IPFM
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# Ending Reprocessing in Japan

## An Alternative Approach to Managing Japan’s Spent Nuclear Fuel and Separated Plutonium

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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 Professor R. Rajaraman of Jawaharlal Nehru University, New Delhi and Professor Frank von Hippel of Princeton University. 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

Japan finds itself trapped politically in a spent fuel reprocessing policy that has insignificant resource conservation and radioactive waste management benefits and is becoming increasingly dysfunctional, dangerous and costly. This paper proposes a way out of this reprocessing quagmire and alternative disposal methods for Japan's accumulated plutonium.

Reprocessing is unnecessary and even detrimental for nuclear power.* Operating the Rokkasho Reprocessing Plant (RRP) will cost the Japanese people about ¥8 trillion more over the 40-year design life of the plant than not operating it and simply storing the spent fuel.

The RRP is designed, when operating at full capacity, to separate about 8 tons of plutonium annually. The current plan is to start operations as soon as the Nuclear Regulation Authority (NRA) gives permission. However, Japan does not have a clear path forward for disposing of the 44 metric tons of separated plutonium that it already has accumulated – enough to make more than 5000 Nagasaki-type bombs.

As the only non-weapon state that reprocesses, Japan is undermining the nonproliferation regime by setting an example that states interested in acquiring a nuclear-weapon option can point to as a legitimate internationally accepted activity. Separated plutonium also is a target for would-be nuclear terrorists.

Like other industrialized countries, Japan began reprocessing spent light water reactor fuel to recover plutonium to provide startup fuel for uranium-efficient, liquid-sodium-cooled plutonium breeder reactors that the nuclear-energy community projected would be deployed worldwide by the thousands starting in the 1980s. As Japan has learned from its experience with its prototype breeder reactor, *Monju*, however, sodium-cooled reactors are much more costly and unreliable than water-cooled reactors. No country has yet succeeded in commercializing breeder reactors, although India and Russia are continuing to try.

With the failure of its breeder-reactor commercialization program, Japan decided to follow the example of France and recycle its accumulating separated plutonium into uranium-plutonium mixed-oxide (MOX) fuel for light water reactors. This program too has failed thus far, however, in large part due to opposition in the prefectures, driven by concerns about the effect of MOX fuel on safety of the reactors in which it is used.

A major driving force today for nevertheless continuing with the plan to operate the Rokkasho Reprocessing Plant is the desire to have an off-site destination for the spent fuel that will be accumulating at those nuclear power plants that the NRA gives permission to operate. The United States and most of the other countries that operate nuclear power plants avoid the costs and risks of reprocessing simply by moving older spent fuel into on-site air-cooled dry casks when their spent fuel pools fill up. But Japan can't change its reprocessing policy without the central government and nuclear utilities making a number of difficult decisions at the same time. They will have to:

* The issue of whether or not nuclear power should be abandoned is beyond the compass of this paper.

1. Negotiate fairly about on-site dry-cask storage with the prefectural and local governments that host Japan's nuclear power plants. This will require an embarrassing reversal of the assurances that the central government and utilities have made for decades that spent fuel would *not* accumulate at the reactor sites because, after a few years of cooling in the reactor pools, it would be shipped offsite for reprocessing.

   In fact, off-site shipments have been delayed by repeated postponements in the completion of the Rokkasho Reprocessing Plant (RRP) which was originally to have begun operating in 1997. The utilities therefore have packed more spent fuel into the nuclear power plant pools than the pools were designed for. This provides an urgent safety reason for making dry-cask storage available at the reactor sites.

2. Renegotiate the deal with Aomori Prefecture and Rokkasho Village, which have accepted spent fuel from around Japan in exchange for fees and grants and the jobs associated with construction and operation of the RRP and the J-MOX uranium-plutonium mixed-oxide (MOX) fuel fabrication facility based on an understanding that reprocessing and plutonium reuse is a necessary and productive process.

   This will be a difficult negotiation but the dependency between Japan's nuclear industry and Aomori Prefecture is mutual. And, if the prefectures that host Japan's nuclear power plants are willing to allow on-site storage as an alternative to reprocessing, Aomori Prefecture will be forced to bargain to retain the current benefits it is receiving in exchange for continuing to provide central interim storage of Japan's radioactive reprocessing waste and the spent fuel already in the RRP's intake pool.

3. Change the law governing the national Reprocessing Fund to allow continued repayment of the loans used to pay for the Rokkasho Reprocessing Plant, even if a decision is made not to start its commercial operation. Under the current law money in the Fund will be given to Japan Nuclear Fuel Limited (JNFL) to repay the bank and utility loans used to pay for the construction of the Rokkasho Reprocessing Plant only if JNFL maintains its commitment to operate the plant.

4. Admit that, contrary to the repeated claims of the Ministry of Economy, Trade and Industry (METI), separating and recycling plutonium in light water reactor fuel does not make the radioactive waste from nuclear power plants significantly less dangerous or easier to dispose of.

5. Have the central government take responsibility for final disposal of spent fuel away from the nuclear utilities and JNFL. Decisions by the governments of both the United States and the United Kingdom to take responsibility for spent fuel disposal were key to making it possible for their utilities to abandon reprocessing. Like the classical Gordian Knot, which Alexander the Great allegedly cut with his sword, Japan's reprocessing policy is too complicated to be untied incrementally.

6. Directly dispose of Japan's 44 tons of already separated plutonium instead of trying to force public acceptance of the use of MOX fuel in Japan's nuclear power plants.

# Introduction

Several months after the Fukushima nuclear accident of 11 March 2011, after reviewing Japan's nuclear power policy, the Noda Administration led by the Democratic Party of Japan made two decisions:

1) Shut down Japan's nuclear power plants by the end of the 2030s, and
2) Continue with the work with regard to the Rokkasho Reprocessing Plant in accordance with the previous plans

The December 2012 election of Japan's Diet brought back to power a coalition led by the Liberal Democratic Party, which had governed Japan for most of the post-World II period and had presided over the buildup of Japan's nuclear-energy program. Under the leadership of Prime Minister Shinzo Abe, the new governing coalition quickly reversed the Noda Administration's nuclear phase-out decision but maintained the policy of going forward with reprocessing.

It is remarkable that two administrations that disagreed totally about the future of nuclear power in Japan did not disagree on the need to continue reprocessing, an area where Japan's policy differs from most other countries with nuclear power plants.

Despite the almost four-decade-long effort by the United States, to persuade Japan to join it in abandoning reprocessing for nonproliferation reasons, Japan is the only non-nuclear-weapon state that reprocesses. It has accumulated 44 tons of separated plutonium and plans, after the Rokkasho Reprocessing Plant (Figure 1) goes into commercial operation, to achieve a plutonium separation rate of about 8 tons per year within a few years.

**Figure 1.** Rokkasho Reprocessing Plant. The capital cost was ¥2.19 trillion (~$22 billion), as of 2012. *Source:* Kyodo News Service. [1]

Plutonium is a nuclear-weapon material and separating it from the highly radioactive fission products in spent fuel makes it an attractive target for would-be nuclear terrorists. The 8 tons that Japan plans to separate annually would be sufficient to make one thousand Nagasaki-type bombs.

Countries can use – and have used – "civilian" reprocessing to mask efforts to obtain nuclear-weapon options. During the late 1960s and early 1970s, India exploited that option and became a nuclear-weapon state.[2] A number of other countries, including South Korea, started down that same path but political pressure from the United States and internal political change resulted in their programs being cancelled before they reached fruition.[3] Japan, by persisting in reprocessing, is, however, providing legitimacy for South Korea to reassert once again its right to reprocess.[4]

South Korea has been campaigning for U.S. acceptance of its right to reprocess in the context of negotiations of a new agreement of nuclear cooperation with the United States. It argues that, just as in Japan, its spent fuel pools are filling up and that its local governments too will not allow the installation of on-site dry-cask storage.[*] South Korea's government therefore argues that it too needs a reprocessing plant to provide an off-site destination for its spent fuel. At the same time, there has been a rise of public support in South Korea for acquiring its own nuclear deterrent as a result of North Korea's recent nuclear threats.[5] Recently, South Korea and the United States agreed to give themselves more time for their negotiations by postponing by two years to 2016 the expiration of their old agreement, which requires U.S. consent for South Korean reprocessing of spent fuel containing uranium enriched in the United States.[6]

If South Korea eventually succeeds in pressing the U.S. into acquiescing to reprocessing in South Korea – as Japan succeeded in 1977 in getting the U.S. to acquiesce to the operation of the already-constructed Tokai reprocessing plant – then it will become easier for other countries to argue that they too should have the same right. South Africa is expressing an interest in reprocessing.[7] Iran has not yet expressed an interest in reprocessing but is preparing to operate a heavy water research reactor near Arak that is very similar to the research reactor that India used to produce the plutonium for its first nuclear weapons.

Reprocessing makes no sense economically. The cost of separating it is huge and separated plutonium has negative value as a fuel. Utilities would not accept separated plutonium even for free since it costs more to fabricate MOX fuel using free plutonium than to fabricate low enriched uranium (LEU) fuel with purchased natural uranium and enrichment services [8]

According to calculations made by Japan's Atomic Energy Commission in 2011, reprocessing will more than double the cost of managing Japan's spent fuel, including the cost of disposal of the radioactive wastes produced by reprocessing, compared to simply storing the spent LEU fuel and disposing of it directly.[9] This is why, of the thirty-one countries that have nuclear power as part of their energy mix, only France and Japan reprocess on a large scale for recycle of the plutonium in light water reactor fuel.[10]

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[*] This is despite the fact that 7,000 tons of on-site dry-cask storage capacity has already been installed at South Korea's Wolsung Nuclear Power Plant whose natural-uranium-fueled heavy water reactors discharge spent fuel at about 7 times the rate of light water reactors of the same generating capacity.

France's national utility, Électricité de France (EDF), has its nuclear fuel reprocessed by AREVA only because France' government insists. Rather than signing a new reprocessing contract, EDF extended the term of its 2009-2012 reprocessing contract only through 2013.

*The Reprocessing "Trap".* In 1993, one of us (FvH) met with the nuclear fuel cycle managers of Tokyo Electric Power Company (TEPCO) and Kansai Electric Power Company (KEPCO) and was told that they felt "trapped" into reprocessing. When asked whether they would choose reprocessing over spent fuel storage again, the response was "never!"

The "trap" was constructed, starting with the 1957 law on Regulation of Nuclear Source Material, Nuclear Fuel Material and Reactors, which required that an application for construction of a new nuclear power reactor specify "the method of spent fuel disposal". It also required that the application should not lead to "hindrance of the execution of the planned development and use of nuclear power." Since the government's Long-Term Plans for nuclear energy made clear that Japan's nuclear-power future would be based on plutonium breeder reactors and required reprocessing, this made reprocessing obligatory for the nuclear utilities. [11]

After the Fukushima accident, in June 2012, when the law was revised to establish the new Nuclear Regulation Authority, the requirement for reprocessing was removed.[12] The Designated Radioactive Waste Final Disposal Act still does not list spent fuel among the types of wastes to be put into a geological disposal facility, however. It includes only vitrified high level reprocessing waste and transuranic waste from reprocessing and MOX fuel production.

Even if that omission were fixed, the nuclear utilities would still be trapped into reprocessing by two other constraints:

1. In most cases, they do not have consent from prefectural and local governments to build dry-cask spent fuel storage at their nuclear power plants. (Of course, the utilities and the government haven't pushed hard for permission because the plan has been to ship spent fuel to a reprocessing plant after it has cooled a few years.)
2. The utilities have guaranteed and made loans to build the Rokkasho Reprocessing Plant that are to be repaid from a special reprocessing fund that would be frozen if a decision is made not to operate the plant.

Also, METI claims reprocessing has environmental advantages. One is that reprocessing and plutonium and uranium recycle are uranium conserving. The net savings of uranium resulting from plutonium and uranium reuse in light water reactor fuel would be up to 25 percent in a best-case scenario that has not yet been achieved anywhere. But similar savings would be possible at one-tenth the cost, for example, by increasing the percentage of U-235 extracted from natural uranium when uranium is enriched. Also, careful studies have established that there are no radioactive waste management benefits from recycling plutonium in light water reactors.

Of the more than 40 tons of plutonium Japan has had separated from its spent fuel reprocessed in Europe – mostly during the 1990s –thirty six tons remain unused (34 still in Europe). Only 2.5 tons have been loaded into Japan's reactors as MOX fuel.[13] At

Rokkasho 3.6 tons of separated plutonium from a test run of the reprocessing plant are in storage awaiting completion of a MOX fuel production plant on which construction has only recently begun.[14] Why then does Japan's Government think it is necessary for JNFL to launch plutonium separation operations at Rokkasho as soon as permission is received from the Nuclear Regulation Authority?

Independent analysts asked the same question of the UK Government in 1993 when it gave the go-ahead to the government-owned company, British Nuclear Fuels Limited, to begin reprocessing operations at its new Thermal Oxide Reprocessing Plant (THORP) at a time when the UK already had 39 tons of separated plutonium[15] and the UK government had decided in 1988 that the Prototype Fast [Breeder] Reactor would shut down in 1994, ending the UK's plutonium use program.[16] In his book, *Nuclear Entrapment*, William Walker discusses the domestic and foreign bureaucratic forces that drove the UK government to this decision. His words describing the bizarre conclusion of the UK policy-making process could be applied today with only minor changes to Japan's plan to start operating the Rokkasho Reprocessing Plant:[17]

> One of Britain's largest industrial facilities was being turned on to provide plutonium that was no longer needed or wanted and whose stockpiling was considered by many to endanger international security. This was a facility which would give rise to significant risks and liabilities; which was "serving" customers several of whom wished to escape their commitments; whose construction had been – and operation would be – funded through surcharges and taxes on electricity consumers … and whose successful operation depended upon governments and other actors sorting out problems…for which there were no assured solutions.

As of the end of 2012, the amount of separated plutonium in storage in the UK had increased to 121 tons of which 97 tons were its own, 17 tons belonged to Japan, with the remaining 7 tons belonging to an assortment of European utilities.[18] The UK finally decided in 2012 to end its reprocessing program[19] and is now facing a choice of costly alternatives for disposing of the plutonium that it separated at such great cost.

By starting the Rokkasho Reprocessing Plant without an operating plutonium disposal program – or even a clear plan for restarting its shutdown reactors – Japan will be proceeding heedlessly down the same road.

In what follows, we discuss:

- The original justification of Japan's reprocessing program;
- Japan's accumulation of separated plutonium and its failure thus far to dispose of much of it in MOX fuel;
- The fact that separated plutonium, whether civilian or military, is weapon usable;
- The spent-fuel storage problem that drives Japan's reprocessing policy today;
- The lack of radioactive waste management benefits of reprocessing;
- On-site dry-cask storage of spent fuel as an alternative to reprocessing;
- The safety benefits of dry-cask storage relative to pool storage for spent fuel that has cooled several years in a pool;

- The need for a radioactive waste repository whether or not spent fuel is reprocessed;
- The negotiations with Aomori Prefecture over the future of the Rokkasho Reprocessing Plant;
- The need to pay off the loans that financed the construction of the reprocessing plant, whether or not the plant is operated;
- The likely need to centralize control over spent fuel management in Japan if a policy shift away from reprocessing is to be accomplished; and
- Alternatives to MOX for disposing of Japan's already separated plutonium.

## The dream of plutonium breeder reactors and the reality of plutonium recycle

Japan's reprocessing program originated in the 1960s and 1970s as part of a worldwide effort by the industrialized countries to commercialize more uranium-efficient plutonium breeder reactors. The plutonium in the spent fuel of water-cooled reactors was to be extracted to provide startup fuel for the breeders.

In 1956, in its first long-term plan, the Japan Atomic Energy Commission (JAEC), like its counterparts in other industrialized countries, expressed its intention to develop plutonium breeder reactors. In its 1961 plan, the JAEC predicted that breeder reactors would be commercialized within twenty years.

In its 2005 plan, almost fifty years after its first long-term plan, however, the JAEC stated that it did not expect commercialization of breeder reactors within forty years.

The outlook for breeders had changed drastically in the 1980s and 1990s because it had been found that:

- Low-cost uranium was more abundant than originally predicted,
- The growth of global nuclear power capacity was much lower than had been predicted, and
- Liquid-sodium-cooled fast-neutron breeder reactors were much more costly to build and much less reliable to operate than water-cooled reactors.

The United States and most European countries therefore decided to abandon reprocessing.[20]

Three countries continued with programs to reprocess virtually all their spent fuel, however: France, Japan and the United Kingdom. In order to avoid further accumulation of separated plutonium in the absence of its demand for breeder reactor fuel, France and Japan decided to recycle their plutonium into uranium-plutonium mixed-oxide (MOX) fuel to be used in some of the light water reactors (LWRs) that had produced it.

The new rationale for reprocessing was to separate long-lived plutonium from the radioactive waste that is to be emplaced in a deep underground repository in the hope that fast-neutron reactors, which could fission all the plutonium isotopes efficiently, would be commercialized. (The proposal by the nuclear energy community now is to "burn" plutonium in the same fast-neutron reactors that originally were justified as plutonium breeders.)

India and Russia continued to reprocess on a smaller scale to support continuing breeder reactor R&D programs and, in 2010, China launched civilian reprocessing on a pilot scale in support of a tentative breeder reactor R&D program.

France and the UK each built second reprocessing plants in the 1980s: UP-3 and THORP (Thermal Oxide Reprocessing Plant) respectively. The construction of these plants was largely financed by Japan and Germany and a few smaller European countries that did not own their own reprocessing plants but wanted to be part of the breeder reactor future.

Of those reprocessing customer countries, however, only one, the Netherlands, has renewed its reprocessing contract with France – and that only for its single nuclear power reactor. The UK therefore has decided to decommission its THORP plant after it has completed its existing contracts – currently projected for 2018. [21] The UK also will decommission a second plant that reprocesses the metal fuel of its first-generation gas-cooled "Magnox" reactors after the last reactor of that type shuts down in 2014 or 2015.[22]

The future of reprocessing in France is the subject of a battle between two huge government-owned companies: the national utility, Électricité de France, which wants to reduce its operating costs, and the national nuclear services company, AREVA, which operates the reprocessing plants.

One consideration that is keeping reprocessing alive in France is that AREVA has been making a major effort, supported by successive presidents of France, to sell China a €20-25 billion ($27-34 billion) reprocessing plant similar to the AREVA-designed Rokkasho Reprocessing Plant.[23] AREVA also has not given up hope of selling a similar reprocessing plant to the U.S. [24]

Japan's huge investment in its breeder program – over $17 billion in research, development and demonstration between 1974 and 2011 (Figure 2) – has similarly made it difficult to change its policy.

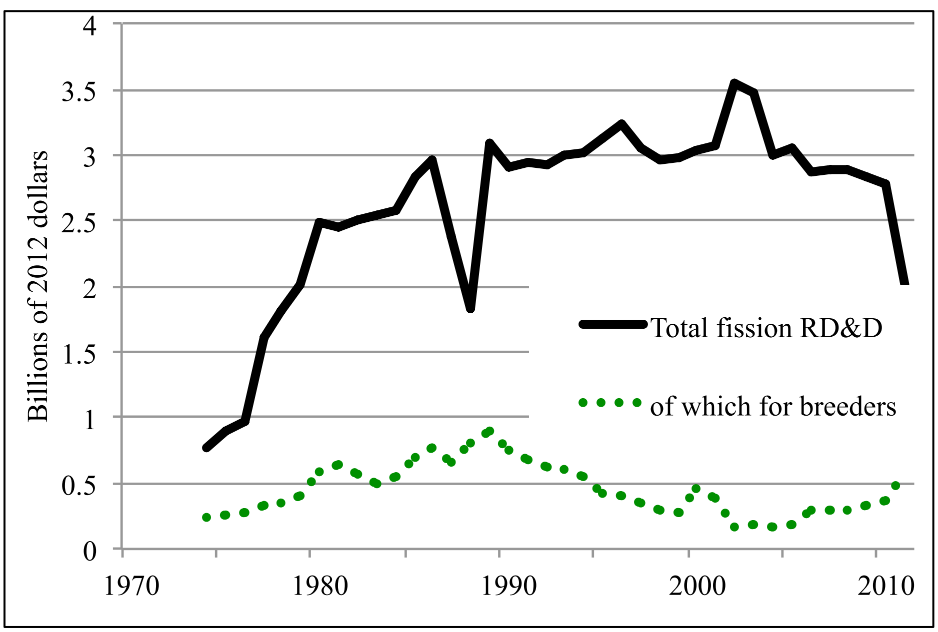


**Figure 2.** History of Japan's annual expenditures on fission energy and breeder research, development and demonstration (RD&D). In total, Japan spent $100 billion on fission RD&D between 1974 and 2011, of which about $17 billion went to breeder RD&D. [25]

The *Monju* (Figure 3, left) and *Joyo* breeder reactors – both of which have been shut down for years by accidents[26] – and the Japan Atomic Energy Agency's huge Nuclear Fuel Cycle Engineering complex at Tokai, which includes the Tokai Pilot Reprocessing Plant (Figure 3, right) and their staffs of thousands of engineers and technicians are the result of these huge investments and understandably hard to abandon.

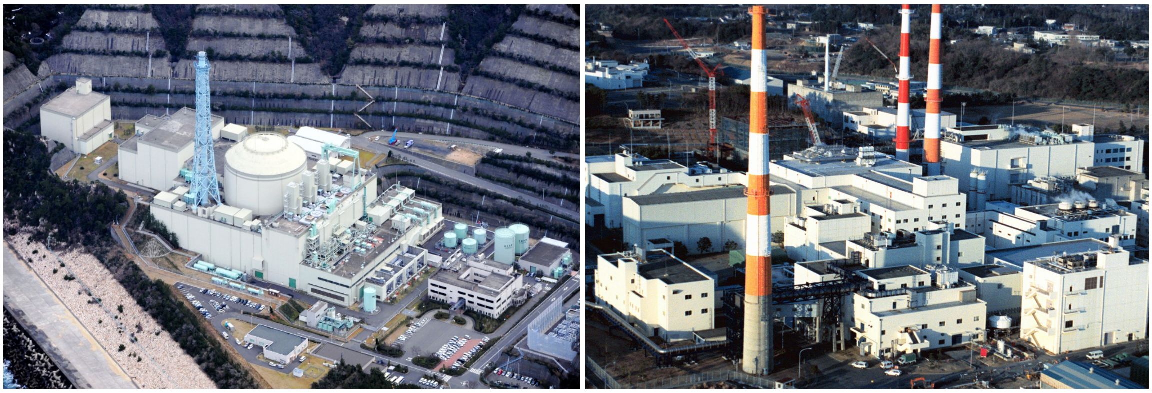

**Figure 3.** The *Monju* (left) sodium-cooled Prototype Fast Breeder Reactor at Tsuruga, Fukui Prefecture (280 MWe) was only connected to the grid from 29 August until 8 December 1995, when it had a sodium fire. Preparations for resumed operations in 2010 were terminated by a refueling accident. Recently, preparations to restart *Monju* were halted by Japan's Nuclear Regulation Authority because of concerns about its safety management system.[27] The Tokai Pilot Reprocessing Plant (right) began operations in 1977 after the Carter Administration failed to convince Japan to join the United States in abandoning reprocessing. *Sources: Asahi Shimbun* and *Kyodo News Service*.

## Japan’s growing stock of separated plutonium

About 40 tons of plutonium were separated from the reprocessing of Japan’s spent fuel in France and the UK, mostly during the 1990s. The original plan was to ship the plutonium back to Japan for use in the fast-neutron breeder reactor (FBR) program and about 2 tons were shipped for mostly this purpose by early 1993. After the FBR program stalled, however, it was decided to fabricate the plutonium into uranium-plutonium mixed-oxide (MOX) fuel in Europe and ship it back to Japan to be used in 16 to 18 of Japan’s light-water power reactors. That is now the plan for plutonium separated by the Rokkasho Reprocessing Plant as well.[28]

The first shipment of MOX fuel to Japan from Europe, in 1999, was a combined shipment from France and the UK. Before the fuel was loaded into reactors, however, it was discovered that workers in the UK MOX pilot fuel fabrication pilot plant had falsified the quality control measurements of the diameters of some of the MOX fuel pellets. That fuel was eventually sent back to the UK.

Loading of the French MOX into Fukushima Daiichi Nuclear Power Plant unit #3 was delayed for a decade because of local concerns that it might bring with it added safety risk, aggravated by the distrust caused by the 1999 MOX data fabrication incident and the 2002 revelation that TEPCO had for decades been submitting reports to the government that concealed incidents of safety concern. In 2010, TEPCO finally obtained consent from Fukushima Prefecture to load the MOX fuel. The presence of this fuel in the reactor was a focus of concern during the 11 March 2011 accident even though it was not a significant factor.

The UK’s commercial Sellafield MOX Plant (SMP), which began operations in 2001 primarily to make MOX fuel for Japan, proved to be able to operate on average at only one percent of its design capacity. The small amount of fuel that it did produce was shipped to European customers. On 30 April 2010, Japan’s ten nuclear utilities, by then the sole remaining customers of SMP, agreed to finance a new effort to increase the SMP’s throughput. After the Fukushima accident, however, the UK Nuclear Decommissioning Authority (NDA) decided to abandon the plant in light of “the changed commercial risk profile for SMP arising from potential delays following the earthquake in Japan and subsequent events”.[29]

In 2001, France shipped MOX fuel for TEPCO’s Kashiwazaki Kariwa Nuclear Power Plant unit #3 but the fuel still has not been loaded. The third and fourth shipments from France, in 2009 and 2010 for five reactors, fared somewhat better. Fuel was loaded into three of the reactors (Genkai #3, Ikata #3 and Takahama #3) but the MOX fuel intended for the other two (Hamaoka #4 and Takahama #4) still has not been loaded.

In total therefore, as of the time of the Fukushima Daiichi accident, 3.5 tons of plutonium in MOX fuel had arrived from France and 2.5 tons had been loaded into four reactors, one of which had (coincidentally) suffered a core meltdown.

After the accident, on 27 June 2013, MOX fuel estimated to contain another 0.9 tons of plutonium arrived at the Takahama #3 plant after a two-month voyage from France. Like other Japanese nuclear utilities intent on getting consent from prefectural and local governments to restart their reactors, however, the owner of the plant, KEPCO, has not disclosed any immediate plans to use MOX fuel. Table 1 shows the situation with regard to the storage of fabricated MOX fuel at nuclear reactors in Japan as of the end of 2012.

| **Nuclear reactor or critical facility** | **Quantity of plutonium** (kg) |
|---|---|
| *Joyo* Experimental Fast Breeder Reactor | 134 |
| *Monju* Prototype Fast Breeder Reactor | 31 |
| Kashiwazaki Kariwa #3 | 205 |
| Hamaoka #4 | 213 |
| Takahama #4 | 184 |
| Ikata #3 | 198 |
| Genkai #3 | 160 |
| Fast Critical Assembly, Tokai R&D Center | 331 |
| Deuterium Critical Assembly, Oarai R&D Center | 87 |
| Static & Transient Experiment Critical Facilities, Tokai R&D C. | 15 |
| Other | 11 |
| **Total** | **1,568** |

**Table 1.** Unirradiated plutonium stored at nuclear reactors and critical facilities in Japan as of the end of 2012.[30] In June 2013, an additional shipment of MOX fuel containing approximately 900 kg of plutonium was delivered to Takahama #3 from France.

Based on advice from the nuclear-weapon states, the International Atomic Energy Agency (IAEA) assumes that eight kilograms of plutonium is enough to make a first-generation, i.e. Nagasaki-type nuclear explosive and defines that amount as "significant quantity (SQ)."[31] Therefore, six of Japan's nuclear power reactors, its two breeder reactors and three different critical facilities are each providing long-term storage for significant quantities of nuclear-weapon-usable material. Even individual MOX fuel assemblies contain significant quantities of plutonium. Long-term storage of weapon-quantities of unirradiated plutonium in so many locations in conditions of inadequate security should be a major international nuclear security concern.

During 2006-2008, the stock of separated plutonium in Japan was increased by 3.6 tons as a result of a test run of the Rokkasho Reprocessing Plant. That test revealed a technical problem with vitrification (solidification in glass) of the liquid high-level radioactive waste. JNFL now believes that the problem has been solved and hoped to declare the plant operational in October 2013 and begin operations in the second half of fiscal year 2013 (October 2013-March 2014). JNFL announced at the end of July 2013, however, that this plan would be delayed because Japan's new Nuclear Regulation Authority (NRA) has announced that it will not be able to review the safety of the RRP until after the NRA's new safety regulation rules for nuclear fuel cycle facilities are finalized in December 2013. A September 21, 2013 article in a local paper *Too Nippo* quoted an anonymous high official of NRA saying: "The delay would be at least one year. It would be better to plan for two years."[32]

A new MOX plant (J-MOX) is being built next to the RRP where plutonium separated at the RRP is to be made into MOX fuel. J-MOX is still officially scheduled to start operations in March 2016. Construction work was delayed for about one year, however, by the Fukushima accident with work on the building only starting in October 2012. Any additional plutonium separated at Rokkasho during the next several years therefore will simply go into storage.

Figure 4 shows the evolution of Japan's plutonium stockpile since the early 1990s and a projection until 2025 assuming that the Rokkasho plant operates and the delay of plutonium recycle in MOX continues.

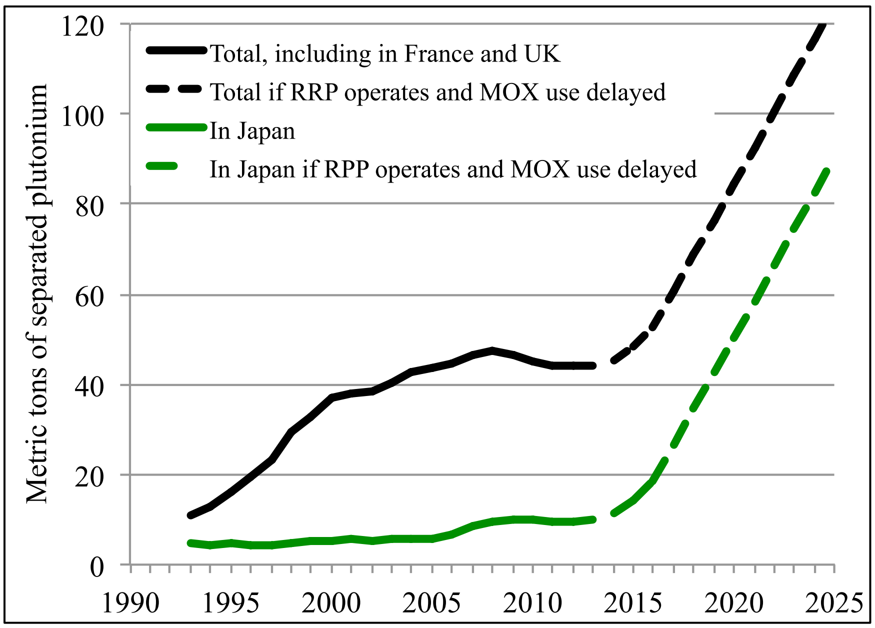


**Figure 4.** Growth of Japan's stock of separated plutonium. In the 1990s and early 2000's the growth was primarily due to reprocessing of Japan's spent fuel in France and the UK. During 2006-8, test operations at the RRP separated 3.6 tons of plutonium. In 2013, France shipped 0.9 tons of plutonium in MOX fuel to Japan. Japan Nuclear Fuel Limited's (JNFL's) 31 January 2013 plan was to start operations at the RRP in the latter half of fiscal year 2013.[33] On 1 November 2013, however, JNFL announced another delay.[34] In the scenario shown here, we have assumed a nine-month delay relative to the January 2013 plan: 1 ton of plutonium separated in calendar 2014, 2.9 tons in 2015, and 4.4 tons in 2016.[35] We assume thereafter the RRP, operating at its design capacity of 800 tons of spent fuel per year, will separate about 8 tons of plutonium annually.[36] If this plan is carried out and the MOX program continues to be stalled, Japan's total stockpile will rise to about 100 tons within a decade.

## Reactor-grade plutonium is weapon-usable

Although some reprocessing advocates still continue to deny it, power reactor plutonium can be used to make nuclear weapons.[37] By the IAEA metric of 8 kg for a Nagasaki-type nuclear weapon, the nine tons of unirradiated plutonium currently in Japan is enough for more than one thousand nuclear explosives. This is of concern for Japan's neighbors and also the United States. In a speech during his visit to South Korea for the Seoul Nuclear Security Summit in March 2012, President Obama urged:[38]

> We simply can't go on accumulating huge amounts of the very material, like separated plutonium, that we're trying to keep away from terrorists.

In April 2013, Vice Chairman of the JAEC, Tatsujiro Suzuki, reported that, during a visit to Washington early that month, two high-level Obama Administration officials had made pointed comments to him about Japan's reprocessing plans:[39]

- Assistant Secretary of State for Nonproliferation Thomas Countryman stated that, Japan's operation of the Rokkasho Reprocessing Plant could undercut US nonproliferation efforts with Iran and its efforts to persuade South Korea not to reprocess; and
- Deputy Secretary of Energy Daniel Poneman expressed deep concern that reprocessing without a credible plutonium use program would further increase Japan's stock of separated plutonium.

Earlier, in September 2012, Poneman had pointed out to emissaries from the Noda Administration the inconsistency in the Noda administration's nuclear policy:[40]

1. If nuclear power is abandoned, reprocessing also must be abandoned because use of the separated plutonium in reactor fuel would become impossible.
2. Conversely, if a policy of plutonium separation is adopted, nuclear power must continue in order to provide a use for the plutonium.

This message was not communicated clearly in Japan, however. Indeed, some turned Poneman's support of nuclear power and fast reactor research and development into a message that "the US wants Japan to reprocess."[41]

In addition to being a nuclear explosive material, plutonium also is extremely radiotoxic if inhaled and therefore could be used to make a very lethal "dirty bomb."[42]

## Japan's spent fuel storage problem as a rationale for continuing reprocessing

A major driver that keeps reprocessing alive in Japan today is the limited space for spent fuel storage at Japan's nuclear power plants. This is a self-perpetuating situation, however. Japan's nuclear utilities have not moved to expand on-site storage because that would be inconsistent with their plans to promptly send spent fuel off site for reprocessing as soon as it is cool enough to transport.

Table 2 (overleaf) shows the current situation at each of Japan's nuclear power plants except for those in Fukushima Prefecture, which are not expected to restart. According to METI's projection, if they are allowed to resume operation, three of Japan's nuclear power plants could run out of storage space in their spent fuel pools after three years. We show four years in Table 2 because we have assumed a higher fuel burnup than METI. At the other extreme, two of the nuclear power plants have space for about 20 more years of spent fuel discharges. Eventually, however, all the pools at operating reactors will fill up if the older cooler spent fuel is not removed.

Instead of doing something about Japan's spent fuel storage situation, the JAEC has been arguing for more than eight years that it would take too long to persuade prefectural and municipal governments to allow expanded on-site storage at the nuclear power plants and that therefore the plans to reprocess must go forward. In 2005, in its long-term plan for nuclear energy in Japan, the JAEC argued:[43]

> "If we make a policy change from reprocessing to direct disposal, it is indispensable for the continuation of nuclear power generation to have communities that up until now have accepted selection as a site for nuclear facility, based on the assumption that spent fuel would be reprocessed, understand the new policy of direct disposal and accept the [temporary] storage of spent fuel at the site. It is clear, however, that it takes time to do so, as it is necessary to rebuild relationships of trust with the community after informing them of the policy change. It is likely that the nuclear power plants that are currently in operation will be forced to suspend operations, one after another, during this period due to the delay of the removal of spent fuel."

This argument has been reinforced by threats from the governments of Aomori Prefecture and Rokkasho Village that, if the Rokkasho Reprocessing Plant (RRP) is not operated, they will demand that the approximately 3,000 tons of spent fuel currently in the RRP intake storage pool be returned to the nuclear power plants from which it came.

Aomori Prefecture also has threatened that, if the RRP is not operated, it will block use of a new interim spent fuel storage facility owned by TEPCO and the Japan Atomic Power Company (JAPC) in Mutsu city in the prefecture. The Mutsu facility is designed to store initially 3,000 tons and, after the construction of a second building, a total of 5,000 tons of spent fuel from reactors belonging to the two companies – but only on the understanding that the stored fuel eventually will be reprocessed.[44]

| Utility | Plant | **Net capacity** GWe | **Annual discharge** Uranium tons | **Spent fuel stored** Uranium tons | **Total available capacity** Uranium tons | **Years till full** | **Years of discharge in pool** |
|---|---|---|---|---|---|---|---|
| Hokkaido | Tomari 1-3 PWR | 1.97 | 27 | 400 | 1020 | 22.7 | 11 |
| Tohoku | Onagawa 1-3 BWR | 2.09 | 33 | 420 | 790 | 11.3 | 9 |
| | Higashidori 1 BWR | 1.07 | 16 | 100 | 440 | 20.7 | 4 |
| TEPCO | Kashiwazaki-Kariwa 1-7 BWR | 7.97 | 126 | 2,370 | 2,910 | 4.3 | 14 |
| Chubu | Hamaoka 3-5 BWR | 3.47 | 55 | 1,140 | 1,740 | 11.0 | 15 |
| Hokuriku | Shika 1-2 BWR | 1.61 | 27 | 160 | 690 | 19.4 | 4 |
| KEPCO | Mihama 1-3 PWR | 1.57 | 27 | 390 | 680 | 10.6 | 10 |
| | Takahama 1-4 PWR | 3.22 | 55 | 1,160 | 1,730 | 10.4 | 15 |
| | Ohi 1-4 PWR | 4.49 | 60 | 1,420 | 2,020 | 10.0 | 17 |
| Chugoku | Shimane 1-2 BWR | 1.22 | 22 | 390 | 600 | 9.6 | 13 |
| Shikoku | Ikata 1-3 PWR | 1.92 | 27 | 610 | 940 | 12.1 | 16 |
| Kyushu | Genkai 1-4 PWR | 3.31 | 49 | 870 | 1,070 | 4.1 | 13 |
| | Sendai 1-2 PWR | 1.69 | 27 | 890 | 1,290 | 14.6 | 24 |
| JAPC | Tsuruga 1,2 BWR, PWR | 1.45 | 22 | 580 | 860 | 12.8 | 19 |
| | Tokai Daini 2 BWR | 1.06 | 16 | 370 | 440 | 4.3 | 16 |
| **Totals** | | **38.11** | **591** | **11,270** | **17,220** | **10.1** | **14** |

**Table 2.** Spent fuel stored and total available capacity for spent fuel at each of Japan's nuclear power plants reported by METI as of the end of September 2013.[45] The Fukushima Daichi and Fukushima Daini nuclear power plants are not shown because METI does not expect them to restart. The 16-month reloads shown in METI's estimates (three-month periodic inspection after 13 months of operation) appear to be for an average burnup of 36.5 MWt-days/kg. Current burnups in Japan are typically 45-50 MWt-days/kg.[46] The annual discharge and years-till-full columns in our table therefore are calculated assuming an average of 50 MWt-days/kg in the future.

It is doubtful that either of these threats would be carried out if Japan abandoned or indefinitely suspended reprocessing and began to expand spent fuel storage at the reactor sites. Due to the delay in the operation of the RRP, Aomori Prefecture has shifted the primary basis for its "nuclear fuel taxes" to the spent fuel stored at the RRP.

In any case, reprocessing is an extravagantly expensive alternative to spent-fuel storage. Instead of the older cooler spent fuel being stored in air-cooled dry casks as in other countries, in Japan, it is to be separated into uranium, plutonium and radioactive wastes that are to be stored in separate locations within JNFL's Rokkasho complex.

This is, of course, not the way reprocessing is being represented to citizens of Aomori Prefecture or of Japan as a whole. They are being told that reprocessing creates a domestic energy source and makes Japan more self-sufficient by reducing its uranium imports by up to 25 percent[47] and also that MOX use reduces the long-term radioactive hazard from spent fuel. As has already been noted, Japan's uranium imports could be reduced a similar amount for one tenth the cost by increasing the percentage of U-235 extracted from natural uranium at uranium enrichment plants.[48] We discuss the alleged radioactive waste management benefits from reprocessing below.

## Do reprocessing and MOX use reduce radioactive waste volume and toxicity?

Japan’s Ministry of the Economy, Technology and Industry (METI) argues that reprocessing and the use of MOX fuel in light water reactors (LWRs) and eventually in sodium-cooled fast-neutron reactors would have important waste-management benefits. According to METI:[49]

1. Plutonium recycle in LWRs and fast-neutron reactors would respectively reduce the volume of high-level waste to about 1/4 and 1/7 of the volume of the original spent fuel; and
2. Reduce the time required for the toxicity of the high-level waste to decay to the same level as the original natural uranium from about 100,000 years to 8,000 years and 300 years respectively.

Careful calculations for the case of France have shown, however, that, if *all* the radioactive waste streams from reprocessing and MOX fuel fabrication that require deep burial are included, the volume of the packaged waste is the same as that of the original spent fuel within uncertainties.[50]

In any case, the area of a deep geological repository is determined not by the volume of the waste but rather by its heat output. Here too, reprocessing and MOX fuel use in light water reactors have negligible benefit since spent MOX fuel, which will most likely be placed in the repository, has about as high a long-term heat output as the uranium spent fuel from which it was produced.[51]

Plutonium recycle in LWRs also does not greatly reduce the long-term radioactive hazard from spent fuel. The irradiation of MOX fuel typically reduces the amount of plutonium in spent fuel only by about 40 percent, even taking into account the plutonium that would have been produced in the low-enriched uranium fuel that otherwise would have been used.[52]

Reducing the plutonium further with multiple recycles in light water reactors has not been attempted. One disincentive is that the recycled plutonium would contain an increasing fraction of plutonium isotopes that are not fissionable by the slow neutrons that dominate in light water reactors. Also, each recycle would produce more curium-244 and other isotopes that fission spontaneously creating a major radiation hazard from penetrating neutrons and requiring very costly remote fuel fabrication behind heavy shielding.[53]

Separation of plutonium and other transuranic elements and their repeated irradiation in sodium-cooled fast-neutron reactors such as *Monju*, redesigned to be “burner” reactors by design changes including the removal of the uranium “blanket” around the core, could, over hundreds of years “transmute” (fission) plutonium and other transuranic elements into other mostly shorter-lived elements, reducing their total presence in reprocessing waste to a few percent of the amount in LWR spent fuel. The cost would be huge, however.

A major review of transmutation by the U.S. National Academy of Sciences (NAS) concluded that:[54]

> "none of the dose reductions [to future generations] seem large enough to warrant the expense and additional operational risk of transmutation."

The "operational risks" discussed in the NAS report did not include the very significant risks of nuclear proliferation and nuclear terrorism associated with separated plutonium.

In any case, even in France, there are as yet no firm plans to separate out and transmute the plutonium in spent MOX fuel. Despite about $100 billion spent by the industrialized countries on research, development and demonstrations, only a few pilot and prototype fast-neutron reactors exist in the world today.[55] It would be foolhardy to separate more plutonium during the next few years on the assumption that fast neutron plutonium burner reactors will be built in significant numbers to fission it.

## Dry-cask storage as an alternative to reprocessing

In most countries that operate nuclear power plants, when the power plant spent fuel pools fill up, the fuel that has cooled longest in the pools is moved into massive casks – usually on the nuclear power plant sites.

Japan has done this on a small scale at two of its nuclear power plants. Interestingly, one was the Fukushima Daiichi plant, where nine casks containing a total of 408 spent fuel assemblies have been stored in a repurposed building since 1995.[56] (Figure5)

Although the structure of the building housing the casks was damaged by the tsunami, in contrast to the situation at the reactor spent-fuel pools, there were no concerns that the spent fuel stored in the casks could overheat, catch fire and release huge quantities of 30-year half-life cesium-137. This is because, unlike the spent-fuel pools, casks have no powered cooling systems that can fail. The radioactive decay heat from the fuel inside is conducted to the surface and removed by passive air convection.

The global nuclear industry considers dry storage a low-cost mature technology. The first dry-cask storage facility in the United States was licensed 27 years ago in 1986.[57] This is well-understood in Japan's nuclear industry. In 2005 and 2011, the Japan Nuclear Energy Safety Organization (JNES) published comprehensive illustrated reports on the status of on-site dry-cask storage in many countries around the world.[58]


**Figure 5.** Spent fuel storage casks at the Fukushima Daiichi nuclear power plant after the tsunami had washed through the building. Each cask is 5.6 meters long with a diameter of 2.2-2.4 meters, weighs about 100 tons and contains 6.3 or 8.8 tons of spent fuel. They are designed for spent fuel that has cooled for 5 to 7 years in a pool. *Source:* TEPCO.[59]

In Germany, after the nuclear utilities agreed with the government in 2000 to end by mid-2005 shipments of spent fuel to France and the UK for reprocessing, every operating nuclear power plant quickly built on-site, air-cooled dry-cask storage for its older fuel to ensure that there would continue to be space in the pools for the discharge of additional spent fuel.[60] In all but one case, the casks are stored in thick-walled buildings. In one case, however, there was no space for an additional building on the site and the casks were emplaced in a tunnel under the site and at four nuclear power plants, temporary air-cooled concrete caskets for the casks were installed until a storage building could be completed (Figure 6).[61] As of the end of 2010, Germany's dry-cask at-reactor storage facilities contained 2,678 tons of spent fuel and were licensed to contain more than 14,000 tons.[62]

**Figure 6.** Storage tunnels under construction (left) and with the first casks emplaced (center) at the Neckarwestheim nuclear power plant in Germany, where there was not enough space for a new building. The image on the right shows temporary protection for German storage casks pending construction of a permanent storage building. *Sources:* Wolfgang Heni and Gesellschaft für Nuklear-Service mbH (GNS).[63]

This method of temporary storage is being copied on the Fukushima Daiichi site today. A temporary dry-cask storage facility, initially for 50 casks, with 15 to be added later as needed, is currently under construction. The idea is to move about half of the 1,100 tons of spent fuel currently in the Fukushima Daiichi common pool, which is almost full, into dry casks to make space for the spent fuel in the four reactor pools, which together contain about 500 tons of fuel (3,100 fuel assemblies including fresh fuel). The transfers will start with the unit #4 pool about which the safety concern is the greatest.[64] Removal of spent fuel from pool of Unit 4 is to begin in November 2013, when it is hoped that the overhead crane to handle spent fuel will have been declared safe to use.[65]

The nine casks stored since 1995 in the now damaged dry-cask storage building are also to be moved into the temporary storage area. The first cask of the nine was transferred to the temporary storage area on 4 April 2013 after being opened for inspection of the contained fuel in the common pool.[66]

According to industry sources, about 100 carbon steel casks can be built per year in Japan without investing in additional production capacity[67] and about 100 more per year could be procured overseas. Two hundred casks could accommodate about 2,000 tons of spent fuel, which is about three times the annual discharges from the power reactors shown in Table 2 if all were allowed to operate.

The larger issue that concerns Japan's nuclear utilities, however, is whether prefectures with operating nuclear power plants will allow the addition of dry-cask storage at the nuclear power plants that they host.

Japan is different from the United States and perhaps other countries in that its nuclear utilities have "gentlemen's agreements" with their host prefectural and local governments that require those governments to consent to construction of new facilities, including dry-cask storage facilities, at the nuclear power reactor sites. The effect of these agreements has been felt keenly recently with regard to another requirement of consent to restarting of the reactors after the periodic inspection which is conducted after 13 months of operation. After the March 2011 accident at Fukushima Daiichi, these consents were refused and, as a result, as of April 2012, all of Japan's nuclear power reactors had been shut down.[68]

The need for expanded interim spent fuel storage has been a concern of Japan's nuclear utilities for at least two decades. This was why the common pool with a capacity of 1200 tons of spent fuel was built and dry-cask storage was introduced into an existing building at the Fukushima Daiichi plant. JAPC also built a dry-cask storage facility at the Tokai Daini (Tokai 2) nuclear power plant with permission to install a total of 24 casks to store 250 tons of spent fuel. [69]

The record of local acceptance of interim storage is not all positive. In 2004, the mayors of the three towns that host Kansai Electric Power Company's (KEPCO's) three nuclear power plants in Fukui Prefecture expressed a willingness to consider hosting an off-site interim spent fuel storage facility but the governor vetoed the idea. [70] Following the 11 March 2011 accident, however, dry-cask storage has become part of the nuclear safety debate. On 5 March and 31 Oct. 2013, the Governor of Shizuoka Prefecture, Heita Kawakatsu, said that construction of on-site dry-cask interim storage would be a safety requirement for restarting of the three nuclear power reactors at the Hamaoka nuclear power plant.[71]

The municipalities hosting nuclear facilities are dependent on economic benefits from these facilities. Their income from property taxes is about twice as much per capita as in the average Japanese municipality. Nuclear-related grants and contributions from the central government and nuclear utilities raise the ratio even higher.[72] If a decision were made not to operate the Rokkasho Reprocessing Plant, the prefectures and municipalities hosting nuclear power reactors that the Nuclear Regulation Authority decides are safe to operate would be faced with a choice: either accept on-site dry-cask storage, which is safer than pool storage, or lose the tax and other economic benefits of hosting operating nuclear power plants when their spent fuel pools fill up.

The prefectures hosting nuclear power plants should be allowed to raise income from special taxes per ton of spent fuel stored in dry casks and share it with the local communities as would be done with the Mutsu facility in Aomori Prefecture. It also would be appropriate to repurpose to the objective of encouraging on-site dry-cask storage the special grants that have been given to municipalities for allowing the use of MOX fuel in the reactors that they host. By accepting expanded safer on-site storage, the host communities would make unnecessary all the costs and dangers associated with the separation and recycle of plutonium.

***The safety argument for dry-cask storage***. The present moratorium on operation of nuclear power reactors in Japan is a result of safety concerns raised by the Fukushima Daiichi accident. Moving older spent fuel from pool into dry-cask storage would reduce one of the safety concerns raised by that accident. Indeed, Shunichi Tanaka, in his first press conference as chairman of the Nuclear Regulation Authority, urged that spent fuel be moved into dry casks after about five years of pool storage:[73]

> "Spent fuel not requiring active cooling should be put into dry casks … for five years or so cooling by water is necessary…I would like to ask utilities to go along those lines as soon as possible."

This reflected the great concern that developed during the Fukushima accident about safety of the spent fuel in the reactor spent fuel pools. Indeed, in response to a request from Prime Minister Naoto Kan, a group led by JAEC Chairman Shunsuke Kondo came up with a worst-case scenario for the potential results of the on-going accident at Fukushima Daiichi. Their worst case was not from the reactor core meltdowns but from a spent fuel fire if the storage pool of unit #4 were to dry out. According to a report in the *Asahi Shimbun*[74]

> "The plan would have ordered mandatory evacuations of everyone within a 170-km radius of the plant. Evacuations would have been voluntary for those living between 170 km and 250 km from the plant, including the Japanese capital…
>
> "The worst-case scenario imagined the melting of 1,535 fuel assemblies, an equivalent of fuel used for two reactors, kept in a spent fuel storage pool at the No. 4 reactor.
>
> "The report also predicted the extent of soil contamination of areas required to evacuate in light of standards set after the 1986 Chernobyl accident in Ukraine.
>
> "The scenario said areas within a 170-km radius of the plant would have been contaminated with 1,480 kBq/m$^2$, a level that requires mandatory evacuation.
>
> "Areas where the government would have requested voluntary evacuations were predicted to have 555 kBq/m$^2$, extending to a 250-km radius, which included Tokyo and surrounding areas…
>
> "The report said it would have taken several decades for radiation levels to decrease naturally in the mandatory and voluntary evacuation zones.
>
> "The report also said high radiation levels could have extended beyond the 250-km radius, and people in those areas would have also been advised to relocate."

Spent pool #4 contained about 20 MegaCuries[*] (MCi) of 30-year half-life cesium-137, the fission product that has caused the long-term evacuation of large areas around the Chernobyl and the Fukushima Daiichi nuclear power plants. In comparison, the Chernobyl release was about 2 MCi and the airborne release from the Fukushima Daiichi reactors has been estimated at about 0.3±0.1 MCi.[75] A circular area with a radius of 250 km considered for mandatory and voluntary evacuation in the worst-case scenario considered by Chairman Kondo's group would have an area of about 200,000 km$^2$. This estimate is consistent with our independent calculations of the consequences if a spent-

[*] A Becquerel (Bq) is the modern unit of radioactivity: the radioactive transformation of one atom per second. The Curie (Ci) is an older unit, is a unit of radioactivity equal to that of one gram of radium-226, 37 billion radioactive transformations per second. Radium-226 has a half-life of 1600 years.

fuel fire released *all* the cesium-137 in pool #4 – i.e. ten times the amount released by the Chernobyl accident – and if the wind direction changed during the fire so that the contamination was blown equally in all directions.[76]

In the United States, most nuclear power plants were designed before the U.S. abandoned reprocessing in 1977. It was assumed that spent fuel would be transported to a reprocessing plant as soon as it was cool enough to be moved in an air-cooled cask, i.e., within a few years. Today, U.S. spent fuel pools contain on average about 25 years of spent fuel discharges in pools originally designed for about five years of discharges.[77]

Japan's spent fuel pools contain on average about 14 years of discharges and have on average a capacity to hold an additional 10 years of discharges (Table 2). This is because they have been re-racked: the storage configuration in the pools has been changed from open rack to dense packed, in which the fuel assemblies are packed almost as tightly as in a reactor core with partitions of steel between them with attached sheets of material containing the neutron absorber boron to prevent a chain reaction. The configuration in Fukushima Daiichi spent fuel pool #4 shows that it was dense-packed (Figure 7).

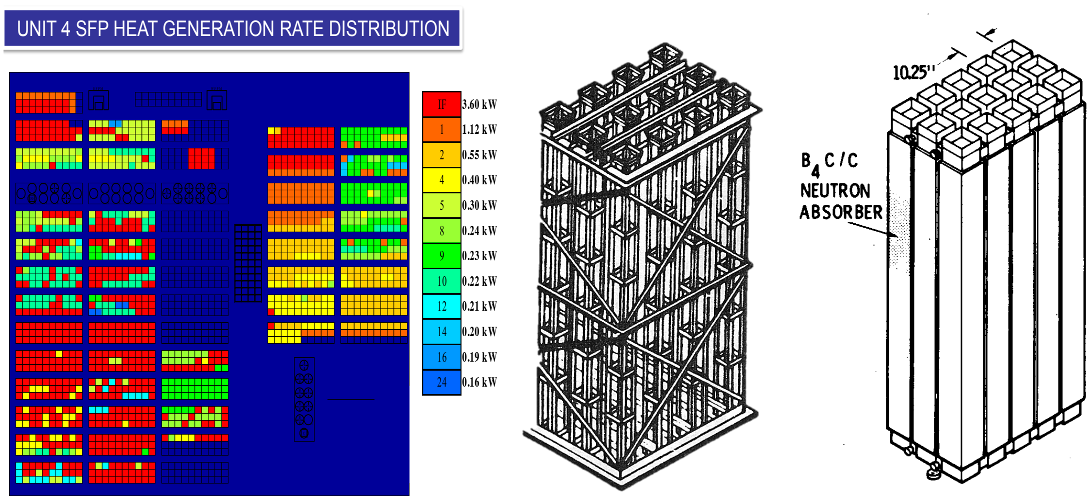


**Figure 7.** *Left:* Spent fuel assemblies stored densely in racks in Fukushima Daiichi spent fuel pool #4 with the radioactive decay heat from each assembly shown for 11 March 2011, the date of the accident. All the fuel assemblies are stored vertically in 53 fuel storage racks of a high-density design. Each rack can hold 30 fuel assemblies in 0.15 m×0.15 m square boxes in a 3 × 10 configuration. The separation walls between cells are made of stainless steel with a sheet of neutron absorbing boron attached. The hottest 548 assemblies (shown in red) belonged to the full core that had been unloaded during the periodic inspection starting on 30 November 2010 to allow inspection of the interior of the reactor pressure vessel. The yellow fuel had been in the pool for about 5 years. Some of the racks were filled with fresh fuel (dark blue). The Fukushima Daiichi reactors are boiling water reactors (BWRs). Each BWR fuel assembly contains about 0.17 tons of uranium, *Source:* US Department of Energy;[78] *Middle*: Open storage racks originally used in some U.S. pressurized water reactor pools. *Right.* High-density closed-box racks similar to those used in the Fukushima spent fuel pool #4 can store four times the amount of fuel in the same area as the open racks but could prevent air cooling if the pool lost water. *Source:* Sandia National Laboratory.[79]

One danger from dense-packing is that the solid walls of the racks would reduce air circulation through the spent fuel assemblies if the pools lost water. This reduction would be total if the drainage were only partial and water still covered the openings at the bottoms of the racks. Thus dense packing increases the danger that, in case of loss of water, the portions of the fuel assemblies not cooled by water will heat up to the point where its zirconium cladding catches fire.

This concern and the vulnerability of many above-ground pools, such as those at the Fukushima Daiichi plant, has led to proposals since 9/11 that spent fuel assemblies older than five years be removed from the pools and placed into passively safe dry casks.[80]

Five years after discharge from a reactor, the radioactive decay heat of spent fuel has declined to about 3 ± 1 kW per ton (Figure 8). The heat generated by radioactive decay in the fuel flows to the exterior of the cask where it is removed by passive air cooling. The heat dissipation rate from the surface of a cask containing ten tons of 5-year old spent fuel would be about the same as from a black sunlit surface at noon on a clear mid-latitude summer day.[81]

Three years after discharge, when the decay heat would be 6 kWt/ton or less, dry-cask storage also is possible, but with fewer fuel assemblies per cask.[82] Conversely, one of the economic incentives for waiting longer than five years is that more spent fuel can be stored in each cask.

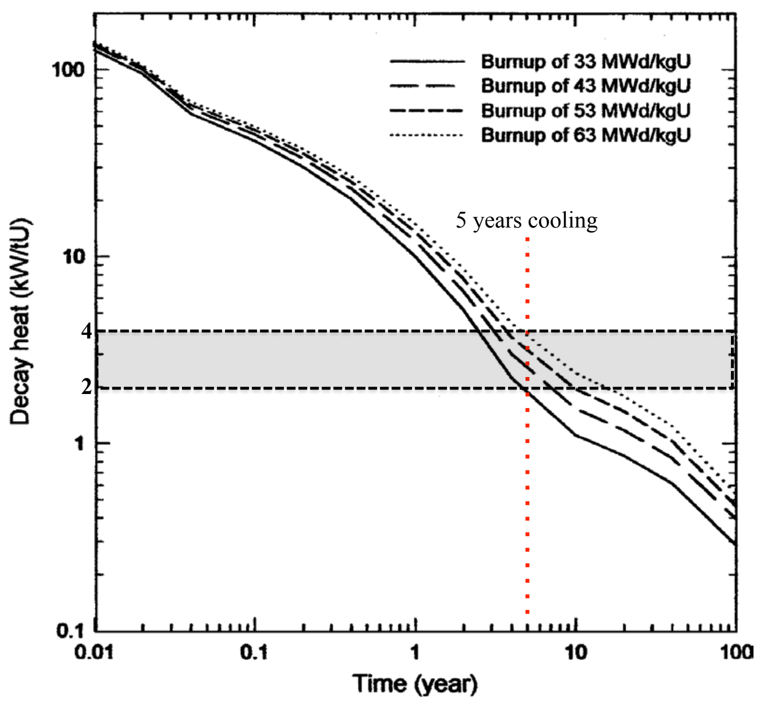


**Figure 8**. Decline of radioactive heat rate from a ton of spent fuel after reactor shut down, *Source: Science & Global Security*.[83]

The same safety concerns relating to reactor pools apply to the large storage pools at the Rokkasho Reprocessing Plant. Indeed, one of the first times that the dangers of dense-packed spent fuel storage pools was raised was in 1977, during a state hearing on a reprocessing plant that was proposed for construction in the town of Gorleben in the state of Lower Saxony, Germany. At the end of the hearing, the state rejected the reprocessing plant[84] and ultimately, the German utilities decided not to build a commercial reprocessing plant. After the reprocessing plant was cancelled, interim storage facilities for spent fuel and vitrified high-level waste were built at Gorleben and Ahaus but dry-cask storage was chosen instead of pool storage because of the safety concerns that had been raised about pool storage.[85]

Given these concerns, it would be desirable on safety grounds alone to quickly establish dry-cask storage so that enough fuel can be removed from spent fuel pools to allow their return to open racking. Today this would require the removal of about 8,000 tons of spent fuel and its storage in about 800 casks.[86] The Mutsu facility is designed to store 3,000 tons. The remaining 5,000 tons could be stored in about 500 casks, i.e. an average of about 30 casks at each of Japan's 15 nuclear power plants. If Aomori Prefecture refused to allow the use of the Mutsu storage facility, that would increase the average number at each nuclear power plant by about 20 casks. For comparison, Germany has established on-site dry cask storage for about 14,000 tons of spent fuel at its 13 nuclear power plants, with an average of more than 100 cask positions per plant.[87]

## The need for a radioactive waste repository

If the central government made a firm decision to end reprocessing and the prefectures were convinced that the nuclear power plants that they host are sufficiently safe, it seems unlikely that they would shut down the plants over the issue of dry-cask spent fuel storage. The real concern that the prefectures would have would be that on-site interim storage might become permanent.

Japan, like other countries, needs a credible strategy for moving forward with spent fuel and high-level-waste disposal. Japan's 2000 Radioactive Waste Final Disposal Act established the Nuclear Waste Management Organization (NUMO). In December 2002, NUMO started soliciting applications from local communities to host a deep underground geological repository for vitrified high-level waste. One community government volunteered, but then withdrew because of local political opposition. The central government's ability to have a geological repository in operation by 2045 therefore is losing credibility. That is the year by which Aomori Prefecture was promised that the reprocessing waste from Europe would begin to leave.[88]

The lack of progress in siting a geological repository does not, however, require reprocessing technically or politically. On-site dry-cask storage has been chosen over reprocessing in Germany, the United States and many other countries that have no near-term prospects for siting a geological repository or a central storage facility.

Indeed, in the United States, in 2010, over 170 non-governmental organizations from all 50 states endorsed a set of principles that included a requirement for low-density, open-framework storage racks in spent fuel pools, "hardened" on-site dry-cask storage (for example, with the casks inside a thick-walled building as in Germany) *and a prohibition against reprocessing*. The manifesto explains that:[89]

> "The reprocessing of irradiated fuel has not solved the nuclear waste problem in any country, and actually exacerbates it by creating numerous additional waste streams that must be managed. In addition to being expensive and polluting, reprocessing also increases nuclear weapons proliferation threats."

## Negotiating with Aomori Prefecture

During the central government's 2012 review of the future of Japan's nuclear-energy policy, the governor of Aomori Prefecture injected himself forcefully into the debate – as he had during the previous (2004-5) review of national reprocessing policy. He suggested that, unless reprocessing proceeded as previously planned, Aomori Prefecture might: [90]

- Demand that the 3,000 tons of spent fuel in the RRP intake pool be taken back by the power plants that produced it; and
- Refuse to accept the wastes from the reprocessing of Japan's spent fuel in Europe or spent fuel from other prefectures for storage at the Mutsu interim storage facility.

Currently, the intake pool at the Rokkasho Reprocessing Plant (RRP) is Japan's *de facto* central interim spent fuel and high-level radioactive waste storage site. It contains about 3,000 tons of spent fuel and returned high-level waste from the reprocessing of Japan's spent fuel in Europe. It also stores the plutonium, uranium and radioactive waste from the reprocessing of 425 tons of spent fuel during test operation of the RRP in 2006-8. If the RRP operates, these stocks of separated materials will increase rapidly.

The prefecture accepts this role in exchange for the economic benefits:

- JNFL is the biggest company in Aomori Prefecture, directly employing 1,400 Aomori Prefecture residents plus almost twice as many indirectly through construction contracts.[91] As of the end of FY2010, JNFL had issued construction contracts in the prefecture cumulatively worth ¥0.51 trillion (~$5 billion).[92]
- The taxes that JNFL pays to the prefectural government on spent fuel imported to and stored in the prefecture account for most of the prefecture's "nuclear fuel taxes," which totaled ¥16 billion (~$160 million) in Fiscal Year (FY) 2012, 14% of the Prefecture's total tax income; [93] and
- The large central government grants that Rokkasho Village receives (¥2.6 billion or ~$26 million in FY 2011) in addition to property taxes from JNFL and contributions from the nuclear industry that in total account for half of the Village's income. [94]

Aomori Prefecture has been levying nuclear fuel taxes since 1991. The tax for spent fuel imported to the RRP is ¥19.4 million/ton (~$200,000/ton). Because of postponements of the RRP startup date, since 2006, Aomori also has been levying an annual tax on stored spent fuel that arrived after 28 September 2006. In January 2010, after yet another postponement of the startup of commercial operations at the plant, Aomori raised this tax from ¥1.3 million/ton to ¥8.3 million/ton (~$83,000/ton) per year. [95]

Thus Aomori has already shifted its "nuclear fuel taxes" from the amount of spent fuel brought in for reprocessing each year to the amount of spent fuel stored. In addition, in April 2012, there was an increase of the taxes for storage of low-level and high-level wastes.[96] This tax shift from reprocessing to storage would tend to insulate Aomori Prefecture from losses in its tax base if the RRP does not operate – unless it implements its threat to return spent fuel in the RRP intake pool to the power plants from which it came and refuses to accept spent fuel for storage in the Mutsu facility.

For Aomori to accept a permanent shift in its role from the processing to the storage of spent fuel and radioactive waste, however, it would be necessary for the government and people of Aomori Prefecture to face the fact that, ever since 1997, when the emphasis for plutonium use shifted from breeder reactors to recycling in MOX back into light water reactors, reprocessing has not been a meaningful enterprise.

If the central government makes the decision to stop reprocessing, it should negotiate fairly with Aomori Prefecture and Rokkasho Village about their choices between the economic benefits of continuing to provide an interim storage site for Japan's high-level waste and spent fuel and the loss of those benefits.

If local authorities agree to interim dry-cask storage at the nuclear power plants, then it would be unnecessary to ship spent fuel from TEPCO and JAPC reactors to Mutsu. Indeed, the casks, which account for 70-80 percent of the estimated cost of the 3,000-ton Mutsu interim storage facility,[97] could be used at the reactor sites instead.[98] These are dual purpose transportation and storage casks[99] and it is already planned to use some of them at the Fukushima Daiichi site (see above).

Hopefully, Aomori Prefecture would agree to continue to store at least the 3,000 tons of spent fuel currently in the receiving pool of the Rokkasho Reprocessing Plant. This fuel could be transferred to the Mutsu dry-cask storage facility.[100] That facility is owned by TEPCO and JAPC but, as a result of the Fukushima accident, the central government has taken over a controlling ownership of TEPCO and JAPC is mostly owned by Japan's nine other nuclear utilities. The storage capacity of the Mutsu facility therefore could be reapportioned between the utilities according to the amount of spent fuel that each has in the Rokkasho storage pool. If Aomori Prefecture agrees to keep the 3,000 tons of spent fuel in the RRP intake pool, but transferred it to the Mutsu storage facility, additional casks would have to be ordered.

Economic development assistance also could be offered to Aomori Prefecture to offset the loss of jobs associated with maintaining and operating the reprocessing plant. Because of the huge amount of work involved in decommissioning a reprocessing plant, however, that decline in workforce would take decades. [101]

***Reprocessing waste from France and the UK.*** Aomori Prefecture has threatened that, if a decision is made not to operate the RRP, it will stop accepting for storage the vitrified high-level reprocessing waste and intermediate-level waste being returned from the reprocessing of 5,628 tons of spent Japanese light-water reactor fuel in France and the UK.[102] Returned wastes are being stored at the Rokkasho complex until a deep geological repository can be sited.

The return to Japan of high-level vitrified waste from reprocessing in France (1,310 canisters) was completed in 2007. However, returns of the associated compacted intermediate-level waste France are yet to begin.[103]

Shipments of vitrified high-level waste from the UK began in 2010 and are currently planned to be completed in 2020. The UK will keep the associated intermediate-level waste and ship some extra high-level waste instead.[104]

The total amount of high-level waste to be shipped from the UK is about 10% of the amount it expects to have accumulated from the reprocessing of its own spent fuel.[105] France's shipments of intermediate-level waste to Japan are similarly a small fraction of its intermediate-level waste. It is likely that, if necessary, Japan could persuade both countries to delay their remaining shipments until it can identify an alternative interim storage site. The UK expects to take about a century to clean up its Sellafield reprocessing site.[106]

Thus, if Japan's central government decided to abandon reprocessing, it would not be without recourse in its negotiations with Aomori Prefecture. Indeed, one must question whether the government of Aomori Prefecture has really blocked a long overdue change in Japan's nuclear fuel cycle policy or whether the defenders of reprocessing are using its threats as an excuse to resist policy change. Such an excuse also may be convenient to politicians who do not want to deal with the complexity of the negotiations and the explanations to local communities that would be required if a radical change were made in Japan's fuel-cycle policy.

## Paying off the loans for construction of the Rokkasho Reprocessing Plant

A problem that helped block serious consideration of changing Japan's reprocessing policy during the Noda Administration was that, if Japan's commitment to reprocessing were abandoned, the money in the Reprocessing Fund would be frozen and Japan Nuclear Fuel Ltd (JNFL) would not be able to pay back the bank loans used to help finance the construction of the RRP.[107]

The construction costs to be covered by the fund soared to ¥2.19 trillion (~$22 billion) from the ¥0.760 trillion (~$8 billion) estimated at the time of the 1989 construction application. As of the end of FY 2004 (31 March 2005), JNFL had borrowed from banks ¥1.1 trillion (~$11 billion) in long-term loans guaranteed by the nuclear utilities in addition to having received advance payments for reprocessing services from the utilities totaling about ¥1 trillion.[108]

JNFL's long-term loans have been gradually paid down and, as of the end of FY2012, the total amount outstanding was about ¥0.758 trillion (~$7.6 billion).[109] The amount due within a year on the long-term loans taken out by JNFL was about ¥0.150 trillion (~$1.5 billion) at the end of FY2011.

If Japan abandoned its reprocessing program, the current legal requirements on the Reprocessing Fund would prevent it from repaying both the bank loans to JNFL and nuclear utility advance payments for reprocessing services that were converted into loans when the Fund was established. The advance payment balance at the end of FY2012 was about ¥0.581 trillion (~$5.8 billion).[110]

Given the currently delicate financial condition of some of the nuclear utilities, nuclear industry officials warned the Noda Administration that a halt in payments from the Reprocessing Fund could drive some of the utilities into bankruptcy and create chaos in Japan's financial markets. [111]

This problem may have been exaggerated, however, because most of the bank loans to JNFL (84% in March 2006) were from the government-owned Development Bank of Japan, which would be unlikely to force JNFL or the nuclear utilities into bankruptcy against the wishes of the government. [112]

In any case, the government could solve the problem by changing the law and making it possible for the loans and prepayments to be repaid even if the Rokkasho Reprocessing Plant is shut down. Such a change would save the ratepayers trillions of Yens in the long run. It therefore should be a part of the comprehensive package of policy changes that would allow reprocessing in Japan to end.

## A government takeover of spent fuel management?

Currently, responsibility for managing spent fuel in Japan is shared by a number of organizations. The central government provides the general policy framework but the policy is executed by three organizations whose Presidents are all former TEPCO officials:

- JNFL, an organization established in 1980 and owned mostly by the nuclear utilities, is responsible for spent fuel reprocessing;[113]
- The Radioactive Waste Management Funding and Research Center (RWMC), a foundation established in 1976, has been designated under law to manage the funds for reprocessing and high-level waste disposal;[114] and
- The Nuclear Waste Management Organization (NUMO), a non-governmental organization established by law in 2000 and authorized by the Ministry of Economy, Trade and Industry (METI), is responsible for siting and building a geological repository for radioactive waste.[115]

To be able to change Japan's dysfunctional reprocessing policy, the central government will most likely have to establish one central organization responsible for interim storage and disposal of spent fuel and reprocessing waste. This was a critical part of the processes of abandoning reprocessing in both the UK and United States.

***United Kingdom.*** British Nuclear Fuel Services Limited (BNFL), a UK government-owned company was established in 1971, after the UK's production of plutonium for weapons ended, to manage the UK's reprocessing facilities. By mid-1975, BNFL had decided to build the Thermal Oxide Reprocessing Plant (THORP) and, even before receiving permission from the government, had negotiated contracts with utilities in Japan, Germany, Switzerland, Sweden and Spain to reprocess their spent light-water-reactor fuel.[116]

Thirty years later, in 2005, in the absence of a renewal of any of the foreign reprocessing contracts and facing rising operating losses, the UK Government decided to establish a Nuclear Decommissioning Authority (NDA) to take over BNFL's sites and the responsibilities for spent fuel from the UK's first and second generation gas-cooled power reactors and for establishing a geological repository for the UK's radioactive waste and spent fuel.

In 2012, the NDA decided on economic grounds to phase out reprocessing in favor of interim storage and direct disposal of spent fuel.[117]

***United States.***[118] Until 1977, civilian reprocessing was expected to be a profitable business for private companies in the U.S. and three companies built or launched on the construction of reprocessing plants:

- Nuclear Fuel Services operated a small reprocessing plant in New York State from 1966-72 before it abandoned the project in the face of rising costs due to stricter worker radiation exposure protection requirements;

- General Electric began in 1967 to construct a plant in Illinois but discovered in 1972 that the design was fundamentally flawed and abandoned the project except for converting the plant's intake pool into an away-from-reactor spent-fuel storage pool; and
- Allied General Fuel Services began in 1970 constructing a reprocessing plant in South Carolina. In 1977, however, after India's 1974 test of a "peaceful nuclear explosive" made with plutonium separated ostensibly for India's breeder program, President Carter suspended the licensing process out of concern that U.S. reprocessing would help legitimize the construction of reprocessing plants in additional countries.

In 1981, President Reagan announced that his Administration was willing to resume the licensing of private reprocessing plants in the U.S. By that time, however, U.S. nuclear utilities had concluded that plutonium recycle was not economically justified and indicated that they would prefer that the federal government take responsibility for disposal of their spent fuel. Congress passed the Nuclear Waste Policy Act (NWPA) the following year giving the Department of Energy responsibility for spent fuel disposal in exchange for a fee of $0.001 per nuclear kilowatt hour – about one tenth the cost estimated by the JAEC for the extra cost of reprocessing in Japan. [119]

In the wake of the political failure of the proposed geological repository under Yucca Mountain, Nevada, Congress is now considering revising the NWPA to give the responsibility for siting and constructing a geological repository – and possibly central spent fuel storage facilities as well – to a new specialized government agency.[120]

## Alternatives to MOX for disposal of Japan's already separated plutonium

If Japan abandons reprocessing, it still will have to dispose of its 44 tons of separated plutonium stored in France, the UK and Japan (Table 3).

***In France.*** Japan had approximately 18 tons of plutonium in France as of the end of 2012. The understanding of Japan's utilities with France's AREVA is that this plutonium is to be made into MOX fuel in France and shipped to Japan as soon as it can be used. Even before the accident at the Fukushima Daiichi nuclear power plant, however, there was strong public resistance to the use of MOX in Japan's reactors. Of the MOX fuel France has shipped to Japan since 1999, only fuel containing 2.5 tons of plutonium had been loaded as of the time of the accident. In the post-Fukushima environment, the resistance to MOX is likely to be at least as great.

One obvious question is whether France could make Japan's plutonium in France into MOX for its own reactors. The UK has offered to do this for Japanese plutonium in the UK (see below) even though the UK, unlike France, does not have an operating MOX plant and has only one light water reactor. France has not offered to use Japan's plutonium, however.

One reason could be that France has been falling behind in recycling its own separated plutonium. France's first declaration of its stock of separated civilian plutonium as of the end of 1995 was 30 tons. As of the end of 2012, the stock had risen to 58 tons.[121]

Also, the twenty-four 900-MWe reactors that are licensed to use MOX fuel are France's oldest; all came into operation between 1977 and 1987.[122] In the wake of the Fukushima accident, the Hollande Administration has committed that France will reduce the nuclear share of its electric power generation from 75 to 50 percent by 2025.[123]

Assuming that France's electric power consumption does not grow significantly and that the oldest reactors are retired first, this would require the retirement of most of the 900-MWe reactors by 2025. The Hollande Administration already has decided to shut down France's two oldest 900-MWe reactors, at the Fessenheim nuclear power plant in 2016, the year they reach age 40.[124] France's National Radioactive Waste Management Agency has raised the possibility that AREVA's reprocessing program may have to end before 2020.[125]

If Japan cannot use the MOX from France in its reactors, it could treat the MOX fuel as a disposal form and store and dispose of it with Japan's spent fuel.[126] If this decision were made in advance of fuel fabrication, the very precise dimensional specifications to which the pellets must be ground for MOX fuel could be relaxed. This would reduce both France's production costs and the fraction of MOX pellets that are rejected at France's Melox MOX fuel fabrication facility because they do not meet specifications.[127]

| **Japan's unirradiated plutonium** (end of 2012) | **Tons** |
|---|---|
| In the United Kingdom | 17.1 |
| In France | 17.9 |
| *Subtotal in Europe* | *35.0* |
| In Japan | |
| At Rokkasho in solution or oxide form | 3.6 |
| At Tokai reprocessing facility in solution or oxide form | 0.8 |
| In fabrication and in fuel product at Tokai fuel fabrication facility and in unirradiated fabricated fuel stored at the *Joyo, Monju* and *Fast Critical Assembly facilities* | 4.0 |
| In unirradiated MOX fuel from France | 1.0 |
| *Subtotal in Japan* | *9.3* |
| **Total** | **44.2** |

**Table 3**. Japan's unirradiated plutonium as of the end 2012.[128] Numbers do not add exactly because of rounding. Of the plutonium in France at the end of 2012, 0.9 tons was shipped to Japan in MOX during 2013 and 0.65 tons were relabeled as German in exchange for 0.65 tons of German plutonium in the UK being relabeled as Japanese.[129]

***In the United Kingdom.*** Seventeen tons of Japan's separated plutonium were stored at the UK's Sellafield reprocessing site as of the end of 2012. The UK had contracted to convert this plutonium into MOX fuel for use in Japan's nuclear power plants. Following the failure of the Sellafield MOX Plant and the UK government's abandonment of it in 2011, however, the UK offered to take ownership and dispose of Japan's plutonium "subject to commercial terms that are acceptable to UK Government."[130]

The preference of the UK's Department of Energy and Climate Change (DECC) is to build another MOX plant and dispose of the UK's own 100 tons of separated plutonium in light water reactor MOX fuel. DECC hopes that Japan's nuclear utilities will help pay for the construction of a new MOX plant – just as they helped pay for the construction of the THORP reprocessing plant and the failed Sellafield MOX plant. This plan cannot be implemented, however, before it is clear that enough light water reactor capacity will be built in the UK to use the MOX fuel and that reactor owners are willing to do so.[131]

There are alternatives to MOX, however. Indeed, the UK National Nuclear Laboratory is setting up a production line at the Sellafield reprocessing site to immobilize for direct disposal 50 to 250 kg of plutonium that is chemically contaminated and considered unsuitable for MOX without costly cleanup.[132] Japan could pay to have its plutonium in the UK immobilized in this way. The immobilized plutonium then would have to be securely stored until disposal.

The immobilization form (Figure 9) is a mix of low-leach zirconolite and pyrochlore ceramic forms, either monolithic or dispersed in glass, depending upon the percentage of plutonium in the waste. It is created by Hot (1,100-1,320 $^{o}$C) Isostatic Pressing (HIP) at 1,000 atmospheres for 8-9 hours.[133] DECC considered immobilization for disposal of all of the UK's separated plutonium but arrived at a preliminary conclusion that the technology is less "mature" than MOX.[134] In fact, HIP technology is mature and in widespread use for the production of low-porosity metals and ceramics, including in Japan.[135]

One option for disposal could be with spent fuel in casks, which, with the end of reprocessing, would be disposed of directly in a geological repository. Another option could be disposal in 3 to 5 km deep boreholes, an option that is currently being explored in the U.S. for spent fuel (Figure 10).[136]

**Figure 9.** Hot isostatic pressing (HIP) for immobilization of impure plutonium in the UK**.** The container at the left is filled with powdered material. For plutonium disposal, it would be a mixture of plutonium, calcium, zirconium and titanium oxides. On the right, after 8 to 9 hours of hot isostatic pressing, the powder has been turned into 5 liters of solid ceramic. *Source*: UK National Nuclear Laboratory.[137]

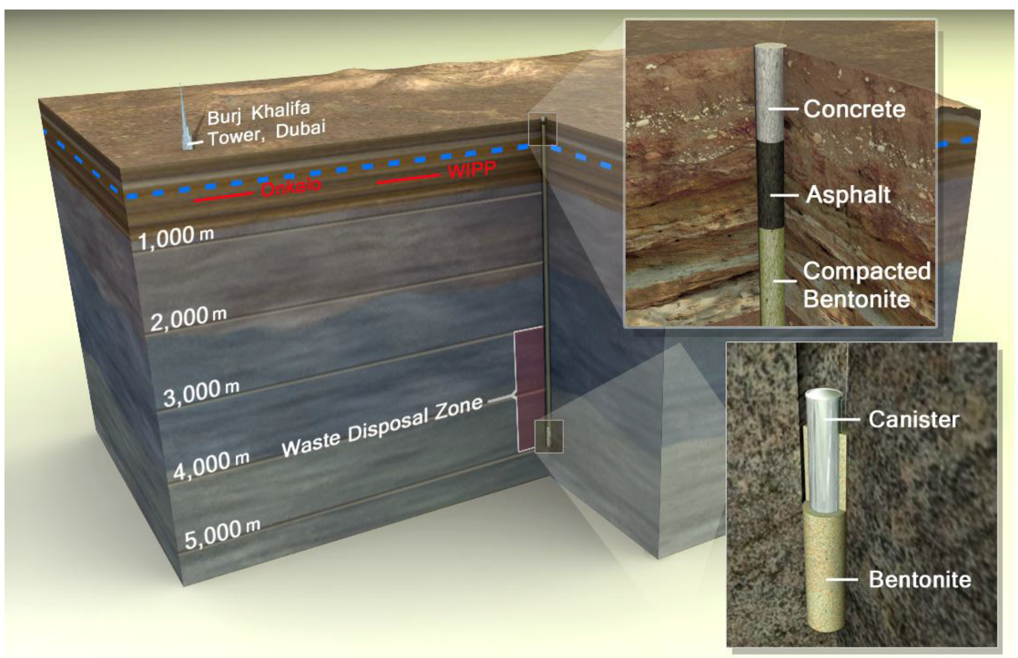


**Figure 10.** Deep borehole concept for the disposal of radioactive waste in crystalline basement rock. Shown are the depths of the U.S. Waste Isolation Pilot Plant for plutonium waste and Finland's Onkalo spent fuel repository, which is under construction. The dashed blue line indicates the approximate boundary between shallow fresh water resources and deeper dense saline water. *Source*: Sandia National Laboratory [138]

***In Japan.*** If Japan decides not to operate the RRP, it would not make sense to complete the J-MOX plant at Rokkasho because Japan has relatively little unfabricated plutonium in country. One option for the plutonium in liquid and powder form could be to immobilize it for direct disposal using the same HIP method that is being used for residue disposal in the UK. The plutonium in Japan that is already in MOX form could be treated as a direct disposal form as discussed above.

Japan and the UK are not the only countries facing challenges in disposing of their plutonium. In 2000, the U.S. and Russia agreed that each would dispose of 34 tons of weapon-grade plutonium. Russia insisted that most U.S. plutonium be disposed in MOX because irradiation in a reactor would change its isotopics from weapon-grade, making it unsuitable for existing weapon designs. AREVA designed and has been building for the U.S. Department of Energy a MOX plant with a smaller capacity than its own Melox MOX plant but the project cost has grown extraordinarily. In 1996, the total projected cost for fabricating 34 tons of excess weapons plutonium into MOX was estimated as $1.4 billion and the value of the fuel to be produced at $1.3 billion (all 2012$).[139] By May 2013, however, the estimated cost had risen to $18 billion.[140] The value of the MOX fuel had not increased.

In April 2013, the Obama Administration announced that the U.S. MOX project "may be unaffordable…due to cost growth and fiscal pressure" and that the administration would "assess the feasibility of alternative plutonium disposition strategies."[141] Japan may therefore find a willing partner in the United States in examining alternative approaches to plutonium disposal.[142]

# Endnotes

[1] Cost from JNFL, Oct. 2012, http://www.jnfl.co.jp/jnfl/establishment.html (in Japanese).

[2] George Perkovich, *India's Nuclear Bomb: The Impact on Global Proliferation* (University of California Press, 1999).

[3] See e.g. Jonathan Pollack and Mitchell Reiss, "South Korea: The tyranny of geography and the vexations of history," in *The Nuclear Tipping Point: Why States Reconsider their Nuclear Choices,* Kurt Campbell, Robert Einhorn and Mitchell Reiss, eds. (Brookings, 2004).

[4] Frank von Hippel, "South Korean Reprocessing: An Unnecessary Threat to the Nonproliferation Regime," *Arms Control Today,* March 2010, p. 22.

[5] "2/3 of S. Koreans Support Nuclear Armament," *Chosun Ilbo*, 21 Feb. 2013.

[6] Dan Horner, "U.S., S. Korea Find 2-Year Fix for Pact," *Arms Control Today,* May 2013.

[7] Terence Creamer, "SA still weighing nuclear-fuel recycling options," *Engineering News,* 28 May 2009; and Dan Yurman, "South Africa tries again to expand its nuclear program", American Nuclear Society Nuclear Cafe (blog), 7 June 2012.

[8] Bruno Lescoeur, then Senior Executive Vice President, International Industrial and Public Affairs, Électricité de France (EDF) confirmed publicly, in response to a question from Mycle Schneider during a conference at Science Po University in Paris on 6 May 2008, that a Netherlands utility paid EDF to take title to plutonium separated in France from the reprocessing of Dutch spent fuel.

[9] JAEC, "Estimation of Nuclear Fuel Cycle Cost and Accident Risk Cost (Statement)", 10 Nov. 2011.

[10] In 2012, the UK decided to abandon reprocessing when existing contracts had been fulfilled (circa. 2018). China, India and Russia reprocess in connection with continuing R&D on plutonium breeder reactor programs. The Netherlands continues to send the spent fuel from its Borssele reactor to France to be reprocessed and the Ukraine continues to send the spent fuel from its two oldest reactors to Russia to be reprocessed.

[11] Masafumi Takubo, "Wake Up, Stop Dreaming: Reassessing Japan's Reprocessing Program," *Nonproliferation Review*, Vol. 15, No. 1, March 2008.

[12] http://law.e-gov.go.jp/htmldata/S32/S32HO166.html.

[13] About two tons were returned from Europe to Japan prior to 1993 and in a shipment that arrived from France on 5 Jan. 1993. This material was used for R&D, Government reply dated 1 Oct. 1993 to a question raised by Diet member Tadatoshi Akiba,
http://www.shugiin.go.jp/itdb_shitsumona.nsf/html/shitsumon/b127003.htm.

[14] Figures as of the end of 2012, "The Current Situation of Plutonium Management in Japan," Japan Atomic Energy Commission, 11 Sept. 2013.

[15] Separated plutonium quantity from David Albright, Frans Berkhout and William Walker, *Plutonium and Highly Enriched Uranium 1996* (Oxford University Press, 1997, Table 7.9.

[16] *Fast Breeder Reactor Programs: History and Status* (International Panel on Fissile Materials [IPFM], 2010), p. 87.

[17] William Walker, *Nuclear Entrapment: THORP and the politics of commitment* (Institute for Public Policy Research, 1999), pp. 113-114.

[18] IAEA, "Communication Received from the United Kingdom of Great Britain and Northern Ireland Concerning its Policies Regarding the Management of Plutonium," NFCIRC/549/Add.8/16, 18 July 2013; and JAEC "The Current Situation of Plutonium Management in Japan," 11 Sept. 2013.

[19] UK Nuclear Decommissioning Authority, *Oxide Fuels: Preferred Option* (2012).

[20] *Fast breeder reactor programs: History and Status* (IPFM, 2010), p. 56.

[21] http://www.sellafieldsites.com/solution/spent-fuel-management.

[22] http://www.magnoxsites.co.uk/remit.

[23] Phil Chaffee, "Is France to Blame for CNNC's Back-End Problems?" *Nuclear Intelligence Weekly,* 19 Dec. 2011; "AREVA signs a series of strategic agreements with its Chinese partners," AREVA press release, April 25, 2013.

[24] See e.g., "Areva sees nuclear waste recycling planning [in the U.S.] by 2015," Reuters, 6 June 2011.

[25] Converted to 2012 dollars, International Energy Agency, online RD&D Database.

[26] The *Joyo* Experimental Fast Reactor (140 MWt) located in Oarai, near Tokai, began operations in 1978 but has been shut down since 2007 by a refueling accident, Tomonori Soga, JAEA, "Improvement of Irradiation Capability in the Experimental Fast Reactor Joyo," IAEA Technical Meeting, 2008.

[27] Hideki Muroya, "Monju reactor faces long-term suspension over lax safety system," *Asahi Shimbun,* May 13, 2013, http://ajw.asahi.com/article/behind_news/social_affairs/AJ201305130090.

[28] Federation of Electric Power Companies of Japan, "Plans for the Utilization of Plutonium to be Recovered at the Rokkasho Reprocessing Plan," 15 March 2010.

[29] NDA [UK Nuclear Decommissioning Authority], "Statement on future of the Sellafield MOX Plant," 3 August 2011.

[30] Data as of the end of 2012 from Japan Atomic Energy Commission, "The Current Situation of Plutonium Management in Japan," 11 Sept. 2013.

[31] Eight kilograms is a "significant quantity" of plutonium, described by the IAEA as "the approximate amount of nuclear material for which the possibility of manufacturing a nuclear explosive device cannot be excluded." *IAEA Safeguards Glossary 2001*, p. 23. A Nagasaki-type design with reactor-grade plutonium would be expected to yield an explosion considerably less powerful than the Nagasaki weapon but still equivalent to at least one thousand tons (one kiloton) of chemical explosives, J. Carson Mark, "Explosive Properties of Reactor-Grade Plutonium," *Science & Global Security*, Vol. 4(1) 1993.

[32] JNFL President's press conference statement on 31 July 2013.http://www.asahi-net.or.jp/~pn8r-fjsk/saiakusinario.pdf; and Jin Nishikawa, "Nuclear watchdog tightening safety regulations on fuel processing plants," *Asahi Shimbun,* 3 July 2013.

[33] Japan Nuclear Fuel Limited, reprocessing plan for FY2013 through FY2015, 31 Jan. 2013, http://www.jnfl.co.jp/press/pressj2012/20130131tenpu.pdf.

[34] cgi.daily-tohoku.co.jp/cgi-bin/tiiki_tokuho/kakunen/news/news2013/kn131102a.htm (in Japanese).

[35] These numbers in JNFL's plan are the amount of plutonium in the mixed-oxide product (50% plutonium oxide, 50% uranium oxide) produced in each period.

[36] METI and the nuclear utilities often assume that one percent of the heavy metal (uranium) of the original uranium fuel turns into plutonium in spent fuel (See e.g. http://www1.kepco.co.jp/plu/5.html). This corresponds roughly to spent fuel with a burn-up of 45 MWt-days/kg and cooling period of four years. However, 3.6 tons of plutonium were recovered from 425 tons of spent fuel reprocessed during the 2006-8 test operation of the RRP for a plutonium recovery of 0.85 percent. This suggests a burnup lower than 35 MWt-days/kg and the decay of a large portion of the 14-year half-life Pu-241 it originally contained. According to the summary provided in page 34 of the JNFL's report on active testing dated 28 Jun 2010, the spent fuel used in the testing had burn-up of 12-47 MWt-days/kg and cooling period of 8-20 years, http://www.jnfl.co.jp/press/pressj2010/100628houkoku.pdf. For a more accurate calculation of future plutonium recovery, it will be necessary for METI and the nuclear utilities to disclose the burn-up and cooling period of the spent fuel expected to be reprocessed annually.

[37] "[A] potential proliferating state or subnational group using designs and technologies no more sophisticated than those used in first-generation nuclear weapons, could build a nuclear weapon from reactor-grade plutonium that would have an assured reliable yield of one to a few kilotons (and probable yield significantly higher than that). At the other end of the spectrum, advanced nuclear weapon states such as the United States and Russia, using modern designs, could produce weapons from reactor-grade plutonium having explosive yields, weight, and other characteristics generally comparable to those of weapons made from weapon-grade plutonium." *U.S. Department of Energy, Nonproliferation and Arms Control Assessment of Weapons-Usable Fissile Material Storage and Excess Plutonium Disposition Alternatives*, DOE/NN-0007, January 1997, p. 39, http://www.osti.gov/bridge/product.biblio.jsp?osti_id=425259.

[38] President Obama, Speech at Hankuk University of Foreign Studies in Seoul, 26 March 2012.

[39] Vice Chairman of JAEC Tatujiro Suzuki's written report on his trip to the United States (April 7-12) presented at a JAEC meeting on April 22, 2013, rough translation from the Japanese, http://www.aec.go.jp/jicst/NC/iinkai/teirei/siryo2013/siryo14/siryo2.pdf.

[40] Masakatsu Ota, "Excessive Plutonium Problem; No. I Priority for Japan after 3/11," Gaiko (Diplomacy), Vol 18, 13 March 2013.

[41] "Japan made secret promise with U.S. to restart plu-thermal nuclear program," *The Mainichi,* 25 June 2013.

[42] The collective inhalation of one gram of plutonium oxide aerosol by a large urban population could result in 3,000-11,000 extra cancer deaths, Steve Fetter and Frank von Hippel, "The Hazard from Plutonium Dispersal by Nuclear-warhead Accidents," *Science & Global Security*, Volume 2 (1990).

[43] JAEC, *Framework for Nuclear Energy Policy* (translation by JAEC) 11 Oct. 2005, p. 33, http://www.aec.go.jp/jicst/NC/tyoki/taikou/kettei/eng_ver.pdf.

[44] The Mayor of Mutsu, in solidarity with the neighboring communities, officially has been maintaining the same stance as the governor of Aomori Prefecture. In an interview with one of us (Takubo) and Tadahiro Katsuta on 23 Dec. 2011, however, he stated that the fate of the spent fuel to be stored at the Mutsu Storage Facility should be decided by future generations.

[45] http://www.enecho.meti.go.jp/info/committee/kihonseisaku/7th/7th-1.pdf (in Japanese), p. 50. Available capacity is the storage capacity minus 1 full core and 1 reload as of the end of March 2013. Data from METI's Agency for Natural Resources and Energy. The figures for Tokai Daini include the dry-cask storage there.

[46] Average burnup calculated using the energy availability factor of 0.669 of 2010 from the IAEA's database, http://www.iaea.org/PRIS/WorldStatistics/ThreeYrsEnergyAvailabilityFactor.aspx, and an average ratio of heat to net electricity of 3.1 for the reactors in Table 1, also from the IAEA's database, http://www.iaea.org/PRIS/CountryStatistics/CountryDetails.aspx?current=JP. The METI data shows 1080 tons of spent fuel discharged per 16-month refueling cycle. So (38.11 GWe)x(3.1 Gwt/GWe)x0.669x(365 days/yr)/[(0.75 refueling cycle per yr)x(1080 tons per refueling cycle)] = 35.6 GWt-days/ton.

[47] http://www.nsr.go.jp/archive/nisa/koho/symposium/files/shimane/program01.pdf. This METI document, written in response to questions from Shimane Prefecture, states that reprocessing of 1,000 kg of spent fuel could result in 130 kg MOX fuel containing about 10 kg of plutonium and 130 kg of fuel made from recovered uranium. In France, which has been reprocessing and recycling plutonium since 1987, the estimated savings from plutonium and uranium recycle in 2010 were 8 percent, projected to rise to 16% in 2020, *Managing Spent Fuel from Nuclear Power Reactors: Experience and Lessons from Around the World* (IPFM, 2011) Table 3.2

[48] In 2012, the average price of natural uranium purchased by U.S. nuclear utilities was about $145/kg and the average cost of a separative work unit (SWU) of enrichment was about $141, US Energy Information Administration, *2012 Uranium Marketing Annual Report*. At these prices, low enriched uranium is produced at the lowest cost when the depleted uranium contains 0.227 percent U-235 (down from the 0.72 percent U-235 in natural uranium). If the amount of U-235 in the depleted uranium were reduced to 0.07

percent, however, the amount of natural uranium required would be reduced by 21 percent and the cost of nuclear fuel would increase by ¥0.1/kWh, which is about one tenth the amount by which the JAEC estimates that reprocessing and plutonium recycle will increase the cost of nuclear power in Japan, "Estimation of Nuclear Fuel Cycle Cost and Accident Risk Cost (Statement)", 10 Nov. 2011.

[49] http://www.enecho.meti.go.jp/info/committee/kihonmondai/33th/33-4.pdf.

[50] Mycle Schneider and Yves Marignac, *Spent fuel reprocessing in France* (IPFM, 2008).

[51] 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.

[52] *Plutonium Fuel* (OECD Nuclear Energy Agency, 1989).

[53] See e.g., Eugene Shwageraus *et al*, "A Combined Nonfertile and $UO_2$ PWR Fuel Assembly for Actinide Waste Minimization," *Nuclear Technology* Vol. 149, March 2005, p. 281.

[54] *Nuclear Wastes: Technologies for Separations and Transmutation* (National Academy Press, 1996), p. 3. In the case of plutonium and the other transuranics, "transmutation" means fission. In the case of long-lived fission products, it means conversion into a shorter-lived or stable isotope.

[55] *Fast breeder reactor programs: History and Status* (International Panel on Fissile Materials, 2010).

[56] T. Aida, et al, TEPCO, "Operating Experience in Spent Fuel Storage Casks," *International Conference on Management of Spent Fuel from Nuclear Power Reactors*, Vienna, 31 May – 4 June 2010, http://www-ns.iaea.org/meetings/rw-summaries/vienna-2010-mngement-spent-fuel.asp, session 10b, Japan 1.

[57] http://www.nrc.gov/waste/spent-fuel-storage/dry-cask-storage.html.

[58] http://www.jnes.go.jp/content/000005899.pdf and http://www.jnes.go.jp/content/000119311.pdf. Additional information may be found in the national reports to the review conferences of the Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management, http://www-ns.iaea.org/conventions/results-meetings.asp?s=6&l=40, and in presentations made at the International Conference on Management of Spent Fuel from Nuclear Power Reactors, 2010, Vienna, http://www-ns.iaea.org/meetings/rw-summaries/vienna-2010-mngement-spent-fuel.asp.

[59] http://photo.tepco.co.jp/library/110909_2/110909_69.jpg.

[60] In most cases license applications for these on-site dry-cask storage facilities in Germany were made by 2000 after the 1998 emergence of the Green-Red government.

[61] Bundesamt fur Strahlnshutz, Desentrale Zwishenlager, 2008 (p.31), http://www.bfs.de/en/bfs/publikationen/broschueren/transport_lagerung/dezentr_zwischenlager.pdf and Dr. Werner Mester, Gesellschaft für Anlagen und Reaktorsicherheit (GRS) mbH, personal communication, 1 Feb. 2013.

[62] *Report of the Federal Republic of Germany for the Fourth Review Meeting of the Joint Convention of the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management,* May 2012, Tables D-1 and L-4.

[63] JNES Report, *op. cit.* p. 3-21.

[64] The initial 50 casks will consist of 20 storage casks (the existing nine plus eleven that were ordered for the existing facility before the accident) and 30 dual capable (i.e. storage/transport) casks that were originally meant for the Mutsu facility, http://www.tepco.co.jp/cc/press/betu12_j/images/121225j0201.pdf and industry sources.

[65] http://www.tepco.co.jp/nu/fukushima-np/roadmap/images/d130926_05-j.pdf.

[66] http://www.tepco.co.jp/nu/fukushima-np/handouts/2013/images/handouts_130404_02-j.pdf (in Japanese).

[67] The forging of cask bodies in Japan is done at Kobe Steel and Japan Steel Works. It takes 18 to 24 months to deliver the first cask of a new order of an existing licensed design. For a new cask design, it would take about two years to prepare the licensing documents and, under ordinary circumstances, another

two years for the design to be reviewed by the licensing authorities. It is expected that design standards for less costly thin steel canisters surrounded by reinforced concrete radiation shields, such as are used for storage in the U.S., will be finalized in a few years.

[68] "Table-Japan nuclear ops (zero reactors online out of total 50)," Reuters, 7 May 2012. Two of the reactors, Ohi 3 and Ohi 4, were permitted to restart in July 2012 by Fukui Prefecture and the town of Ohi because of a special plea by the Noda administration, which was concerned about summer blackouts in the Kansai area, including Osaka and Kyoto. After 13 months of operation, however, those reactors were shut down again in September 2013 for periodic inspection. To restart any power reactor in Japan will first require clearance from the Nuclear Regulation Authority (NRA) under its new safety regulations of July 2013. Even after the NRA approves applications for restart, however, the consent of prefectural and local governments still will be required.

[69] As of 2010, Fukushima Daiichi had 9 casks with a permit to install a total of 20, "Interface Issues Arising Between Storage and Transport for Storage Facilities Using Storage/Transport Dual Purpose Dry Metal Casks". Seventeen casks were installed at Tokai Daini, two of which were empty as of the end of 2010, with a permit to install a total of 24, "Inspection of Fuel Cladding and Metal Gasket in Metallic Dry Cask at Tokai Daini Power Station," International Conference on Management of Spent Fuel from Nuclear Power Reactors, 2010, Vienna, http://www-ns.iaea.org/meetings/rw-summaries/vienna-2010-mngement-spent-fuel.asp.

[70] "Further developments re spent-fuel storage facility," Citizens Nuclear Information Center, *News Watch 101,* July/August 2004, http://www.cnic.jp/english/newsletter/nit101/nit101articles/nw101.html.

[71] http://www.at-s.com/news/detail/828835187.html; http://www.at-s.com/news/detail/474572128.html (in Japanese).

[72] National Citizen Ombudsman Association, http://www.ombudsman.jp/nuclear/yugami.pdf.

[73] http://www.nsr.go.jp/kaiken/data/20120919sokkiroku.pdf.

[74] "Government envisioned Tokyo evacuation in worst-case scenario," *Asahi Shimbun,* 7 January 2012. The document mentioned in the article, "Fukushima Daiichi Genshiryoku Hatsudensho no Fusoku Jitai Shinario no Sobyo (sketch of an unexpected contingency at Fukushima Daiichi) by JAEC's Chairman Shunichi Kondo is posted at http://www.asahi-net.or.jp/~pn8r-fjsk/saiakusinario.pdf (in Japanese).

[75] *Estimation of Radioactive Material Released to the Atmosphere during the Fukushima Daiichi NPS Accident* (TEPCO, 2012).

[76] The inventory of irradiated fuel in pool #4 was the 548 fuel assemblies of the full core discharged to allow the periodic inspection that started on Nov. 30 2010 and 783 assemblies discharged in earlier refuelings. The remainder of the fuel in the pool was fresh fuel. We assume that each fuel assembly contains 170 kg LEU. This means a total of about 100 tons in the full core discharge and 140 tons of older spent fuel. We assume that the average burnup of the full core was 20 MWt-days/kg and that of the spent fuel was 40 MWt-days/kg. Cesium-137 is produced at a rate of about 3 Ci/MWt-day. So about 20 MCi of Cs-137 was in the pool. We assume for a worst-case spent fuel fire that essentially all of this Cs-137 would be released to the atmosphere. We did a simple "wedge model" calculation as described at the bottom of p. 7 of Robert Alvarez et al, "Reducing the Hazards from Stored Spent Power-Reactor Fuel in the United States," *Science and Global Security*, Vol. 11 (2003) pp. 1–51. Then, if the wind blew so that the cesium-137 was dispersed in all directions equally, the deposition density in Ci/km$^2$ would be (6000/r)exp(-r/500), where r is measured in km. This gives 15 Ci/km$^2$ or 555 kBq/m$^2$ at 250 km.

[77] U.S. power reactors discharge about 2,000 tons of spent fuel each year. Almost all are full today and, together, their pools contain about 50,000 tons of spent fuel, *Accumulating Quantities at Commercial Reactors Present Storage and Other Challenges* (U.S. General Accounting Office, 2012), Figure 7.

[78] John E. Kelly, Deputy Assistant Secretary for Nuclear Reactor Technologies, **"**DOE Response to Fukushima Dai-ichi Accident," 15 June 2011, slide 17.

[79] Allan Benjamin, *et al, Spent Fuel Heat-up Following Loss Of Water During Storage* (Sandia National Laboratory, NUREG/CR-0649, 1979), Figure 2.

[80] Robert Alvarez et al, "Reducing the Hazards from Stored Spent Power-Reactor Fuel in the United States," *Science and Global Security,* Vol. 11, 2003*,* p. 1. For another review of the issue see *Safety and Security of Commercial Spent Nuclear Fuel Storage* (U.S. National Academy Press, 2005).

[81] A CASTOR V/21 cast-iron cask for 21 PWR fuel assemblies (about 10 tons of spent fuel) is 4.9 meters high and 2.4 meters in diameter, W. C. Bare and L. D. Torgerson, *Dry Cask Storage Characterization Project- Phase l: CASTOR V/21 Cask Opening And Examination* (Idaho National Laboratory, INEEL/EXT-01-00183, 2001). It therefore has a surface area excluding its base of 40 $m^2$. A heat dissipation rate of 30 kWt from an area of 40 $m^2$ would be 0.75 kWt/$m^2$. "V", the Latin numeral 5 in the name of the cask, indicates that it is designed to hold spent fuel 5 years or more after discharge.

[82] Dry casks have even been designed to store spent fuel only one year after discharge but only about two tons vs. the 10-15 tons of older spent fuel that are typically stored in dry casks. The German CASTOR Ic was designed to hold 16 BWR fuel assemblies (about 3 tons) and was tested for fuel aged 1.2 years, *CASTOR-1C Spent Fuel Storage Cask Decay Heat, Heat Transfer and Shielding Analyses* (Pacific Northwest Laboratory, PNL-5974, 1986), http://www.osti.gov/bridge/servlets/purl/7174903/7174903.pdf.

[83] "Reducing the Hazards from Stored Spent Power-Reactor Fuel in the United States," *op. cit.* The fuel is assumed to have operated at a power level of 37.5 MWt/tU in the reactor.

[84] Ernst Albrecht, Minister-President of Lower Saxony, "Declaration of the state government of Lower Saxony concerning the proposed nuclear fuel center at Gorleben" (English translation), May 1979.

[85] Klaus Janberg and Frank von Hippel, "Dry Cask Spent Fuel Storage, How Germany Led the Way," *Bulletin of the Atomic Scientists,* Sept/Oct. 2009.

[86] Assuming that, if Japan's at-reactor pools were converted from dense-rack to open-rack storage, they could store about 20 percent of their current design capacity of about 17,000 tons (see Table 2). That would require the removal of about 8,000 of the approximately 11,000 tons of spent fuel currently stored in the pools.

[87] *Report of the Federal Republic of Germany for the Fourth Review Meeting of the Joint Convention of the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management,* May 2012, Table D-1.

[88] In November 1994, the Director General of the Science and Technology Agency promised Aomori Prefecture that it would not be a final disposal site. In December 1994, JNFL signed an agreement with the prefecture and Rokkasho Village, with the Federation of Electric Power Companies (FEPC) as a witness. According to that agreement, high-level waste from the reprocessing of Japanese spent fuel in Europe would remain in the Vitrified Waste Storage Center at the Rokkasho complex for no more than 50 years. The first shipment of high-level waste from Europe arrived off the coast of Rokkasho on 25 April 1995. The then Governor Morio Kimura refused the entry of the ship into the Mutsu-ogawara port and asked for a further confirmation from the central government that Aomori Prefecture would not be a site for the final disposal. (The Governor has jurisdiction over the use of ports in the prefecture.) With the central government's assurance, the ship was allowed to dock and the high-level waste was transported to the Vitrified Waste Storage Center. Adding 50 years to this date means that an interim storage facility or a geological repository will have to become available in another prefecture by April 2045.

[89] "Principles for Safeguarding Waste at Nuclear Reactors," 24 March 2010, http://www.psr.org/nuclear-bailout/resources/principles-for-safeguarding.html.

[90] Asked about once-through idea at the 2 Nov. 2010 JAEC meeting considering the need to develop a new Framework for Nuclear Energy Policy, Aomori Prefecture Governor Shingo Mimura said that, if a "once-through" (no recycling) fuel cycle were adopted "what we are storing should naturally be immediately be taken back. This is a promise." In September 2011, he became a member of the JAEC council on a new Framework for Nuclear Energy Policy (Dec. 2010 – March 2012). In various meetings of the council, the Governor stressed that a policy of reprocessing all spent fuel was the precondition for the prefecture's acceptance of high-level radioactive waste and spent fuel at the Rokkasho complex and to construction of the interim storage facility spent fuel at Mutsu City. At the 22 Dec 2011 meeting he said, "Just in case, let me say that, in the case where the spent fuel is not reused as resources, we might return it to its origin." At

the 23 May 2012 meeting, commenting on a JAEC document that mentioned the risk of Aomori demanding return of the spent fuel in the RRP intake pool back to the nuclear power plants and refusal of accepting any more high level waste from Europe, he said: "I would like you to understand that these are not just the things that might happen but are the promises that should be surely implemented with a change of the national policy" Minutes of the meetings of the new Framework for Nuclear Energy Policy, http://www.aec.go.jp/jicst/NC/tyoki/tyoki_sakutei.htm.

The possibility that spent fuel could be returned to the nuclear power plants is in the 29 July 1998 agreement between the prefecture, Rokkasho village, and JNFL, with the Federation of Electric Power Companies (FEPC) as a witness. The agreement states: "In the case where it is extremely difficult to ensure the execution of reprocessing, upon consultation between Aomori Prefecture, Rokkasho village, and JNFL, JNFL shall promptly take necessary and appropriate measures including the removal of the spent nuclear fuel from the site." Although the agreement does not refer to an automatic return of spent fuel to the original sites, reprocessing proponents use it as an argument that there is no alternative to operating the Rokkasho plant as soon as possible. The government of Aomori Prefecture cites the agreement from time to time when it demands, as at a Framework planning meeting held on 24 September 2004, that all arrangements for the nuclear fuel cycle proceed smoothly, www.aec.go.jp/jicst/NC/tyoki/sakutei2004/sakutei10/siryo5.pdf.

[91] Out of 608,000 worker-days (2400 worker years, assuming 250 days worked per year) spent on construction work at the complex in FY 2011, 85% were by local Aomori Prefecture workers. Out of 66,000 worker years from FY 1985 through 2011 (2500 per year on average), 62% were for local workers. Out of the total of ¥3.55 trillion construction related orders in the same period, 18% were for local companies, http://www.pref.aomori.lg.jp/soshiki/energy/g-richi/files/2013_yutaka.pdf.

[92] "Aomori Prefecture rejects nuclear waste, eyes continued reprocessing," *Mainichi Shimbun,* 14 Sept. 2012 http://mainichi.jp/opinion/news/20120913ddm003010154000c.html (in Japanese).

[93] http://cgi.daily-tohoku.co.jp/cgi-bin/tiiki_tokuho/kakunen/kikaku/tenki/money_02.htm and http://www.pref.aomori.lg.jp/soshiki/soumu/zaisei/files/zaiseijijou_201206_all.pdf.

[94] National Citizen Ombudsman Association, http://www.ombudsman.jp/nuclear/yugami.pdf

[95] The present system, approved by the central government on 9 March 2012, has seven categories for the nuclear fuel taxes, http://www.soumu.go.jp/main_content/000150052.pdf

[96] http://cgi.daily-tohoku.co.jp/cgi-bin/tiiki_tokuho/kakunen/kikaku/tenki/money_02.htm. Aomori followed the example of Fukui Prefecture, which was the first one to introduce the fuel tax system in 1976. In addition, Aomori Prefecture instituted a new annual tax of about ¥0.9 billion on the output capacity of the Higashidori nuclear power plant, which is charged whether or not the plant is operating. Ishikawa and Kagoshima prefectures also introduced this method of taxing reactors not in operation. Other prefectures are expected to follow. For the taxes in each of the 13 prefectures see: http://www.zengenkyo.org/katudou/kaku.pdf.

[97] *Managing Spent Fuel from Nuclear Power Reactors: Experience and Lessons from Around the World* (IPFM, 2011, p. 57.

[98] Only casks for BWR spent fuel have been licensed for Mutsu thus far. Mitsubishi Heavy Industries is to produce PWR casks for Mutsu but licensing has been delayed due to a documentation problem. The PWR casks are to be used for spent fuel from Tsuruga #2.

[99] http://criepi.denken.or.jp/research/topics/pdf/201211vol14.pdf.

[100] The Recyclable Fuel Storage Company has announced that construction of the Mutsu storage facility was completed on 29 August 2013, http://www.rfsco.co.jp/hontai/construction2508.html.

[101] JAEC Fuel Cycle Planning Subcommittee Presentation, 25 Oct. 2011, slide 12.

[102] Quantity of Japanese light-water reactor spent fuel shipped to Europe according to METI's Agency for Natural Resources and Energy, 16 Jan. 2013 reply to the office of Diet member Mizuho Fukushima. In addition, the same document shows that Japan shipped about 1510 tons of spent Magnox fuel from the

Tokai I reactor (operated from 1965-98) to the UK for reprocessing. However, the UK did not require high-level waste take-back in that early reprocessing contract (Martin Forwood, personal communication). Tokai I produced 1,175 GW-days of net electrical power (IAEA-PRIS) or about 4,200 GWt-days of thermal power. That would correspond to about 2.8 GWt-days/ton and about 2.8 tons of plutonium recovered total, Albright et al, op. cit., Table C.2.

[103] According to AREVA, an estimated 1,750 canisters of compacted intermediate-level waste remain to be shipped, *Traitement des combustibles usé provenant de l'étranger dans les installations d'AREVA NC La Hague* (AREVA, 2011), pp. 33-34. According to a local newspaper in the Aomori area, the maximum would be 4,400 canisters of compacted waste and 28 canisters of vitrified waste, http://cgi.daily-tohoku.co.jp/cgi-bin/tiiki_tokuho/kakunen/news/news2013/kn130327a.htm.

[104] JNFL estimates 850 canisters of high-level waste from the UK, http://www.jnfl.co.jp/recruit/business/chozou.html. A local newspaper states 900 canisters, including 70 for the Curie equivalent of the amount of intermediate-level waste that would be left in the UK. One hundred and thirty two canisters had been shipped as of 27 Feb. 2013, with about 770 more to be shipped, http://cgi.daily-tohoku.co.jp/cgi-bin/tiiki_tokuho/kakunen/news/news2013/kn130228a.htm.

[105] A total of up to 8,000 canisters of UK high-level waste are expected by the time reprocessing-relating operations at Sellafield end. As of the end of 2012, there were about 5,500 canisters in storage; production had averaged about 200 per year during the previous four years; and it was expected that future production would be in the 200-350 per year range (Martin Forwood, personal communication, 30 November 2012).

[106] UK Nuclear Decommissioning Authority, *Strategy effective from April 2011,* p. 80.

[107] Prior to 2005, Japan's nine regional utilities with nuclear power plants and the Japan Atomic Power Company accumulated internal reserves of about ¥3 trillion (~$30 billion) to cover future reprocessing costs, Hitoshi Yoshioka, memo to the AEC dated 24 September. 2004, available at http://www.aec.go.jp/jicst/NC/tyoki/sakutei2004/sakutei08/siryo12.pdf. This money was collected based on the quantity of spent fuel each utility generated each year. In 2005, however, a law was passed that mandated that funds to cover the cost of reprocessing future spent fuel discharges and decommissioning of the RRP should be deposited every year into the Reprocessing Fund. The law also stipulated that the utilities' existing internal reprocessing reserves be moved to this fund within 15 years and, since the cost of decommissioning the RRP had not been taken into account in the existing reserves, a charge should be added and deposited into the new fund to cover this cost for the spent fuel that had been generated prior to 2005.

[108] http://www.uforeader.com/v1/se/E04785_0050AW4K_16_32.html##E0062. The total amount of the long-term loans to the company as a whole were ¥1.1 trillion but, due to the dominance of the investment in the reprocessing facility, we assume the loans were mostly for it. About ¥0.28 trillion (~$2.8 billion) has been paid annually to JNFL from the reprocessing fund, most of which is an annual "basic charge" which is paid to JNFL regardless of the actual amount of spent fuel reprocessed in that year, http://www.rwmc.or.jp/financing/file/saisyori_unyozisseki23.pdf. See also the LDP's Taro Kono comments on the "basic charge" sum disclosed by METI at http://www.taro.org/2012/10/post-1280.php. As of the end of FY2012, a total of about ¥4.74 trillion (~$47 billion) had been put into the Reprocessing Fund and the unexpended balance was about ¥2.57 trillion (~$26 billion) http://www.rwmc.or.jp/financing/reprocess/financing4.html.

[109] http://www.jnfl.co.jp/public_archive/7-2-34.pdf.

[110] http://www.jnfl.co.jp/public_archive/7-2-34.pdf.

[111] On 12 April 2012, in a JAEC subcommittee meeting, in response to a question by JAEC Chair Kondo about a possible decision by the government to prohibit reprocessing, Yuka Matayoshi, Vice President, Morgan Stanley MUFG Securities Co., Ltd., stated: "In a situation where the operation of Rokkasho Reprocessing Plant is stopped for five years by a policy change of the government...the financial market will probably pull out swiftly. This is true for the existing loans and you should better consider that it will be even quicker at flight with regard to provision of future loans. If by any chance, the effect on the balance sheet to be caused by a policy change is expected to be large, I would think it is necessary for the

organization that decides a policy change should prepare a safety net to back up the situation. I hope you would consider that as a cost. The financial market is very sensitive in this regard." http://www.aec.go.jp/jicst/NC/tyoki/hatukaku/siryo/siryo15/siryo4.pdf.

[112] A document accompanying the notice of the 27th regular shareholders meeting of JNFL dated 14 June 2006 shows that, as of the end of March 2006, ¥0.924 trillion (~$9 billion) or 84% of the outstanding long term loans were from the government-owned Development Bank of Japan Inc. Such detailed information about the loans has not been disclosed since.

[113] http://www.jnfl.co.jp/english, President Yoshihiko Kawai.

[114] http://www.rwmc.or.jp/english/#index, President Ikuro Namiki.

[115] https://www.numo.or.jp/en, President Toru Yamaji.

[116] William Walker, *Nuclear Entrapment: THORP and the politics of commitment* (Institute for Public Policy Research, 1999) p. 10.

[117] UK Nuclear Decommissioning Authority, *Oxide Fuels: Preferred Option* (2012).

[118] Anthony Andrews, *Nuclear Fuel Reprocessing: U.S. Policy Development* (U.S. Congressional Research Service, 2008), http://www.fas.org/sgp/crs/nuke/RS22542.pdf.

[119] JAEC, "Estimation of Nuclear Fuel Cycle Cost and Accident Risk Cost (Statement)", 10 Nov. 2011, assuming one yen equals $0.01.

[120] "The Nuclear Waste Administration Act of 2013", http://www.gpo.gov/fdsys/pkg/BILLS-113s1240is/pdf/BILLS-113s1240is.pdf. The proposed law builds on the recommendations of the 2012 report of President Obama's Blue Ribbon Commission on America's Nuclear Future, http://cybercemetery.unt.edu/archive/brc/20120620211605/http:/brc.gov.

[121] IAEA, INFCIRC/549/Add. 5a 6 April 1998; INFCIRC/549/Add.5/17, August 2013.

[122] IAEA, Power Reactor Information System. In 2011, 20 reactors in France were fueled with up to 30% MOX fuel, an additional 2 reactors had just been licensed to use MOX fuel and EDF had requested licenses for 2 more (recently granted). Four additional 0.9-GWe reactors were fueled with recycled uranium. *Managing Spent Fuel from Nuclear Power Reactors: Experience and Lessons from Around the World* (IPFM, 2011), p. 34. France had an additional six 0.9-GWe reactors fueled with LEU.

[123] Palais de Elysee (Office of the President of France), "Communiqué - Conseil de politique nucléaire", 28 September 2012.

[124] "France: Nuclear Policy Leaves Proglio in the Cold," *Nuclear Intelligence Weekly,* 19 Oct. 2012.

[125] Phil Chaffee, "A 2019 Halt to La Hague?" *Nuclear Intelligence Weekly,* 10 May 2013, but see the rebuttal, "Many Options for French Plutonium," by Dominique Greneche, a consultant for AREVA, in the 31 May issue. Currently, the control systems of France's 1300-1500 MWe reactors, which began operating between 1984 and 1999, are not configured for MOX fuel and their conversion could be costly. France's new 1650 MWe EPR reactor is designed to be able to use up to 100% MOX fuel, AREVA, "EPR reactor: The Very High Power Reactor," http://www.areva.com/EN/global-offer-419/epr-reactor-one-of-the-most-powerful-in-the-world.html. Thus far only one EPR is under construction in France and, as of the end of 2012, had been afflicted by a three-fold cost increase and at least a four-year schedule slippage, "Flamanville EPR to cost at least €8 billion," *Nuclear Intelligence Weekly,* 7 Dec. 2012. EDF does not plan to start up the unit on MOX fuel and has not indicated whether or not it might do so later.

[126] J. Kang, F. N. von Hippel, A. MacFarlane, R. Nelson, "Storage MOX: A Third Way for Plutonium Disposal?" *Science and Global Security*, Vol. 10 (2002) p. 85.

[127] In its annual report to the IAEA on its holdings of civilian plutonium, France's number for "plutonium contained in unirradiated MOX fuel or other fabricated products at reactor sites or elsewhere" has risen from 3.6 tons at the end of 1995 to 30.6 tons at the end of 2012, IAEA, "Communication(s) Received from France Concerning its Policies regarding the Management of Plutonium," INFCIRC/549/Add.5-17.

[128] Japan Atomic Energy Commission, "The Current Situation of Plutonium Management in Japan," 11 Sept. 2013.

[129] Phil Chaffee, "Plutonium Swaps to Increase UK-Owned Stockpiles," *Nuclear Intelligence Weekly,* 26 April 2013.

[130] 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, http://www.decc.gov.uk/assets/decc/Consultations/plutonium-stocks/3694-govt-resp-mgmt-of-uk-plutonium-stocks.pdf, para. 1.8.

[131] The UK currently has only a single light-water power reactor, Sizewell B. To dispose of 100 tons of separated plutonium in 20 years would require about 10 GWe of LWR capacity, assuming that MOX fuel containing 7.5% plutonium constituted one third of the fuel. An equivalent MOX-irradiation capacity would be created, however, if an agreement with EDF to build two EPRs in the UK goes ahead and those reactors were loaded with full-core MOX.

[132] UK Nuclear Decommissioning Authority, *Conditioning of Plutonium Residues by Hot Isostatic Pressing and Options for Packaging and Disposal (Pre-Conceptual stage) Summary of Assessment Report*, 2009, www.nda.gov.uk/documents/upload/Executive-Summary-Letter-of-Compliance-Assessment-Report-Conditioning-of-Plutonium-Residues-July-2009.pdf.

[133] J.W. Hobbs, et al, "A Programme to Immobilise Plutonium Residues at Sellafield," *op. cit.*

[134] *Management of the UK'S Plutonium Stocks: A consultation response, op. cit.*, para. 3.31.

[135] See e.g. "Recent trends in Hot Isostatic Pressing (HIP) technology http://www.ipmd.net/articles/001746.html; "Avure Technologies to Build World's Largest Hot Isostatic Press for Kinzoku Giken Co. LTD of Japan," http://www.avure.com/news/archive/avure-technologies-to-build-worlds-largest-hot-isostatic-press-for-kinzoku-giken-co.-ltd-of-japan.asp; and *Proceedings of the 2011 International Conference on Hot Isostatic Pressing: HIP '11*, April 12-14, 2011, Kobe, Japan.

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

[137] J.W. Hobbs et al, "A Programme to Immobilise Plutonium Residues at Sellafield," *Annual Meeting of the Institute for Nuclear Materials Management,* Orlando, FL, 15-19 July 2012.

[138] Bill Arnold et al, *Reference Design and Operations for Deep Borehole Disposal of High-Level Radioactive Waste* (Sandia National Laboratory, SAND2011-6749, 2011), Fig. 1.

[139] Craig Johnson and Zachary Davis, *Nuclear Weapons Disposal Options for Surplus Weapons-Usable Plutonium* (Congressional Research Service, #97-564 ENR, 1997) Table 1, assuming $1 (1996$) = $1.38 (2012$).

[140] U.S. Department of Energy *Fiscal Year 2014 Congressional Budget Request,* Vol. 1: $7.7 billion construction cost for the Mixed Oxide Fuel Fabrication Facility (p. DN-119); $8.2 billion for operations and security costs over 15 years (p. DN-147); $0.4 billion for the associated Waste Solidification Building and $1.9 billion for its operation over 20 years (p. DN-148), April 2013.

[141] U.S. Department of Energy, fact sheet on fiscal year 2014 budget, http://www.whitehouse.gov/sites/default/files/omb/budget/fy2014/assets/energy.pdf.

[142] Tom Clements, Edwin Lyman and Frank von Hippel, "The Future of Plutonium Disposition," *Arms Control Today,* July/August 2013, p. 8.

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