobilized product. This argument would appear to rule out any serious consideration of immobilization by the UK Government because the Government's desired timescale for a plutonium disposal program was 25 years (i.e. by around 2036) while there is no realistic possibility of a repository being available in the UK before the 2040s at the earliest.

In late 2011, DECC produced its response to the earlier 2011 consultation, confirming its policy preference for MOX. A timeline was presented, suggesting that the "justification" required by the regulators, i.e. a proof that the benefits would outweigh the costs, might be completed by the end of 2014, and that construction of a MOX fuel fabrication plant could then begin by 2019.⁸⁵ DECC produced a flurry of documents in 2012 and 2013, setting out its conclusions and guidance to developers.⁸⁶

New developments during 2013 delayed the policy-making process. In January 2014, NDA produced a report describing these developments:⁸⁷

1. A delay in the launch of construction of the first of the hoped-for new generation of LWRs in the UK, two 1,650-MWe EPRs to be built by AREVA and operated by EDF. The European Commission (EC) was reviewing the high price guarantee being offered by the UK for the electric power that the reactors would generate. The EC's approval in October 2014⁸⁸ initially appeared likely to encourage other vendor-utility combinations to move toward firm construction plans for additional LWRs but, in early 2015, the Austrian Government announced that it would appeal the EC approval of "state aid" for the project to the European Court of Justice. If, as appears likely, the Court hears the appeal, there will be a further delay of at least two years.⁸⁹ If the project survives, there will be additional years before the NDA can negotiate with the utility operators of proposed follow-on LWRs over their use of MOX fuel.⁹⁰
2. Further analysis of the UK's stock of plutonium had led to the conclusion that it would only be cost effective to clean 85–90 percent for fabrication into MOX.⁹¹ Between 14 and 21 tons might therefore have to be immobilized.
3. Finally, Candu Energy and GE-Hitachi had offered other reactor options for irradiating the UK's plutonium and the NDA had encouraged them to develop these ideas into proposals.⁹² Candu Energy proposed building two 700-MWe CANDU-6 heavy water reactor reactors and GE-Hitachi proposed to build two 311-MWe PRISM sodium-cooled fast-neutron reactors.⁹³ GE-Hitachi claimed that the full inventory of UK plutonium, including the 10–15% not suitable for LWR MOX, could be turned into PRISM metal uranium-plutonium-zirconium alloy fuel.⁹⁴

Both Candu Energy and GE-Hitachi proposed to build their reactors adjacent to the Sellafield reprocessing site. Both argued that fabricating plutonium-uranium fuel for their reactors would be less costly than fabricating MOX fuel for LWRs. This would make it possible for them to finance the construction of their reactors in part with some of the funds that the UK government might otherwise have paid to build an LWR MOX fuel fabrication plant. Also, the extraordinarily high £8 billion (\$7,760/kWe) estimated capital cost (not including interest during construction) for each of AREVA's 1.65 GWe LWRs,⁹⁵ which resulted in the high UK Government price guarantees for the power they would generate, also created an unprecedented opportunity for the costly heavy water and sodium-cooled reactors.

NDA apparently regarded the CANDU-6 proposal as credible because: eleven units are operating around the world;⁹⁶ the MOX fuel fabrication process would be similar to that used for LWR MOX; and there were some possible equity investors. PRISM by contrast is a “paper reactor,” i.e. it has never been built; and liquid-sodium-cooled fast-neutron reactor systems have a troubled past and many safety issues that the UK safety regulatory system has not confronted since the shutdown of the UK Prototype Fast Reactor in 1994.

Also, irradiated PRISM fuel would raise what the NDA acknowledges as “unique challenges” to disposal.⁹⁷ The fuel rods contain sodium to conduct heat from the fuel “meat” to the rod cladding. This could make the spent fuel pyrophoric, i.e. capable of igniting spontaneously on contact with water, and therefore unacceptable for disposal underground. The U.S. decided that this was the case for the “sodium-bonded” spent fuel from its Experimental Breeder Reactor II (EBR II, 20-MWe, 1963–94) on which the PRISM design is based and, in 2006, launched a program to turn 3 tons of EBR II spent fuel containing about 0.6 tons of plutonium into an acceptable waste form. The estimated cost of this program in 2006 was about \$0.2 billion or \$330 million per ton of plutonium.⁹⁸ It would be ironic if the UK’s costly program to dispose of the legacy plutonium from its reprocessing program required the reprocessing of the disposal form. NDA may be interested, in encouraging Candu Energy and GE-Hitachi to compete with AREVA for the UK plutonium disposal contract in order to drive the cost down.⁹⁹

In the meantime, the UK National Nuclear Laboratory is setting up a plutonium immobilization process at the Sellafield reprocessing site where contaminated plutonium oxide is to be immobilized in relatively insoluble crystals in a glass matrix. The process to be used to turn the powder into this solid composite is “hot isostatic pressing” in which the powder is simultaneously put under high pressure (1,000 atmospheres) and high temperature (1,200–1,300 °C) for eight or nine hours.¹⁰⁰

The cylinders of material produced by the process could each contain up to 10 weight percent or about 2 kg of plutonium.¹⁰¹ Initially, only about 0.1 metric tons of plutonium is to be immobilized in this way but, if the UK opts for MOX and 14 to 21 tons of its 140 tons of separated plutonium are too impure for MOX fuel, the process might be scaled up.

The neo-liberal climate of UK public decision-making and the absence of a commercial technology vendor for an immobilization option has made it difficult for it to be considered seriously for disposing of all of the UK’s separated plutonium.

United States

In 1994, given the drastic down-sizing of its Cold War nuclear arsenal, the U.S. declared 38.2 tons of its 85 tons of weapon-grade plutonium excess for nuclear weapon purposes.¹⁰² It also declared excess the 7.5 tons of non-weapon-grade plutonium that had been separated at the short-lived (1966–72) commercial West Valley Reprocessing Plant in New York State and acquired from abroad before the U.S. abandoned both its breeder and civilian reprocessing programs in 1983.¹⁰³

Some of the excess weapon-grade plutonium was in dilute form in contaminated waste from nuclear-weapon production. As of the end of 2009, 4.5 tons of this plutonium had been disposed of in the Department of Energy's (DOE's) Waste Isolation Pilot Plant (WIPP), a deep repository under New Mexico.¹⁰⁴ This subtraction was more than offset, by a declaration of an addition 9 tons of excess weapon-grade plutonium in 2007. The U.S. therefore has a total of about 50 tons of excess separated plutonium.

DOE decided to consolidate all U.S. excess plutonium other than that in weapons "pits" in the K-Area Materials Storage facility at its Savannah River site (Figure 7).¹⁰⁵ More than ten thousand excess plutonium-containing nuclear-weapon "pits" are stored in bunkers at the DOE's Pantex warhead assembly/disassembly plant in Amarillo, Texas until facilities are ready to extract their plutonium.



Figure 7 Plutonium storage containers in the U.S. DOE's Savannah River Site K-Area Material Storage Facility where approximately 13 tons of U.S. excess plutonium are stored. Each storage container is about 0.9 meters high and 0.5 meters in diameter and contains up to 4.4 kilograms of plutonium. In addition to protecting the small cans of plutonium within, the outer containers are large enough to prevent a fission chain reaction involving the contents of neighboring cans.¹⁰⁶ Source: H. Allen Gunter, Senior Technical Advisor and Assistant Manager, Nuclear Material Stabilization Project, Savannah River Operations Office, briefing to the Citizens Advisory Board Nuclear Materials Committee, 28 April 2009.

Originally: A dual-track disposal strategy

In 1997, DOE decided to pursue in parallel two plutonium disposal tracks:¹⁰⁷

1. MOX fuel for light water reactors (LWRs), and
2. Immobilization in the reprocessing waste being embedded in glass (vitrified) at the DOE's Savannah River and Hanford sites.

One reason for pursuing immobilization as well as MOX was because some of the plutonium being declared excess was not from warhead pits and was contaminated with materials that would be costly to remove to make it usable in MOX fuel. In addition

“Pursuing both immobilization and MOX fuel fabrication... provides important insurance against uncertainties of implementing either approach by itself.”¹⁰⁸

In 2000, the DOE therefore decided to build both a MOX fuel-fabrication facility and a plutonium immobilization plant at the Savannah River Site. The plan was to fabricate up to 33 tons of plutonium into MOX fuel and immobilize at least the 17 tons of impure plutonium included in the 50 tons.¹⁰⁹

That same year, Russia and the U.S. signed a Plutonium Management and Disposition Agreement in which they agreed to each eliminate in parallel 34 tons of excess weapon-grade plutonium. The Russian negotiators opposed U.S. immobilization of any of the 34 tons of U.S. weapon-grade plutonium covered by the agreement, arguing that only irradiation in a reactor would change the plutonium isotopic mix from weapon-grade to non-weapon-grade. The compromise was that the U.S. would dispose at least 25.6 of its 34 tons of plutonium via MOX.¹¹⁰ The DOE apparently planned to dispose of plutonium not covered by the agreement via immobilization.

The immobilization approach that DOE selected – “can-in-canister” – would have involved converting the plutonium into oxide that then would be mixed at a concentration of about 10 weight percent into ceramic “pucks” that would have been stacked inside steel cans, 6 cm in diameter and 25 cm high, each of which would contain about 1 kg of plutonium. Twenty-eight of these cans would be placed on a framework inside a three-meter-high canister that would be filled around the cans with molten high-level waste glass.¹¹¹ The resulting waste form was then to be stored at the Savannah River Site with the other canisters of vitrified high-level waste being produced there until a radioactive waste repository became available. Since each canister would contain about 28 kg of plutonium, about 1800 canisters of vitrified high-level waste would be required to dispose of 50 tons of plutonium.

The purpose of embedding the plutonium in high-level waste glass was to create a “self-protecting” gamma radiation barrier around the canister to satisfy the National Academy of Sciences’ “spent fuel standard.” Almost all this radiation field would be associated with decays of the 30-year half-life fission product cesium-137.

The decision to focus on MOX

In 2002, the Bush Administration decided that it would be less costly to have a single-track plutonium disposal program and, given Russia's insistence that the U.S. dispose of most of the 34 tons covered by the Plutonium Management and Disposition Agreement (PMDA) in MOX fuel, decided to dispose of all of it in that manner. The Department of Energy informed the Congress that the net cost of building and operating the MOX fuel fabrication plant during the disposition period would be \$2.15 billion (\$2.8 billion in 2014 dollars).¹¹²

The program to dispose of the 34 tons of excess weapons plutonium covered in the agreement with Russia is the responsibility of the National Nuclear Security Administration within the Department of Energy. The disposal of the plutonium not covered by the PMDA is the responsibility of the DOE's Office of Environmental Management (EM). The Bush Administration's decision left the 17 tons of excess plutonium not covered by the PMDA without a well-defined disposal path.

In 2007, the Bush Administration announced that it would be possible to dispose of four of the remaining 17 tons of excess plutonium in MOX. Two tons could be mixed into the radioactive waste tanks at Savannah River before the waste was vitrified and 7 tons could be immobilized in glass for can-in-canister disposal with the Savannah River Site's high-level waste for an estimated cost of \$0.8 billion.¹¹³ Four tons in the metal fuel plates used in the Idaho National Laboratory's Zero Power Physics Reactor (ZPPR) were withdrawn for "future programmatic use" – a decision that was reversed again in 2012.¹¹⁴

A study that was apparently a partial basis for this decision had concluded that 13 tons could be disposed of via the can-in-canister route in six years starting in 2011. The cans of vitrified plutonium would be produced in the K-Area facility on the Savannah River Site where the non-pit plutonium was being stored.¹¹⁵

Despite almost annual changes in the plans between 2000 and 2013,¹¹⁶ no program to deal with the non-pit plutonium was actually launched.¹¹⁷

MOX becomes "unaffordable"

By 2013, it was clear that both the schedule and the cost of the under-construction MOX Fuel Fabrication Facility (MFFF) at the Savannah River Site were out of control. When it released its proposed budget for fiscal year 2014, the Obama Administration therefore announced "this current plutonium disposition approach may be unaffordable... due to cost growth and fiscal pressure."¹¹⁸

The cost estimates by the prime contractor, Shaw AREVA (now CB&I-AREVA) MOX Services had been increasing by leaps and bounds. Part of the increase was due to the need to more than double the size of the MFFF to include an "aqueous polishing" area. Aqueous polishing would involve dissolution and chemical processing of the plutonium to remove impurities that could degrade the MOX product and then conversion

back to oxide. Additional causes for the cost increases included the need to redesign the MOX fabrication portion of the plant to meet U.S. safety and security requirements, the inability of suppliers to meet DOE's nuclear quality standards, underestimates of the salaries and overestimates of the productivity of nuclear-qualified personnel, and their rapid turnover as they left to work on nuclear power plant construction projects in the Southeast.¹¹⁹

By 2013, the prime contractor estimated the construction cost of the MFFF and the associated Waste Solidification Building (WSB) at \$8.3 billion and the operating cost of the MFFF and WSB at "\$0.64 billion per year for 15 years for a total cost of \$18 billion to dispose of 34 tons of plutonium.¹²⁰ This was a six-fold increase from the 2002 estimate in constant dollars. In 2015, a review done for the DOE by the Army Corp of Engineers increased this total cost estimate by another 40% to \$25 billion.¹²¹ This cost estimate did not include the cost of decommissioning the plutonium-contaminated MFFF and WSB after the completion of their missions. Nor did it include the cost of extracting plutonium from the weapons "pits" nor did it include the cost of disposing of the plutonium-contaminated waste or the security costs for the MFFF and Waste Solidification Building.

A number of DOE nuclear-weapons-related programs also were experiencing huge cost overruns and Congress was imposing stringent budget caps on all discretionary spending. The Administration therefore proposed that the partially completed MOX plant (Figure 8) be placed

"into cold standby [while the Administration evaluated] alternative plutonium disposition technologies ... that will achieve a safe and secure solution more quickly and cost effectively."¹²²



Figure 8 U.S. MOX Fuel Fabrication Facility (MFFF) under construction, 25 October 2014, at the DOE's Savannah River Site in South Carolina. Source: High Flyer, Savannah River Site Watch.

The Congressional delegations from South Carolina, the state in which the MFFF was being built, and from Georgia across the Savannah River, home of a significant fraction of the site's workforce, which included 1,585 working on construction of the MOX plant,¹²³ fought back, and obtained funding for continued construction in fiscal years (FY) 2014 and 2015 of \$343 and \$345 million respectively. In January 2015, with a new Republican majority in the Senate, the Obama Administration didn't wait for Congress to act but simply included another \$346 million for FY 2016 in its budget proposal to Congress.¹²⁴ At that rate, given the cost projected by the Obama Administration in the same budget submission, it would take 20 more years to complete the plant.

Some key members of the Congressional Appropriations Committee appear to have recognized the problem and, in the Appropriations Act for FY 2015, the National Nuclear Security Administration (NNSA), which manages the plutonium-disposition project within DOE, was directed

“to submit to the Committees on Appropriations of the House of Representatives and the Senate not later than 120 days after enactment of this Act [on 16 December 2014] an independently-verified lifecycle cost estimate for the option to complete construction and operate the MOX facility and the option to downblend and dispose of the material in a repository.”¹²⁵

The House and Senate Armed Services Committees included a more detailed reporting requirement in the National Defense Authorization Act for FY 2015.¹²⁶

In the meantime, the Department of Energy is under pressure to begin to remove plutonium from the Savannah River Site, one way or another. According to an agreement that South Carolina's Congressional delegation had embedded in law, if the MOX Fuel Fabrication Plant did not come into operation by 2014, at least one ton of plutonium should be removed from the Savannah River Site by 2016 and all of the plutonium that had been brought there since 15 April 2002 should be removed by 2022. The fines associated with not meeting these requirements require Congressional appropriations, and the 2016 deadline was changed by amendment from an earlier deadline of January 2011.¹²⁷

In April 2014, the Obama Administration's Plutonium Disposition Working Group issued a preliminary assessment of the alternatives to MOX.¹²⁸ The alternatives considered were:

1. Dilution and disposal in the DOE's deep-underground transuranic Waste Isolation Pilot Plant (WIPP);
2. The can-in-canister approach for embedding the plutonium in glassified reprocessing waste;
3. Disposal in boreholes up to 5 km deep; and
4. Irradiation in one or two new liquid sodium-cooled fast-neutron reactors – one of the options also being discussed in the UK (see above).

There has also been at least one independent study of alternatives to MOX.¹²⁹

Waste Isolation Pilot Plant

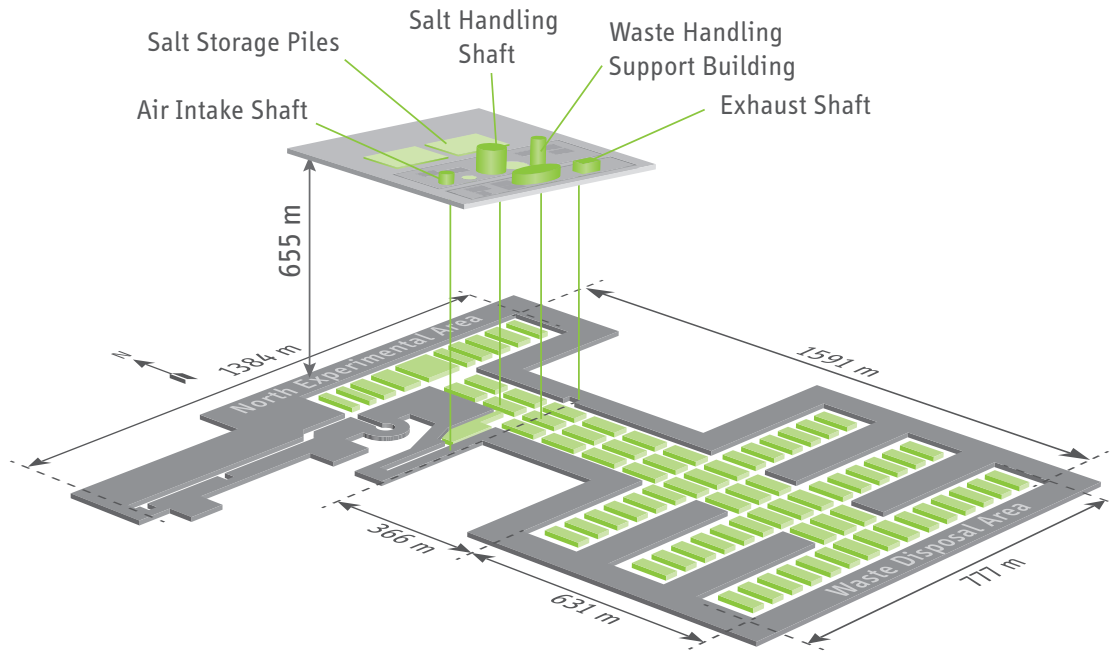


Figure 9 The U.S. Department of Energy's Waste Isolation Pilot Plant (WIPP) near Carlsbad, New Mexico where plutonium-contaminated waste from weapons R&D and production is being disposed. *Source: Improving Operations and Long-Term Safety of the Waste Isolation Pilot Plant* (National Academy Press, 2001), Figure 1.2.

The working group found “down-blending” (dilution) and disposal in WIPP (Figure 9) to be the least costly option – about \$3 billion.¹³⁰

The DOE has already been implementing this disposal approach on a small scale. In 2011, it authorized the down-blending and disposal in “pipe-overpack containers,” 6-inch (15 cm) pipes centered in 55-gallon (200-liter) drums¹³¹ of 0.585 tons of plutonium oxide powder stored at its Savannah River Site.¹³² The plutonium oxide is mixed to a concentration of less than 10 percent by weight with a classified “Termination of Safeguards” material from which it would be difficult to separate chemically.

Because inhaled plutonium particles are extremely carcinogenic,¹³³ the removal of the plutonium oxide powder from its “DOE-3013” standard storage containers and mixing with a dilutant in the pipes is done in a glovebox within which the air pressure is lower than outside so that any leakage is inward. The inside air is exhausted through high-efficiency filters (Figure 10).



Figure 10 Glovebox line at the former Sellafield MOX Fuel Fabrication Plant. *Source:* UK Nuclear Decommissioning Authority.

For this initial disposal operation, the amount of plutonium per drum was limited to less than 175 grams.¹³⁴ The estimated disposal cost is about \$100,000 per kilogram of plutonium.¹³⁵ The DOE's Plutonium Disposition Working Group concluded that, with additional wooden disks to hold the inner pipe in place inside the 55-gallon drums, they could be considered "criticality control overpack" containers,¹³⁶ and the loading could be increased to 380 fissile grams equivalent, i.e. plutonium-239 grams equivalent per drum.¹³⁷ This would reduce the disposal cost to an estimated \$68,000 – 88,000 per kilogram of plutonium,¹³⁸ i.e. to about one tenth the currently estimated cost for disposal via MOX.

To accomplish the task, the Plutonium Disposition Working Group estimated that two additional glove-box lines would have to be installed in the Savannah River Site's plutonium-storage and two hundred additional staff would have to be hired at Savannah River and WIPP. Each glove-box line would fill one drum per shift. Assuming that each drum contained on average 340 grams of plutonium and that the blending and packaging process operated around the clock, this would accumulate to 0.4 tons per glove-box line per year or 1.2 tons per year for three glove-box lines. This throughput could be doubled if a similar processing capacity were installed in the Los Alamos National Laboratory plutonium processing facility in New Mexico.¹³⁹

At 340 grams per drum, approximately 150,000 drums would be required to dispose of all the DOE's 50 tons of plutonium. Theoretically, about 90,000 drums could be accommodated in one of the seven-room "panels" planned for WIPP (Figure 9). In practice, the average volume of waste that has actually been loaded into each of the six closed

panels is equivalent to 75,000 drums.¹⁴⁰ Given the volume requirements for plutonium-contaminated waste from DOE's other sites, the 2014 report of the DOE's Plutonium Disposition Working Group concluded that only 13 tons of down-blended plutonium could be accommodated into WIPP without an increase in WIPP's legislated volume limit.¹⁴¹ Edwin Lyman, a Senior Scientist at the Union of Concerned Scientists' Global Security Program, has argued that the space reserved for the other wastes is not fully subscribed and that the available space could accommodate more than one hundred thousand 55-gallon drums. Since some of the existing panels of rooms in WIPP were walled off before they were full, more than the originally planned number of panels would have to be constructed to accommodate the licensed volume of waste.¹⁴²

Both the DOE Plutonium Disposition Working Group and Lyman suggested options for increasing the amount of plutonium per drum. If the amount of plutonium in each 55-gallon barrel were increased to 1 kg or more, U.S. Government regulations would require much more strict security and safeguards arrangements.¹⁴³ Even at the lower loadings, an independent review might recommend enhanced security. The pipes within the drums that contain the plutonium have a length of slightly over 0.6 meters (2 feet) and a diameter of about 15 cm (6 inches). In the absence of strict monitoring of the personnel, materials and shafts to the surface, it might be possible to break a significant number of the pipes free and remove them from the repository. The theft of fewer than 20 pipes, containing 340 grams of plutonium each, would be required to obtain the equivalent of the 6 kg of plutonium in the Nagasaki bomb. If not already installed, instrumentation should be installed in the repository's access shafts to detect neutrons emitted by spontaneous fissions in the plutonium.¹⁴⁴

On 14 February 2014, a small chemical explosion occurred in one of the waste drums stored in WIPP and released plutonium and americium-contaminated smoke that lightly contaminated the facility and some workers on the surface near its ventilation exhaust. Chemical reactions had occurred in a drum of waste from the Los Alamos National Laboratory.¹⁴⁵ According to DOE's current recovery plans, rooms in WIPP containing containers with similar contents to the drum that exploded will be walled off and the contents of containers with similar contents that are still aboveground will be stabilized before burial. It is hoped that the facility will be put back into operation early in 2016, but shipments from the Savannah River Site are not expected to resume before 2018.¹⁴⁶

The future of WIPP will depend in good part on whether DOE can regain the hard-won trust of New Mexico. From 1978–2004 DOE provided funds to New Mexico's Health and Environment Department for an Environmental Evaluation Group to provide independent advice on the safety of WIPP.¹⁴⁷ DOE would be well advised to fund the group's reestablishment.

The report of the DOE's Plutonium Disposition Working Group raises the possibility that, if it becomes impossible to get permission to expand the mission of WIPP to include disposal of all U.S. excess plutonium, a new repository could be established for that purpose. WIPP was built during the 1980s at a cost of \$700 million (\$1.47 billion in 2013\$), but would cost "substantially more than this due to today's design, construction, and operation standards."¹⁴⁸ Even so, it would be far less costly than the MOX option.

Cans in canisters

With regard to the can-in-canister immobilization option, the DOE's Plutonium Disposition Working Group found, in line with previous DOE analyses, that immobilization of 34 tons of excess U.S. plutonium in this manner would no longer be possible at the Savannah River Site (SRS)

“since nearly half of SRS's HLW [high level waste] has already been remediated, there is not enough HLW remaining to dispose of 34 MT of surplus plutonium. In addition, DWPF [the Defense Waste Processing (glassification) Facility at Savannah River] is scheduled to complete operations by 2032, which would likely be before a new immobilization facility could be designed and constructed.”¹⁴⁹

The working group therefore argued that, if the can-in-canister route were to be pursued, an immobilization plant would have to be built at the Hanford site, where a huge Waste Treatment and Immobilization Plant, including a high-level waste glassification unit, is under construction. This was found to be about as costly as the MOX option, because Hanford no longer has the plutonium-management and security infrastructure that has been preserved at Savannah River, including the K-Area plutonium storage facility and the associated capability for assessing the condition of and repackaging plutonium containers.¹⁵⁰

An almost identical statement had been made two years earlier, when the projected completion date for vitrification was six years earlier.¹⁵¹ In fact, virtually none of the cesium-137 that would provide the protective gamma-ray field around plutonium-containing high-level waste canisters has been glassified at the Savannah River Site, because the process to separate cesium-137 out of the salt in the high-level waste tanks failed and it has been necessary to construct a new facility, the Salt Waste Processing Facility, whose completion has been delayed for many years and whose costs have soared. As of the end of 2014, the facility was projected to go into operation sometime between December 2018 and January 2021.¹⁵² In the meantime, sludge that contains very little cesium-137 from the bottoms of the tanks is being vitrified. As of the end of fiscal year 2013, the high-level-waste tanks at Savannah River still contained about 73 million Curies of cesium-137 in their liquid and salt cake layers.¹⁵³

The standard for self-protection that the DOE has been using for the can-in-canister method is a dose level of at least 1 Sv/hr at one meter from the canister 30 years after the filling of the canister.¹⁵⁴ This would require about 11,000 Curies of cesium-137 (about 125 grams) per canister.¹⁵⁵ At an average of 0.6 kg of plutonium per can and 28 cans per canister,¹⁵⁶ it would require about 3,000 canisters of glassified waste containing a total of 33 million Curies of cesium-137 to hold 50 tons of plutonium. As of the end of 2014, the Department of Energy had filled about 4,000 canisters with high-level waste at the Savannah River Site since 1996 and projected that it had about 4,600 more canisters to fill.¹⁵⁷ Its commitment is to fill an average of 200 canisters per year, which would result in the task being completed in 2037, but in recent years, has been filling about 125 per year.¹⁵⁸

If it were possible to begin can-in-canister immobilization in 2020 at a rate of 2 tons of plutonium per year, as envisioned in the 2004 design study,¹⁵⁹ thirty-four tons could be immobilized by 2037. After the end of vitrification at Savannah River, the DOE could ship cans of immobilized plutonium out to its Hanford site for emplacement in the canisters of vitrified waste that are to be produced there. A secure building would be required to receive the cans and load them into canisters, but no other plutonium-related infrastructure would be required.

In the Defense Authorization Act for fiscal year 2015, the Congressional delegation from Washington State included a prohibition against the DOE even considering bringing plutonium to that State as long as it was not in full compliance with its cleanup commitments at the Hanford site.¹⁶⁰ Washington State is currently suing the DOE because of its failure to meet agreed commitments and timelines.¹⁶¹

Deep Boreholes

The DOE's Plutonium Disposition Working Group thought that the total cost of deep borehole disposal would be between that of the WIPP and immobilization options, but that "the costs for disposition in a deep borehole would be closer to the down-blending [WIPP] option."¹⁶² It argued that not enough R&D had been done to allow for a detailed assessment of deep-borehole disposal but noted that, in 2012, the Sandia National Laboratory had proposed a 5-year, \$75 million dollar project to drill a demonstration deep borehole suitable for the disposal of some of DOE's radioactive waste.

In September 2014, the DOE's deep borehole assessment project reported on a preliminary assessment of possible sites suitable for deep borehole disposal and found that, of 110 DOE sites, the Savannah River Site (SRS) had the third highest suitability score, based on its area, distance from urban areas, the presence of crystalline basement rock within two kilometers of the surface, flatness, low geothermal heat flux, and low volcanism. The negatives included the complexity of the basement rock and the seismic hazard. Interestingly, the site that ranked highest in the screening was the Pantex, warhead assembly/disassembly and plutonium pit storage site outside Amarillo, where the basement rock is at a shallower depth. The Pantex site was disadvantaged relative to SRS, however, by a higher density of oil drilling nearby.¹⁶³

The report of the borehole assessment project also included a preliminary discussion of DOE radioactive wastes that are already in or could be placed in small enough packages to be suitable for borehole disposal. The proposed approach would embed the waste packages in water-retarding clay or other material within stainless steel canisters with walls thick enough to resist the great hydrostatic pressures at the borehole depth.¹⁶⁴

Liquid-sodium-cooled reactors

Building and operating two 0.311-GWe fast-neutron reactors¹⁶⁵ and the associated fuel fabrication facility was found to be more costly than completing and operating the MOX Fuel Fabrication Facility. In addition, as discussed above in connection with GE-Hitachi's identical proposal made to the UK Government, treating the sodium-bonded spent fuel could cost additional billions.

Lessons from the U.S. experience

The disastrous U.S. experience has been in substantial part self-inflicted. Although it is the successor to the remarkable U.S. World War II Manhattan Project, the National Nuclear Security Administration within the DOE has trouble managing large projects and has developed a pattern in which the costs of such projects multiply while their schedules slip.¹⁶⁶ The UK Nuclear Decommissioning Authority has similar problems with project management.¹⁶⁷

Disposing of plutonium in MOX is particularly demanding, because it requires high quality standards and adherence to a disciplined schedule that nuclear utilities can depend on. Direct disposal would be far simpler to execute.

The U.S. DOE's Plutonium Disposition Working Group focused in on the simplest possible direct-disposal strategy: down-blending the plutonium and packaging it in drums to be deposited in an already operating underground waste-plutonium repository. Unfortunately, an accident in that repository has blocked that route for a few years at least. Can another potential destination for the down-blended plutonium be found? Deep borehole disposal, building on the drilling technology developed by the U.S. oil, gas and geothermal industries, appears to be one possibility.

Other options, such as can-in-canister disposal and packaging for disposal in a geological repository with U.S. spent fuel and/or vitrified high-level waste probably would require a solid rather than a powdered mix. The solid mix could be produced via vitrification, pressing and sintering, or hot isostatic pressing. These processes are more demanding than simple down-blending but still much less demanding than the manufacture of MOX fuel.

A second lesson from the above history would appear to be "don't put all your eggs in one basket." This is, in fact, one of the reasons why the U.S. plutonium disposal program was originally designed to pursue two tracks in parallel: MOX and direct disposal with high-level waste. Going forward, at least two options should be kept open unless and until the cost of doing so becomes significant on the multi-billion-dollar scale of this problem. Indeed, given the potential limitations of the quantities of plutonium that can be accommodated in some options and the development requirements of others, it is quite possible that the optimal strategy may end up being two or more disposal routes implemented as they become available.

If this is the case, the DOE should compare in an open and reviewable fashion the potential processing capacities and costs for producing different plutonium immobilization forms at existing facilities at Savannah River and Los Alamos while the uncertainties about the possible ultimate disposal destinations are clarified.

Finally, there is no hurry. U.S. excess plutonium currently is relatively securely stored at the DOE's Savannah River Site and in the weapon "pit" storage bunkers at the Pantex warhead assembly/disassembly site.

Negotiating with Russia

Reviving direct disposal options will require either persuading Russia to drop its insistence that the U.S. irradiate most of its weapon-grade plutonium or defying that insistence. Ideally, Russia would accommodate the U.S. as the U.S. accommodated Russia in 2010 when Russia decided to irradiate its plutonium using breeder reactors rather than LWRs.

In any case, Russia's plan to separate out the plutonium after it has been irradiated essentially eliminated any security benefit in Russia from implementation the Plutonium Management and Disposition Agreement (PMDA). Indeed Russia's program to separate and reuse the plutonium increases the risk of its theft relative to simply keeping 25 of the 34 tons of plutonium covered by the agreement in the high-security Mayak Fissile Material Storage Facility that was built for the purpose with U.S. financial assistance and the remaining 9 tons in an underground plutonium storage facility in Zheleznogorsk.¹⁶⁸

The U.S. therefore would have little to lose, even in the unlikely case that Russia decided to renounce the PMDA rather than agree to the U.S. shifting to a direct disposal option. The PMDA is an executive agreement and can be renegotiated or terminated by agreement between the executive branches of the two countries.

Direct-disposal options

It is important to understand that, if direct disposal is chosen, the amount of plutonium that will end up being buried will not be much larger than the amount that otherwise would have been buried in spent MOX fuel. Irradiation only reduces the quantity of plutonium and other long-lived transuranic elements in MOX fuel by about 25%. This is in part because the even-numbered isotopes of plutonium (Pu-238, Pu-240, Pu-242) are “non-fissile.” Although they can be fissioned by fast neutrons in fast-neutron reactors or nuclear explosions, they have a low probability of being fissioned by the slow neutrons that mediate the chain reaction in LWRs. Even Pu-239, which dominates the fissions in MOX fuel, has a probability of about one quarter of not being fissioned after absorbing a slow neutron. Instead, it simply becomes Pu-240.¹⁶⁹ Also, for every ten plutonium atoms fissioned in MOX, about six new ones are produced by neutron absorption in the U-238 that makes up more than 90 percent of its heavy-metal mass.¹⁷⁰

One would think that, if a country is interested in plutonium separation and use, its spent MOX fuel would be the richest “ore” because the percentage of plutonium in spent MOX fuel is about six times that in spent LEU fuel. However, the fuel value of plutonium in spent MOX fuel is diminished for LWRs by the fact that the percentage of non-fissile isotopes in the plutonium increases with every cycle. If in fresh MOX fuel the percentage of non-fissile plutonium is, for example, 35 percent, after irradiation it is 54 percent.¹⁷¹ Not even France has separated the plutonium in its spent MOX fuel on more than a demonstration scale. Instead, France’s spent MOX fuel has been accumulating for a quarter of a century in the huge spent fuel storage pools at La Hague awaiting the potential commercialization of fast-neutron reactors. In 2005, ANDRA, the agency responsible for disposing of France’s radioactive waste (Agence Nationale pour la Gestion des Déchets Radioactifs), began considering scenarios in which the spent MOX fuel would be disposed of in an underground repository.¹⁷²

Interim storage

As discussed in the U.S. and UK chapters, various alternative approaches are being considered for the immobilization and then direct disposal of separated plutonium in mined tunnels or rooms deep underground or in deep boreholes. Until underground destinations become available, however – in some cases not for decades¹⁷³ – interim storage will be required, either before or after processing the plutonium into a disposal form.

It might be thought that the dilution of plutonium that is involved in the production of disposal forms creates a reason to wait until a repository becomes available, lest the dilution create the need for more high-security storage space. It will be seen from figures 6 and 7, however, that pure plutonium oxide cannot in any case be stored compactly because of the need to prevent criticalities, i.e. fission chain reactions between neighboring cans of plutonium. Also, if a neutron “poison” (neutron-absorbing material) is mixed into the immobilization form, concerns about criticalities will be reduced. Finally, plutonium oxide is an extremely potent carcinogen and converting it into a solid eliminates the risk that it might be dispersed into the atmosphere, either accidentally or deliberately.

Below we provide first an overview of possible plutonium disposal forms and then strategies for putting them underground.

Disposal forms

Three alternative approaches to creating plutonium waste forms for disposal have been discussed above:

1. Mechanical mixing of the plutonium oxide with a dilutant from which it would be difficult to recover;
2. Immobilization in non-radioactive glass or ceramic; and
3. “Low-spec” or “storage” MOX as a specific form of ceramic immobilization.

Mechanical mixing. Mechanical mixing of plutonium oxide with a dilutant from which it would be difficult to separate is being pursued on a small scale in the U.S. as a way to take advantage of an already existing deep underground repository for plutonium-contaminated waste.¹⁷⁴ As discussed above, the U.S. DOE Plutonium Disposition Working Group identified this as the lowest-cost option for the disposal of all U.S. plutonium – if the legislated limit on the volume of waste that can be emplaced in the Waste Isolation Pilot Plant (WIPP) can be increased slightly. The explosion of a drum of waste in WIPP in February 2014 damaged the relationship between the DOE and the State of New Mexico, and it remains to be seen whether an expansion of WIPP’s mission to accept more plutonium in much more concentrated forms will be politically acceptable.¹⁷⁵

Immobilization. Two plutonium immobilization forms were developed in the U.S. program: mixing into a ceramic or glass.

Ceramic. Plutonium-containing ceramics are made by processes involving pressure and high temperature. The approach developed for the U.S. plutonium-disposal program is similar to that used for making MOX fuel pellets, except that the immobilization form would have about one hundred times the approximately one cubic centimeter volume of a MOX fuel pellet.¹⁷⁶

Plutonium dioxide is mixed with uranium dioxide and the mixture is milled into a fine powder (about one micron particle size). Other materials are added, including organic binders and possible neutron absorbers for criticality control. The mix is granulated and pressed into the desired shape at a pressure of 140 to 350 atmospheres. The resulting “green” pucks then would be heated and stay at a temperature of about 1,350°C for several hours to fuse the grains into one solid piece.¹⁷⁷ A study done for the DOE estimated that the labor force for around-the-clock operation immobilizing 5 tons of plutonium a year would be about 300 persons.¹⁷⁸

A second approach to producing a ceramic or a mix of crystals and glass is to apply pressure and heat simultaneously in what is called “hot isostatic pressing” (HIP). The Australian Nuclear Science and Technology Organization (ANSTO) has developed synthetic rock forms, “synroc” to sequester various radionuclides, including plutonium, in

low-leach matrices.¹⁷⁹ The UK National Nuclear Laboratory (NNL) has partnered with ANSTO to set up a process at the Sellafield reprocessing site to immobilize contaminated plutonium oxide in a glass containing relatively insoluble crystals in which the plutonium is segregated. The powder is simultaneously put under high pressure (one thousand atmospheres) and high temperature (1,200–1,300°C) for eight or nine hours. The average concentration of plutonium in this mix can be up to 10 weight percent or about 2 kg of plutonium in the 5-liter volume final waste form being developed by NNL. In the initial UK application, because the waste to be immobilized contains only an average of 20% plutonium before being mixed with the matrix-forming materials, each 5-liter waste form is expected to contain only 0.3 to 0.5 kg.¹⁸⁰

Vitrification. The vitrification (glassification) approach mixes plutonium oxide with a neutron absorber and glass powder (“frit”) in a melter. The molten mix is then poured into a container to cool and solidify.¹⁸¹ This is less costly than pressing and sintering and is being used in several countries on a large scale to solidify reprocessing waste. A special lanthanum borosilicate glass was developed in the U.S. program to dissolve up to 0.5 grams of plutonium per cubic centimeter, or one kilogram in a 2-liter can. Achieving complete dissolution of the plutonium at this concentration requires a high temperature in the range of 1,450–1,500°C.¹⁸² At lower temperatures, plutonium-rich crystals tend to crystalize out of the glass as in the HIP process. As with the HIP process, the crystals are relatively insoluble and the resulting inhomogeneous form could be acceptable.

Storage MOX. An approach to plutonium immobilization that was examined by some non-governmental analysts in the 1990s was to produce low-quality MOX for direct disposal – perhaps just cans of MOX pellets.

The cost of building a MOX plant solely to produce storage MOX would be very high. If an existing MOX fuel fabrication plant, such as the Sellafield MOX Plant in the UK, no longer had a mission, consideration might be given to using it to produce storage MOX. The capital investment would be a “sunk” cost and operating costs would be reduced because dimensional tolerances could be relaxed.

In fact, the fuel fabricators in Western Europe have produced MOX containing tens of tons of plutonium that is de facto storage MOX because it cannot be used as fuel. AREVA has refused to offer any explanation¹⁸³, but this appears to be the primary reason why the amount of unirradiated plutonium in fabricated form in France has increased from 3.6 tons in 1995 to about 30 tons in 2011–13 (Figure 3).

The unusable MOX fuel stored in France includes:

1. A full core of unirradiated MOX fuel containing about 6 tons of plutonium that was fabricated for France's failed Superphénix fast breeder reactor;¹⁸⁴
2. Another core of unirradiated MOX fuel containing 1.6 tons of plutonium that was produced for Germany's never-operated SNR-300 breeder reactor¹⁸⁵ – probably traded to France in exchange for a payment to AREVA and an equivalent amount of plutonium in MOX fuel for Germany's LWRs;¹⁸⁶ and
3. An unknown amount of plutonium in scrap that was fabricated into sub-spec MOX as a way to make the plutonium transportable when AREVA's Cadarache,¹⁸⁷ Belgium's Dessel¹⁸⁸ and Germany's Hanau¹⁸⁹ MOX fuel fabrication plants were decommissioned – and in scrap fabricated into sub-spec MOX during ongoing operations at AREVA's Melox fuel fabrication plant.¹⁹⁰

Except for the Superphénix core, which is still at the reactor site on the Rhone River near Geneva, this unusable MOX fuel is in interim storage in one of the spent fuel pools at France's reprocessing plant at La Hague.

How much of this unirradiated MOX will be dissolved and refabricated into LWR MOX fuel is unknown. Currently, France's La Hague reprocessing plant has a license to process MOX powder and pellets but not rods or assemblies. Ultimately, some or all of the unusable MOX fuel may be disposed of directly to France's future repository for high-level radioactive waste.

The excess U.S. plutonium stored at the DOE's Savannah River Site includes 0.7 tons of plutonium in unusable MOX fuel originally fabricated for the DOE's terminated sodium-cooled Fast Flux Test Facility.¹⁹¹ Japan has about 1.6 tons of plutonium in unusable unirradiated MOX fuel.¹⁹²

Underground destinations

Once plutonium is immobilized and packaged, it could be placed deep underground in mined rooms, tunnels, or deep boreholes.

Mined repositories. Spent MOX fuel most likely will be disposed in casks mixed with spent LEU fuel when a repository becomes available. Unirradiated MOX and immobilized plutonium in suitable forms could be disposed along with the spent fuel. In the near term, the gamma radiation field associated with the spent fuel would provide some protection against theft of the MOX pending the closure of the repository. In the long term, mixing materials containing a high percentage of plutonium with spent LEU fuel would reduce the danger of criticality millennia hence when water penetrates the casks and their contents start to leach out.

Vitrified high-level waste also is expected to go into a mined repository. Any plutonium immobilized in the glass – either homogeneously or embedded in cans – would go with it.

Plutonium not protected by a radiation barrier would require special security arrangements underground prior to repository closure or at least the walling off of rooms within the repository containing such plutonium with backfill and engineered barriers.

Deep boreholes. The option of boreholes, 3 to 5 km deep is of particular interest for immobilized plutonium.¹⁹³ This would be up to ten times deeper than a mined repository, which would make retrieval of the plutonium difficult. Also, the possibility that the plutonium might dissolve and be carried back to the surface in the contaminated water is reduced by at least three factors:

1. The great pressure from the rock above closes cracks at these depths, resulting in very slow water movement;
2. Plutonium is relatively insoluble in deep, old ground water whose oxygen has been depleted by reactions with the surrounding rock; and
3. Water at such depths generally contains dissolved salts, which make it dense, impeding its ability to rise and mix with the lighter fresh water in aquifers near the surface.¹⁹⁴

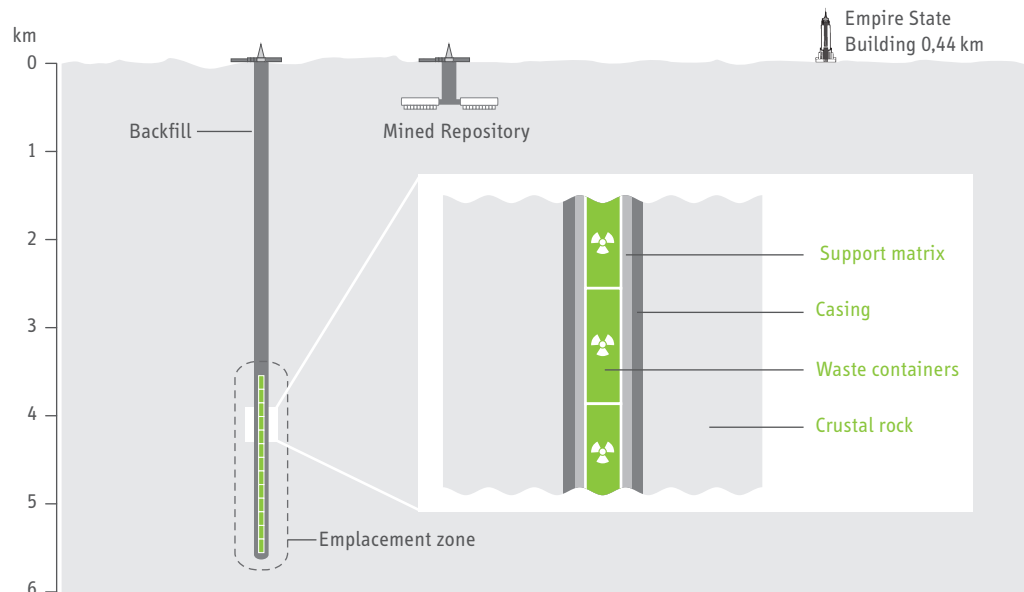


Figure 11 Schematic of a deep borehole for disposal of immobilized plutonium. In this example, the borehole has a depth of about 5 km. The bottom half, which is surrounded entirely by basement crustal rock, is loaded with immobilized plutonium while the borehole is filled and blocked with a series of seals cut into the rock around the borehole. The top portion of the borehole, which passes through rocks that are more porous, is filled and blocked by more seals, possibly made of a variety of materials: cement, clay, asphalt, etc. For comparison, a typical mined geological repository would be at a depth of about 0.5 km – comparable to height of the tallest skyscrapers of the 20th century. *Source:* Harold Feiveson, Alexander Glaser, Zia Mian and Frank von Hippel, *Unmaking the Bomb* (MIT Press, 2014) Figure 9.3.

There has been a considerable amount of analytical work in the United States and elsewhere on the possibility of disposing radioactive waste in deep boreholes.¹⁹⁵ A demonstration project that would emplace nonradioactive materials is in preparation, coordinated by the U.S. DOE's Sandia National Laboratory.¹⁹⁶ Although the Sandia researchers have not yet discussed borehole disposal of plutonium, they have discussed the possibility of disposing spent fuel in a 5-kilometer-deep borehole. The cylindrical cavity occupied by the fuel inside a robust container within the bottom two kilometers of the borehole would have a diameter of about 16 centimeters (6 inches) and have a volume of about 40 cubic meters.¹⁹⁷

If 50 tons of weapon-grade plutonium oxide were diluted with depleted uranium oxide to an average of 3 percent concentration so that it could not go critical in the borehole,¹⁹⁸ the disposal of 50 tons of plutonium would involve 1,700 tons of "heavy metal" – uranium plus plutonium in the mix.

If the mix were processed into ceramic with the same heavy metal density as in fuel pellets (9.6 grams per cubic centimeter), the volume required would only be 177 cubic meters and could be accommodated in five boreholes. Processing 1,700 tons of heavy metal oxide into ceramic would be costly, however, even if the pieces were large and the quality requirements much less stringent than for fuel pellets.

At the other extreme, the heavy-metal oxide could be left as a powder. Indeed, in order to minimize plutonium handling, the cans of plutonium oxide stored at Savannah River could be packed into canisters filled with uranium oxide. But the density of the heavy metal in the powder is only 1.4 grams/cc, about one seventh of that in ceramic.¹⁹⁹

An intermediate strategy would involve compressing the uranium oxide powder around the cans of plutonium oxide to a density of about 4 grams uranium/cc.²⁰⁰ This would make it possible to emplace about 4 tons of plutonium in each borehole and require 13 boreholes for 50 tons of plutonium. The cost of making, loading and sealing a 5-km deep borehole has been estimated at \$40 million.²⁰¹

There is a whole literature on low-leach ceramics in which plutonium could be embedded.²⁰² Specially designed low-leachable waste forms may be unnecessary, however. Much larger quantities of plutonium will be emplaced in geological repositories in spent fuel containing pellets fractured by thermal expansion and contraction and by fission-product gases.

A key question is whether the siting of boreholes would be politically more feasible than the siting of a mined geological repository, i.e. does the great depth and narrowness of a deep borehole make its safety more intuitively apparent to the public? The U.S. DOE Plutonium Disposition Working Group assumed not.²⁰³ This assumption could be tested with focus groups at candidate sites.

One potential problem with regard to public acceptance could be the fact that, in recent years, the “reversibility” of disposal of radioactive waste in mined repositories has been emphasized.²⁰⁴ For example,

- France’s 2006 Act on Sustainable Management of Radioactive Materials and Waste specified that, “As a precaution, the license shall prescribe the minimum period for which the reversibility of the disposal process must be guaranteed. In any case, that minimum period shall not be less than 100 years;”²⁰⁵ and
- Canada’s Nuclear Waste Management Organization recommended in 2005 that underground monitoring of the performance of a spent fuel repository continue for 240 years before the access tunnels or shafts are finally closed.²⁰⁶

International transparency

In the non-weapon states, the burial of plutonium, including that in spent fuel, will be monitored by the IAEA to verify that none is diverted before the repository is back-filled. The IAEA also will have the responsibility to monitor repositories in perpetuity to assure that, if they are reentered, none of the plutonium within them is diverted from safeguarded activities.

The five nuclear weapon states that are parties to the Nonproliferation Treaty (NPT) have committed in Article 6 of the treaty to “pursue negotiations [on] nuclear disarmament” that, if successful, would end with them becoming non-weapon states. It would facilitate verification of their non-weapon status in the future – and increase confidence in deep cut agreements in the nearer term – if the IAEA monitored the disposal of their excess plutonium.

The first program to bury large quantities of plutonium in the weapon states may be the U.S. program to consolidate and bury plutonium-contaminated waste in its Waste Isolation Pilot Plant (WIPP). As of the end of 2013, the U.S. had reported to the IAEA that 4.5 tons of plutonium had been disposed in WIPP.²⁰⁷

While there has been some exploration by experts at the DOE’s Sandia National Laboratory of the possibility of using WIPP as a demonstration site for transparency in an underground repository,²⁰⁸ there has been no actual IAEA verification of the quantity of plutonium contained in the waste being buried in WIPP. In part this is because the IAEA, which has a tight budget, is not eager to undertake verification tasks in the weapon states.

The Russian-U.S. Plutonium Management and Disposal Agreement of 2000 contains a commitment by the two countries to negotiate IAEA monitoring arrangements for their plutonium disposal. As of the end of 2014, these negotiations had not been completed.

Conclusions

The huge cost overruns in the under-construction MOX plant at the DOE's Savannah River Site in South Carolina led the Obama Administration to conclude in 2013 that plutonium disposal via MOX "may be unaffordable." This has revived policy interest in the U.S. in the possibilities of direct disposal of plutonium as a waste.

Efforts to convert foreign separated plutonium into MOX fuel encountered technical problems in the UK, forcing the abandonment of the Sellafield MOX Plant. The UK has therefore looked, in at least a *pro forma* way, at direct-disposal alternatives.

Japan and France are still focused exclusively on MOX – and will be as long as their government policies are to reprocess spent fuel. But Japan's program has been much delayed and France's may soon be confronted with the retirement of the reactors that have been irradiating its MOX fuel.

In the late 1990s, the U.S. studied in considerable depth a "can-in-canister" option in which immobilized plutonium would be embedded in some of the high-level reprocessing waste from which it had been originally separated. This was a way to create a radiation barrier around the plutonium like that around the plutonium in spent fuel, which makes plutonium inaccessible except via chemical and mechanical operations controlled remotely from behind thick radiation shields. The can-in-canister approach also shares the merit with MOX that it just adds marginally to the quantity of an already existing waste form for which a geological repository has to be found in any case. This option may still be of particular interest in the United States, which will be disposing of reprocessing waste for several decades into the future.

In France and the UK, where high-level waste vitrification has been ongoing in parallel with reprocessing, it may be impossible to pursue the "can-in-canister" option unless it is planned well before reprocessing ends.

There are other options, however. One that appears increasingly attractive is deep-borehole disposal. It does not involve a radiation barrier, but retrieval would be much more difficult than from a closed geological repository.

There is also the possibility of disposing of plutonium in a mined repository without a radiation barrier, as the U.S. is doing in its Waste Isolation Pilot Plant. In such cases, special security arrangements will be required as long as any room or tunnel in the repository that contains disposal plutonium is open. The U.S. Department of Energy considers that, below one kilogram per drum, the plutonium will be dilute enough so that this will not be necessary – especially if the plutonium is mixed with chemicals from which it would be difficult to separate. This should be debated, however. In the WIPP case, the pipe in the center of the drum that actually contains the plutonium has a volume of only about 12 liters and could potentially be separated from the drum.²⁰⁹

In the long term, after repositories are closed and 30-year-half-life cesium-137, which provides most of the gamma-ray field has died away, it will be the depth of the repository underground and perpetual national and international monitoring arrangements that will provide the protection against the misuse of the plutonium they contain.

For some countries, a single method for plutonium disposal may be insufficient. France, as devoted as it is to MOX fuel, might in the end dispose directly more than 20 tons of plutonium that it has in the form of de facto “storage MOX.” Given that none of its disposal options are problem-free, the United States should return to at least a dual-path approach. WIPP, can-in-canister and deep-borehole disposal all appear worth pursuing on different timelines.

MOX once seemed to be affordable and produced a waste form that could be disposed of with spent fuel. It has turned out to be more costly and technically challenging than expected. Each of the direct disposal alternatives has its own complications, but it is time to examine them as well.

Ideally, the countries that share the problem of excess plutonium stocks could develop joint programs to examine the direct-disposal options. The near-term possibilities for such collaboration will be limited, however, as long as the governments of France, Japan and Russia remain committed to reprocessing and the UK government continues to depend on the nuclear industry to propose solutions. If and when MOX programs are abandoned, the nuclear establishments of all these countries have relevant know-how and industrial capacity and would have a commercial interest in getting involved.

Endnotes

- ^{1.} The spent fuel of light (ordinary) water-cooled reactors (LWRs), the dominant power-reactor type, contains about one percent plutonium.
- ^{2.} IAEA, Communication Received from Certain Member States Concerning their Policies Regarding the Management of Plutonium, INFCIRC/549, 16 March 1998.
- ^{3.} For decades, starting in the 1970s, advocates of reprocessing in France and Japan argued that the plutonium separated from power-reactor plutonium was *not* weapon usable because it had a different isotopic composition from “weapon-grade” plutonium, which is separated from uranium that has been irradiated much less intensely than reactor fuel. This claim is made less frequently, but is still heard today. In 1978, a senior U.S. weapon designer, Robert Selden, gave briefings to the leaderships of the French and Japanese reprocessing establishments, explaining that “reactor-grade” plutonium was weapon-usable. The response from the French reprocessing proponents was, “no matter what you say, our plutonium is innocent!” In 1995, a senior official in France’s Commissariat à l’Énergie Atomique, when asked what France’s weapons designers were telling their reprocessing establishment about the weapon-usability of reactor-grade plutonium, responded, “Not what they say!” In 1993, a former head of the Los Alamos weapons design division published an unclassified explanation of why even the Nagasaki design would give a yield equivalent to at least one thousand tons of TNT with any mix of plutonium isotopes, J. Carson Mark, “Explosive Properties of Reactor-Grade Plutonium,” *Science & Global Security* Vol. 4 (1993) pp.111–128. In 1997, a group of U.S. weapons laboratory experts published a two-page unclassified summary statement on the subject that concluded, “reactor-grade plutonium is weapons-usable, whether by unsophisticated proliferators or by advanced nuclear weapon states. Theft of separated plutonium, whether weapons-grade or reactor-grade, would pose a grave security risk.” *Nonproliferation and arms control assessment of weapons-usable fissile material storage and excess plutonium disposition alternatives* (U.S. Department of Energy, DOE/NN-0007, 1997), pp. 38–39. As a result of such advice, the IAEA, in its safeguarding of plutonium in non-weapon states does not distinguish between different grades of plutonium except that it does exempt plutonium that is more than 80% plutonium-238. (Because of its relatively short 88-year half-life, Pu-238 generates more than 0.5 kilowatts of decay heat per kilogram.)
- ^{4.} Assuming 3 kg of military plutonium per warhead and conservatively using the IAEA’s assumption of 8 kilograms of civilian plutonium for a first-generation (Nagasaki-type) nuclear weapon, including production waste, *IAEA Safeguards Glossary*, 2001 Edition, p. 23.
- ^{5.} For Russia and the U.S., 34 tons of weapon-grade plutonium declared excess by each in the 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 (2000 Plutonium Management and Disposition Agreement as amended by the 2010 Protocol <http://fissilematerials.org/library/PMDA2010.pdf>) covers. The U.S. declared an additional 9 tons of weapon-grade plutonium excess in 2005. In its 2014 declaration to the IAEA (INFCIRC549/A6/17) the U.S. stated that it had disposed “to waste,” i.e. in the Waste Isolation Pilot Plant, a deep geological repository in New Mexico, an additional 4.5 tons. The UK declared excess 0.3 tons of weapon-grade in 1998 (*Global Fissile Material Report 2010*, p. 78).
- ^{6.} India has declared plutonium separated for its breeder reactor program “strategic” and therefore not subject to IAEA safeguards. In that way, it preserves the option of using for weapons purposes this plutonium or plutonium produced by its breeder reactors. Under the 23 September 1997 Agreement Between the Government of the United States of America and the Government of the Russian Federation Concerning Cooperation Regarding Plutonium Production Reactors, Russia agreed not to use in weapons any plutonium produced by its production reactors after September 1994, *Global Fissile Material Report 2011*, endnote 120. An estimated six tons of this plutonium is not included in

the 34 tons of Russian declared excess, *Global Fissile Material Report 2010* (IPFM, 2010) Table 3.5. In its 1998 Strategic Defense Review, the UK declared excess for weapons purposes 4.1 tons government-owned reactor-grade plutonium held at the Sellafield Reprocessing Plant. Of 49 tons of U.S. government-owned separated plutonium declared as “excess to national security needs” and not disposed of in waste in the deep underground Waste Isolation Pilot Plant, 6.6 tons are not weapon-grade, IAEA, “Communication Received from the United States of America Concerning its Policies Regard the Management of Plutonium, INFCIRC/549/Add.6/17, 6 October 2014 and *United States Plutonium Balance, 1944–2009* (U.S. Department of Energy, 2012), Table 3.

7. Foreign separated plutonium in France and the UK not belonging to Japan.
8. 2000 Plutonium Management and Disposition Agreement as amended by the 2010 Protocol, *op. cit.*
9. 2000 Plutonium Management and Disposition Agreement as amended by the 2010 Protocol, *op. cit.*, Annex on Quantities, Forms, Locations, and Methods of Disposition.
10. *Department of Energy (DOE) FY 2016 Congressional Budget Request*, Vol. 1, pp. 635-6.
11. *Department of Energy (DOE) FY 2014 Congressional Budget Request*, Vol. 1, p. DN-113.
12. Plutonium is created by neutron capture on uranium-238 followed by radioactive decay of the resulting uranium-239 (24-minute half-life) into neptunium-239 (2.4-day half-life) and then plutonium-239 (24,000-year half-life). Plutonium is produced in LWR fuel and some of it is fissioned, but LWRs do not produce enough plutonium to switch from their primary dependence on U-235.
13. R.B. Fitts and H. Fuji, IAEA, “Fuel Cycle Demand, Supply and Cost Trends,” *IAEA Bulletin* Vol. 18 (1975) p. 19.
14. *International Nuclear Fuel Cycle Evaluation*, Vol. 5, “Fast Breeders” (IAEA, 1980), p. 53, *Superphénix* case.
15. Assuming 53 MWt-days/kg, a thermal to electric energy conversion efficiency of 1/3 and 8.5 kg of natural uranium per kg of low-enriched uranium (4.4% enriched uranium with a depleted uranium assay of 0.23%).
16. *Uranium 2014: Resources, Production and Demand* (OECD Nuclear Energy Agency and International Atomic Energy Agency, 2014) p. 130.
17. See e.g. Erich A. Schneider and William C. Sailor, “Long-Term Uranium Supply Estimates,” *Nuclear Technology*, Vol. 162 (2008) p. 379.
18. Belgium, Italy and the Netherlands participated in the French and German breeder reactor programs, *Fast Breeder Reactor Programs: History and Status* (IPFM, 2010).
19. “Rosenergoatom already learning from BN-800,” *World Nuclear News*, 10 December 2014.
20. “India’s nuclear power,” *Frontline*, 3 October 2014.
21. Cumulatively, as of the end of 2013, the CEFR had generated only 20 MWe-hrs of electric power, IAEA Power Reactor Information System, <http://www.iaea.org/PRIS/>. For its operation in Dec. 2014, see http://www.heneng.net.cn/index.php?mod=news&category_id=9&action=show&article_id=33209&category_id=9 (in Chinese).
22. Mycle Schneider and Yves Marignac, *Spent Nuclear Fuel Reprocessing in France* (IPFM, 2008) chapter VI.
23. Kari Ikonen and Heikki Raiko, *Thermal Dimensioning of Olkiluoto Repository for Spent Fuel* (Posiva, Working Report 2012-56, 2012), http://www.posiva.fi/files/3143/WR_2012-56.pdf.

24. Roald A. Wigeland et al, Argonne National Laboratory, "Repository Impact of Limited Actinide Recycle," *Proceedings of Global 2005, Tsukuba, Japan, Oct 9–13, 2005*, Paper No. 496.
25. *Sources and Effects of Ionizing Radiation*, Vol. I. "Sources," (UNSCEAR, 2000), Tables 42–44. Releases of carbon-14 to the atmosphere from reprocessing per unit of nuclear output in the fuel reprocessed had declined by an order of magnitude since the 1970s
26. The isotopes, Neptunium-237, Pu-238, Pu-240, Pu-242, Americium-243 and Curium-244 all have fission probabilities in LWRs ten to one hundred times smaller than those of Pu-239, "Le Projet ASTRID," (Société Française de Energie Nucléaire, SFEN/GR21, 2013) p. 6.
27. *Long-term safety for the final repository for spent nuclear fuel at Forsmark: Main report of the SR-Site project. Volume III* (SKB, TR-11-01, 2011) http://www.skb.se/upload/publications/pdf/TR-11-01_vol3.pdf. See e.g. Figure 13–18. In order of contributions to the estimated dose from leakage (from large to small) the radioisotopes are: radium-226, a decay product of U-238; iodine-129, a fission product; neptunium-237, a transuranic isotope; selenium-79, a fission product; lead-210, a decay product of uranium-238; nickel-59, an activation product of steel alloys; actinium-227, a decay product of U-235; and niobium-94, another activation product of steel alloys.
28. Translation from "Avis no. 2013-AV-0187 de l'Autorité de sûreté nucléaire du 4 July 2013 sur la transmutation des éléments radioactifs à vie longue" ["Opinion No. 2013-AV-0187 of the Nuclear Safety Authority of July 4, 2013 on transmutation of long-lived radioactive elements"]. See also the conclusion of IRSN, the research institute that supports the ASN, "Avis IRSN n° 2012 – 00363, Objet: Plan national de gestion des matières et des déchets radioactifs...Etudes relatives aux perspectives industrielles de séparation et de transmutation des éléments radioactifs à vie longue: Examen du rapport d'étape du CEA, d'octobre 2010, relatif aux évaluations technicoéconomiques des options de séparation-transmutation" ["IRSN review No. 2012-00363 of National management of radioactive materials and waste...Studies on the industrial prospects of separation and transmutation of long-lived radioactive elements: Review of the CEA October 2010 interim report on technical and economic assessments for partitioning and transmutation"].
29. Osamu Tochiyama, chair of METI's technical working group on waste disposal and Director of the Radioactive Waste Disposal Safety Research Center at the Nuclear Safety Research Association, quoted in Daisuke Yamada, "As I See It: Gov't needs to look at options on handling, disposal of radioactive waste," *Mainichi*, 1 May 2014.
30. See e.g. George Perkovich, *India's Nuclear Bomb: The Impact on Global Proliferation* (University of California Press, 1999).
31. J. Carson Mark, Theodore Taylor, et al, "Can Terrorists Build Nuclear Weapons?" in *Preventing Nuclear Terrorism*, Paul Leventhal and Yonah Alexander, eds. (Lexington Books, 1987).
32. Steve Fetter and Frank von Hippel, "The Hazard from Plutonium Dispersal by Nuclear-warhead Accidents," *Science & Global Security*, Volume 2 (1990) pp.21–41.
33. *Management and Disposition of Excess Weapons Plutonium* (National Academy Press, 1994) p. 31.
34. *Management and Disposition of Excess Weapons Plutonium*, op. cit. p. 34.
35. IAEA, *Nuclear Security Recommendations on Physical Protection of Nuclear Material and Nuclear Facilities* (INFCIRC/225/Revision 5, 2011) para. 4.6.

36. Russia and the U.S. agreed to define weapon-grade plutonium as plutonium in which the ratio of Pu-240 to Pu-239 is less than 0.1, "2000 Plutonium Management and Disposition Agreement as amended by the 2010 Protocol," *op. cit.* Article I. Neutron irradiation in a reactor will increase that ratio because the neutrons will fission some of the Pu-239 and convert some of it to Pu-240. A smaller offsetting effect involves neutron capture on Pu-240 that converts it into Pu-241.
37. "2000 Plutonium Management and Disposition Agreement as amended by the 2010 Protocol," *op. cit.* Article VII.3.
38. Also, breeder reactors, as normally configured, produce weapon-grade plutonium in the uranium "blankets" around their cores, Mortitz Kütt, Fredericke Frieß and Matthias Englert, "Plutonium disposition in the BN-800 Fast Reactor: An assessment of plutonium isotopics and breeding," *Science & Global Security* Vol. 22 (2014) pp. 188–208.
39. According to the declarations of France, the UK and Japan to the IAEA, as of the end of 2013, there were only 5 tons of non-Japanese foreign separated plutonium stored in France and the UK. This was down from 11 tons as of the end of 2012 and 16 as of the end of 2011.
40. Cost from JNFL, Oct. 2012, <http://www.jnfl.co.jp/jnfl/establishment.html> (in Japanese).
41. JNFL Press release, 31 October 2014, <http://www.jnfl.co.jp/press/pressj2014/pr141031-1.html> (in Japanese).
42. IAEA Nuclear Fuel Cycle Information System (INFCIS).
43. Quantities of spent fuel sent to France and the UK from reply of the Agency for Natural Resources and Energy of Japan's Ministry of Economy, Trade and Industry to Diet member Mizuho Fukushima, 16 January 2013, http://kakujoho.net/ndata/pu_jp.html.
44. *Rapport fait au nom de la Commission D'enquête relative aux coûts passés, présents et futurs de la filière nucléaire*, [Report of the Commission of Enquiry relative to the costs past, present and future of nuclear power] (National Assembly, 5 June 2014), <http://www.assemblee-nationale.fr/14/rap-enq/r2007-tl.asp>, p. 217, recommendation 11.
45. Dates for first connections to the grid from the IAEA Power Reactor Information System.
46. Tara Patel, "France May Face Reactor Shutdowns in 2020, Regulator Says," *Bloomberg News*, 3 December 2013.
47. "French MPs back cut to nuclear energy reliance," (Reuters, 10 October 2014).
48. *Plan National de gestion des matières et déchets radioactifs, 2013–2015* [National Plan for Radioactive Waste Management, 2013–2015] (ASN, 2013) p. 16; Phil Chaffee, "A 2019 Halt to La Hague?" *Nuclear Intelligence Weekly*, 10 May 2013, p. 5. ASN is incorrectly identified as ANDRA, which is responsible for radioactive waste disposal in France.
49. The UK Nuclear Decommissioning Authority continued to operate the last of the UK's first-generation Magnox reactors, Wylfa-1 (460 MWe) in 2014 but planned to shut it down during 2015, <http://www.magnoxsites.co.uk/site/wylfa/>.
50. Japan Atomic Energy Agency, "MOX Fuel Technology Development," <http://www.jaea.go.jp/english/04/tokai-cycle/03.htm>.
51. <http://www.jaea.go.jp/04/ztokai/facilities/sisetu/PuHP/report/Today/pudaily1.htm>; <http://www.jaea.go.jp/04/ztokai/summary/center/plutonium/> (in Japanese).
52. Japan Atomic Energy Commission, "The Situation of Separated Plutonium Management in Japan as of the End of the Year 2013" (in Japanese).

- ^{53.} Japan Nuclear Fuel Limited Press Releases, 11 April 2014, <http://www.jnfl.co.jp/press/pressj2014/pr140411-2.html>, and <http://www.jnfl.co.jp/press/pressj2014/20140411besshi.pdf> (in Japanese).
- ^{54.} “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,” (UK Office for Nuclear Regulation, 18 Feb. 2000) <http://www.onr.org.uk/mox/mox1.htm>.
- ^{55.} *Sellafield MOX Plant: Lessons Learned Review* (UK Department of Energy and Climate Change, 18 July 2012); Brian Brady, “Revealed: £2bn cost of failed Sellafield plant,” *The Independent*, 9 June 2013.
- ^{56.} IAEA, “Communication Received from Certain Member States [Japan] Concerning their Policies Regarding the Management of Plutonium,” INFCIRC/549/Add. 1, 31 March 1998.
- ^{57.} The November 2000 publication of the Japan Atomic Energy Commission, *Long-Term Program for Research, Development and Utilization of Nuclear Energy*, includes a discussion in the reference section, http://www.aec.go.jp/jicst/NC/tyoki/siryotyoki_e/siryoe.htm#_Toc496950128, describing the planned utilization of Japan’s separated plutonium: “After Monju [Japan’s prototype breeder reactor] resumes operation [this still had not happened as of the end of 2014] some hundreds of kilograms of plutonium will be needed annually for research and development purposes... According to plans by the utility companies, use of MOX fuel will be gradually increased up to 16–18 LWRs by 2010... according to plans already specified, approximately 0.3–0.4 tons of plutonium are expected to be used annually at each unit. Approximately 1.1 tons of plutonium per year are expected to be used at the full-MOX-core Oomas nuclear power station.” The earliest English translation we have of the Japan Federation of Electric Power Utilities’ (FEPCo’s) plan is “Utilization plan for plutonium recovered at Rokkasho Reprocessing Plant (Fiscal years 2005–2006),” <http://www.cnic.jp/english/topics/cycle/MOX/pluplanFEPCO6Jan06.html>. Released in January 2006, that plan named the 16 to 18 nuclear power reactors that were to be using MOX “in and after FY 2012.” The purpose of the plan was and is to justify the operation of the Rokkasho Reprocessing Plant (RRP), which went into hot testing in 2006. At the time, J-MOX was expected to go into operation in FY 2012 with a “projected [total] amount [of fissile plutonium (Pu-239 and Pu-241)] to be used annually” of 5.5–6.5 tons. In the Japan Atomic Energy Commission’s 11 September 2013 statement on “The Current Situation of Plutonium Management in Japan,” the ratio between total plutonium and fissile plutonium is given as 1.5. FEPCo reissued its “Utilization of Plutonium” plan annually and sometimes semi-annually until 17 September 2010 when it changed the “start of utilization” in all the reactors to “after FY 2015”, <http://www.cnic.jp/english/topics/cycle/MOX/pdf/puplan17sep10.pdf>.
- ^{58.} Fukushima #3, Genkai #3, Ikata #3 and Takahama #3. As of the end of 2014, unused MOX fuel containing 2.5 tons of plutonium was stored at six nuclear power reactors: Genkai #3, Hamaoka #4, Kashiwazaki Kariwa #3, Takahama #3 and Takahama #4, Masa Takubo, “MOX Fuel Transportation/Use/Storage,” <http://fissilematerials.org/blog/MOXtransportSummary10June2014.pdf>.
- ^{59.} Mari Saito, *et al*, “Japan may only be able to restart one-third of its nuclear reactors,” Reuters, 1 April 2014.
- ^{60.} Federation of Electric Power Companies of Japan, “MOX Fuel Use in Thermal Reactor[s]”, http://www.fepec.or.jp/english/nuclear/fuel_cycle/mox_fuel/index.html. The year had been changed from 2010 to 2015 in 2009 to adjust the 1997 statement to the reality of the delays of the MOX plan. The 2009 statement said “at the latest by fiscal 2015, when the MOX fuel fabrication plant starts operation.” http://www.fepec.or.jp/about_us/pr/sonota/1198266_1511.html (in Japanese).
- ^{61.} Tsuyoshi Nagano and Hiroshi Ishizuka, “Completion of nuclear fuel processing plant postponed for 21st time,” *Asahi Shimbun*, 31 October 2014.

62. Japan Atomic Energy Commission, "The Current Situation of Plutonium Management in Japan," 26 September 2014 (in Japanese).
63. "Even if the electric power companies can restart their nuclear reactors, they could be forced to shut them down if the Rokkasho plant cannot accept additional nuclear fuel and their own storage pools become filled," Tsuyoshi Nagano and Hiroshi Ishizuka, "Completion of nuclear fuel processing plant postponed for 21st time," *Asahi Shimbun*, 31 October 2014. In fact 12 out of Japan's 15 nuclear power plants could operate for at least an additional 10 years before their spent fuel pools filled up, Masafumi Takubo and Frank von Hippel, *Ending reprocessing in Japan: An alternative approach to managing Japan's spent nuclear fuel and separated plutonium* (IPFM, 2013) Table 2. See also, "Utilities balk at safer storage of spent nuclear fuel to avoid 'wasted investment,'" *Asahi Shimbun*, 4 January 2015.
64. "Interim storage startup to be postponed to Oct. 2016, Nuclear Fuel Cycle," *Daily Tohoku*, 10 January 2015 (in Japanese).
65. The UK Nuclear Decommissioning Authority estimated in January 2014 that, "On completion of reprocessing operations there will be around 140 tonnes of civil separated plutonium in the UK," *Progress on approaches to the management of separated plutonium* (2014), p. 3.
66. 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*, 2011, para. 6.3. As of the end of 2013, the UK had 23.4 tons of foreign separated plutonium, IAEA, "Communication Received from the United Kingdom of Great Britain and Northern Ireland Concerning its Policies Regarding the Management of Plutonium," INFCIRC/549/Add.8/16, 18 July 2013.
67. Fiona Harvey, "Sellafield MOX nuclear fuel plant to close," *The Guardian*, 3 August 2011. Through 1970, the UK Atomic Energy Authority (AEA) fabricated some 3 tons of MOX fuel for light water reactors at Sellafield for use in six different overseas reactors. The UK AEA – and later British Nuclear Fuels Limited (BNFL), which took over reprocessing from the UK AEA in 1971 – also fabricated some 18 tons of MOX fuel with plutonium content of up to 33% for the UK Dounreay Fast Reactor (11 MWe) and the Prototype Fast Reactor (234 MWe), both at Dounreay, Scotland, ending in 1988. BNFL then built a MOX Demonstration Facility at Sellafield that fabricated limited amounts of MOX for overseas light water reactors in the early 1990s before being shut down after a quality control data falsification scandal, *BNFL View of UK Plutonium Usage*, UK Nuclear Safety Advisory Committee (98) P4, January 1998, p. 2.
68. *BNFL View of UK Plutonium Usage*, submission to the UK Nuclear Safety Advisory Committee, *op. cit.* p. 2.
69. *Management and Disposition of Excess Weapons Plutonium* (National Academies Press, 1994) *op. cit.*
70. *Management of Separated Plutonium* (Royal Society, 1998), Summary, paragraph 9.
71. The Environment Council, *BNFL National Stakeholder Dialogue Plutonium Working Group Final Draft Report*, November 2002, p. 1.
72. *BNFL National Stakeholder Dialogue Plutonium Working Group Final Draft Report*, *op. cit.* p. 42.
73. F. Barker and M. Sadnicki, *The Disposition of Civil Plutonium in the UK*, 2001, p. xii.
74. NDA *Uranium and Plutonium: Macro-economic Study*, 2007.
75. Royal Society, *Strategic Options for the UK's Separated Plutonium*, Policy, 2007.
76. NDA, *Plutonium Options: for Comment*, 2008.

- ⁷⁷ NDA (2009), *Plutonium Topic Strategy: Credible Options Technical Analysis*, 30 January 2009. For EDF views, see p. 16.
- ⁷⁸ NDA (2009) *op. cit.* Figure 5, p. 34.
- ⁷⁹ NDA (2010) *Plutonium Credible Options Analysis (Gate A)* (2010). In the 2010 report, a few new cost numbers were not redacted, presumably by mistake.
- ⁸⁰ NDA (2010) *op. cit.* p. 18.
- ⁸¹ AREVA advised specifically that the maximum tolerable percentage of in-grown americium-241 from plutonium-241 acceptable for MOX fabrication would be 4%, which could be achieved by blending. This would reduce the proportion of the plutonium stock that would need to be treated as waste for that reason from the 5% assumed in the 2009 report to as little as 0.2%. Another 11.7 tons of plutonium would need chemical cleanup if it were to be made into MOX, NDA (2010) *op. cit.* pp. 143, 148, 153.
- ⁸² NDA (2010) *op. cit.* p. 55.
- ⁸³ DECC (2011a) *Management of the UK's Plutonium Stocks – a consultation on the long-term management of UK owned separated civil plutonium*, February 2011, para. 20, p. 8. The report was accompanied by a brief NDA document, *Plutonium Strategy Current Position Paper* (2011) that added little to NDA's earlier reports.
- ⁸⁴ DECC (2011a) *op. cit.* p. 19. Assuming MOX fuel containing 8.5% plutonium, 140 tons of plutonium would produce 1,650 tons of MOX. The average rate of use over 60 years therefore would be 27.5 tons per year. If this constituted 40% of the two reactors' fuel, they would use a total of about 70 tons of fuel per year. Today, a 1,000-MWe reactor uses about 20 tons of LEU fuel per year. Two 1,700 MWe reactors would use about 70 tons. AREVA's EPR reactor, the most powerful on offer, has a generating capacity of 1,650 MWe, <http://www.aveva.com/EN/global-offer-419/epr-reactor-one-of-the-most-powerful-in-the-world.html>.
- ⁸⁵ DECC, *Management of the UK's Plutonium Stocks: A consultation response on the long-term management of UK-owned separated civil plutonium*, 1 December 2011.
- ⁸⁶ DECC, *Management of the UK's Plutonium Stock – a consultation on the proposed Justification process for the reuse of plutonium*, 28 May 2012; DECC, *Management of the UK's Plutonium Stock – a consultation response on the proposed Justification process for the reuse of plutonium*, May 2013; and DECC, *Guidance for Applicants on the justification process for the reuse of plutonium*, May 2013.
- ⁸⁷ NDA (2014), *Progress on Approaches to the Management of Separated Plutonium – Position Paper*.
- ⁸⁸ "EC Approval of UK Nuclear Subsidy Sets Off European Firestorm," *Nuclear Intelligence Weekly*, 10 October 2014.
- ⁸⁹ *The Guardian*, 22 January 2015, <http://www.theguardian.com/environment/2015/jan/22/uk-nuclear-ambitions-dealt-fatal-blow-by-austrian-legal-challenge-say-greens>.
- ⁹⁰ Both EDF and Horizon, the two most active potential developers of nuclear reactors in the UK, have declared publicly their strong opposition to using MOX fuel. Or, as NDA puts it, "the appetite of developers to ultimately include MOX in their considerations remains uncertain," NDA (2014) *op. cit.* p. 6.
- ⁹¹ NDA (2014) *op. cit.* p. 6.
- ⁹² NDA (2014) *op. cit.* p. 7.
- ⁹³ *Fast Breeder Reactor Programs: History and Status* (IPFM, 2010), p. 93.

- ⁹⁴. NDA (2014) *op. cit.* p. 16.
- ⁹⁵. *Nuclear Intelligence Weekly*, 10 October 2014, p. 1.
- ⁹⁶. Argentina, China, Canada, South Korea and Romania all have CANDU 6 reactors.
- ⁹⁷. NDA (2014) *op. cit.* p. 18.
- ⁹⁸. U.S. Department of Energy *Preferred Disposition Plan for Sodium-Bonded Spent Nuclear Fuel*, Report to Congress (March 2006) tables 1 and 3, assuming that the fuel is 20% plutonium. See also Department of Energy, *Fiscal Year 2014 Congressional Budget Request*, Vol. 3, p. NE-51 for information on the program's painfully slow progress. In fiscal year 2012, only 68 kilograms of EBR II spent fuel were processed with similar projections for 2013 and 2014.
- ⁹⁹. NDA (2014) *op. cit.* pp. 9–10.
- ¹⁰⁰. J.W. Hobbs, C.R. Scales, *et al.*, "A Programme to Immobilise Plutonium Residues at Sellafield," Institute of Nuclear Materials Management 53rd Annual Meeting, Orlando, Florida, July 15–19, 2012.
- ¹⁰¹. The initial batch would contain only 0.3–0.5 kg per can, because the mixture to be immobilized contains an average of only about 20% plutonium, C. R. Scales, UK National Nuclear Laboratory, personal communication, 11 April 2014.
- ¹⁰². U.S. DOE, *Plutonium: The First 50 Years* (DOE/DP-0137, 1996) Figure 3 and Table 15.
- ¹⁰³. The United States declared excess for military purposes 14.5 tons of government-owned fuel grade and reactor grade plutonium in 1996, U.S. DOE, *Plutonium: The First 50 Years* (1996), Figure 3. But 7 tons of that plutonium was in spent fuel, *Draft Surplus Plutonium Disposition Supplemental Environmental Impact Statement: Summary* (US DOE, DOE/EIS-0283-S2, 2012) Figure S-7, including 5 tons in unprocessed production reactor (mostly N-reactor) fuel at the DOE's Hanford Site, *Management of Spent Nuclear Fuel from the K Basins at the Hanford Site, Richland, Washington* (Draft Environmental Impact Statement (DOE, DOE-EIS-0245, 1995) p. 1.1.
- ¹⁰⁴. IAEA, *Communication Received from the United States of America Concerning its Policies Regarding the Management of Plutonium*, INFCIRC/549/Add.6/17, 6 October 2014.
- ¹⁰⁵. US DOE, "Amended Record of Decision: Storage of Surplus Plutonium Materials at the Savannah River Site," *Federal Register*, 11 September 2007, pp. 51807-11.
- ¹⁰⁶. "Designing a container for safe, long-term storage: A primer on the DOE 3013 Standard," <http://www.lanl.gov/orgs/nmt/nmtdo/AQarchive/04fall/primer.html>.
- ¹⁰⁷. US DOE, "Record of decision for the Storage and Disposition of Weapons-Usable Fissile Materials Final Environmental Impact Statement," *Federal Register*, Vol. 62, No. 13, 21 January 1997, p. 3014.
- ¹⁰⁸. US DOE, *Surplus plutonium disposition: Final Environmental Impact Statement* (DOE/EIS-0283, 1999) Vol. 1, p. 10.
- ¹⁰⁹. US DOE, "Record of Decision for the Surplus Plutonium Disposition Final Environmental Impact Statement," *Federal Register*, Vol. 65, No. 7, 11 January 2000, p. 1608.
- ¹¹⁰. 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, Annex on Quantities, Forms, Locations, and Methods of Disposition (2000), hereafter the PMDA.

- ¹¹¹. U.S. Department of Energy, *Surplus Plutonium Disposition Final Environmental Impact Statement* (1999) Vol. 1a, pp. 2–26 to 2–29.
- ¹¹². DOE, National Nuclear Security Administration, Office of Fissile Materials Disposition *Report to Congress: Disposition of Surplus Defense Plutonium at Savannah River Site* (2002) Table ES-3 and US DOE, “Amended Record of Decision, Plutonium Disposition Program,” *Federal Register*, Vol. 67. No. 76, 19 April 2002, p. 19432. DOE had commissioned cost studies for disposal of plutonium via the MOX fuel and can-in-canister routes. The cost of converting 33 tons of plutonium into MOX was calculated to be \$2 billion, K. A. Williams, *Life Cycle Costs for the Domestic Reactor-Based Plutonium Disposition Option* (Oak Ridge National Laboratory, ORNL/TM-1999–257, 1999) Table 1. The cost of immobilization for can-in-canister disposal of 50 tons of plutonium was estimated to be \$1.3 billion, *Design-Only Conceptual Design Report: Plutonium Immobilization Plant* Prepared by Bechtel for Lawrence Livermore National Laboratory (Lawrence Livermore National Laboratory, UCRL-ID-I31617, Rev. 1, 1999) Table 9.3. The cost studies were done by different groups and therefore not necessarily on a consistent basis. A lower cost for plutonium immobilization is plausible, however, because it would produce rough plutonium “pucks” containing about 50 grams of plutonium each (based on 1 kg of plutonium per can and 20 pucks per can, see above) while MOX pellets contain only about one gram of plutonium each and have to be machined to fine tolerances to fit snugly into fuel rod cladding tubes. In its Report to Congress (Table ES-3) the Bush Administration assumed an LEU fuel displacement credit of \$733 million – approximately the full cost of LEU fuel at the time. U.S. reactors would require amendments to their licenses to use MOX fuel, and special security requirements might be required for MOX fuel transport and on-site storage. Also, LEU fuel is a commodity that is available from multiple vendors while the MOX fuel would be produced by the government on an uncertain schedule. Factoring in the extra costs and risks, the 1999 Oak Ridge study estimated that the MOX fuel would sell at a discount factor of between 0.5 and 0.9, *Life Cycle Costs for the Domestic Reactor-Based Plutonium Disposition Option*, *op. cit.* p. 9.
- ¹¹³. U.S. DOE, *Plan for Alternative Disposition of Defense Plutonium and Defense Plutonium Materials that were Destined for the Cancelled Plutonium Immobilization Plant* (2007). The choice of glass instead of ceramic was because the Savannah River Site had a great deal of expertise with vitrification. The average amount of plutonium per can was reduced from 1 kg to 0.6 kg, because much of the plutonium was mixed with other materials. This would reduce the amount of plutonium per high-level waste canister from 28 kg to 16 kg. The plan was to build the plutonium-vitrification plant in the high-security K-Area Facilities on the Savannah River Site where non-pit plutonium was being gathered from the DOE’s other sites.
- ¹¹⁴. *Plan for Alternative Disposition of Defense Plutonium* *op. cit.* p. 1. In 2012, “the bulk” of the ZPPR plutonium was declared surplus again, DOE, *Draft Surplus Plutonium Disposition SEIS* (2012), p. S-3.
- ¹¹⁵. DOE, *Alternative Study for Locating a Plutonium Vitrification Process in Existing Savannah River Site Process Facilities*, Report Y-ADS-G-00002, 8 June 2004, cleared for public release, 9 October 2014, p. 4. The study assumed that two glovebox lines would be used for the plutonium vitrification. It is possible that the later plans assumed only one line.
- ¹¹⁶. Edwin S. Lyman, *Excess Plutonium Disposition: The Failure of MOX and the Promise of Its Alternatives* (Union of Concerned Scientists, December 2014) <http://www.ucsusa.org/sites/default/files/attach/2015/01/Excess%20Plutonium%20Disposition.pdf>, Figure 1.
- ¹¹⁷. The Obama Administration revisited the issue of the 13 tons of non-pit plutonium in a Draft Supplementary Environmental Impact Statement (SEIS) in 2012. The preferred option was now to purify as much plutonium as possible to be used as MOX and to dilute the remaining 2 tons for disposal in the Waste Isolation Pilot Facility in a salt bed deep under southeast New Mexico. DOE, *Draft Surplus Plutonium Disposition SEIS* (2012), p. B-17. The Supplementary EIS process was suspended

in 2013 when the main U.S. plutonium disposition program, MOX fuel fabrication, again became the focus of concern.

- ¹¹⁸. “Department of Energy”, factsheet on fiscal year 2014 budget, April 10, 2013, www.whitehouse.gov/sites/default/files/omb/budget/fy2014/assets/energy.pdf.
- ¹¹⁹. DOE, *Improving Project Management: Report [to the Secretary of Energy] of the Contract and Project Management Working Group*, November 2014, p. 21.
- ¹²⁰. *Department of Energy FY 2014 Congressional Budget Request*, Vol. 1, *National Nuclear Security Administration* (2013) pp. DN-119, 129, 137.
- ¹²¹. Construction and operating cost of MFFF from *Department of Energy FY 2016 Congressional Budget Request*, Vol. 1, *National Nuclear Security Administration*, pp. 628, 636 plus \$2.3 billion for the cost of building and operating the associated Waste Solidification Building, *Department of Energy FY 2015 Congressional Budget Request*, Vol. 1, *National Nuclear Security Administration*, pp. 542, 564.
- ¹²². “Department of Energy,” factsheet on fiscal year 2015 budget, 4 March 2014, www.whitehouse.gov/sites/default/files/omb/budget/fy2015/assets/energy.pdf.
- ¹²³. Savannah River Site Force, Report, 30 September 2014.
- ¹²⁴. Explanatory Statements Submitted by Mr. Rogers of Kentucky, Chairman of the House Committee on Appropriations Regarding the Consolidated Appropriations Act, 2014” *Congressional Record*, 15 January 2014, p. H879, column 3; the Consolidated and Further Continuing Appropriations Act, 2015, *Congressional Record*, 11 December 2014, p. 9705, column 2; and *DOE FY 2016 Congressional Budget Request*, Vol. 1, *National Nuclear Security Administration*, p. 623.
- ¹²⁵. Explanatory Statement Submitted by Mr. Rogers of Kentucky, Chairman of the House Committee on Appropriations Regarding the Consolidated and Further Continuing Appropriations Act, 2015, *op. cit.*
- ¹²⁶. “Not later than 30 days after the date of the enactment of this Act [19 December 2014], the Secretary shall seek to enter into a contract with a federally funded research and development center to conduct a study to assess and validate the analysis of the Secretary with respect to surplus weapon-grade plutonium options...Not later than 180 days after the date of the enactment of this Act, the federally funded research and development center conducting the study...shall submit to the Secretary a report on the study, including any findings and recommendations...Not later than 270 days after the date of the enactment of this Act, the Secretary shall submit to the congressional defense committees a report on the study...The report...shall include...The report of the federally funded research and development center...Identification of the alternatives to the MOX facility considered by the Secretary, including a life-cycle cost analysis for each such alternative... Identification of the portions of such life cycle cost analyses that are common to all such alternatives... Discussion on continuation of the MOX facility, including a future funding profile or a detailed discussion of selected alternatives determined appropriate by the Secretary for such discussion... Discussion of the issues regarding implementation of such selected alternatives, including all regulatory and public acceptance issues, including interactions with affected States...Explanation of how the alternatives to the MOX facility conform with the Plutonium Disposition Agreement, and if an alternative does not so conform, what measures must be taken to ensure conformance... Identification of steps the Secretary would have to take to close out all activities related to the MOX facility, as well as the associated cost...”. National Defense Authorization Act for fiscal year 2015, Section 3120, Disposition of Weapons-Usable Plutonium, <https://www.congress.gov/113/bills/hr3979/BILLS-113hr3979enr.pdf>.

- ¹²⁷ U.S. Code 50, Chapter 42, Subchapter III, section 2566, "Disposition of weapons-usable plutonium at Savannah River Site" as amended in the National Defense Authorization Act For FY 2013. The January 2016 deadline was originally set in 2011 in the National Defense Authorization Act for FY 2003.
- ¹²⁸ U.S. DOE, Report of the Plutonium Disposition Working Group, *Analysis of Surplus Weapon Grade Plutonium Disposition Options*, April 2014, <http://nnsa.energy.gov/aboutus/ourprograms/dnn/fmd/plutonium/pudispositionoptions>.
- ¹²⁹ Edwin S. Lyman, *Excess Plutonium Disposition: The Failure of MOX and the Promise of Its Alternatives* (Union of Concerned Scientists, 2014).
- ¹³⁰ DOE, Report of the Plutonium Disposition Working Group (2014), *op. cit.* Tables F1 and F2.
- ¹³¹ "Pipe Overpack Container for Transuranic Waste Storage and Shipment," U.S. Patent 5,998,800, 7 December 1999.
- ¹³² Eighty-five kilograms in "Amended Interim Action Determination, Disposition of Plutonium Materials from the Department of Energy (DOE) Standard 3013 Surveillance Program at the Savannah River Site, Savannah River Operations Office," Aiken, South Carolina, 30 March 2011. Five hundred kilograms by David C. Moody, Manager, Savannah River Operations Office, "Interim Action Determination: Disposition of Certain Plutonium Materials Stored at the Savannah River Site," 17 October 2011. As of 9 December 2014, 27 containers of plutonium had been processed, e-mail to Tom Clements from Rich Olsen, Planning Analyst, DOE-Savannah River. The quantity of contained plutonium was not given but the amount allowed in a 3013 storage container is 4.4 kg.
- ¹³³ The inhalation of a total of a milligram of weapon-grade plutonium by a large group of workers would be expected to cause very roughly ten cancer deaths, Steve Fetter and Frank von Hippel, "The Hazard from Plutonium Dispersal by Nuclear-warhead Accidents," *op. cit.*
- ¹³⁴ David C. Moody, Manager, "Disposition of Certain Plutonium Materials Stored at the Savannah River Site," *op. cit.*
- ¹³⁵ Patrick W. McGuire, Assistant Manager for Nuclear Material Stabilization Project, Savannah River Operations Office to Edgardo Deleon, Director, Office of Nuclear Material Disposition, U.S. Department of Energy, "Proposed Cost for Receipt and Disposition of GAP Plutonium Materials," 12 June 2012.
- ¹³⁶ CH TRAMPAC, Rev. 4, April 2012, <http://pbadupws.nrc.gov/docs/ML1214/ML12145A261.pdf>, Figure 2.9–23.
- ¹³⁷ *Report of the Plutonium Disposition Working Group, op. cit.* (April 2014) p. 29.
- ¹³⁸ DOE, *Report of the Plutonium Disposition Working Group, op. cit.* (2014) Table F1.
- ¹³⁹ DOE, *Report of the Plutonium Disposition Working Group, op. cit.* (2014) Attachment F.
- ¹⁴⁰ *WIPP Status Report*, (DOE, WIPP Waste Data System, 14 February 2015).
- ¹⁴¹ DOE, *Report of the Plutonium Disposition Working Group* (2014), *op. cit.* p. C-F-6. The Waste Isolation Pilot Plant Land Withdrawal Act limits the volume of transuranic waste that can be deposited in WIPP to 6.2 million cubic feet (176,000 cubic meters). As of 14 February 2015, about 91,000 cubic meters had been emplaced, *WIPP Status Report*, (DOE, WIPP Waste Data System, 14 February 2015).
- ¹⁴² Lyman, *Excess Plutonium Disposition* (2014), *op. cit.*, p. 65.
- ¹⁴³ DOE, *Report of the Plutonium Disposition Working Group, op. cit.* (2014) p. C8 and Appendix C-F.

- ¹⁴⁴. A kilogram of weapon-grade plutonium emits about 56,000 penetrating neutrons per second, Steve Fetter et al, "Detecting Nuclear Warheads," *Science & Global Security*, Vol. 1 (1990) p. 229.
- ¹⁴⁵. Patrick Malone, "Missteps & Secrets: LANL [Los Alamos National Laboratory] officials downplayed waste's dangers even after WIPP leak," *Santa Fe New Mexican*, 15 November 2014.
- ¹⁴⁶. *Waste Isolation Pilot Plant Recovery Plan* (US Department of Energy, 30 September 2014); and Meg Mirshak, "Repository work delays Savannah River Site nuclear waste shipments," *Augusta [South Carolina] Chronicle*, 28 January 2015.
- ¹⁴⁷. Robert Neill, "New Mexico Environmental Evaluation Group Experience in Reviewing WIPP," *Waste Management Symposium*, 1983, <http://www.wmsym.org/archives/1983/V1/17.pdf>. "The New Mexico Environmental Evaluation Group (EEG) used to conduct independent technical evaluation of WIPP to ensure protection of the public health, safety, and the environment. DOE ceased funding their organization in 2004 and the web site was taken down." <http://www.nmenv.state.nm.us/wipp/wiplinks.html>.
- ¹⁴⁸. *Report of the Plutonium Disposition Working Group* (DOE, 2014), *op. cit.* p. 25.
- ¹⁴⁹. *Report of the Plutonium Disposition Working Group*, *op. cit.* (DOE, April 2014), C-8.
- ¹⁵⁰. *Report of the Plutonium Disposition Working Group*, *op. cit.* (April 2014), pp. C-E-4 to C-E-11. We have been told that an unpublished DOE assessment has concluded that safety upgrades required to use the K-Area Facility for plutonium vitrification would cost billions of dollars. This claim should be independently reviewed.
- ¹⁵¹. "Plutonium immobilization would need to be completed by 2026 to avoid affecting the current DWPF [Defense Waste Processing Facility] schedule for HLW [high-level waste] vitrification; the schedule is determined by compliance with applicable permits and consent orders...Based on the proposed rates and schedule for treatment of HLW at DWPF, there would be insufficient HLW having the characteristics needed to enable vitrification of more than approximately 6 metric tons ... of surplus plutonium. Under these conditions it is possible that the remaining approximately 7.1 metric tons ... of plutonium could not be immobilized and vitrified under this alternative, but would need to be dispositioned by another method," DOE, *Draft Surplus Plutonium Disposition SEIS* (2012) p. S-26.
- ¹⁵². Meg Mirshak, "Costs increase nearly \$1 billion for salt waste facility at Savannah River Site," *Augusta Chronicle*, Sept. 17, 2014.
- ¹⁵³. Savannah River Remediation, *Liquid Waste System Plan* (SRR-LWP-2009-00001, Revision 19, May 2014) Figure 7-1. The characteristic 0.66-MeV gamma ray associated with Cs-137 decays is actually emitted by the short-lived meta-stable radioisotope, barium-137, that Cs-137 decays into 95% of the time.
- ¹⁵⁴. Leonard W. Gray and Thomas H. Gould, *Immobilization Technology Down-Selection: Radiation Barrier Approach* (Livermore National Laboratory, UCRL-ID-127320, 1997) p. 4.
- ¹⁵⁵. L. W. Gray and J. M. McKibben, *The Spent Fuel Standard – Does the Can-in-Canister Concept for Plutonium Immobilization Measure Up?* (Lawrence Livermore National Laboratory, UCRL-JC-134620, 1999); L.J. Jardine, G.A. Armantrout, and L.F. Collins, "Utilization of Cs137 to Generate a Radiation Barrier for Weapons Grade Plutonium Immobilized in Borosilicate Glass Canisters," *Waste Management '95 Winter Meeting, Tucson, AZ, 26 Feb. to 2 March 1995*; and Dr. Jungmin Kang (unpublished).
- ¹⁵⁶. U.S. DOE, *Plan for Alternative Disposition of Defense Plutonium and Defense Plutonium Materials that were Destined for the Cancelled Plutonium Immobilization Plant* (2007).

- ^{157.} 3,912 canisters filled out of a projected total of 8,582, Rich Olsen, Planning Analyst, DOE-Savannah River, presentation to the SRS Citizens Advisory Board, 27 January 2015, slide 9.
- ^{158.} DOE FY 2016 Congressional Budget Request, Vol. 5, *Environmental Management*, pp. 263, 287.
- ^{159.} DOE, *Alternative Study for Locating a Plutonium Vitrification Process in Existing Savannah River Site Process Facilities*, 8 June 2004, cleared for public release, 9 October 2014, p. 4.
- ^{160.} National Defense Authorization Act for Fiscal Year 2015, Section 3120, part d.
- ^{161.} Austin Jenkins, “[Governor] Inslee Announces Court Action In Hanford Cleanup Fight,” KPLU, 3 October 2014.
- ^{162.} U.S. DOE, *Report of the Plutonium Disposition Working Group*, *op. cit.* (2014) p. C-G-3.
- ^{163.} Bill W. Arnold, Patrick Brady, *et al*, *Deep Borehole Disposal Research: Geological Data Evaluation, Alternative Waste Forms, and Borehole Seals* (Sandia National Laboratory, SAND2014-17430R, 2014) Appendix A. A former surface radioactive waste disposal site at Maxey Flats, Kentucky also ranked above the Savannah River Site. SRS was tied for third place with the site of the U.S. Atomic Energy Commission’s short-lived sodium-cooled Hallam Nuclear Power Plant in Nebraska.
- ^{164.} *Deep Borehole Disposal Research* (2014) *op. cit.* chapter 3.
- ^{165.} Apparently, the DOE was constrained from describing these as GE-Hitachi PRISM reactors but all the parameters were identical to those of PRISM.
- ^{166.} See e.g. *Project And Program Management: DOE Needs to Revise Requirements and Guidance for Cost Estimating and Related Reviews* (U.S. Government Accountability Office, GAO-15-29, 2014).
- ^{167.} “Sellafield firm loses £9bn clean-up contract,” BBC, 13 January 2015, <http://www.bbc.com/news/business-30785623>.
- ^{168.} Pavel Podvig, *Consolidating Fissile Materials in Russia’s Nuclear Complex* (IPFM, 2009) pp. 10–13.
- ^{169.} For a neutron velocity of 2.2 km/sec, whose energy translated to a temperature via the relationship $E = 0.0252 \text{ eV} = kT$, where k is the Boltzman constant, corresponds to a temperature of 20 degrees Centigrade, *Handbook Of Nuclear Data For Safeguards: Database Extensions, August 2008* (IAEA, INDC[NDS]-0534, 2008) Table A-5.
- ^{170.} For MOX fuel with a 50-MWt-day per kilogram heavy metal burnup, if the fresh MOX fuel contains 8.6% plutonium, the spent fuel after 5-years cooling will contain 6% plus 0.7% percent other transuranics (neptunium, americium and curium), *MIT Study on the Future of the Nuclear Fuel Cycle* (2011) p. 74.
- ^{171.} Calculations by Jungmin Kang for the case of plutonium from LEU fuel with a burnup of 53 MWt-days/kg used in MOX fuel with a burnup of 53 MWt-days/kg, 18 November 2014.
- ^{172.} ANDRA, *Architecture et gestion du stockage géologique [Architecture and management of geological storage]* (2005), p. 74.
- ^{173.} In January 2013, the Obama Administration announced that its strategy was “to facilitate the availability of a geologic repository by 2048,” *Strategy for the Management and Disposal of Used Nuclear Fuel and High-Level Radioactive Waste* (U.S. Department of Energy, 2013). Programs to site geological repositories for radioactive waste have also stalled in both Japan and the UK.
- ^{174.} The waste is sometimes described as “transuranic” – perhaps because it includes small percentages of americium-241 produced by the decay of short-lived (14.4-year half-life) Pu-241.

- ¹⁷⁵. The quantity of plutonium currently assumed in WIPP risk assessments is 12 metric tons, DOE, *Title 40 CFR Part 191 Subparts B and C Compliance Recertification Application 2014 for the Waste Isolation Pilot Plant Appendix SOTERM-2014 Actinide Chemistry Source Term*, Table SOTERM-9, http://www.wipp.energy.gov/library/CRA/CRA-2014/CRA/Appendix_SOTERM/Appendix_SOTERM.htm#Figure_SOTERM-6.
- ¹⁷⁶. PWR and BWRs have pellet diameters of 1.04 and 0.82 cm respectively, http://ocw.mit.edu/courses/nuclear-engineering/22-06-engineering-of-nuclear-systems-fall-2010/lectures-and-readings/MIT22_06F10_lec06a.pdf, slide 12.
- ¹⁷⁷. Bechtel, *Design-Only Conceptual Design Report: Plutonium Immobilization Plant*, *op. cit.* (1999) p. 5.
- ¹⁷⁸. *Plutonium Immobilization Plant Using Ceramic in New Facilities at the Savannah River Site* (Lawrence Livermore National Laboratory, UCRL-ID-128273, 1998) p. 1–6, Table 6–2.
- ¹⁷⁹. “Synroc Wasteform” (World Nuclear Association), <http://www.world-nuclear.org/info/Nuclear-Fuel-Cycle/Nuclear-Wastes/Synroc/>
- ¹⁸⁰. C. R. Scales, UK National Nuclear Laboratory, personal communication, 11 April 2014.
- ¹⁸¹. U.S. DOE, *Technical Summary Report for Surplus Weapons-Usable Plutonium Disposition*, *op. cit.* (1996) Figure 2–4.
- ¹⁸². *Alternative Study for Locating a Plutonium Vitrification Process in Existing Savannah River Site Process Facilities*, *op. cit.* p.6.
- ¹⁸³. Pascal Aubret, Director of AREVA La Hague, to Mycle Schneider, 2 February 2015.
- ¹⁸⁴. Mycle Schneider, “Fast Breeder Reactors in France,” *Science & Global Security* Vol. 17 (2009) pp. 67–84.
- ¹⁸⁵. Antwort der Bundesregierung auf die Kleine Anfrage der Abgeordneten Sylvia Kotting-Uhl, Cornelia Behm, Harald Ebner, weiterer Abgeordneter und der Fraktion BÜNDNIS 90/DIE GRÜNEN – “Stand der Wiederaufarbeitung deutscher Brennelemente im Ausland und des deutschen Plutonium-Inventares” [Reply of the Federal Government [of Germany] to questions of Members Sylvia Kotting-Uhl, Cornelia Behm, Harald Ebner, other Members and the Green Faction on the “State of the reprocessing of German fuel abroad and German plutonium Inventories”, 31 January 2012.
- ¹⁸⁶. Klaus Janberg, personal communication, 15 May 2014.
- ¹⁸⁷. “On 30 June 2008, plutonium removal and treatment operations were completed for the AREVA La Hague site. As such, between 2003 and 2008, the equivalent of 3 years of production was recycled in the fabrication of new fuels,” <http://www.aveva.com/EN/operations-1094/the-cadarache-facility-activities--cleanup-and-disassembly.html>. Based on the production rate of 40 tons a year shown for Cadarache in *Status and Advances in MOX Fuel Technology* (IAEA, 2003) Table 2, and assuming 6 percent plutonium, this would have been about 7 tons of plutonium.
- ¹⁸⁸. “Residues conditioned into rods and shipped back to customers: 2007,” J. M. Cuchet et al, “Decommissioning the Belgonucleaire Dessel MOX Plant: Presentation Of The Project and Situation, End August 2013”, ICEM’2013, Session 3.11, slide 6. The ownership of the storage MOX from Dessel was transferred to its customers who probably shipped it to La Hague in exchange for payments to AREVA and an equivalent amount of plutonium in MOX fuel.
- ¹⁸⁹. “[T]he authorities demanded that the old MOX facility be shut down. Approval for operation to be resumed also failed to be given in the years that followed. This meant that a fully operative production line was brought to a standstill from one day to the next, leaving an inventory of 2.25 metric tons of plutonium in various stages of processing... Of the material which was suitable for

shipment from the start, 550 kg of plutonium in the form of PuO₂ powder and mixed oxides have so far been shipped to England and France,” Helmut Rupa et al, “Decommissioning of Four German Fuel Cycle Facilities,” Waste Management 2000 Conference, February 27 – March 2, 2000, Tucson, AZ; “the nuclear fuel that was still in the MOX plant was processed until the plant was cleaned out and placed in “storage elements” which are capable of being stored long-term and could not be used in any nuclear power plants. These storage elements were sent for processing to AREVA NC in La Hague, France,” Werner Koenig et al, “Release and Disposal of Materials During Decommissioning of Siemens MOX Fuel Fabrication Plant At Hanau, Germany,” *Proceedings of the 11th International Conference on Environmental Remediation and Radioactive Waste Management IREM2007, September 2–6, 2007, Bruges, Belgium*, IREM07-7205.

- ¹⁹⁰. About 5 percent of the plutonium throughput of the Melox plant ends up in such sub-spec MOX, Yves Marignac, personal communication.
- ¹⁹¹. David Kossen et al, *External Technical Review of the Plutonium Preparation Project at Savannah River Site* (2008), <http://energy.gov/sites/prod/files/em/PuPPETRreport.pdf>.
- ¹⁹². Japan Atomic Energy Commission, “The Situation of Separated Plutonium Management in Japan as of the End of the Year 2013” (in Japanese).
- ¹⁹³. To our knowledge, the first analysis of borehole disposal of plutonium was done by Johan Swahn, *The Long-Term Nuclear Explosives Predicament: The Final Disposal of Militarily Usable Fissile Material in Nuclear Waste from Nuclear Power and from the Elimination Of Nuclear Weapons* (Technical Peace Research Group, Institute of Physical Resource Theory, Göteborg, Sweden, 1992.)
- ¹⁹⁴. A proposed design requirement for borehole disposal in the U.S. is that, below a depth of 2 km, the host rock be basement granite or basalt rock, *Deep Borehole Disposal Research, op. cit.* (Sandia, 2014). Such rock does not have layers that create the possibility for trapped, pressurized, i.e. artesian water.
- ¹⁹⁵. See for example A. John Beswick, Fergus G. F. Gibb and Karl P. Travis, “Deep borehole disposal of nuclear waste: engineering challenges,” *Proceedings of the Institution of Civil Engineers* (2014) <http://dx.doi.org/10.1680/ener.13.00016>.
- ¹⁹⁶. U.S. Department of Energy, *FY 2015 Congressional Budget Request*, Vol. 3 (2014), pp. 449–450.
- ¹⁹⁷. The Sandia borehole design can accommodate 253 metric tons of heavy metal in spent fuel in the bottom 2 km of the borehole, Pat Brady et al, *Deep Borehole Disposal of Nuclear Waste: Final Report* (Sandia National Laboratory, SAND2012-7789, 2012), p. 9. The fuel is in the form of cylindrical rods. In their densest (hexagonal) packing, 91% of the volume in a canister would be occupied by rod material. About 73% of the cross-section of a rod is taken up by the uranium-oxide “meat” of the fuel. The remainder is taken up by the rod cladding and the gap between the meat and the cladding. Roughly two thirds of the container volume therefore would be occupied by fuel pellets. The density of uranium in a pellet is about 9.6 grams/cc. The average density of the uranium in the canister is therefore 6.3 grams/cc and the volume required to hold the 253 tons of heavy metal in the form of spent fuel rods is about 40 cubic meters. This corresponds to the volume of 2-kilometer-long cylinder with an inside diameter of 16 cm (6 inches).
- ¹⁹⁸. For an infinite cylinder containing an optimal heterogeneous mix of water and 3% enriched uranium surrounded with water, i.e. an unrealistic extreme case, the minimum diameter that will go critical is about 27 cm, *Critical Dimensions of Systems Containing U-235, Pu-239, and U-233* (Los Alamos National Laboratory, LA-10860-MS, 1987), Fig. 24. Results with MOX mixes with the same percentage of plutonium mixed with depleted uranium are comparable, *op. cit.* Table 18. Three percent is also the average concentration of fissile plutonium (Pu-239 + Pu-241) in spent MOX fuel, *Plutonium Fuel: An Assessment* (OECD Nuclear Energy Agency, 1989) Table 12B.

- ¹⁹⁹. The cans are 5 inches in diameter and 10 inches tall so that they have a volume of 3.2 liters and they contain up to 4.4 kg of plutonium, <http://www.lanl.gov/orgs/nmt/nmtdo/AQarchive/04fall/primer.html>.
- ²⁰⁰. Aurică Barbu and Mihai Ovidiu Cojokaru, "The Cold Pressing Behavior of Uranium Dioxide and Triuranium Octoxide Mixed Powders," *Universitatea Politehnica Bucuresti, Bulletin Stiintific, Series B*, Vol. 75, Issue 4 (2013) pp. 221–230.
- ²⁰¹. Pat Brady et al, *Deep Borehole Disposal of Nuclear Waste: Final Report op. cit.* Table 1.
- ²⁰². See e.g. William Weber and Rodney Ewing, "Ceramic Waste Forms for Uranium and Transuranium Elements," in *Uranium: Cradle to Grave*, Peter C. Burns and Ginger E. Sigmon, eds. (Mineralogical Association of Canada Short Course Series Volume 43, 2013).
- ²⁰³. DOE, *Report of the Plutonium Disposition Working Group, op. cit.* (April 2014), p. 29.
- ²⁰⁴. This point was brought to our attention by Johan Swahn, Director of Sweden's NGO Office for Nuclear Waste Review.
- ²⁰⁵. *Radioactive materials and waste Planning Act of 28 June 2006 (ANDRA)*
<http://www.andra.fr/download/andra-international-en/document/editions/305cva.pdf>, Article 12.
- ²⁰⁶. *Choosing a Way Forward: The Future Management of Canada's Used Nuclear Fuel, Final Study* (Nuclear Waste Management Organization of Canada, 2005) p. 27.
- ²⁰⁷. IAEA, "Communication received from the United States of America concerning its policies regarding the management of plutonium," INFIRC/549/Add. 6/17, 6 October 2014.
- ²⁰⁸. *Concepts and Strategies for Transparency Monitoring of Nuclear Materials at the Back End of the Fuel/Weapons Cycle: Summary of the [Cooperative Monitoring Center] WIPP Monitoring Workshop February 16–18, 1999, Albuquerque, NM and Carlsbad, NM*; David Betsill, et al, *Nuclear Waste Repository Transparency Technology Test Bed Demonstrations at WIPP*, and DOE, *Report to Congress on the Use of the Waste Isolation Pilot Plant to Develop and Demonstrate Transparency Technologies* (2000).
- ²⁰⁹. "Pipe Overpack Container for Transuranic Waste Storage and Shipment," Patent Number 5,998,800, 7 December 1999.

Authors

Gordon MacKerron, who authored chapter 3, was until 2014 Director of the Science Policy Research Unit (SPRU) and Professor in the School of Business, Management and Economics at Sussex University in the UK. He previously directed the Energy Group within SPRU. In 2001, he was Deputy leader of the UK Government's Energy Review team. He also was the founding chair of the UK Committee on Radioactive Waste Management (2003–2007) and served a three-year term on the UK Royal Commission on Environmental Pollution, which advises the UK government and the public on environmental issues (2010–2013). He is a member of IPFM.

Frank von Hippel, a Senior Research Physicist and Professor of Public and International Affairs emeritus in Princeton University's Program on Science and Global Security, has worked on fissile material policy issues for forty years. He co-founded the IPFM, Princeton's Program on Science and Global Security and the journal, *Science & Global Security*. During 1983–89, he partnered with Gorbachev's arms control advisor Evgenyi Velikhov to propose measures to end the nuclear arms race. During 1993–94, as Assistant Director for National Security in the White House Office of Science and Technology Policy, he helped launch U.S.-Russian cooperative nuclear security programs and led the inter-agency group on plutonium disposition. He is a member of IPFM.

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Program on Science and Global Security
Princeton University
221 Nassau Street, 2nd Floor
Princeton, NJ 08542, USA

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