Ending the separation of plutonium: An alternative approach to the management of Japan's spent nuclear fuel

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Introduction and summary

The Noda administration's review of Japan's nuclear power policy after the Fukushima nuclear accident of March 2011 resulted in two decisions:

1) To shut down Japan's nuclear power plants by the end of the 2030s, and

2) To continue with the plan to start the Rokkasho Reprocessing Plant in 2013.

The new Abe administration has reversed the nuclear phase-out decision but has maintained the policy of going forward with reprocessing.

As of the end of 2011, Japan had a stockpile of about 44 tons of separated plutonium: nine tons in Japan and 35 tons in France and the UK. If the Rokkasho Reprocessing Plant (RRP) in Aomori Prefecture operates at design capacity (800 tons of uranium in spent fuel per year) it will separate about eight metric tons of plutonium per year.[1] Most likely, Japan's program for using plutonium in fuel will continue to be delayed and Japan could, in a decade or so, be the owner of about 100 tons of separated plutonium. Today, the total global stockpile of separated civilian plutonium is about 250 tons. Including weapons plutonium, about 70 tons of which has been declared excess, raises the total to about 500 tons.

Plutonium—whether power-reactor-grade or weapon-grade—is nuclear weapons-usable.[2] Eight tons would be enough for 1,000 Nagasaki-type weapons—more if modern designs were used. An increase in the amount of separated plutonium anywhere is therefore of global concern. Indeed, Russia and the U.S. are spending billions of dollars to dispose of 34 tons of excess Cold War plutonium each.

The purpose of this report is to lay out the basis for an alternative approach that would allow Japan to end plutonium separation and dispose of its existing stocks irrespective of the future of nuclear power in Japan. It also lays out a strategy for safer spent fuel storage in Japan.

Originally, like other industrialized countries, Japan launched its plan to separate civilian plutonium in the expectation that it would be needed to fuel liquid-sodium-cooled fast-neutron breeder reactors (FBRs) that would produce more plutonium than they consumed. But the FBR commercialization program stalled in Japan, as it did in all other countries that pursued it. The plan for using Japan's plutonium stockpile and the additional plutonium to be separated at Rokkasho therefore is to mix it with depleted uranium to make "mixed-oxide" (MOX) fuel for use in current-generation water-cooled reactors.

This plan too has experienced a series of delays. At the time of the Fukushima Daiichi accident, MOX fuel had been loaded into only four of Japan's 54 power reactors.

After the Fukushima Daiichi accident, during which much attention was focused on the presence of a small amount of MOX fuel in the core of unit #3, public resistance to MOX fuel is likely to increase again. The nuclear utilities, focused on getting as many as possible of their reactors back into operation, are therefore not proposing to use MOX fuel anytime soon.

The Abe administration wants a decision on whether or not to restart each of Japan's power reactors within three years, as promised during the election campaign of 2012.

Shunichi Tanaka, chairman of the newly created Nuclear Regulation Authority (NRA), has responded that the NRA will not be able to process all the applications for restarts so quickly even if applications are submitted promptly. If earthquake fault lines under or near some nuclear power reactors cannot be proven to have been inactive for at least the past 120,000-130,000 years, the reactors may be permanently shut down. [3]

The main argument for continuing with the plan for reprocessing at Rokkasho is the need to find a destination for spent fuel accumulating in Japan's nuclear power plant cooling pools. Eventually – on average seven years after restart for those plants that do restart – the pools will become full unless older cooler spent fuel is removed. Reprocessing advocates argue that the only option is to send the fuel to RRP. Since the RRP intake pool is full, reprocessing would be necessary to make space in the pool for shipments from the nuclear power plants.

This argument is accompanied by an assertion that local communities would not accept an expansion of spent fuel storage capacity at the nuclear power plants and that, if a decision is made to postpone or abandon the operation of the RPP, Aomori Prefecture will demand that all the spent fuel in the intake pool be sent back to the original power plants and will refuse to accept spent fuel from other prefectures at the interim storage facility under construction in Mutsu city in Aomori Prefecture or to store any more waste from the reprocessing of Japan's spent fuel in Europe.

It is ironic that Aomori Prefecture is using dry cask interim storage, which is an alternative to reprocessing, as leverage to promote reprocessing. The interim dry-cask storage facility at Mutsu is being built by the Tokyo Electric Power Company (TEPCO) and the Japan Atomic Power Company (JAPC) . The facility will have the same storage capacity (3,000 metric tons) as the intake pool at the RRP. Before the Fukushima accident, TEPCO and JAPC had plans for a further 2,000-ton expansion of the Mutsu Facility. JAPC also built a dry cask storage facility at the Tokai Daini (Tokai 2) nuclear power plant and TEPCO built a dry cask storage facility and a common pool at the Fukushima Daiichi (Fukushima I) nuclear power plant that together hold about 1200 tons of spent fuel. Now, in order to make room for the spent fuel in reactor pools 1-4, TEPCO plans to remove about half of the fuel in the common pool to a temporary dry cask storage facility being built on the Fukushima Daiichi site. The dry casks in the storage building damaged by the tsunami will be moved there as well.

Although the government of Fukui Prefecture was opposed, in 2004, the mayors of three towns in Fukui Prefecture that host Kansai Electric Power Company's (KEPCO's) three nuclear power plants expressed a willingness to be considered for an interim spent fuel storage facility.

TEPCO, KEPCO and JAPC together accounted for 59 percent of Japan's pre-Fukushima 50 GWe nuclear generating capacity.

Thus, although contentious, the alternative to operating the RRP that has been emerging is interim storage in dry casks.

Resistance to such storage would be reduced if the public understood that dry cask storage, if used to reduce the amount of spent fuel stored in nuclear power plant spent fuel pools, would reduce the risk from that fuel. Originally the pools were designed to hold only several years of spent fuel discharges because it was expected that the fuel would be shipped off site for reprocessing as soon as its radioactivity had decayed enough to allow transport. Today, the spent fuel pools at Japan's nuclear power plants contain on average about 14 years of discharges and they have been re-racked to hold more than 20 years of discharges. This "dense-packing" of spent fuel creates a dangerous situation, however, in which, if the pool cooling water were lost, air cooling would be ineffective and the fuel would heat up to a temperature at which it could catch fire. Indeed, concern about the possibility for such fires drove the desperate efforts to add water to the pools at Fukushima Daiichi in the days after the 11 March 2011 events.

Nuclear Regulation Authority Chairman Shunichi Tanaka has been promoting the idea of dry cask storage of spent fuel, saying at his first press conference [4]

> "I would like to have spent fuel moved to the ground level as soon as possible…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."

One thing that must not be forgotten is the fact that Aomori Prefecture and Rokkasho Village are quite dependent on nuclear facilities for their income. They would lose a great deal of revenue if the present tax and grant arrangements associated with the Rokkasho Reprocessing Plant ended due to their refusal to negotiate over a moratorium on its operation. The same could be said about the communities and prefectures hosting nuclear power plants. Assuming that these local governments consider nuclear power plants safe enough to be operated, there should be room for negotiations on interim dry-cask storage.

Japan's central government, which has been promoting reprocessing for years, should not be allowed to pretend that Aomori Prefecture and the communities hosting Japan's nuclear power plants are forcing the separation of more nuclear-weapon-usable material by refusing to allow an expansion of the interim storage space for spent fuel.

Another argument that is used by reprocessing proponents behind closed government doors is that, if the RRP is not operated, its owner, Japan Nuclear Fuel Limited (JNFL) and some the utilities that own it will go bankrupt causing chaos in Japan's financial markets. JNFL borrowed a huge sum of money to pay for the construction of the plant. The central government established a surcharge on all electric energy sold in Japan to pay for cost related to reprocessing and this money is being paid into an outside fund established for the purpose. JNFL can use money it receives from this fund each year to pay off its debt. According to the current law, however, the fund cannot be used if reprocessing is abandoned.[5]

The solution to this problem is to change the law.

We therefore propose that Japan's central government take the responsibility to negotiate with Aomori prefecture and the communities and prefectures hosting nuclear power plants around the country and implement the following alternative to Japan's current reprocessing policy:

- Construct dry cask storage facilities at Japan's nuclear power plants – as has been done at most nuclear power plants in other countries – after explaining the safety benefits to the host communities and prefectures;

- Postpone indefinitely restart of spent fuel reprocessing at the RRP, which would simply add to Japan's already excessively large stockpile of separated plutonium;
- Improve the safety of the RRP site by moving the dense-packed spent fuel in the intake pool to dry storage and solidifying the large volume of dangerous liquid high-level waste produced by its trial operations, in addition to taking any other measures required to manage the facility's vulnerability to earthquakes; and
- Study alternatives to MOX fabrication and use for disposing of separated plutonium, possibly in collaboration with the United Kingdom and the United States, which have respectively failed and troubled MOX plutonium disposal programs, as well as France, which holds about one third of Japan's separated plutonium.

Japan is the only non-weapon state that separates plutonium today but its example is being cited by South Korea, which is negotiating a new agreement of nuclear cooperation with the United States. South Korea argues that the U.S. should give it blanket consent to reprocessing because the U.S. gave such consent to Japan. Other countries interested in reprocessing can be expected to cite Japan's example. Some of these countries may be motivated by a desire to acquire a nuclear-weapon option.

Unlike uranium enrichment, reprocessing is unnecessary for today's nuclear power plants. In fact, it increases the cost of nuclear power relative to storing spent fuel. Japan, and the remaining weapon states that maintain a commitment to civilian reprocessing (the U.S. stopped in 1972 and the UK recently decided to abandon reprocessing), would be making a great contribution to strengthening the nonproliferation regime if, like most other countries with nuclear power plants, they switched from reprocessing to on-site dry cask storage of spent fuel.

I. **Why reprocess?**

In the 1960s and 1970s, the purpose of reprocessing in Japan and other industrialized countries, including Germany, France, the Soviet Union, the United Kingdom and the United States, was to recover plutonium to provide initial fuel for a new generation of liquid-sodium-cooled plutonium "breeder" reactors. These reactors would be designed to eventually (over hundreds of years) turn a large fraction of the 99.3 percent non-chain-reacting uranium-238 in a given quantity of natural uranium into chain-reacting plutonium. This would increase by up to one-hundredfold the amount of energy that could be extracted from the uranium.

In 1956, the Japan Atomic Energy Commission (JAEC), like its counterparts in other industrialized countries, predicted that breeder reactors would be commercialized in the 1970s. Fifty years later, in 2006, however, the JAEC did not expect commercialization before 2050. The reason was that liquid sodium-cooled reactors had been found to be costly and unreliable relative to the water-cooled reactors that are used today.[6]

The failure of their efforts to commercialize breeder reactors resulted in Japan and other countries that had separated plutonium needing to find a way to dispose of it. This led to the strategy of using the plutonium in uranium-plutonium mixed-oxide (MOX) fuel in some of the light water reactors (LWRs) that had produced it. Once this policy was established, however, plutonium recycling became a justification for continued reprocessing – especially for countries whose nuclear establishments still hoped eventually to commercialize plutonium breeder reactors. Given that no shortage of uranium is now expected for at least a century, another interim rationale has been developed for reprocessing: to separate long-lived plutonium from the radioactive waste that eventually will be emplaced in a deep underground repository. Separating all the plutonium in low-enriched uranium spent fuel and using it in MOX fuel would reduce the amount of plutonium in spent fuel only by about 40 percent, however. In France, spent MOX fuel is stored at its reprocessing plant but not reprocessed. Reprocessing spent fuel and using the plutonium in MOX therefore has simply become a very costly rationale for shipping spent fuel from nuclear power plants to a central facility.

II. **The problems with reprocessing**

The problems with reprocessing include:

- The high cost, which is projected to increase the cost of nuclear electricity in Japan by at least ¥ 1 ($0.01)* per kilowatt hour in comparison with storing spent fuel;
- Inadequate on-site spent fuel storage capacity leading to dangerously dense-packed storage pools at Japan's nuclear power plants because of delays in reprocessing;
- Large stocks of separated plutonium, a nuclear-weapon-usable material, and the need to ship it and/or fresh MOX fuel over large distances, creating targets for terrorists;
- Destabilization of the nonproliferation regime with stockpiles of separated plutonium that give countries the ability to quickly produce nuclear weapons in a crisis. (This danger was demonstrated in 1974 when India used the first plutonium separated by its "civilian" reprocessing program for a nuclear explosion.); and
- A more complex and dangerous radioactive waste disposal problem because spent fuel, a stable waste form, has been converted into a number of waste streams, including liquid high-level waste, which is extremely dangerous until it is solidified.

Cost

In November 2011, JAEC estimated that plutonium separation and use will increase the cost of nuclear power in Japan by 0.8 to 1 Yen per kWh relative to using only low-enriched uranium fuel and storing the spent fuel for direct disposal.[7] Over the 40-year design lifetime of the RRP, this extra cost to the citizens of Japan would cumulate to 8 to 10 trillion Yen ($80-100 billion).[8] Even given that the reprocessing plant has been built and contaminated, it will cost about ¥200 billion ($2 billion) a year to operate. Not operating it for 40 years therefore would save about ¥8 trillion ($80 billion).

Inadequate on-site spent fuel storage capacity

As of the end of March 2012, Japan had 12,600 tons of spent fuel in pools at its nuclear power plants. Total storage capacity in the pools was 19,130 tons. Table 1 shows the

* For convenience, we use in this report the round number Yen to dollar exchange rate of ¥100 = $1.

number of years of additional storage capacity available at each plant, as calculated by the Ministry of Economy, Technology and Industry (METI) assuming an average burnup of 36.5 MWdays/kg. If Japan's 44 GWe of nuclear capacity ran at its pre-accident 70% capacity factor and with a currently typical average spent-fuel burnup of 50 MWdays/kg, it would discharge about 700 tons of spent fuel annually. On average, in the absence of further re-racking to increase their capacity, the pools therefore would have about 10 years before they are full.

Because of the delays in the operation of the RRP and the fact that its 3,000-ton intake pool is now essentially full,[9] however, the pools at the nuclear power plants contain on average the equivalent about 15 years of discharged spent fuel, much more than they were originally designed for.

Utility	**Plant**	**Net generating capacity** (Gwe)	**16 month fuel reload** (tU)	**Spent fuel stored (31March2012)** (tU)	**Total available capacity** (tU)	**Years till full**
Hokkaido	Tomari 1-3	1.97	50	390	1000	16.3
Tohoku	Onagawa 1-3	2.09	60	420	790	8.2
	Higashidori	1.07	30	100	440	15.1
TEPCO	Fukushima Daiichi 5-6	1.83	53	320	570	6.3
	Fukushima Daini 1-4	4.27	120	1,120	1,360	2.7
	Kashiwazaki-Kariwa	7.97	230	2,310	2,910	3.5
Chubu	Hamaoka 3-5	3.47	100	1,140	1,740	8.0
Hokuriku	Shika 1-2	1.61	50	150	690	14.4
KEPCO	Mihama 1-3	1.57	50	390	680	7.7
	Takahama 1-4	3.22	100	1,150	1,730	7.7
	Ohi 1-4	4.49	110	1,430	2,020	7.2
Chugoku	Shimane 1-2	1.22	40	390	600	7.0
Shikoku	Ikata 1-3	1.92	50	600	940	9.1
Kyushu	Genkai 1-4	3.31	90	860	1,070	3.1
	Sendai 1-2	1.69	50	880	1,290	10.9
JAPC	Tsuruga 1-2	1.45	40	580	860	9.3
	Tokai 2	1.06	30	370	440	3.1
Total		44.21	1,253	12,600	19,130	6.9

Table 1. Spent fuel stored and total available capacity for spent fuel at each of Japan's nuclear power plants. The 16-month reloads shown in METI's estimates appear to be for an average burnup of 36.5 MWt-days/kg. Current typical burnups are 50 MWt-days/kg.[10]

Large stocks of separated plutonium

As of the end of 2011, Japan had 44 metric tons of separated plutonium, i.e. plutonium separated from fission products: 9 tons in Japan and 35 tons in Europe. This separated plutonium is a legacy of decades of reprocessing at the domestic Tokai pilot reprocessing plant, from testing of the RRP in 2006-2008 and from the reprocessing of Japan's fuel overseas in France and the United Kingdom.

One ton of separated plutonium would be sufficient for 125 Nagasaki-type nuclear explosives and about twice as many nuclear warheads, if more modern designs were used.[11]

The long-delayed RRP (see figure 1) is currently planned to start commercial operations in 2014.

Figure 1. Rokkasho Reprocessing Plant.[12]

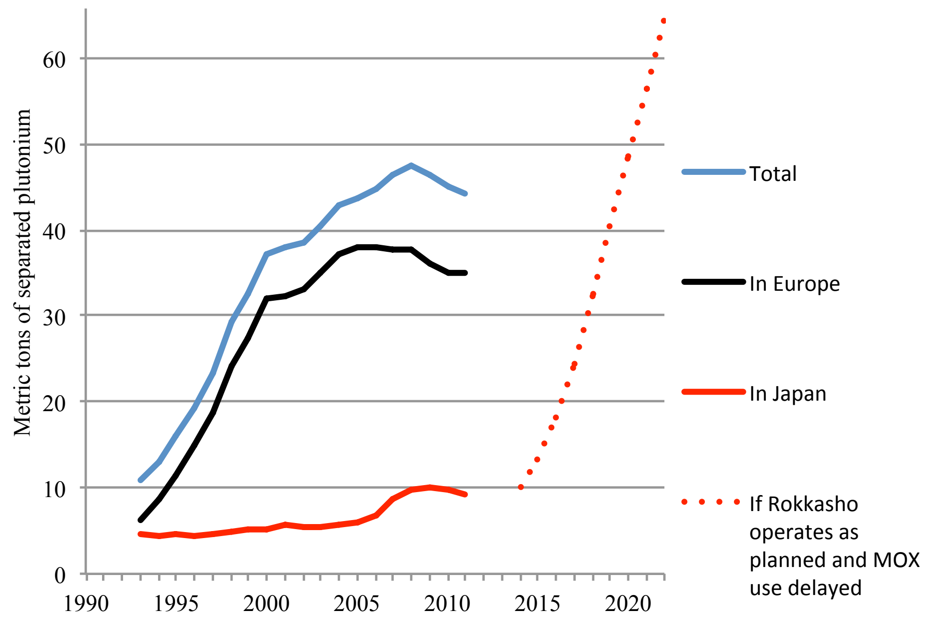

Figure 2. Japan's stockpile of separated plutonium grew in the 1990s due primarily to separation in Europe and the failure of the fast breeder reactor and MOX programs in Japan. In the late 2000s, test separation began at the RRP but then halted because of an inability to solidify the liquid high-level waste. The current plan is to start commercial operations in 2014. If this plan is carried out and MOX use is delayed, Japan's total stockpile could rise to 100 tons by 2022.

In the absence of any plutonium disposition and with RRP starting operations in 2014 as planned,[13] Japan's stockpile of separated plutonium would reach one hundred tons in eight years (figure 2). This would make Japan equal to the UK, currently the owner of the world's largest stock of separated civilian plutonium, and also the U.S., which is struggling with its Cold War legacy of weapons plutonium.[14]

Japan's utilities still have plans for plutonium disposition in MOX but, even before the Fukushima accident, these plans had been delayed for years by safety concerns at the municipal and prefectural level.[15] Currently, the focus of the utilities and the Abe Administration is on restarting the reactors and they have no interest in increasing the obstacles to restart. No MOX is therefore currently being manufactured from Japan's plutonium in Europe.[16] Japan will not make MOX in Japan for years because construction of a domestic MOX plant is just beginning.

A total of about one ton of plutonium in fresh MOX fuel from France is stored at five Japanese nuclear power plants. The MOX stored at the Kashiwazaki-Kariwa nuclear power plant has been there for 12 years. There is no prospect of this MOX being loaded into reactors soon, if ever. While ships carrying MOX fuel originally scheduled to be shipped in 2011 to KEPCO's Takahama Unit 3 left France on 17 April 2013, KEPCO stated on 21 March that no decision had been taken to load it in the reactor.[17] There is no doubt therefore that Japan's stocks of separated plutonium would increase rapidly if the RRP began to operate at design capacity.

Legitimization of interest in reprocessing in other non-weapon states

Japan has had enough separated plutonium to make nuclear weapons since about 1970[18] but has not done so. Japan ratified the Non-proliferation Treaty as a non-nuclear-weapon state in 1976.[19] Japan would jeopardize its relationships with the United States and the rest of the world if it went nuclear now.

Our major concern, therefore, is not that Japan will acquire nuclear weapons in the foreseeable future. It is that Japan's reprocessing program undermines the nonproliferation regime. After India used for its 1974 nuclear test the first plutonium it separated for its plutonium breeder program, the U.S. reviewed its nuclear policy. As a result, the Carter Administration decided that reprocessing was unnecessary and uneconomic and ended the U.S. civilian reprocessing program, believing that this would strengthen the legitimacy of its efforts to discourage other countries from reprocessing. U.S. diplomatic efforts to stop the spread of reprocessing technology, along with a growing understanding that reprocessing and plutonium recycle are not economic, resulted in all non-weapon states other than Japan ending their reprocessing programs.

Currently, however, in its negotiation of a new agreement of nuclear cooperation with the United States, South Korea is campaigning for U.S. acceptance of its right to reprocess. It argues that its spent fuel pools too are filling up and that its local governments too will not allow the installation of on-site dry cask storage (despite the fact that 7,000 tons of on-site dry cask storage have already been installed at one of its four reactor sites[20]). It therefore argues that it too needs a reprocessing plant to provide an off-site destination for its spent fuel.[21] The case has been complicated by a recent rise of public support for South Korea acquiring its own nuclear weapons in the face of North Korean nuclear threats.[22] 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 their old agreement, which requires U.S. consent for South Korean reprocessing of spent fuel containing uranium enriched in the United States.[23]

If South Korea eventually succeeds in pressuring the U.S. to accept its reprocessing – as Japan did in 1977 for the Tokai reprocessing plant and more broadly in the 1988 U.S.-Japan nuclear cooperation agreement – 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.[24] Iran has not yet expressed an interest in reprocessing but is preparing to operate a heavy water research reactor at Arak very similar to the research reactor that India used to produce the plutonium for its first nuclear weapons.

We also are concerned that Japan's separated plutonium – like that of other countries – is vulnerable to theft by terrorists. The danger of plutonium theft in the weapon states has become a leading argument for nuclear disarmament as well as for ending reprocessing. In addition to being a nuclear explosive material, plutonium also is extremely radiotoxic if inhaled.[25]

Japan and the nuclear weapon states that still reprocess therefore could significantly strengthen the nonproliferation and security regime by joining the other countries that have abandoned reprocessing.

Lack of waste management benefits

Japan’s Ministry of the Economy, Technology and Industry (METI) argues the waste-management benefits of reprocessing and MOX use in light water reactors (LWRs) and eventually in sodium-cooled fast-neutron breeder reactors as follows[26]:

- The volume of high-level waste would be reduced to about 1/4 and 1/7 by plutonium recycle in LWRs and fast reactors respectively.
- The time required for the toxicity of the high-level waste to decay to the same level as the original natural uranium would be reduced from about 100,000 years to 8,000 years and 300 years respectively.

In fact, however, reprocessing and plutonium recycle in LWRs complicate the radioactive waste disposal problem by converting stable spent low-enriched uranium fuel into three streams of radioactive waste: high-level liquid reprocessing waste that must be solidified, plutonium waste from fabricating MOX fuel, and spent MOX fuel. Reprocessing also leads to the highest man-made radioactive emissions into the environment. For various radioactive isotopes gaseous and liquid discharges are hundreds of times higher than those from a nuclear power plant. Furthermore, plutonium recycle in LWRs does not greatly reduce the long-term hazard from spent fuel. The irradiation of MOX fuel typically reduces the amount of plutonium in the MOX by only about 25 percent – 40 percent including the plutonium that would have been produced in the low-enriched uranium fuel that would otherwise have been used.[27]

Separation of plutonium and other transuranic elements and repeated irradiation in fast neutron reactors for hundreds of years could reduce the total amount of plutonium in waste to a few percent of the amount in LWR spent fuel but a major U.S. National Academy of Sciences (NAS) review concluded that the total hazard would not necessarily be reduced. Inevitably, some plutonium would be left on the surface as a result of all of the processing. In contrast, if it were kept in the spent fuel, it would all be deposited in a geological repository hundreds of meters underground. Also, there would be increased doses to workers involved in the plutonium recycling that would tend to offset any doses from leakage from a deep repository hundreds of thousands of years in the future. The NAS report concluded therefore that "none of the dose reductions seem large enough to warrant the expense and additional operational risk of transmutation".[28] In any case, there are no firm plans yet – even in France, which has been the leader in introducing reprocessing and plutonium recycle in light water reactor fuel – to separate out and recycle the plutonium in spent MOX fuel in fast reactors. Despite about $100 billion spent promoting their commercialization, only a few pilot and prototype fast reactors exist in the world today.[29]

III. **The dry-cask storage alternative**

Despite all the problems discussed above, the principal argument used today for continuing with the plan for reprocessing at Rokkasho is the need to find a destination for the spent fuel in Japan's nuclear power plant cooling pools. Ironically this problem has been caused by Japan's nuclear planners not providing for backup options should their reprocessing policy fail.

Even with the planned RPP, however, a shortage of storage was foreseen. The government's Long-Term Plan of 1987 pointed out the need for interim storage capacity. It was assumed that the amount of spent nuclear fuel discharged annually by Japan's 54 nuclear power reactors would be about 1,000 metric tons (MT). Even operating at full capacity, the RRP (RRP) is designed to only process 800 MT a year. It was therefore concluded that the only way to keep operating Japan's nuclear power plants was to build interim storage facilities, either on- or off-site. In 1997, Japan's government made a decision to have off-site interim storage capacity by 2010, and an amendment to the Nuclear Reactor Regulation Law in 1999 established a system whereby companies can be licensed to operate such facilities.

Two of the utilities with spent fuel storage pools that are closest to full, TEPCO and JAPC, decided some years ago to build dry-cask storage capacity for themselves in Mutsu City in Aomori Prefecture, not far from the RRP. This capacity is being constructed in two modules. The first module, currently nearing completion is to have a capacity of 3,000 tons. The second is to have a capacity of 2,000 tons. As will be discussed below, however, Aomori Prefecture has stated that it will allow this storage capacity to be used only if reprocessing goes forward.

Another way to reduce the amount of spent fuel in nuclear power plants spent fuel pools would be by installing on-site dry cask storage at the power plants to which fuel could be transferred after several years cooling in the reactor cooling ponds. This is the strategy that has been pursued in other countries that operate nuclear power plants. In the United States, as of the end of 2012, about 20,000 tons out of a total of about 70,000 tons of spent fuel were in dry cask storage and the tonnage in dry storage has been increasing by about 2,000 tons per year.[30]

Advocates of reprocessing in Japan have argued, however, that on-site dry cask storage is politically impossible in Japan. Thus, JAEC argued in its 2005 *Framework for Nuclear*

Energy Policy report that reprocessing had to go forward because the host communities would block any expansion of storage at the nuclear power plants, with the result that Japan's nuclear power plants would be forced to shut down one-by-one as their pools filled up.[31]

> "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."

In fact, however, before the Fukushima accident, permission had been received for dry cask storage facilities for about 150 and 250 tons of spent fuel at the Fukushima Daiichi and Tokai Daini nuclear power plants respectively.[32] Also, in 2004, although the government of Fukui Prefecture was opposed, the mayors of Mihama, Ohi, and Takahama in Fukui Prefecture, which host KEPCO's three nuclear power plants, expressed a willingness to be considered for interim spent fuel storage facilities, although only Mihama approached KEPCO officially asking for consideration.[33]


Figures 3 Left: Carbon steel spent fuel storage casks at the Fukushima Daiichi nuclear power plant after the tsunami had washed through the building.[34] Right: Dry cask storage at Tokai Daini nuclear power plant.[35] Each cask is 5 to 6 meters long and contains about 10 tons of spent fuel.

The continued concern over the safety of the spent fuel in the unit #4 pool of the Fukushima Daiichi nuclear power plant has dramatized the need to tackle the task of storing spent fuel more safely. The accident also demonstrated that dry cask storage is relatively safe. Before the accident, the Fukushima Daiichi site had one of the two operating on-site dry-cask storage facilities in Japan, with nine casks containing a total of 408 spent fuel assemblies stored in a building there since 1995[36] (Figure 4 left). Although the structure of the building was damaged by the tsunami, there have been no reports of any safety concerns about the spent fuel stored in the casks. The casks used there and, since December 2001, at the Japan Atomic Power Company's Tokai Daini nuclear power plant facility (Figure 3 right) are thick carbon steel. The design standards for less costly thin steel canisters surrounded by reinforced concrete radiation shields are expected to be finalized in a few years.

On-site dry cask storage is already widespread among the thirty-one countries that have operating nuclear power plants. Only six of the thirty-one have reprocessing plants (China, France, India, Japan, Russia and the United Kingdom). In many of the other countries – and in Russia and the UK (for its LWR) as well – when a pool is almost full, the oldest fuel is removed into air-cooled dry cask storage. This has been the practice since 1986 in the United States, which accounts for 27 percent of global nuclear capacity.[37] 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.[38]

Figure 4. All the spent fuel (412 tons) discharged by the U.S. Connecticut Yankee Reactor (528 MWe), which operated from1968 to 1998, is stored in 43 casks. The nuclear power plant itself has been completely removed and its site has been made available for other uses.[39]

In the United States and some other countries, storage casks are simply placed on concrete pads in the open air (Figure 4). In Germany, Japan and some other countries, the casks are stored in thick-walled buildings that provide additional shielding for passers by against the gamma radiation emitted by the spent fuel in the casks and also protection against anti-tank-type weapons or the engine spindles of a possible crashing jet aircraft.

Germany's nuclear power plants installed on-site dry cask storage relatively quickly after the then unofficial agreement in 2000 between the German government and utilities to end as of mid-2005 shipments of spent fuel to France and the UK for reprocessing. As it was no longer politically acceptable to ship spent fuel to Germany's two central interim storage facilities, each operating nuclear power plant had to establish an on-site dry cask storage facility. In most cases the application was made before 2000 with the 1998 emergence of the Green-Red government. 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.[40] At four nuclear power plants, temporary air-cooled concrete caskets for the casks were installed until a storage building could be completed (Figure 5).[41]

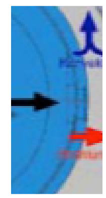

Figure 5. Left. Temporary protection for German storage casks pending construction of a permanent storage building. Right. The air around the casks is warmed by radioactive decay heat, rises and flows out of the slot at the top, and is replaced by cooler air entering through a slot at the bottom.[42]

This method of temporary storage is being copied at 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 common pool, which is almost full, into dry casks to make space for the spent fuel in the four reactor pools (about 500 tons [3,100 fuel assemblies] including fresh fuel), starting with the unit 4 pool (Figure 6). The nine casks stored in the damaged dry cask storage building are also to be moved there. The initial 50 casks will consist of 20 storage casks (the existing 9 plus 11 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.[43] The first cask of the nine in the damaged building was transferred to the temporary facility on 4 April 2013 after being opened up for inspection of the contained fuel in the common pool.[44] Unloading of the spent fuel in the pool of Unit 4 is to begin in November 2013, when the special crane next to the reactor building has been completed and declared to be safe to use.[45]

According to industry sources, about 100 carbon steel casks can be built per year in Japan without investing in additional production capacity and about 100 more per year could be procured overseas. Whether manufacturers invest in expansion of their cask production capacity depends on their estimate of the demand. 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.

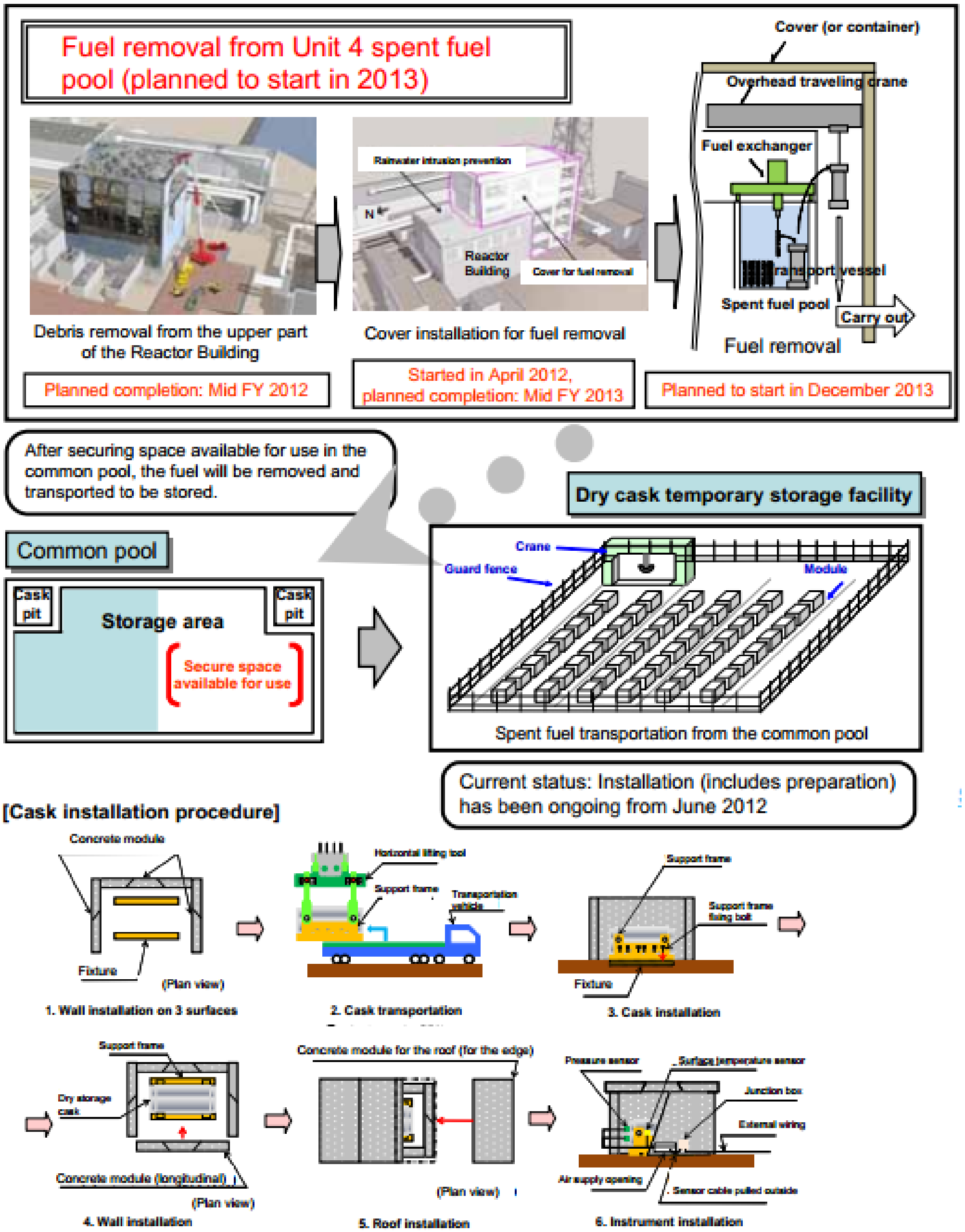

Figure 6. TEPCO's plan to move half of the older spent fuel in the Fukushima Daiichi common pool into on-site dry-cask storage to make space for the more recently discharged fuel in the unit 1-4 pools.[46]

Safety benefits

Dry cask storage of older spent fuel is significantly safer than keeping it in dense-packed pools. This has triggered calls in both the United States and Japan to remove spent fuel from reactor pools as quickly as possible when its radioactivity has died down to the point where it can be stored in air-cooled dry casks.

In the United States, most nuclear power plants were designed before 1977 when the U.S. abandoned reprocessing. It was assumed that spent fuel would be transported to a reprocessing plant as soon as it was cool enough to be moved, 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.[47] As a result, the fuel assemblies in the pools are "dense-packed"; the spent fuel is packed almost as densely as in a reactor core. To prevent a sustained neutron chain reaction (i.e. a criticality) each fuel assembly is placed in a square steel tube in a rack with an open top and a hole in the bottom to allow water circulation (Figure 7). The steel partitions between the fuel assemblies are impregnated with neutron-absorbing boron. The bottom of the rack is raised on short legs above the floor of the pool to allow water to circulate beneath.

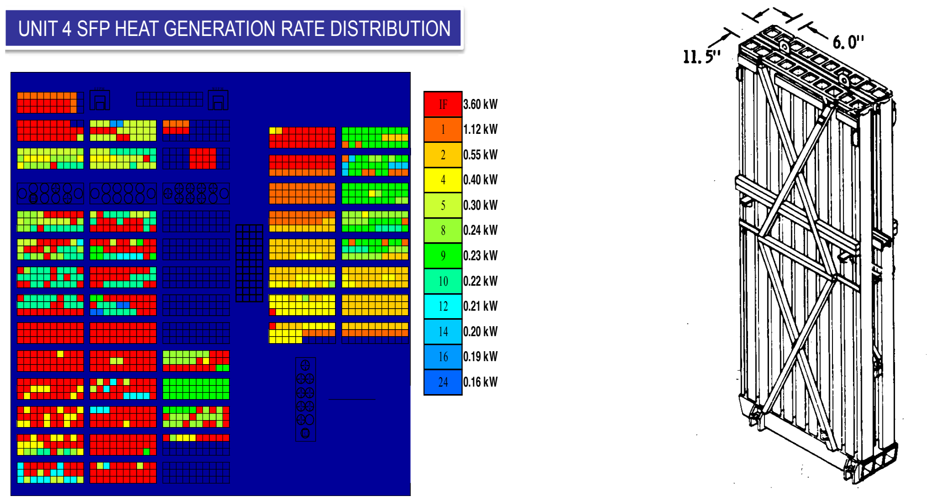

Figure 7. Left: Spent fuel assemblies stored densely in racks in Fukushima Daiichi 4 spent fuel pool with the radioactive decay heat from each assembly shown for 11 March 2011, the date of the accident. All the fuel assemblies are stored vertically in 53 fuel storage racks and the fuel storage racks are of a high density design. Each rack can hold thirty 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 impregnated with neutron absorbing boron. The hottest 548 assemblies (shown in red) belonged to a 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 Fukushima Daiichi reactors are boiling water reactors (BWRs). Each BWR fuel assembly contains about 0.17 tons of uranium. To get the decay heat per ton of uranium, the thermal power shown for each assembly therefore should be multiplied by 5.9. Right: A diagram of two rows of 2 x 10 array of a very similar dense-pack rack used in U.S. BWR pools. [48]

One danger from dense-packing is that the racks prevent air circulation through the spent fuel assemblies if the pools lose water – especially if the drainage is only partial and water still covers the openings at the bottoms of the racks. Thus dense packing increases the danger that the fuel will heat up to the point where its zirconium cladding catches fire in case of loss of water. This safety concern and the vulnerability of many pools to external impact (airplane crash or terror attack) has led to proposals that spent fuel assemblies older than five years be removed from the pools and placed into passively safe dry casks.[49] Five years after discharge from a reactor, the radioactive decay heat has declined to about 3 kW per ton (Figure 8).

About ten tons of spent fuel is typically stored in a dry cask and its heat transfers 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 5 year old fuel would be about the same as from a black sunlit surface on a clear mid-latitude summer day.[50] Three years after discharge, when the decay heat would be 6 kW/t or less, dry cask storage also is possible, but with fewer fuel assemblies per cask.[51] Conversely, one of the economic incentives for waiting longer than five years is that more spent fuel can be stored in each cask.

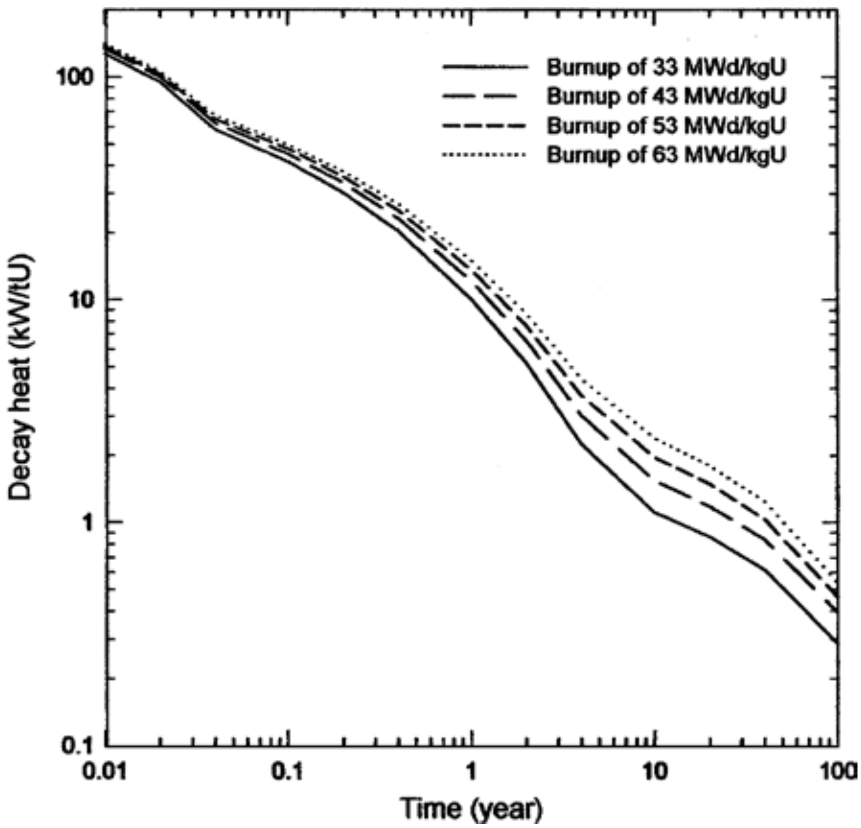

Figure 8. Decline of radioactive heat rate from a ton of spent fuel after reactor shut down.[52]

Immediately after he was appointed chairman of Japan's new Nuclear Regulation Authority, Shunichi Tanaka stated in a press conference that he would push reactor operators with elevated pools, such as those at the Fukushima Daiichi nuclear power plant, to move toward dry cask storage for safety reasons.[53]

> "I would like to have spent fuel moved to the ground level as soon as possible…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."

After spending so much effort and money to persuade the prefectural governments that host their nuclear power plants accepting MOX fuel use would guarantee that it would continue to be possible to ship the spent fuel away for reprocessing, however, the utilities reportedly are reluctant to ask for permission to install dry-cask storage at the nuclear power plants.[54]

The same safety concerns relating to reactor pools apply to the large storage pools at the RRP. 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[55] and its proposed location was moved to another state, Bavaria. Ultimately, the German utilities decided not to build the reprocessing plant. Before it was abandoned altogether, however, its design was changed to accommodate the criticisms that had been made in Lower Saxony. One change was to replace the 3,000-ton intake pool with dry cask storage.

After the German reprocessing plant was cancelled, an interim storage facility for spent fuel and vitrified high-level waste was built at Gorleben but, because of the concerns that had been raised about dense-packed pool storage, dry-cask storage was chosen. The same change from a spent fuel pool (1,500 tons in this case) to dry cask storage was made at the second German central interim storage facility at Ahaus.[56]

IV. **Are the political obstacles to policy change insuperable?**

Japan as a nation would benefit greatly from abandoning its reprocessing policy and shifting its spent fuel to dry cask storage after cooling about five years in pools:

- Japan's electricity ratepayers would save a great deal of money;
- The safety risks associated with the dense-packed pools at Japan's nuclear power plants and at the RRP would be reduced and
- The whole world would benefit from the reduced nuclear security and proliferation related risks.

It is difficult to mobilize politically for such widely dispersed benefits, however, in the face of concentrated opposition from stakeholders who obtain huge benefits from the *status quo*.[57]

Motohisa Furukawa, the former Minister of State for National Policy, who was chairman of the Energy and Environment Council when it developed the Noda administration's energy policy, said that he managed the whole discussion from the beginning based on the understanding that the reprocessing program would continue. Furukawa explained [58]

> "Nuclear power (policy) has been built up through a history of half a century and cannot back up suddenly like a car. The life of local people is also at stake."

The main argument for reprocessing is that it is necessary to provide a destination for spent fuel in order to prevent shutdowns of nuclear power plants. This is based on two assumptions:

1. If reprocessing is abandoned or postponed, Aomori Prefecture will actually try to implement its threat not to host spent fuel from the rest of Japan and the solidified high-level waste returning from Europe; and

2. Communities hosting nuclear power plants will not accept on-site dry cask storage, even if that means closure of nuclear power plants in their communities.

A third concern that is not openly discussed is that, if reprocessing is abandoned or postponed, the government-controlled fund set up to pay for reprocessing will not be available to pay JNFL's debts, and JNFL and some the utilities that own it will go bankrupt, causing chaos in Japan's financial markets.

Below, we examine the validity of these concerns. As essential background, however, we first review the level of dependence of Aomori prefecture and Japanese communities hosting nuclear power plants on the payments that they receive in exchange for hosting nuclear facilities.

Dependence of municipalities and prefectures on nuclear facilities

Aomori Prefecture is heavily dependent on its nuclear facilities for income that comes in the form of special prefectural taxes on the facilities, central government grants to municipalities that host or neighbor them and to the prefecture itself, and "donations" from the nuclear utilities and JNFL.

Taxes. In addition to the reprocessing plant, the JNFL complex at Rokkasho Village contains Japan's High-Level Radioactive Waste Storage Center, a Low-Level Radioactive Waste Storage Center (disposal site), JNFL's Uranium Enrichment Plant, and its MOX Fuel Fabrication Plant construction project.

The prefecture also has a number of other nuclear facilities, mostly under construction:

- The Higashidori Nuclear Power Plant, with one unit operated by Tohoku Electric Power Company and one TEPCO unit that was under construction before the Fukushima accident but has been suspended since;
- A 1,383-MWe Advanced Boiling Water Reactor designed to accommodate a full MOX core being built by J-Power at Ohma;[59] and
- The under-construction Interim Spent Fuel Storage Facility in the city of Mutsu.

Since 1991, Aomori Prefecture has been levying "nuclear fuel" taxes on all these nuclear facilities. The tax for spent fuel brought to the RRP is ¥19,400 yen/kg ($194/kg). Since 2006, because of postponements of the RRP startup date, however, Aomori also has been levying in addition 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 more than six-fold from ¥1300/kg to ¥8300/kg ($83/kg) per year. [60] It is important to note that this tax shift from reprocessing to storage would tend to insulate the Prefecture from losses in its tax base if the RRP does not operate *unless it implements its threats to refuse to accept spent fuel from other prefectures for storage at the Mutsu facility and to insist that spent fuel in the RRP intake pool be returned to the power plants from which it came* (see below).

The prefecture's Fiscal Year (FY) 2012 (April 2012-March 2013) budget shows that "nuclear fuel" taxes amounting to ¥15.9 billion, account for 13.9% of the tax income of the Prefecture.[61] In addition, in April 2012, there was an increase of the taxes on low-level and high-level wastes.[62]

Municipalities hosting or neighboring nuclear facilities also depend upon special nuclear-related fees and grants from the government. These payments are mandated by the three 1974 Laws on Power-Source Siting.[63]

Municipalities in Aomori Prefecture received ¥19.1 billion ($190 million) under these laws in FY 2011 (including for Mutsu ¥3 billion, Rokkasho ¥2.6 billion, Ohma ¥0.96 billion, Higashidori ¥3.7 billion). The cumulative total from 1981 to FY2011 was ¥233.4 billion ($2.3 billion), mostly for hosting nuclear facilities.[64]

A comparison of municipalities hosting nuclear facilities to the average Japanese municipality shows that the income from property taxes in nuclear municipalities is about twice as much per capita as in the average Japanese municipality. The ratio for Rokkasho Village is 7.5 times the national average. Nuclear-related grants and contributions raise the ratio even higher.[65]

Jobs. JNFL is the biggest company in Aomori Prefecture, employing 1,400 Aomori Prefecture residents. Also, as of the end of FY2010, JNFL had issued construction contracts in the prefecture worth ¥509.5 billion ($6.2 billion).[66]

If reprocessing were terminated, however, the economic benefits to Aomori Prefecture from the jobs at the RRP would continue for decades, although at a declining rate. In a timeline projected by JAEC, cleanup costs for the RRP were estimated to continue for more than three decades after reprocessing ends. Cumulatively, they were estimated to amount to ¥1.4 trillion ($14 billion).[67]

Nevertheless, the dislocation would be greater than in urban prefectures, where industrial shutdowns and startups tend to average out. Presumably, Aomori Prefecture, as a poorer, rural region, would continue to be given priority consideration for new national facilities and infrastructure.

Aomori Prefecture's threats

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 declared that, unless reprocessing proceeded as previously planned, the Prefecture would:

- 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.

The governor's motivations presumably included:

- A desire for continuation of the tax and grant income to Rokkasho Village and Aomori Prefecture from JNFL's reprocessing activities;
- A desire not to lose the jobs associated with the reprocessing plant and the MOX fuel fabrication plant that is under construction;

- A concern about losing the role of contributing to the seemingly productive activity of extracting an energy resource from Japan's spent fuel and being reduced to a site for the indefinite storage of Japan's spent fuel and high-level waste; and
- Negotiating tactics to assure that, if reprocessing is abandoned, the prefecture will receive the maximum possible compensation.

With regard to tax income, we have already seen, however, that the Prefecture would lose less than it might initially appear if the RRP did not operate and if it provided interim spent fuel storage to the nation. In fact it could lose much more if it refused to negotiate and tried to implement its threats. Also, by eliminating the large quantities of liquid high-level radioactive wastes associated with reprocessing at Rokkasho, Aomori Prefecture could eliminate a major potential radioactive threat to both the prefecture and the nation.

Hopefully, as a result of negotiations, Aomori would not try to implement the governor's threats and as a result lose taxes and grants. Below, however, we discuss possible contingency plans in case it does.

Reprocessing waste from France and the U.K. Vitrified high-level reprocessing waste and intermediate-level waste are being returned from the reprocessing of 5,628 tons of spent Japanese light-water reactor fuel in France and the U.K.[68] Currently, these returning wastes are being stored at the RRP 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 and France plans to begin returning the associated compacted intermediate-level waste.[69]

Shipments of vitrified high-level waste from the UK began in 2010 and are expected to be completed in 2020. These shipments will include some extra high-level waste in exchange for keeping Japan's intermediate-level waste.

The total amount of high-level waste to be shipped from the UK is about 10% of that which it expects to have accumulated from the reprocessing of its own spent fuel.[70] 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.

Spent fuel in the RRP intake pool. Given limitations on the availability of transport casks and ships, and the need for approval from local authorities hosting the power plants, arrangements for shipment of the spent fuel from the RRP back to the originating nuclear power plants, if possible at all, would take some time. It would be desirable from a safety point of view if the returned fuel were stored in dry casks at the reactor sites instead of being loaded back into their spent fuel pools, exacerbating their dense-packing problem. Hundreds of casks would be required for on-site storage of this fuel. Dual-purpose transport and storage casks could be used.

Spent fuel to be stored in the Mutsu facility. If at-reactor interim dry-cask storage is agreed to by local authorities, then it would be unnecessary to ship spent fuel from TEPCO and JAPC reactors to Mutsu. Indeed, the casks that would account for 70-80 percent of the cost of the 3,000-ton Mutsu interim storage facility[71] could be used at the reactor sites instead.[72] These are dual purpose transportation and storage casks[73] and it is already planned to use some of them at the Fukushima Daiichi site (see above).

If Aomori Prefecture refused to store the spent fuel, the central government could shift the taxes it is paying to the prefecture for storing spent fuel to the prefectures and municipalities that would be keeping it or taking it back.

Thus the central government would not be without recourse in its negotiations with Aomori Prefecture.

So is the position of the Governor of Aomori Prefecture, with a population of 1.5 million, really blocking a long overdue change in Japan's nuclear fuel cycle policy? Or are the defenders of reprocessing using his threats as an excuse to resist policy change, with the politicians accepting their judgment because they do not want to deal with the complexity of the negotiations and the apologies that would be required if a radical change were made in Japan's fuel-cycle policy?

Host communities' refusal

When permission was originally obtained from the prefectures to build nuclear power plants, the expectation was that their spent fuel would be shipped out for reprocessing after several years of on-site cooling. Today, because of the delays in the operation of the RRP, the reactor pools contain about 15 years of spent fuel discharges (see Table 1).[74]

The cancellation of Japan's reprocessing program probably would mean that the spent fuel would stay mostly on site at the nuclear power plants until a national geological repository becomes available. This is the same situation that has been reluctantly accepted – but accepted – by communities hosting nuclear power plants in the United States, Germany and many other countries.

Would local opposition to the expansion of spent fuel storage at the NPPs force those plants that the NRA and the local communities themselves consider safe enough to operate to nevertheless shut down one after another?

One consideration that would tend to give host prefectures second thoughts is the fact that so much of the revenues of municipal governments hosting nuclear power plants would end if the plants shut down permanently.

The central government could encourage acceptance of expanded on-site spent fuel storage by offering payments to the host communities and prefectures. The special grants that have been given to municipalities for allowing the use of MOX fuel in the reactors that they host could be repurposed. This would be appropriate because, by accepting expanded on-site storage, the host communities would be making unnecessary the further separation of plutonium with all the associated costs and dangers.

The central government has made policy change more difficult, however, by promoting MOX fuel use with the opposite argument: that reprocessing and plutonium recycle would prevent nuclear power plant shutdowns by providing a destination for spent fuel.[75]

The government and other proponents of reprocessing therefore will have to acknowledge their mistake and explain to the host communities that the best interim solution for the spent fuel problem is in fact that adopted by most other countries, dry cask on-site storage, and negotiate the necessary agreements to facilitate its adoption in Japan.

An important additional incentive for accepting the policy change would be if priority were given to reducing the risks from the reactor spent fuel pools by removing to dry cask storage the older spent fuel stored in them.

The natural concern that the local governments and prefectures will have is that, in the absence of a reprocessing plant, the spent fuel accumulating at the nuclear power plants that they host will lack an offsite destination. Reprocessing transferred that concern to Aomori Prefecture.

In fact, when Aomori Prefecture agreed to host the reprocessing plant, the central government committed that radioactive waste would remain there for no more than 50 years. This means that an interim storage facility or a geological repository would have to become available in another prefecture by 2045.[76] If the communities hosting nuclear power plants accept the responsibility for interim storage of spent fuel produced by the plants, they too should be given the same assurance.

One essential part of a policy package for ending reprocessing, therefore, must be a credible process for siting a national geological repository. On 26 November 2012, Japan's central government wrote to the governors of all of Japan's prefectures asking them to participate in a consultation on the siting of spent fuel interim storage facilities and a high-level waste disposal site.[77]

A useful bit of perspective that could be provided for this consultation is that, objectively, the hazards from deep geological storage of spent fuel are far less than from nuclear power plants or even surface storage of spent fuel. This may explain why the communities that volunteered to host Finland's and Sweden's geological repositories already host nuclear power plants.

After promoting reprocessing for decades, Japan's central government must take the responsibility for negotiating with Aomori Prefecture and communities hosting Japan's nuclear power plants a transition to a safer arrangement for spent fuel management.

"The nuclear utilities would be bankrupted"

One of the major factors, if not the major consideration behind the Noda Administration's quick decision to continue reprocessing was the fear that cancelling the operation of the RRP would bankrupt JNFL and some of the nuclear utilities that own it and cause chaos in Japan's financial markets. (Nine regional semi-monopoly utilities and JAPC own more than 90% of the JNFL shares.)[78]

This is a surprising concern because, as explained above, not operating Rokkasho would save Japan many trillions of Yen (tens of billions of dollars). The issue relates, however, to the funding mechanism for the construction, operation, and decommissioning of RRP.

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.[79] This money was collected based on the 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 a Spent Fuel Reprocessing Fund managed by a national Radioactive Waste Management Funding and Research Center (RWMC). 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.

The first introduction of spent fuel into the RRP on 31 March 2006, the last day of FY2005, was the decisive step in creating the huge future cleanup costs now projected for after the shutdown of the RRP.

The construction costs to be covered by the fund soared to ¥2.19 trillion ($22 billion) from the ¥760 billion estimated at the time of the 1989 construction application. As of the end of FY 2004 (31 March 2005), therefore, 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 another ¥1.1 trillion.[80] Since the reprocessing is now to be paid for from the reprocessing fund, the utilities' advance payments are being repaid from the money JNFL receives from the fund. The advance payment balance at the end of FY2011 was about ¥0.6 trillion ($6 billion). JNFL's long term loans also have been gradually paid down and, as of the end of FY2011, the total amount outstanding was about ¥0.8 trillion ($8 billion).

In recent years, about ¥280 billion ($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.[81] As of the end of FY2011, a total of ¥4.6 trillion ($46 billion) had been put into the reprocessing fund and the unexpended amount was ¥2.7 trillion ($27 billion).[82] The amounts due annually on the long term loans taken out by JNFL were about ¥110 billion ($1.1 billion) at the end of FY2004 and ¥150 billion ($1.5 billion) at the end of FY2011.

Under current law, if reprocessing were cancelled, there could be no further payments to JNFL from the reprocessing fund. It was argued during the Noda Government's internal discussions on the future of Japan's nuclear energy policy that even talk of a moratorium on the operation of the RRP would cause chaos in Japan's financial markets. This was one reason why policy debate on this matter was not carried out openly. In a JAEC subcommittee meeting on 12 April 2012, in response to a question by JAEC Chair Kondo about a possible decision by the government to prohibit reprocessing, the following comment by Yuka Matayoshi, Vice President, Morgan Stanley MUFG Securities Co., Ltd., provides a hint of the concern: [83]

> "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."

The obvious solution to this problem would be for the government to change the law controlling the reprocessing fund to allow for paying off the JNFL loans even if the reprocessing plant does not operate. This would be the government "safety net" called for by Yuka Matayoshi. As already noted, the net effect for the ratepayers would be positive because they would no longer have to pay for the cost of operating the RRP.

At the same JAEC subcommittee meeting, a section head in charge of nuclear waste management in METI's Agency for Natural Resources and Energy stated:

> "It's not that you cannot change a policy because there is an existing system. I think it's the task of us bureaucrats to develop interim measures and the like if there is a policy change. It's absolutely not that the policy cannot be changed because there is this reserve system [to pay for reprocessing], in my view."

Here again, what is necessary is political will.

V. **Options for disposal of Japan's separated plutonium**

The current plan: MOX

Japan's plan for disposing of its separated plutonium has been and still is to irradiate it in the form of uranium-plutonium mixed-oxide (MOX) fuel in LWRs. In 1997, JAEC and the Federation of Electric Power Companies announced plans for using MOX fuel in 16 to 18 reactors by 2010. The plan was delayed considerably, however, by safety concerns in the prefectures hosting Japan's nuclear power plants. These concerns were fed by a number of safety scandals starting with the disclosure in 1999 that quality control data had been fabricated in the UK for MOX fuel produced for the Kansai Electric Power Company (KEPCO). In June 2009, the federation pushed back its MOX use goal to 2015.[84] As of the time of the Fukushima Daiichi accident, MOX fuel had been loaded into only four reactors.

The plan has been that Japanese-origin plutonium in Europe would be fabricated into MOX fuel and then shipped to Japan. Construction of a MOX-fuel fabrication plant (J-MOX) adjacent to the RRP is only just beginning for producing MOX from plutonium separated at the RRP. Therefore, if the RRP were to start commercial operation in 2014 as planned, separated plutonium would accumulate there for at least several years (Figure 2). In the past, the pilot MOX fuel fabrication plant at Tokai (Figure 9) has been used to fabricate MOX fuel for Japan's experimental and prototype fast-neutron reactors, *Joyo* and *Monju* (Figures 10), as well as for the shut-down heavy-water reactor *Fugen* (148 MWe, 1979-2003).

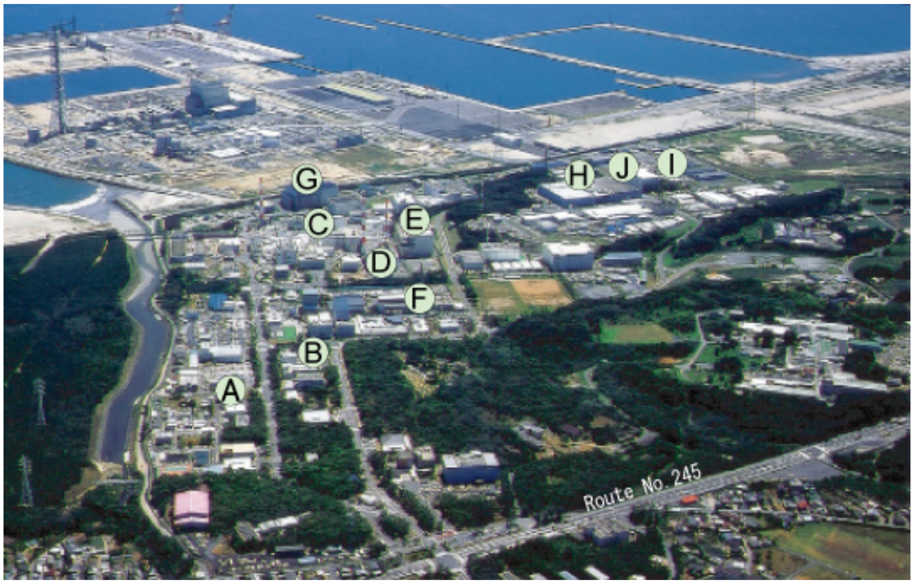

Figure 9. Japan Atomic Energy Agency Tokai Nuclear Fuel Cycle Engineering Laboratories: A. Emergency Control Center, B. Health and Safety Administration Building, C. Tokai Reprocessing Plant, D. Tokai High-level-liquid waste vitrification facility, F. Chemical processing Facility, G. Engineering Demonstration Facility, H. Plutonium Fuel Production Facility, I. Engineering Scale Test and Research Facility, and J. Quantitative Assessment Radionuclide Migration Experimental Facility.[85]

Figure 10. Japan's two breeder reactors. Left: The *Joyo* Experimental Fast Reactor (140 MWt) located in Oarai, near Tokai, began operations in 1978 and was shut down by a refueling accident in 2007. Right: The *Monju* 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.[86] Recently, preparations to restart *Monju* were halted again by the Nuclear Regulation Authority because of concerns about its safety management system.[87]

The J-MOX plant, like the RRP, will be owned by JNFL, which in turn is largely owned by Japan's nuclear utilities. According to JNFL's website, JNFL's projection for beginning of operations at the J-MOX plant have slipped till March 2016.[88] That date was set in 2010, however, and has not been updated officially despite a year's suspension of construction activities due to the Fukushima disaster. The construction was 3.5% complete as of 3 April 2013 when the work was restarted after the winter break.[89] JNFL's

March 2010 estimate of the capital cost of J-MOX ¥190 billion ($1.9 billion) also has not been updated.[90]

Experience with MOX in other countries has been mixed. France's government-owned corporation, AREVA, has been relatively successful in operating its MELOX MOX plant in Marcoule, southern France since 1995. The plant's capital cost has been given as €(2012) 1.4 billion ($1.8 billion)[91] but its operating cost has not been reported publicly.

AREVA has designed and is building for the U.S. Department of Energy a MOX plant with a much smaller capacity 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 $1.3 billion (all 2012$).[92] By May 2013, however, the estimated construction cost had risen to $7.7 billion and the operating cost over 15 years to $10 billion, i.e. to a total of $18 billion.[93] Given this situation, in April 2013, the Obama Administration announced that[94]

> "considering…the current budget environment, the Administration is conducting an assessment of alternative plutonium disposition strategies in FY 2013 [ending 30 Sept. 2013], and identifying options for FY 2014 and the out years. As a result, [the National Nuclear Security Administration] will slow down the MOX project and other activities associated with the current plutonium disposition strategy during the assessment period."

The UK built a MOX plant in 2001 – in large part to produce MOX fuel out of the plutonium it had separated for Japan – but abandoned it in August 2011 after an expenditure of £1.4 billion ($2.1 billion) after the plant had been able to operate at an average of only one percent of its design capacity for a decade.[95] In December 2011, the U.K. Department of Energy and Climate Change estimated, based on consultation with AREVA, that the discounted cost of building and operating a MOX plant in the U.K. for converting about 100 tons of separated plutonium into MOX fuel would be about £3 billion ($4.8 billion).[96] The basis for the cost estimate has been kept secret.[97] General arguments have been made, however, that the alternative of immobilization and direct disposal should be less costly.[98]

More delays expected after the Fukushima accident. After a decade of delay, about two tons of plutonium in MOX fuel were finally loaded into four Japanese reactors in 2009 and 2010.[99] But the 11 March 2011 accident made MOX fuel controversial again. Public concerns focused on the 200 kg of plutonium in MOX fuel in the core of Fukushima Daiichi unit #3.[100] Japan's utilities will likely again face a huge political challenge in gaining widespread acceptance of MOX fuel use.

But public acceptance must be obtained first for restarting the reactors. Only two of Japan's 50 theoretically operable nuclear power reactors are operating. Those two (Ohi 3 and 4) were put back into operation only because the central government feared that otherwise there would be serious power shortages in the Kansai area. Their seismic safety is currently being debated. The seismic safety of four other nuclear power plants – Higashidori (1 unit), Mihama (3), Shika (2) and Tsuruga (1) plus the *Monju* prototype breeder reactor – is also under investigation.[101] Three of the seven units at Kashiwazaki-Kariwa have been shut down since a powerful earthquake shook the region in July 2007. It is possible that a significant fraction of Japan's nuclear power capacity will not return into operation.

The new Nuclear Regulation Authority (NRA) plans to carry out a safety review of each of Japan's power reactors using new standards that are to be finalized in July 2013. The Abe Administration wants all the reviews to be completed within three years but NRA chairman Shunichi Tanaka believes that is unrealistic.[102]

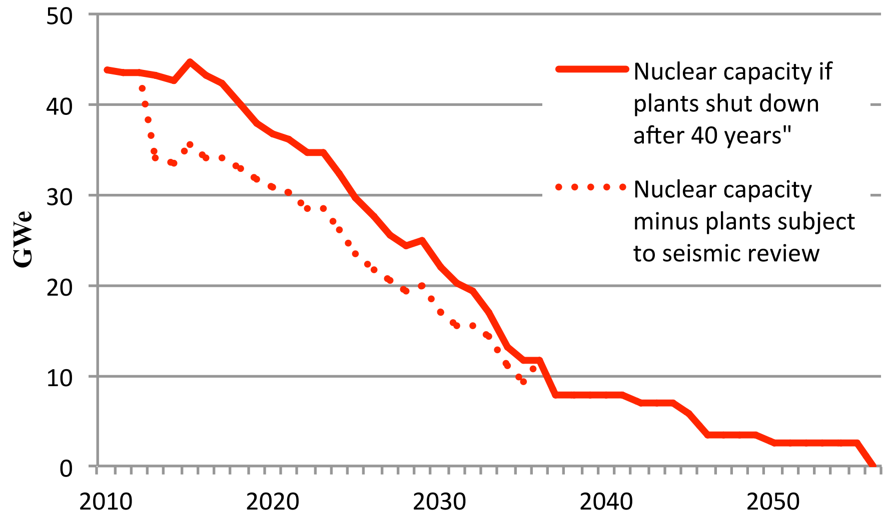

Figure 11. Japan's nuclear capacity if all reactors are shut down after 40 years of operation and the Ohma and Shimane 3 reactors are completed in 2015 but no other new reactors are constructed. Dashed line if the Higashidori, Mihama, Ohi, Shika and Tsuruga plants are not restarted.

For those reactors that return to operation, the question will be for how long? Figure 11 shows how Japan's nuclear capacity would decline with time if nuclear power reactors were forced to shut down after 40 years, as is often assumed.[103] It has been assumed for this scenario that the two reactors currently under construction (Ohma and Shimane 3) will be completed in 2015 but that there will be no new construction starts. The dashed line reflects a situation in which the plants currently subject to seismic review are not returned to operation. Assuming 20 tons of fresh fuel is charged per GWe-year and that one third of that could be MOX containing 8 percent plutonium, it would take 11 GWe of nuclear capacity plus the 1.4 GWe Ohma full-MOX-core reactor to absorb 8 tons of plutonium a year. In the scenario shown in Figure 11, Japan's nuclear capacity would drop below that level in 2035 – assuming that all Japan's nuclear power plants could be licensed to use MOX fuel. Fuel fabrication would have to end a year or two earlier and the separation of plutonium some years before that in order to eliminate Japan's stock of separated plutonium. Assuming that large-scale MOX use does not begin in Japan before 2020, the window for full-scale operation of Rokkasho would be relatively brief – about a decade. This makes even more acute the question, "what is the purpose of such a costly and controversial program?"

In the meantime, about a ton of unirradiated plutonium in MOX fuel is being stored indefinitely at five of Japan's nuclear power plants.[104] From a security perspective, this is not satisfactory. One Pressurized Water Reactor (PWR) MOX fuel assembly weighing half a ton contains about 36 kg of plutonium, enough for more than four Nagasaki-type nuclear explosives. One Boiling Water Reactor (BWR) MOX fuel assembly weighing

1/6 of a ton contains about 15 kg of plutonium, enough for about two nuclear explosives.[105] Thus, some of Japan's nuclear power plants are providing long-term storage for significant quantities of nuclear-weapon-usable material, a purpose that neither the plants nor their security arrangements were designed for.

Alternative disposition options

Japan's unirradiated plutonium (end of 2011)	**Metric tons**
In the United Kingdom	17.0
In France	18.0
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
– Oxide form, in fabrication, fuel product at Tokai fuel fabrication facility or 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	*9.4*
Total	**44.4**

Table 2. Japan's unirradiated plutonium as of the end 2011[106]

Table 2 shows the locations and forms of Japan's separated plutonium as of the end of 2011. Today, most of Japan's unirradiated plutonium is in Europe. The original plan for this plutonium was to make it into MOX fuel there and ship it to Japan for use.[107] Such shipments are controversial and costly and increase security risks, however. It therefore would be desirable to devise a strategy that would dispose of Japan's plutonium in the countries where it is currently stored.

Plutonium in the United Kingdom. The UK has volunteered to dispose of Japanese separated plutonium stored at the Sellafield reprocessing site, along with its own 100 tons "provided the commercial terms are right."[108] How the U.K. would do this remains to be decided.

In December 2011, the UK Department of Energy and Climate Change (DECC) tentatively concluded that the best option for disposing of the UK plutonium would be to build a new MOX-fuel fabrication plant.[109] The fuel would be for LWRs, however, and the UK currently has only one LWR in operation. The UK government is encouraging foreign nuclear utilities to build LWRs in the UK to replace 7.55 GWe of Advanced Gas-cooled Reactor capacity that is scheduled to be shutdown between 2016 and 2023.[110]

In the meantime, the U.K. National Nuclear Laboratory is setting up a production line at the UK reprocessing site in Sellafield to immobilize plutonium that is chemically contaminated and considered unsuitable for MOX without costly cleanup. The immobilization form 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.

The immobilization form is created by HIP, hot (1,100-1,320 ^{o}C) isostatic pressing (1,000 atmospheres) for 8-9 hours.[111] 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.[112]

In fact, HIP technology is in worldwide use, including in Japan.[113] In light of the problems that UK and U.S. have encountered with MOX, the relative maturity of MOX-production technology maybe less clear than DECC assumed. In any case, by the time the UK has enough LWR capacity to make a firm decision on MOX – perhaps a decade hence – the National Nuclear Laboratory project will likely have moved the immobilization of plutonium significantly down the road toward maturity. Japan might engage with the UK National Nuclear Laboratory so that it could understand the possibilities for immobilization of Japan's plutonium stocks in both the UK and Japan.

Plutonium in France. France might be willing to fabricate the Japanese separated plutonium in France into MOX and irradiate it in its own reactors. The 22 French reactors with capacities of approximately 900 MWe that are licensed to use MOX fuel all came into operation between 1977 and 1987 and are among France's oldest, however.[114] Furthermore, the new Hollande Administration has committed that France will reduce the nuclear share of its electric power generation from 75 to 50 percent by 2025.[115] Assuming that France's electric power consumption stays constant 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 the age of 40.[116] If that timing were followed for the remaining 900 MWe reactors, they all would shut down by the end of 2026. Currently, the control systems of France's 1300-1500 MWe reactors, which are ten years younger (beginning operation between 1984 and 1999) are not configured for MOX fuel and the conversion could be costly. France's new 1650 MWe EPR reactor is designed to use up to 100% MOX fuel[117] but thus far only one 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.[118] In any case, EDF has no intention to start up the unit on MOX fuel and has not indicated whether or not it might do so later. If the 900-MWe reactors are shut down after they have operated 40 years, France's ability to irradiate even its own plutonium will quickly decline and it may have to end its reprocessing program before 2020.[119] It is possible that, if Japan could not irradiate MOX either, AREVA might consider marketing MOX as an immobilization form that could be disposed of directly. Making "low-specification" MOX for direct disposal is one of the plutonium-disposition options considered by the UK Nuclear Decommissioning Authority in its "credible options" screening process.[120]

Direct disposal of plutonium in Japan. If Japan were able to have its plutonium in Europe dealt with there and decided not to operate the RRP, then its remaining plutonium disposal problem would be reduced to the approximately 9 tons of unirradiated plutonium currently in Japan, plus the estimated 0.9 tons of plutonium in the MOX fuel for Takahama Unit 3 expected to arrive in Japan in the latter half of June 2013.

Of this plutonium, as of the end of 2011, about one ton was in the form of fabricated fuel for Japan's experimental and prototype breeder reactors, *Joyo* and *Monju* and the *Fast*

Critical Assembly at Tokai that has been used to mock up breeder reactor (fast-neutron reactor) core designs.[121] If Japan's fast neutron reactor program is finally abandoned rather than being indefinitely postponed, these reactors could be shut down. In fact, *Monju* has been shut down since it had a sodium fire in 1995. *Joyo* too has been shut down since a 2007 refueling accident.[122] The prolonged shutdowns resulting from these refueling accidents illustrates the unreliability of sodium-cooled reactors that comes from the elaborate arrangements required to refuel and maintain them without exposing the sodium to air.

If these reactors are abandoned, then the associated unirradiated MOX fuel would have to be disposed of. When Germany decided in 1985 to abandon its SNR-300 prototype breeder reactor without operating it, its fuel was dissolved and the plutonium recovered for disposal in MOX fuel.[123] If permission cannot be obtained within a reasonable time period for loading the one ton of plutonium MOX fuel currently stored at Japan's nuclear power plants plus the 0.9 tons in MOX scheduled to arrive in June 2013, then the same could be done with it. All of Japan's domestic stock of unirradiated plutonium then would be in oxide form.

The question then would be simplified to one of what to do with approximately 10 tons of plutonium in oxide form in Japan? It would not be cost effective to build the costly J-MOX plant to dispose of such a relatively limited tonnage of plutonium.

One possible alternative would be to immobilize the plutonium in a ceramic form for direct disposal. As noted above, the UK is developing the capability to dispose of contaminated UK plutonium in this manner. The canned ceramic waste form is to have a volume of 5 liters and can easily contain 10 percent plutonium by weight, i.e. about 2 kg.[124] This is about five thousand times the amount of plutonium in a pellet of MOX fuel.[125] About 0.02 percent as many cans of ceramic as MOX pellets therefore would be required to dispose of the same amount of plutonium.

The dimensions required of the immobilization form also would be much less precise than those of the pellets. The gap specified between the outside of a MOX pellet and the zirconium fuel-rod tube in which it is placed is less than 0.1 mm[126] and the grinding accuracy for the pellet diameter is required by Japan to be ±0.0125 mm.[127] By contrast, disposal forms would not have to be ground to such exact dimensions.

Thus, there are good reasons to expect that the production of immobilization forms of plutonium could be much less costly than the production of MOX fuel per kilogram of disposed plutonium. The issue then would be to see whether the savings in production would be offset by the fuel value of the MOX or by greater disposition costs.

The latest estimates of U.S. MOX fuel production costs show them ten times higher than the fuel value of the MOX.[128] This would likely be the case in Japan as well – especially given the relatively small amount plutonium it would have to dispose of if reprocessing were not resumed.

What about the disposal costs of immobilized plutonium? Spent MOX fuel will require several times as much space in a geological repository as LEU spent fuel. Its long-term heat output is several times higher and therefore several times more casks would be required to maintain the same limit on the cask surface temperature.[129] If loaded into a repository, the immobilized plutonium that otherwise would have been used to make a ton of MOX fuel and the ton of spent LEU fuel that would replace the ton of MOX fuel would generate together somewhat less heat than the ton of spent MOX fuel that would otherwise have been produced.[130] The disposal costs associated with the immobilization option therefore should not be greater than for the MOX option. To increase its security in a repository, the immobilization form could be enclosed with spent fuel in a welded-shut cask. Alternatively, embedding immobilized plutonium in glassified high-level waste, as the U.S. discussed in the 1990s, could provide a protective radiation barrier.

Borehole disposal. A much less reversible option than repository disposal of immobilized plutonium would be deep borehole disposal. This also was investigated briefly during the mid-1990s in the United States for the disposal of surplus U.S. weapons plutonium. It was concluded that the isolation from the surface and fresh water aquifers could be greater than for a 0.3-0.5 km deep mined repository because movement of water through the deep compressed rock would be very slow. [131] Geothermal wells with diameters of 0.27 m have been drilled to 5 km at an estimated cost of about $8 million and could store about 8 tons of plutonium per borehole, i.e. about the amount in Japan's domestic stockpile.[132] Deep borehole disposal is being examined today in the U.S. for spent fuel disposal.[133] It would be worth examining whether there are regions with suitably stable basement rock in Japan.

Given that the United Kingdom is pursuing immobilization for some of its plutonium and that alternatives to MOX are now being examined in the United States, a coordinated R&D program on direct disposal might be of interest to all three countries. France's AREVA might be interested in joining as well. It would have a conflict of interest, however, as long as it is trying to persuade the UK to contract with it and United States to continue to contract with it for the construction and operation of MOX fuel fabrication facilities.

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[2] Japan stores its domestically separated plutonium mixed with an equal amount of uranium but, because of the absence of highly radioactive fission products, separation of the plutonium from the mix could be done safely and easily in a glove box (plutonium is highly carcinogenic if inhaled.)

[3] The NRA's policy is that, if the proof is not decisive, the history of seismic activity going back 400,000 years has to be researched and taken into consideration, document on earthquake and tsunami examination guidance (in Japanese) distributed at the 5 April 2013 meeting of NRA's working group, http://www.nsr.go.jp/committee/yuushikisya/shin_taishinkijyun/data/0012_02.pdf

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

[5] We have been told by different sources within the central government that this argument was made repeatedly during the internal government debate over Japan's reprocessing policy. It was claimed that even talk of a reprocessing moratorium would make it impossible for JNFL to borrow more money until the operation of RRP makes it possible to begin to draw money from the reprocessing fund.

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[7] "Estimation of Nuclear Fuel Cycle Cost and Accident Risk Cost (Statement)" (JAEC, 10 Nov. 2011).
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[12] http://www.jnfl.co.jp/english/business/reprocessing.html
[13] Assumed reprocessing rate of 80 tons of spent fuel in 2014, 320 in 2015, 480 in 2016, 640 in 2017 and 800 annually thereafter, based on JAEC Fuel Cycle Planning Committee presentation, 25 Oct. 2011 with reprocessing assumed to be delayed by two years.
[14] *Global Fissile Material Report 2011*, Figure 4.
[15] A chronology of the successes and failures and reversals of utilities in obtaining permission from municipal and prefectural governments to use MOX fuel in 13 power reactors may be found at http://www.cnic.jp/english/topics/cycle/MOX/pluthermplans.html
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[17] http://www.fukuishimbun.co.jp/localnews/nuclearpower/41190.html
[18] Japan launched MOX fuel production at its Pilot Fuel Fabrication Facility in 1966 with 0.26 kg of plutonium provided by the United States, Japan Atomic Energy Agency, "MOX Fuel Development in Japan," (undated), http://insaf-net.org/mox_wg/JAEA.pdf. Between 1970 and the end of 1984, Japan received about 1 ton of plutonium from the reprocessing of the fuel from its Magnox reactor (Tokai 1) in the UK, about 0.25 tons from reprocessing its LWR fuel in France as well as about 0.75 tons of foreign plutonium purchased from the United States, United Kingdom, France and Germany. By the end of 1984, Japan had a total of 1.3 tons of fissile plutonium (0.66 tons from reprocessing Japan's Magnox fuel in the UK, 0.16 tons from reprocessing Japan's LWR fuel in France) and 0.48 tons of foreign plutonium – corresponding to almost 2 tons total plutonium. See "Plutonium - Do We Really Need It?" *Nuke Info Tokyo,* #16, March/April 1990, p. 2, http://www.cnic.jp/english/newsletter/pdffiles/nit16_.pdf. Starting in 1977, domestic reprocessing began at the Tokai Reprocessing Plant (210 ton/year design capacity), first on a test scale and then, in 1981, on full scale. By 1993, the Tokai Reprocessing Plant had separated 5.2 tons of plutonium, see David Albright, Frans Berkhout and William Walker, *Plutonium and Highly Enriched Uranium 1996* (Oxford University Press, 1997), Table 6.8.
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[28] *Nuclear Wastes: Technologies for Separations and Transmutation* (National Academy Press, 1996), p. 3.
[29] *Fast breeder reactor programs: History and Status* (IPFM, 2010), p. 56.
[30] *Spent Nuclear Fuel: Accumulating Quantities at Commercial Reactors Present Storage and Other Challenges* (US Government Accountability Office, 2012) pp. 20-21.
[31] 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
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[60] 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

[61] http://www.pref.aomori.lg.jp/soshiki/soumu/zaisei/files/zaiseijijou_201206_all.pdf

[62] http://cgi.daily-tohoku.co.jp/cgi-bin/tiiki_tokuho/kakunen/kikaku/tenki/money_02.htm. Aomori followed the example Fukui Prefecture, which also 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

[63] Laws on Electric Power Development Taxation, Special Budget for the Development of Electric Power, and for the Adjustment of Areas Adjacent to Power Generating Facilities.

[64] http://cgi.daily-tohoku.co.jp/cgi-bin/tiiki_tokuho/kakunen/news/news2012/kn120531a.htm

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

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

[67] Slide from of JAEC Fuel Cycle Planning Committee presentation, 25 Oct. 2011.

[68]METI's Agency for Natural Resources and Energy, 16 Jan. 2013 reply to the office of Diet member Mizuho Fukushima. Only France is sending back intermediate-level waste. The U.K. is sending an equivalent (in Curies) extra amount of high-level waste. In addition, Japan shipped about 1510 tons of spent Magnox fuel from the Tokai I reactor (operated from 1965-98) to the UK for reprocessing (White Paper on Nuclear Energy 2003 (in Japanese), page 148, http://www.aec.go.jp/jicst/NC/about/hakusho/hakusho2003/23.pdf) but 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 1,400 tons of spent fuel containing about 3 tons of plutonium total for a burnup of about 3GWt-days/ton, Albright et al, op. cit., Table C.2.

[69] 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, 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

[70] 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, 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 by 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. 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 in store; production had averaged about 200 cans per year during the previous four years; and it was expected that future production would be in the 200-350 can/year range (Martin Forwood, personal communication, 30 Nov. 2012).

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

[72] Only casks for BWR spent fuel have been licensed for Mutsu thus far. Mitsubushi 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 the Tsuruga nuclear power plant.

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

[74] Assuming that the average burnup of the spent fuel in the reactor pools is 36.5 MWt-days/kg.

[75] METI, ''Purusamru Jisshi ha Nihon to Chiiki no Mirai no Tameni Hitsuyodesu'' ("The Implementation of the Plu-thermal Program is Necessary for the Future of Japan and the Region), kakujoho.net/mox/hiranm.html

[76] The first shipment of high-level waste from France arrived at Rokkasho in 1995, "Japanese Waste and MOX Shipments From Europe," World Nuclear Association, http://www.world-nuclear.org/info/inf39.html

[77] *Daily Tohoku*, http://cgi.daily-tohoku.co.jp/cgi-bin/tiiki_tokuho/kakunen/news/news2012/kn121128b.htm
Fukui Shimbun Dec.5, 2012, http://www.fukuishimbun.co.jp/localnews/nuclearpower/38404.html (in Japanese).

[78] http://ja.wikipedia.org/wiki/%E6%97%A5%E6%9C%AC%E5%8E%9F%E7%87%83

[79] This amount is mentioned by Hitoshi Yoshioka in his memo to the AEC dated 24 September 2004: http://www.aec.go.jp/jicst/NC/tyoki/sakutei2004/sakutei08/siryo12.pdf

[80] http://www.uforeader.com/v1/se/E04785_0050AW4K_16_32.html##E0062

[81] http://www.rwmc.or.jp/financing/file/saisyori_unyozisseki23.pdf
LDP's Taro Kono comments on "basic charge" sum disclosed by METI at http://www.taro.org/2012/10/post-1280.php

[82] The projected amounts for the end of FY2012 (31 March 2013) were ¥4.7 trillion and ¥2.6 trillion respectively)http://www.rwmc.or.jp/english/fund_administration_1/

[83] http://www.aec.go.jp/jicst/NC/tyoki/hatukaku/siryo/siryo15/siryo4.pdf

[84] http://www.fepc.or.jp/about_us/pr/sonota/1198266_1511.html

[85] http://www.jaea.go.jp/english/04/tokai-cycle/01.htm

[86] Image of *Joyo* from Yukimoto Maeda, Japan Atomic Energy Agency, "Retrieval of Damaged Components from Experimental Fast Reactor *Joyo* Reactor Vessel," 8 June 2010, https://secure.inl.gov/atrproposal/Documents/UsersWeekPresentations2010/LunchPresentations/JoyoWorkingLunch68Maeda.pdf. Image of *Monju* from Image from "Monju, Mihama nuke plant sites must be checked for active faults: panel," 12 Aug. 2012, http://www.houseofjapan.com/local/monju-mihama-nuke-plant-sites-must-be-checked-for-active-faults-panel

[87] 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

[88] http://www.jnfl.co.jp/english/business/mox.html (accessed 3 May 2013).

[89] http://cgi.daily-tohoku.co.jp/cgi-bin/tiiki_tokuho/kakunen/news/news2013/kn130404c.htm

[90] *Mainichi,* 4 April 2010, cited by http://www.wise-uranium.org/epasi.html#JNFLMOX

[91] 7.5 billion French Francs, Jean-Michel Charpin, Benjamin Dessus, René Pellat, *Economic Forecast Study of the Nuclear Power Option* (Report to France's Prime Minister, 2000), Annex II, Chapter II, "Bilan Économique du Parc Nucléaire Actuel," p. 148, footnote 1, http://www.ladocumentationfrancaise.fr/var/storage/rapports-publics/014000107/0002.pdf

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

[93] 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.

[94] U.S. Department of Energy (DoE), *FY 2014 Congressional Budget Request, Vol. 1. National Nuclear Security Administration* (NNSA), p. DN-119.

[95] Phil Chaffee, "Sellafield Mox Plant to Close," *Nuclear Intelligence Weekly,* 8 August 2011.

[96] *Management of the UK's plutonium stocks: A consultation response on the long-term management of UK-owned separated civil plutonium* (UK Department of Energy and Climate Change, 1 Dec. 2011, p. 15.

[97] The UK Nuclear Decommission Authority published a redacted version of its *Plutonium: Credible Options Analysis* (2010) but costs and even the titles of the documents referenced had been redacted.

[98] Frank von Hippel, Rodney Ewing, Richard Garwin and Allison Macfarlane, "Time to bury plutonium," *Nature* 10 May 2012, p. 167.

[99] Genkai 3 (starting 5 Nov. 2009, 677 kg), Ikata 3 (2 March 2010, 633 kg), Fukushima 3 (8 Sept. 2010, 210 kg), and Takahama 3 (25 Dec. 2010, 368 kg), http://www.cnic.jp/english/topics/cycle/MOX/pluthermplans.html#table%201

[100] For the flavor of the debate in English, see John Matson, "MOX Battle: Mixed Oxide Nuclear Fuel Raises Safety Questions: One of the troubled Fukushima Daiichi reactors contains a blend of uranium and plutonium fuel that may soon find use in the U.S. Does it pose more risks than standard uranium fuel?" *Scientific American,* March 2011, http://www.scientificamerican.com/article.cfm?id=mox-fuel-nuclear.

[101] "NRA in Spotlight Over Payments and Ohi Seismic Study," *Nuclear Intelligence Weekly,* 9 Nov. 2012.

[102] *Nuclear Intelligence Weekly,* 11 January 2013.

[103] By this standard, three nuclear power reactors would not re-start: Tsuruga 1, and Mihama 1 and .2

[104] Genkai #3 (PWR, 4 assemblies, 161 kg plutonium, 9% assuming 450 kgHM/assembly); Hamaoka #4 (BWR, 28 assemblies, 213 kg plutonium, 4% assuming 180 kgHM/assembly); Ikata #3 (PWR, 5 assemblies 198 kg plutonium, 9%); Kashiwazaki Kariwa #3 (BWR, 28 assemblies, 205kg plutonium, 4%); Takahama #4 (PWR, 4 assemblies; 184 kg plutonium, ~10%), http://www.cnic.jp/english/topics/cycle/MOX/pluthermplans.html#table%201.

[105] 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 of chemical explosives, J. Carson Mark, "Explosive Properties of Reactor-Grade Plutonium," *Science & Global Security*, Vol. 4(1) 1993.

[106] "The Current Situation of Plutonium Management in Japan," 11 Sept. 2012 (in Japanese). http://www.aec.go.jp/jicst/NC/iinkai/teirei/siryo2012/siryo39/siryo2.pdf

[107] AREVA, "Transport of Mox Fuel from Europe to Japan," http://www.areva.com/EN/operations-1391/transport-of-mox-fuel-from-europe-to-japan-the-stakes.html; see also http://www.pntl.co.uk/our-fleet/

[108] "Britain can reuse plutonium extracted from Japan's spent fuel: expert," *Japan Times,* 24 Nov. 2012, http://www.japantimes.co.jp/text/nn20121124b5.html, quoting Adrian Simper, strategy and technology director at the UK Nuclear Decommissioning Authority.

[109] 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*, 1 Dec. 2011.

[110] http://www.edfenergy.com/about-us/energy-generation/nuclear-generation/nuclear-power-stations/

[111] J.W. Hobbs, et al, UK National Nuclear Laboratory, "A Programme to Immobilise Plutonium Residues at Sellafield, " *Annual Meeting of the Institute for Nuclear Materials Management,* Orlando, FL, 15-19 July 2013.

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

[113] See e.g., "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.

[114] 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. 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.

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

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

[117] 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

[118] "Flamanville EPR to cost at least €8 billion," *Nuclear Intelligence Weekly,* 7 Dec. 2012.

[119] Phil Chaffee, "A 2019 Halt to La Hague?" *Nuclear Intelligence Weekly,* 10 May 2013.

[120] UK Nuclear Decommissioning Authority, *Plutonium: Credible Options Analysis* (2010).

[121] Japan Atomic Energy Commission, "The Current Situation of Plutonium Management in Japan" (as of end of 2011, in Japanese).

[122] Yukimoto Maeda, Japan Atomic Energy Agency, "Retrieval of Damaged Components from Experimental Fast Reactor *Joyo* Reactor Vessel," 8 June 2010, https://secure.inl.gov/atrproposal/Documents/UsersWeekPresentations2010/LunchPresentations/JoyoWorkingLunch68Maeda.pdf

[123] *Managing Spent Fuel from Nuclear Power Reactors: Experience and Lessons from Around the World* (IPFM, 2011) p. 47.

[124] "A Programme to Immobilise Plutonium Residues at Sellafield, " *op. cit*.

[125] A MOX pellet contains 0.38 grams of plutonium, assuming 8 percent plutonium in the fuel and that the pellet is 0.8 cm in diameter and 1 cm long,

[126] Framatom, "Fuel Qualification Plan Prepared for the US Department of Energy Office of Fissile Material Disposition," submitted to the US Nuclear Regulatory Commission, 2001, Table 6-1, http://pbadupws.nrc.gov/docs/ML0133/ML013390597.pdf

[127] *An Investigation into the Falsification of Pellet Diameter Data in the MOX Demonstration Facility at the BNFL Sellafield Site and the Effect of this on the Safety of MOX Fuel in Use* (.UK Office of Nuclear Regulation, 1999), http://www.hse.gov.uk/nuclear/mox/mox1.htm, para. 84. The UK Office of Nuclear Regulation claimed, however, that diameter deviations of 0.1 mm would be required to create a safety problem, *op. cit.,* para. 85

[128] At 4 weight percent, 34 tons of weapon-grade plutonium produced at a currently estimated cost of $18 billion will result in 850 tons of MOX fuel that would replace LEU fuel worth about $2 billion for a uranium cost of $100/kgU and an enrichment cost of $120/SWU, (see Frank von Hippel, "National Fuel Stockpiles: An Alternative to a Proliferation of National Enrichment Plants?" *Arms Control Today,* Sept. 2008, p. 20). The MOX fuel would have to be sold at a deep discount, however, because of the licensing cost, security requirements before the fuel is loaded and public aversion to MOX fuel.

[129] Roald A. Wigeland et al, "Repository Impact of Limited Actinide Recycle," Proceedings of Global 2005, Tsukuba, Japan, Oct 9-13, 2005, Paper No. 496. ANDRA, the agency responsible for designing France's radioactive waste repository, expects that a disposal container would hold either four LEU or one MOX spent pressurized-water reactor fuel assemblies, personal communication to FvH, 18 March 2013.

[130] J. Kang, F. N. von Hippel, et al, "Storage MOX: A Third Way for Plutonium Disposal?" *Science and Global Security*, Vol. 10, p. 85, 2002.

[131] William G. Halsey, et al, *Disposition of Excess Fissile Materials in Deep Boreholes* (Lawrence Livermore National Laboratory, UCRL-JC-120053 1995).

[132] F.G.F. Gibb, "The 'granite encapsulation' route to the safe disposal of Pu and other actinides," *Journal of Nuclear Materials* Vol. 374 (2008) p. 364; *The Future of Geothermal Energy: Impact of Enhanced Geothermal Systems (EGS) on the United States* (MIT, 2006), Figure 6.8.

[133] U.S. Department of Energy, *Strategy for the Management and disposal of Used Nuclear Fuel and High-level Radioactive Waste*, January 2013, p. 13.