From reprocessing and breeder reactor development to dry cask storage of spent fuel

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1. Historical Background

Why civilian reprocessing began in the 1970s. Reprocessing was originally developed during World War II to obtain plutonium for the U.S. nuclear-weapon program. But even during World War II, some of the scientists involved hoped that, after the war, the focus would shift to using uranium as fuel for power reactors.

It was believed that uranium was too scarce to support large-scale nuclear energy based primarily on the fission energy obtainable from the rare chain-reacting isotope U-235 (0.7 percent of natural uranium). In 1944, therefore, Leo Szilard invented the liquid-sodium-cooled plutonium breeder reactor to exploit the fission energy latent in non-chain-reacting U-238 that makes up 99.3 percent of natural uranium.[1] The idea was to turn U-238 into chain reacting Pu-239 in a plutonium-fueled "breeder reactor" that would produce more plutonium than it consumed.

Belgium, France, Germany, India, Italy, Japan, Russia, the UK and the United States, separately and in various combinations, all launched breeder reactor and civilian reprocessing programs to recover the plutonium in spent power reactor fuel in the expectation that the plutonium would be needed for initial cores of the plutonium breeder reactors, which were expected to be commercialized in the 1970s.[2]

Why breeder reactors have failed commercially. In 1975, the IAEA projected that global nuclear power capacity would grow to 1600 GWe by 2000 while also estimating that the global uranium resource amounted to 3.5 million tons, only enough to support 500 GWe of light-water reactor capacity for about 40 years.[3] But nuclear power did not grow that rapidly and more uranium was found. Today, global capacity is 375 GWe, the IAEA projects that the capacity in 2050 will be between 560 and 1230 GWe[4], and global uranium resources recoverable at current low prices are estimated at 17.5 million tons, enough to support 2500 GWe for 40 years

The price of natural uranium has fluctuated. The underlying trend has not been upward, however. At the current price of $130/kg, which is higher than the historical average, uranium contributes about 3 percent to the price of a kilowatt-hour of nuclear electricity. The elimination of this cost for breeder reactors would be approximately offset by the cost of reprocessing breeder reactor fuel. In order to compete with a water-cooled reactor, therefore, the capital cost of a sodium-cooled reactor would have to be approximately the same.

There is, in fact, one important factor that would tend to reduce the relative capital cost of a sodium-cooled reactor: it operates far below the boiling temperature of sodium (883 ºC) and therefore at low pressure, while water-cooled reactors operate above the boiling temperature of water and hence require thick pressure vessels and piping.

Another key factor cuts in the opposite direction, however: sodium burns when exposed to air or water. Leakage is therefore much more damaging than from a water-cooled reactor. Also, it is impossible to simply open up the reactor during refueling or for maintenance, as is done with light-water reactors. As a result, as Admiral Hyman Rickover stated in 1956, after trying a sodium-cooled propulsion reactor in the second U.S. nuclear submarine, sodium-cooled reactors are "expensive to build, complex to operate, susceptible to prolonged shutdown as a result of even minor malfunctions, and difficult and time-consuming to repair."[5]

Experience has mostly borne out Rickover's assessment. Of the highest-power sodium-cooled reactors built by France, Germany, Japan, Russia, the U.K. and United States, only one achieved any longevity or a capacity factor above 20 percent. That reactor is Russia's BN-600 reactor, which has operated for more than 30 years with a cumulative capacity factor slightly greater than 70 percent despite 14 sodium fires in its first 17 years.[6]

The OECD countries, including France, Germany, Japan, the UK and the United States, on average devoted about half of their nuclear-energy research, development and demonstration (RD&D) budgets to breeders until the early 1980s but today, Japan is the only OECD country that reports expenditures on breeder R&D -- about 10 percent of its total budget for fission R&D. India and Russia, which are not members of the OECD, however, are building large prototype reactors (500 and 800 MWe respectively). Overall about $100 billion has been spent on breeder reactor R&D thus far.[7]

Unlike other major OECD countries, Japan has delayed abandoning breeder reactor R&D and reprocessing . The U.S., Germany and now the U.K. have abandoned both for economic and nonproliferation reasons. France is the other OECD country that has not completed the process. France has decommissioned its fast-neutron breeder reactors but continues – for now – a commitment to reprocessing, despite the complaints about the cost from its major utility, Électricité de France. That is probably in part at least because of the continuing efforts by the French government-owned nuclear services company, AREVA, to sell reprocessing plants to China and the United States, and a MOX plant to the U.K.

2. Present situation around the world

Country choices with regard to reprocessing. With the failure of their breeder commercialization efforts, France and Japan decided nevertheless to continue to reprocess and to recycle the resulting separated plutonium once into fresh fuel for their light-water-cooled reactors. France also has begun to re-enrich the uranium it recovers by reprocessing and recycle the product once as well. This reduces the uranium requirements of a light water reactor by about 25 percent but that saving is more than offset by the cost of reprocessing.

Japan has built a $27 billion (¥2.2 trillion[8]) plant designed to reprocess 800 tons of light water reactor fuel annually. It was supposed to start up in 1997 but has only reprocessed 425 tons so far because the melters, which are supposed to immobilize high-level reprocessing waste in glass, are not functional. Recently, Japan's Atomic Energy Commission (JAEC) estimated that proceeding with the program will increase the cost of electricity in Japan by about $130 billion (¥10 trillion) over the 40-year design life of the new reprocessing plant relative to interim storage and then disposal of spent fuel in a deep underground repository.[9] The cost of the construction and the estimated ¥1.9 trillion cost to decontaminate the plant are now committed but the estimated ¥7 trillion that it will cost to operate the plant over 40 years could still be saved.[10]

Because of the high cost of reprocessing and the fact that high-level reprocessing waste is no easier politically to dispose of than spent fuel, most countries are currently storing their spent fuel moving older fuel to "dry casks" cooled by air pending the availability of a deep geological repository or a later decision to reprocess.[11]

Of the 31 countries with operating nuclear power plants:

- Eleven have never reprocessed their spent power reactor fuel. A twelfth, the United States, has not reprocessed since 1972.[12]
- Eleven countries sent spent fuel to France, Russia or the U.K. for reprocessing but decided not to renew their contracts. Ten decided to store their spent fuel instead. The eleventh, Japan, decided to build a domestic reprocessing plant.
- Six reprocess. France and the U.K. have large operating reprocessing plants, although the U.K. plans to end reprocessing when its current contracts have been fulfilled (currently estimated as 2018).[13] Japan has a large reprocessing plant that is not fully operational yet. India operates three small reprocessing plants. China and Russia operate pilot reprocessing plants.[14] China, India and Russia all are reprocessing because they still believe that plutonium breeder reactors will be required.
- The Netherlands and Ukraine have renewed their reprocessing contracts for small amounts of spent fuel that they are shipping to France and Russia respectively.

3. Japan's situation and problems

Japan's choice. Japan is currently debating whether or not to continue with reprocessing. The arguments for stopping include:

- The cost savings associated with shifting to dry cask storage,
- That some other non-weapon states that may be interested in separating plutonium to obtain a nuclear-weapon option may cite Japan, the only non-weapon state that still reprocesses, as a model, and
- That separating plutonium puts it closer to the reach of terrorist groups.

Supporters of the existing reprocessing policy argue that:

- Reprocessing and plutonium recycle save uranium and greatly reduce the presence of plutonium in radioactive waste;
- Ending reprocessing would mean no place for spent fuel to go and thus require nuclear power plants to build dry cask storage for their older spent fuel. If local governments withhold permission for doing so, the nuclear power plants would have to shut down when their spent fuel storage pools are full;[15] and
- It is too late to change policy because of all the commitments that have made – the construction of the Rokkasho Reprocessing Plant, the funds that have been established to support reprocessing, the workers who have been hired to work on operating the Rokkasho Reprocessing Plant and building a MOX fuel plant next to it

plant, and the political commitments and tax payments that are being made to the governments of Aomori Prefecture and Rokkasho Village.

I discuss some but not all of these issues in this paper. With regard to some of the arguments for reprocessing, I make only the following observations:

- As has already been made clear, reprocessing and plutonium and uranium recycle in current generation reactors only reduce uranium demand by about 25 percent and cost many times more than the value of the uranium saved. The fuel value in the unreprocessed fuel would remain available if, in the distant future, it was decided that it would be worthwhile to recover it and recovery would be less costly because of the decay of the main gamma-emitter, 30-year half-life cesium-137.
- With regard to reducing the radioactive threat to future generations, plutonium removal from high-level reprocessing waste reduces the quantity of long-lived transuranic elements to about one fifth the amount in spent uranium fuel.[16] If spent MOX fuel is treated as a waste as currently seems likely, however, the amount of plutonium in radioactive waste will be reduced by less than half. In a 1996, the U.S. National Academy of Sciences published a detailed cost-benefit assessment of proposals to eliminate long-lived radioisotopes in spent uranium fuel using fast-neutron reactors or accelerators and concluded that "[e]stimates of changes in dose [to future generations from nuclear power and radioactive waste] are small…Taken alone, none of the dose reductions seem large enough to warrant the expense and additional operational risk of transmutation." The report also raised the issue of the proliferation dangers from reprocessing.[17]
- Spent fuel storage is much less costly than reprocessing. That is why so many countries have abandoned reprocessing. It is also a much more secure way of storing plutonium because of the self-protection provided by the gamma-emitting fission products – especially 30-year half-life cesium-137. Finally, in the absence of breeder reactors, it simplifies radioactive waste disposal. All the waste is confined in the spent fuel. In contrast, reprocessing creates multiple waste types, including ultimately the reprocessing plant itself.
- Initially, when it is discharged from a reactor, spent fuel must be water cooled in a pool next to the reactor. After several years of cooling, however, it can be shifted to a dry air-cooled cask. Figure 1 shows dry casks stored at the Fukushima Daiichi nuclear power plant that survived the earthquake and tsunami and the consequent damage to the building housing them with their contents undamaged. There was so little concern about possible damage to the spent fuel inside that Japan's public still is generally unaware that there was dry-cask storage of spent fuel at the plant.
- Japan has stayed with reprocessing because of concern about the consequences of upsetting long-standing financial and political arrangements. Now, however, all arrangements relating to nuclear power in Japan are under reconsideration as a result of the Fukushima accident. In addition to all the costs associated with that accident, Japan could also realize offsetting benefits by ending its breeder reactor commercialization and reprocessing programs, which make no economic or environmental sense.

- With regard to the difficulties of changing a reprocessing policy, it might be useful for Japan’s policy makers to review how the United Kingdom did it. The process included a decision by the government in 2005 to replace British Nuclear Fuels Limited (the UK analogue of Japan Nuclear Fuels Limited) with the government-owned Nuclear Decommissioning Authority. In the U.S. too, when the nuclear utilities decided in 1982 that reprocessing would be more costly than direct disposal, they asked the government to take responsibility for direct disposal in exchange for a tax on nuclear-generated electricity that, based on an estimate of disposal costs, has been set at 0.1 cents (¥ 0.08) per kilowatt hour.[18]

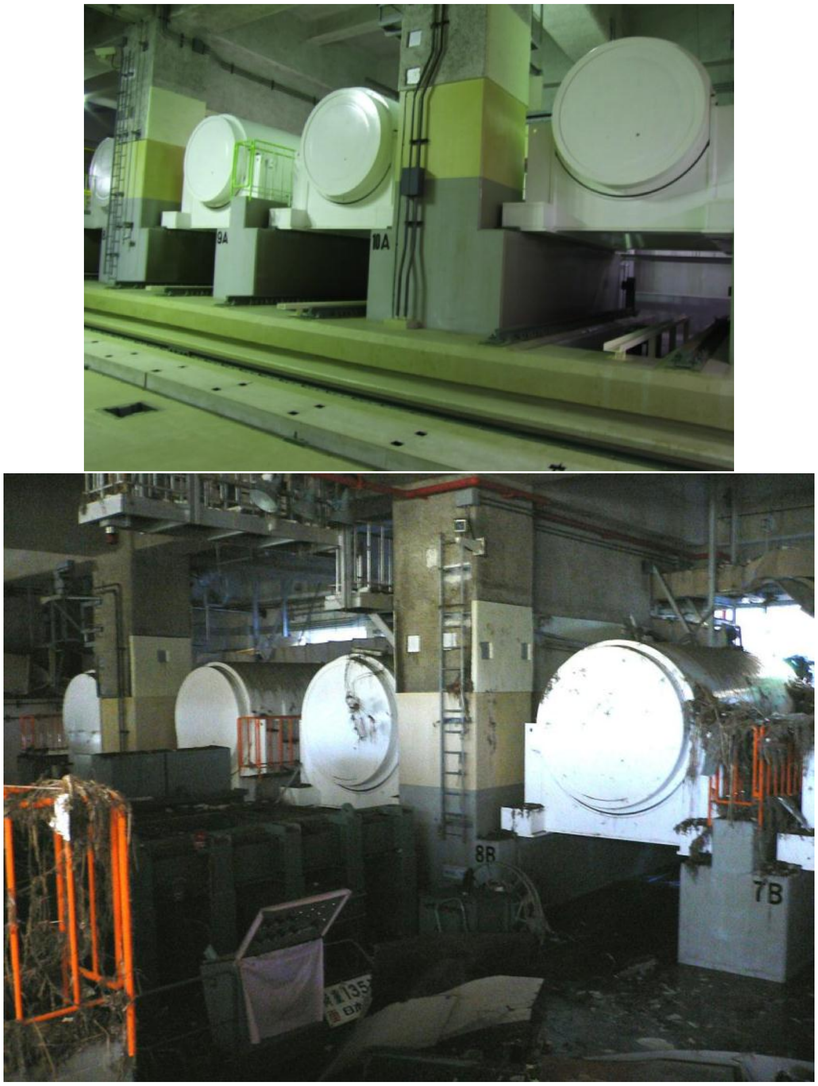

Figure 1. Spent fuel storage casks at the Fukashima Daiichi Nuclear Power Plant before (top) and after (bottom) the tsunami. The casks have not yet been opened but it is believed that the fuel within is undamaged.[19]

The dangers of possible use of separated plutonium for nuclear or radiological weapons. Historically, in almost all cases, the near-term objective for acquiring reprocessing capabilities has been to obtain separated plutonium for weapons. This includes France and India, which claimed that their reprocessing programs were being launched to prepare for the commercialization of breeder reactors, and a number of other countries, including Argentina, Brazil, South Korea, Sweden and Taiwan, which sought reprocessing plants for weapon purposes, although they abandoned those ambitions as a result of internal political change and external pressure. Japan is the notable exception of a country that persisted in reprocessing and not used the separated plutonium for weapons, but its example – and those of the weapon states (China, France, India and Russia) that continue to reprocess for nominally civilian purposes – provides an argument for other countries that may want a civilian pretext to develop a nuclear-weapon option.

In fact, Japan's example is being used by South Korea, in its negotiation of a new agreement on nuclear cooperation with the United States, to argue that the U.S. should give South Korea the same right to reprocess fuel enriched in the United States or irradiated in U.S.-designed reactors as it agreed to in 1988 with Japan.[20]

There is also the risk of theft by terrorists. About 250 tons of separated civilian plutonium have accumulated as result of civilian reprocessing – about as much as was separated by the Soviet Union and United States for weapons during the Cold War. Most of the civilian plutonium is not weapon grade but all of it is weapon useable. Eight kg is more than sufficient for the manufacture of a Nagasaki-type nuclear weapon.[21] The 250 tons of separated civilian plutonium is therefore sufficient for more than 30,000 Nagasaki-type nuclear weapons and should be guarded as a weapons material. In many cases, however, because of cost concerns and civilian cultures, civilian separated plutonium is not guarded to anywhere near the same security standards as military plutonium and is therefore at greater risk of theft.[22]

Civilian plutonium is mostly stored as PuO_2, which is exceedingly dangerous if dispersed in the air. The inhalation of one gram by a large population would cause on the order of 10,000 cancer deaths.[23]

4. An Alternative Path forward for Japan

Figure 2. Dense-packed spent fuel in the spent fuel Storage pool of Fukushima Daiichi Unit #4.[24]

Making spent fuel storage safer. As indicated, the key to an alternative path forward for Japan is dry-cask, on-site storage at the nuclear power plants, as in the U.S. and most other countries, so that, if decisions are made to restart nuclear power plants, that will not result in pressure to start the Rokkasho reprocessing plant. But the nuclear power plants need on-site dry cask storage capacity in any case for safety reasons.

These safety reasons have been dramatized by the situation in the spent fuel pool of Fukushima Daiichi unit number 4 (Figure 2). It will be seen that the spent fuel assemblies in the pool are in individual boxes. This is necessary because packing them so densely – almost as densely as in a reactor core – creates the danger that a fission chain may start. The walls of the boxes are therefore impregnated with neutron-absorbing boron to prevent this. But, in case of a loss of water, the boxes would prevent air cooling and increase the likelihood of a catastrophic spent fuel fire.

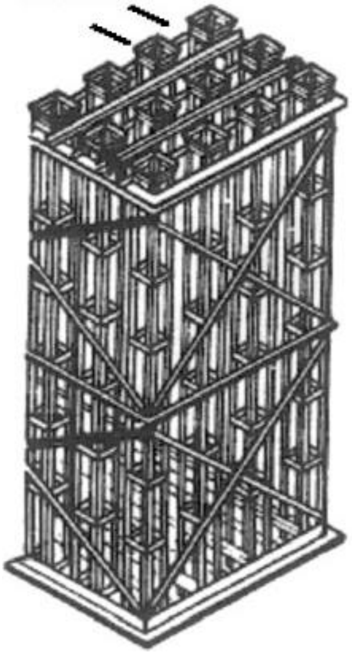

Figure 3. Originally, when it was expected that spent fuel would be shipped off site after a few years cooling, fuel was stored in open racks that would permit more air circulation in case of a loss of water.[25]

It is not necessary to pack the fuel so densely. Most spent fuel pools were sized to store discharged spent fuel in open racks for about five years (Figure 3), after which the fuel can be moved to air-cooled dry cask storage. If spent fuel were, in fact moved to dry cask storage after five years, then the danger of over-packed spent fuel pools could be reduced.

The danger from large quantities of stored high-level liquid reprocessing waste. Japan could also end another danger by ending its reprocessing policy. Reprocessing plants dissolve spent fuel to separate out the plutonium and uranium. The plan is then to "vitrify" the residual liquid, containing fission products and minor transuranic elements by mixing it with molten glass to form a solid waste form that can be deposited into a deep underground geological repository. In practice, however, the vitrification process has proven difficult with the result that large quantities of high-level liquid waste (HLLW) have accumulated in the reprocessing plants.

Public information about HLLW is most available in the case of the UK. According to a report issued in 2000 by the UK Nuclear Installations Inspectorate (NII), the amount of

HLLW stored at the Sellafield reprocessing site is the equivalent of three to four years output of the reprocessing plants. The UK Office of Nuclear Regulation proposes that the quantity of dissolved fission products from oxide fuel stored in this form be limited to the equivalent of that in 2,000 tons of spent fuel, and that the total, including fission products from uranium metal "Magnox" fuel be limited to the equivalent of 5,500 tons of spent fuel. This is roughly equivalent to a limit of 140 MCi of Cs-137, about 70 times the amount released by the Chernobyl accident. The volume of HLLW at France's reprocessing plant at La Hague is comparable to that at Sellafield.

In Japan, in a test run of the Rokkasho Reprocessing Plant, one of the two melters that mixes HLLW into glass clogged in 2008. As a result, reprocessing operations at the $27 billion plant were shut down for four years while the engineers tried to understand the problem. In 2012, they tried the second melter, and it too clogged. As a result, 240 m^3 of high-level waste from the reprocessing of about 425 tons of spent fuel remains in liquid form. Japan's Tokai Pilot Reprocessing Plant held a total of 380 m^3 of HLLW as of the end of March 2011.

The difficulties of HLLW vitrification have provided an incentive for the designers of reprocessing plants to build high-volume HLLW tanks so that a delay in vitrification will not interrupt reprocessing. A proposed reprocessing plant at Gorleben in Germany was to have had a HLLW storage capacity of 7,000 cubic meters. A non-governmental critique, however, convinced the German regulatory authorities to rule in 1979 that, because of safety concerns, HLLW should be stored, if at all, only in small quantities in inherently-safe tanks. That ruling is consistent with best practice in chemical-plant design, which is to eliminate storage of hazardous intermediates. Unfortunately, that practice has not been followed for the reprocessing plants that have been built.

The current practice in the reprocessing industry, therefore, is to store large amounts of radioactive material in a liquid form that, because of the heat generated by radioactive decay requires constant cooling. This creates both economic and safety risks. The economic risks are that, if vitrification does not work at all, then reprocessing will have made the spent-fuel disposal problem worse. And, if vitrification is delayed for years, then a choice is forced between accumulating hazardous liquid wastes indefinitely or idling a costly facility, as has occurred in Japan. If a radioactive release occurs inside a reprocessing plant, it also can idle the facility for years. That happened in 2005 at the THORP plant where a pipe broke and a building was flooded with liquid high-level waste, resulting in plant closure for two years.

The greatest concern, however, is the possibility of a large airborne radioactive release contaminating a significant part of a country due to an accident or malevolent act.

As far as is publicly known, there has been no comprehensive assessment of these risks for any actual or proposed reprocessing plant. In 2000, the UK Nuclear Installations Inspectorate (NII) conducted a limited assessment for various possible release initiators including loss of tank cooling and accidental aircraft crash. It was found that loss of tank cooling could result in the contents heating up to boiling in a time as short as 12 hours. NII argued, however, that, due to redundant cooling arrangements, this was very improbable. For an aircraft crash into the HLLW storage building, it was estimated by the plant operator that the probability of penetrating the building containing the tanks would be 1.7 percent or less. Since the likelihood of an accidental crash in the first place was estimated as less than one chance in a million per year, this scenario was not analyzed further. (This was before the attacks of 11 September 2001, however, and terrorist attacks were not considered.)

5. Conclusion

Governments usually require two good reasons to change existing policy. Japan has at least three good reasons to abandon reprocessing and its fast breeder reactor demonstration program, and to switch to dry cask storage instead:

- Reducing the safety risks from the densely packed spent fuel in its reactor pools;
- Saving many trillions of yen by moving to dry cask storage instead of operating the Rokkasho Reprocessing Plant and building the Rokkasho MOX plant and continuing with its plutonium breeder reactor R&D program; and
- Strengthening the non-proliferation regime by joining the vast majority of countries with nuclear power plants that have ended their separation of weapon-usable plutonium from spent fuel.

On the other side, making change difficult, are the political commitments that have been made to Aomori Prefecture and all the complex funding and subsidy arrangements that have been required to make reprocessing possible.

The great Tōhoku earthquake has shaken the Japan's nuclear power system to its roots. These policy changes should be made now before Japan's nuclear village is able to resume business as usual. The result would be a nuclear establishment that is less costly and less dangerous to Japan and to the world.

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[1] Leo Szilard, “Liquid Metal Cooled Fast Neutron Breeders,” in *The Collected Works of Leo Szilard: Scientific Papers*(MIT Press, 1972) p. 369.

[2] Richard Garwin pointed out at the time, however, that it would be more uranium efficient to enrich uranium to 20% to provide the startup cores for breeder reactors than to use the uranium in burner reactors to produce plutonium for that purpose, "The Role of the Breeder Reactor" in Nuclear Energy and Nuclear Weapon Proliferation, F. Barnaby, et aI., ed. Taylor and Francis.,1979, p. 141.

[3] R.B. Fitts and H. Fujii, “Fuel Cycle Demand, Supply and Cost Trends,” *IAEA Bulletin*, Vol.18, No.1, 1975, p. 19.

[4] *Energy, Electricity and Nuclear Power Estimates for the Period up to 2050*(IAEA, 2011), Table 3.

[5] Richard G. Hewlett and Francis Duncan, *Nuclear Navy: 1946–1962* (University of Chicago Press, 1974), pp. 272–273.

[6] O. M. Saraev, “Operating Experience with Beloyarsk Power Reactor BN600 NPP, Beloyarsk Sverdlovsk Nuclear Power Plant,”1997, IAEA Fast Breeder *Reactor database,*

[7] *Fast Breeder Reactor Programs: History and Status*(International Panel on Fissile Materials, 2010), pp, 6-7.

[8] *Uranium Intelligence Weekly*, 13 Sept. 2010, p. 7.

[9] The JAEC estimated that reprocessing and plutonium recycle would increase the cost of nuclear electricity by ¥0.8-1.0 per kWh relative to simply disposing of the spent fuel, “Estimation of Nuclear Fuel Cycle Cost and Accident Risk Cost,” 10 November 2011. The plan is for the plant to process 32,000 tons of spent fuel over its design life. Assuming an average of 45 megawatt-days per kg uranium fission energy release in the spent fuel, and a conversion of one third of the heat to electrical power, the extra cost incurred over the life of the reprocessing plant would be ¥9-12 trillion or $115-145 billion at current exchange rates.

[10] Slide 12 from a Japan Atomic Energy Commission Powerpoint dated 25 October 2011, *op. cit.*

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[11] International Panel on Fissile Materials, *Managing Spent Fuel from Nuclear Power Reactors: Experience and Lessons from Around the World* (2011).

[12] The U.S. had a reprocessing plant from 1966-72 that operated under private ownership before being shutdown and transformed into a government-owned multi-billion dollar cleanup project that continues today and is expected to continue for at least a decade, U.S. Department of Energy, “West Valley Demonstration Project,” http://www.wv.doe.gov/.

[13] UK Decommissioning Authority, *Oxide Fuels: Credible Options*, 2011.

[14] Russia started construction on a large reprocessing plant near Krasnoyarsk in 1984 but abandoned the effort in 1989 because of lack of funding and public opposition. Russia now plans to build a new experimental reprocessing plant at that site, which has become Russia’s central spent-fuel storage site.

[15] This was the main argument made for reprocessing in 2005 by the Japan Atomic Energy Commission’s Nuclear Policy Planning Council.

[16] In 20-year-old 53-MWt-day/kg burn-up spent fuel, about 15 percent of the mass of the transuranics are neptunium-237 (2-million year half-life) and americium-241 which decays into Np-237. Another 2 percent is americium-243 (7400-year half-life, which decays in Pu-239, Jungmin Kang and Frank von Hippel, “Limited Proliferation-resistance Benefits from Recycling Unseparated Transuranics and Lanthanides from Light-Water Reactor Spent Fuel,” *Science and Global Security, 13,* 2005, p. 169.

[17] *Nuclear Wastes: Technologies for Separations and Transmutation* (Washington, D.C: National Academy Press, 1996), Summary.

[18] International Panel on Fissile Materials, *Managing Spent Fuel from Nuclear Power Reactors, op. cit.*

[19] T. Saegusa, et al, Central Research Institute of the Electric Power Industry, “Issues and Countermeasures for Long-Term Storage of Spent Fuel by Dry Cask,” US Nuclear Regulatory Commission, Regulatory Information Conference, 13-15 March 2012. A high resolution image for after can be found at http://cryptome.org/eyeball/daiichi090911/daiichi090911.htm

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

[21] IAEA, *Safeguards Glossary* (2001), p. 23. For plutonium isotopic mixtures with high percentages of Pu-240, the yield in a Nagasaki-type design is likely to be less than the 20-kiloton yield of the Nagasaki bomb but more than the detonation of 1000 tons of chemical explosive, J. Carson Mark, “Explosive Properties of Reactor-Grade Plutonium,” *Science & Global Security* ,Vol. 4, 1993, p 111.

[22] For a discussion of the exposure of civilian plutonium during transport in Europe, see, for example, International Panel on Fissile Materials, *Global Fissile Material Report 2007,* pp. 17-18.

[23] Steve Fetter and Frank von Hippel, “The Hazard from Plutonium Dispersal by Nuclear-warhead Accidents,” *Science & Global Security*, 1990, Vol. 2, p.2.

[24] Koji Shirai and Toshiari Saegusa, CRIEPI, “Impact of Fukushima Accident on Spent Fuel Management in Japan,” Institute for Nuclear Materials Management, Spent Fuel Management Seminar, Washington, DC, 31 Jan. 2012.

[25] Robert Alvarez, Jan Beyea, Klaus Janberg, Jungmin Kang, Ed Lyman, Allison Macfarlane, Gordon Thompson and Frank von Hippel, “Reducing the Hazards from Stored Spent Power-Reactor Fuel in the United States,” *Science and Global Security,* Vo1.1, 2003, pp. 1–51.