CHAPTER 12

THE COSTS AND BENEFITS OF REPROCESSING

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Since 1974, when India tested a nuclear bomb made with plutonium that it separated with U.S. assistance under the Atoms for Peace Program, there has been a debate within the global nuclear-power community about the desirability of reprocessing spent power reactor fuel. Today, about one-quarter of the world's spent fuel is reprocessed (see Table 12-1). Seven of the 31 countries with nuclear power reactors are having at least some of their spent power-reactor fuel reprocessed. A dozen more countries that had been sending their spent fuel to one of the three merchant reprocessing countries (France, Russia and the United Kingdom (UK) have decided, however, not to renew their contracts.

In the 1960s and 1970s, reprocessing of spent light water reactor fuel was justified by the need to obtain plutonium for startup cores for liquid-sodium-cooled plutonium-breeder reactors. The concern was that the world's resources of high-grade uranium ore would not be able to support the thousands of gigawatts (GWe) of nuclear capacity then projected by the year 2000. Current generation reactors can efficiently exploit only the fission energy stored in chain-reacting U-235, which makes up 0.7 percent of natural uranium. Breeder reactors would turn the U-238 that constitutes virtually all the remainder of natural uranium into chain-reacting plutonium.

Countries that reprocess or plan to (GWe, [109 Watts])	Customer Countries that have quit or plan to quit (GWe)	Countries that have not reprocessed (GWe)
China (30%) 8.4	Armenia (in Russia) 0.4	Argentina 0.9
France (80%) 63.3	Belgium (France) 5.8	Brazil 1.8
India (≈50%) 3.8	Bulgaria (Russia) 1.9	Canada 12.6
Japan (90% planned) 46.1	Czech Republic (Russia) 3.6	Lithuania 1.2
Netherlands (in France) 0.5	Finland (Russia) 2.7	Mexico 1.3
Russia (15%) 21.7	Germany(France/UK) 20.5	Pakistan 0.4
United Kingdom 10.1	Hungary (Russia) 1.9	Romania 1.3
	Slovak Republic (Russia) 1.7	Slovenia 0.7
	Spain (France, UK) 7.5	South Africa 1.8
	Sweden (France/UK) 9.0	South Korea 17.6
	Switzerland (France/UK) 3.2	Taiwan 4.9
	Ukraine (Russia) 13.1	U.S. (since 1972) 100.6
Total (65%) 153.9	**Total 71.3**	**Total 145.1**

Table 12-1. Status of Reprocessing in the Countries with Nuclear-Power Reactors.[1]

However, the commercialization of breeder reactors has therefore not happened because:

1. global nuclear capacity is still below 400 GWe;
2. rich deposits of uranium were found in Australia, Canada, and Kazakhstan;

3. it was learned from demonstration breeder-reactor projects that liquid sodium brings with it many reliability and safety problems; and.

4. that breeder reactors would be *much* more costly than light water reactors.[2]

Nevertheless, a commitment to reprocessing persists in seven countries (see Table 12-1), with France recycling the separated plutonium into the fuel for the light water reactors from which it came, Japan is about to start doing so, and others are simply stockpiling their separated plutonium. The result is a global stockpile of about 250 tons of separated civilian plutonium—about as much as was separated for nuclear weapons by Russia and the United States during the Cold War—i.e., enough to make tens of thousands of nuclear weapons.[3] Most of this separated plutonium is stored at the reprocessing plants where it was separated, with some also at France's Melox mixed-oxide (MOX, plutonium-uranium) fuel fabrication plant.

As discussed below, both France and Japan have published analyses comparing the costs of reprocessing and plutonium recycling from their light-water reactors with the costs of simply storing the spent fuel—i.e., the "once-through" fuel cycle. Both nations have found that the once-through fuel cycle is lower in cost. However, they continue to be committed to reprocessing. Why?

At the same time, as noted above, a dozen countries that sent their spent fuel abroad for reprocessing have not renewed their contracts. Why did these countries find reprocessing attractive in the first place, and why did they change their minds?

The UK has lost its foreign reprocessing customers and had its government-owned reprocessing company go bankrupt. The reprocessing site has been taken over by a Nuclear Decommissioning Authority that has not yet decided whether or not to continue to reprocess UK domestic spent fuel. Russia and India continue to justify their reprocessing programs by expectations of the imminent commercialization of plutonium breeder reactors. Finally, China is patterning its nuclear-energy program on those of France and Japan and has completed the construction of a pilot reprocessing plant and plans to build a commercial-scale plant.

The "once-through" fuel cycle as currently practiced in the United States and many other countries is shown above the dotted horizontal line in Figure 12-1. Low-enriched uranium (LEU) fuel is irradiated in a light-water reactor and then stored. The reprocessing and recycle system that is in operation in France and soon will be in Japan is shown below the line. It involves the separation and recycle of the plutonium in "mixed-oxide" (MOX, uranium-plutonium) fuel. The spent MOX fuel is then stored. Because of the high cost of reprocessing, the cost of this MOX fuel is much higher than the cost of LEU fuel and most countries have decided that it is not worthwhile.

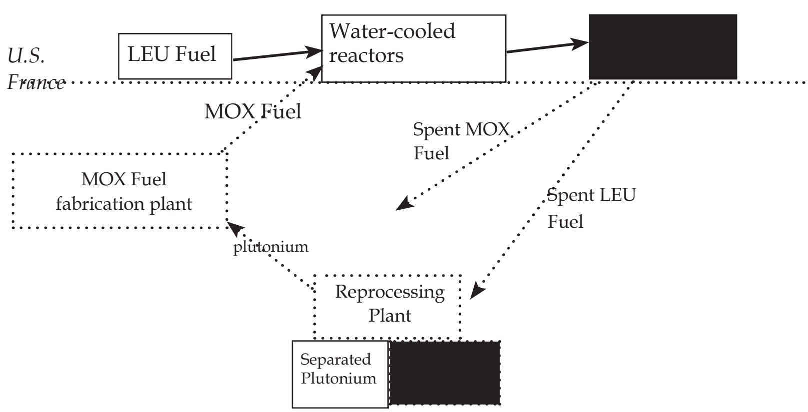


Figure 12-1. Currently Competing Spent Fuel Management Strategies.

Figure 12-2 depicts a U.S. nuclear power plant dry cask storage facility. Each cask weighs over 100 tons and typically holds about 10 tons of heavy metal (mostly uranium) in spent fuel that was discharged from a reactor 20 or more years earlier. A 1-GWe light-water reactor discharges about 20 tons per year. Each cask costs $1-2 million. Reprocessing of 10 tons of spent fuel would cost on the order of $20 million.

Source is available from *www.connyankee.com/html/fuel_storage1.html*.

Figure 12-2. Dry-Cask Storage of Older Spent Fuel at a U.S. Nuclear Power Plant.

THE FUEL CYCLES

Figure 12-1 shows the two different fuel cycles in use in the world today. Above the horizontal dotted line is the once-through fuel cycle in which low-enriched uranium (LEU) fuel is used in a reactor and the spent fuel stored. The United States has the largest group of nuclear power plants operating in this mode, with the spent fuel accumulating on the reactor sites because of the lack of a central site to ship to (see Figure 12-2). Utility dissatisfaction with this situation led the G.W. Bush administration to advocate reprocessing and plutonium recycling, but Congress was skeptical. The Obama administration shares this skepticism and is likely to limit U.S. reprocessing activities to research and development (R&D).

Shown below the horizontal dotted line in Figure 12-1 is the light-water reactor fuel cycle as practiced in France, the country that has gone the furthest in recycling plutonium. There, spent LEU fuel is reprocessed and the plutonium recovered from about seven tons of spent LEU fuel is mixed with depleted uranium to make a ton of mixed-oxide (MOX) fuel, which replaces about one-seventh of the LEU fuel that otherwise would have been used. The spent MOX fuel is then shipped back to the reprocessing plant but is not reprocessed again, despite the fact that it still contains about five times as much as plutonium as spent LEU fuel.[4] The reason given is that the mix of plutonium isotopes in the spent MOX fuel contains a lower fraction of chain-reacting Pu-239 and a larger fraction of even atomic number isotopes (Pu-238, Pu-240, and Pu-242) that are not as effectively fissioned as the odd isotopes by the slowed neutrons in light-water reactors.[5]

France therefore proposes to leave this plutonium in the spent MOX fuel until the commercialization of liquid sodium-cooled fast-neutron plutonium-burner reactors—the same reactors previously designed to be plutonium breeder reactors—is achieved. Reconfigured as plutonium-burners, they could fission the even plutonium isotopes more effectively than can light-water reactors. The only problem with this strategy is that liquid-sodium-cooled reactors are so much more costly than light-water reactors, so there is little prospect that they will be commercialized in the foreseeable future. In that case, France will only have complicated its radioactive-waste disposal problem by creating multiple waste streams—some of them quite voluminous—where previously there was only one waste form.[6]

France, like all other countries with nuclear power plants, does not yet have an operating geological repository for its high-level radioactive waste. The net effect of its reprocessing and plutonium recycle therefore is to shift the storage of spent fuel from France's reactor sites to its reprocessing facility. The plutonium is stored both in separated form (about 55 tons, enough for about 7,000 nuclear weapons, as of the end of 2007[7]) and in spent MOX fuel, while the uranium recovered from the spent LEU fuel is stored separately.[8] The fission products and the transuranic elements other than plutonium are stored in liquid form and then mixed into glass and the resulting "vitrified" high-level waste is stored on site. Long-lived medium and low-level radioactive wastes produced by reprocessing and MOX-fuel fabrication are also stored on site pending identification of one or more ultimate disposal sites.[9] France has also turned La Hague into a central storage site for LEU spent-fuel, holding in its pools about 60 percent as much French spent fuel as it has reprocessed. As of the end of 2008, only about 10 percent of that stored fuel was spent MOX fuel.[10]

ECONOMICS OF DOMESTIC REPROCESSING IN FRANCE

Through 2005, almost half of the spent fuel reprocessed in France was of foreign origin—about 10,000 metric tons.[11] At perhaps $2 million per ton,[12] those reprocessing contracts were a significant source of foreign exchange and France's policy of reprocessing its own spent fuel may have been in part a way to help support this important industry. Reprocessing has not gone completely unquestioned, however. In 2000, Socialist Prime Minister Jospin requested an analysis of the costs and benefits of continuing to reprocess most of France's spent fuel. Three scenarios were considered:

1. Continue reprocessing about 70 percent of France's low-enriched uranium (LEU) spent fuel with the separated plutonium being recycled in mixed oxide (MOX, plutonium-uranium) fuel;

2. Increase reprocessing to 100 percent of LEU spent fuel but stop when the separated plutonium could no longer be recycled because of the approaching end-of-life of the reactors—in effect, reprocess about two thirds of the LEU fuel discharged during the reactors' lifetimes); and,

3. End reprocessing in 2010 (corresponding to reprocessing 27 percent of the LEU fuel discharged during the reactors' lifetimes).

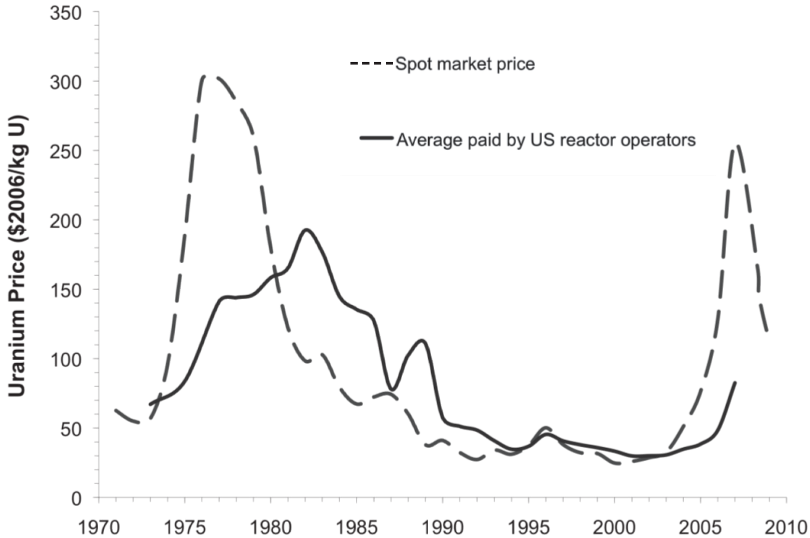
The panel also constructed a counterfactual scenario in which France had never embarked on reprocessing at all. Finally, from scenarios 1 and 2, one also can derive a second counterfactual scenario in which all of the LEU fuel is reprocessed and the plutonium recycled—one-third of it in a successor generation of light-water reactors. Table 12-2 shows the front and back-end costs of the fuel cycles for these four scenarios along with the inputs of materials and separative work and outputs of spent fuel and various radioactive wastes.

	Percentage of Spent LEU Fuel Reprocessed			
	67% (S6)	27% (Reprocessing Ends in 2010, S4)	100% (Derived Scenario)	No Reprocessing (S7)
Fuel cycle costs (billions of 2006 $ undiscounted, assuming $0.2 per 1999 French Franc)				
Front End	116	120	112	122
Back End	74	61	84	41
Total	190	182	196	162
Cost/kWhr (cents)	0.94	0.91	0.97	0.80
INPUTS				
Natural Uranium Mined (10^3 metric tons)	437	460	418	475
Separative Work (millions SWUs)	313	330	299	341
LEU Fuel Fabricated (10^3 tons uranium)	54	56	52	58
MOX Fuel Fabricated (10^3 tons)	4.8	2	7.1	0
LEU Fuel Roprocessed (10^3 tons)	36	15	52	0
WASTES				
Depleted Uranium (10^3 tons)	379	401	360	417
LEU Spent Fuel (10^3 tons)	18	41	0	58
MOX Spent Fuel (10^3 tons)	4.8	2	7.1	0
Transuranic Waste (10^3 cubic meters)	18	12	23	0
High-level Waste (10^3 cubic meters)	4.8	1.6	7.5	0
Plutonium/Americium in Spent Fuel (tons)	514	602	441	667
Reprocessed Uranium (10^3 tons)	34	14	50	0

Table 12-2. Costs, Inputs, and Outputs for Different Scenarios for the Future of France's Nuclear Fuel Cycle Based on a Study Done for the Prime Minister in 2000 (20.2×10^{12} nuclear kWh).[13]

With regard to the inputs, it will be seen that by dividing the front-end costs and the quantities of natural uranium and separative-work used in the no-reprocessing scenario by the tonnage of LEU fuel produced, that the average cost of the LEU fuel was estimated to be about $2,000, with inputs of 8.2 kg of natural uranium and 5.9 SWU per kilogram of LEU fuel.

It was assumed in the French government's analysis that the price of uranium would climb slowly from $60/kg in 2000 to $80/kg in 2050.[14] As Figure 12-3 shows, uranium prices have been volatile—especially the spot market—but this still seems a reasonable average. The price spike in the late 1970s was due to the expectation that global nuclear power capacity—and therefore demand for natural uranium—would grow rapidly. In fact, new orders stopped, and it took decades for the utilities to use and sell off the uranium that they had contracted for. Hence the slump in prices. The more recent spike reflects a temporary panic over the future availability of uranium when it was realized that the selling off of the utility stockpiles and the blending down of excess Cold War weapons HEU to LEU for use in civilian power-reactor fuel had resulted in the global output from uranium mines shrinking to about half the size required to sustain the world's current fleet of nuclear power reactors.



Spot market price is the broken line.

Figure 12-3. Price of Uranium, 1970-2008.[15]

As Table 12-2 also shows, the estimated cost of the 100-percent-reprocessing scenario was $34 billion higher than that of the no-reprocessing scenario—despite the fact that the consumption of uranium would be 57 million kilograms less. If the price of uranium increased by $600/kg while all other prices were unchanged, the cost of the once-through would be the same as the closed fuel cycle. Such a price increase is highly unlikely, however. There are over 5 million tons of identified resources of natural uranium—more than 70 years of consumption at the current rate—recoverable at an estimated cost of less than $130/kg and, despite mining and inflation, identified resources at less than this cost continue to increase.[16] Understandably, there has been little exploration of higher-cost resources but the resource base is expected to increase very rapidly with recovery cost.[17]

It is seen in Table 12-2 that the cost of the back end of the fuel cycle associated with reprocessing is about 43 billion dollars greater for the 100 percent reprocessing scenario than for the no-reprocessing scenario. If, as seems reasonable, most of this extra cost is attributable to reprocessing, the derived cost estimate for reprocessing France's own spent fuel would be about $800/kg. This is about half of the price charged to France's foreign customers because those foreign contracts included pre-payment of the cost of building the new UP3 reprocessing plant.

As Table 12-2 also shows, although it amounts to about a billion dollars per year, the cost difference estimated by the French Government in 2000 between no reprocessing and all reprocessing amounts to only about 0.2 cents per kilowatt-hour or perhaps 5 percent the total cost of generating nuclear power. In the past, France's national utility *Électricité de France* (EDF) has been able to pass this extra cost on to its customers. As Europe's electric power market has been deregulated, however, foreign competition has become more of a concern. As the reprocessing contract drew to an end in 2007, EDF tried hard to get a lower price for reprocessing, while Areva, the government-owned company that provides reprocessing services, lost virtually all of its foreign customers and insisted on a higher price. It took a year after the old contract had expired for a new one to be agreed upon, and with the old contract extended to bridge the gap.[18]

So why has the French government decided to continue its commitment to reprocessing despite the higher cost to the economy and the loss of almost all of its foreign reprocessing business? Probably part of the answer is that so much of the extra cost is now sunk cost, which was spent building the reprocessing and MOX-fuel fabrication plants.[19] Another part is the political weight of 6,000 jobs in rural Normandy.[20] The ability to move spent fuel off the nuclear power plant sites to a central location and thereby delay confronting the problem of siting a radioactive waste repository may also have been a consideration, as is suggested by the case of Japan.

REPROCESSING IN JAPAN[21]

Japan's continued commitment to reprocessing is in large part a result of the unwillingness of local governments to allow increased storage of spent fuel on-site. This is in contrast to the situation at almost all U.S. power-reactor sites, where, when storage pools fill up, the oldest spent fuel is removed to make way for newly discharged spent fuel. The old fuel is stored on-site in dry casks (see Figure 12-2).

Japan's utilities were unable to interest any prefect in hosting a central spent-fuel storage facility. They therefore took the only option open to them at the time, which was to ship the spent fuel abroad to France and the UK to be reprocessed. This only bought time, however, because public opinion in France and the UK—and hence their reprocessing contracts—required Japan to take back the high-level waste resulting from the reprocessing of its spent fuel. Therefore, when Japan built a domestic reprocessing plant, it obtained an agreement from the local host government of Aomori Prefecture that the site would also accommodate the high-level waste coming back from Europe.

Reprocessing—like all things nuclear—is controversial in Japan, and the government periodically feels obliged to justify its policies as prudent. In 2004, the

Planning Committee of Japan's Atomic Energy Commission (JAEC) published, as a backup to the Japan Atomic Energy Commission's (JAEC) Long-Term Nuclear Plan, an evaluation of the costs of four scenarios for spent-fuel management in Japan:

1. Full reprocessing of all spent fuel;
2. Reprocessing only of the spent fuel that could be accommodated by the new Rokkasho Reprocessing Plant operating at nominal capacity (800 metric tons/year);
3. Direct disposal of all spent fuel; and,
4. Interim storage of all spent fuel.

The resulting cost estimates, shown as costs in cents per nuclear kilowatt hour (approximating one 2004 yen = one cent), are given in Table 12-3.

	Full Reprocessing	Direct Disposal	Partial Reprocessing	Interim Storage
Front-end cost	0.63	0.61	0.63	0.61
Back-end cost	0.93	0.32-0.46	0.77-0.85	0.48-55
Total fuel-cycle cost	1.56	0.93-1.07	1.4-1.48	1.09-1.16

Table 12-3. Estimated Cost of Different Back-End Fuel-Cycle Options in Japan (cents/kWh).[22]

As in France, it was found that reprocessing and plutonium recycling are more costly than the once-through fuel cycle. The cost difference between full reprocessing and direct disposal was found to be about 0.6 cents/kWh. This is more than twice as large as the corresponding cost difference found by France based on Table 12-1 and reflects the fact that Japan spent about as much to build its French-designed reprocessing plant as Areva claims to have spent for its UP2 and UP3 reprocessing plants, which together have more than twice the capacity. Also, Japan appears to be incurring about twice the annual operating cost as France—or about four times as much per ton of reprocessing capacity.[23]

The Planning Committee concluded that, nevertheless, reprocessing would be the less costly option for Japan for two reasons:

1. The Rokkasho Reprocessing Plant was already built and the $20 billion for its construction plus the projected $13 billion decommissioning cost would have to be paid in any case. These costs, divided by the nuclear kWhrs expected to be generated from the spent fuel reprocessed during the plant's 40-year planned life come to about 0.24 yens/kWh.

2. If Rokkasho became unavailable as an off-site destination for the spent fuel from Japan's nuclear power plants, they would have to shut down as soon as their spent-fuel storage pools filled up and replacement electricity would have to be generated by fossil-fueled plants. The JAEC estimated that the replacement electricity would cost 0.7-1.3 Yen/kWh. This cost seems remarkably low,[24] but it is large enough to tip the balance in favor of reprocessing.

Thus, this analysis clearly bases the rationale for the reprocessing of Japan's spent fuel on the need to have an off-site destination for this spent fuel or shut down all of Japan's power reactors.

THE DOZEN COUNTRIES THAT DID NOT RENEW THEIR REPROCESSING CONTRACTS

What about the dozen countries listed in Table 12-1 that did not renew their reprocessing contracts? Here the situation is different for the seven countries that sent their spent fuel to Russia (Armenia, Bulgaria, the Czech Republic, Finland, Hungary, the Slovak Republic, and Ukraine) and the five that were customers of France and the UK (Belgium, Germany, Spain, Sweden, and Switzerland).

For the seven countries that sent their spent fuel to Russia, the cost was low, \$300-620 per kg of heavy metal,[25] and nothing came back! In fact, only the fuel that was sent to Russia from first-generation VVER-440 light-water reactors was actually reprocessed at Russia's small RT-1 reprocessing plant in the Urals.[26] The spent fuel from the VVER-1000s is sent to a large spent-fuel storage pool at the never-completed RT2 reprocessing plant near Krasnoyarsk.

In the post-Soviet era, however, Russia began to raise its prices. Also, the leadership of Russia's nuclear-energy establishment came under public pressure not to make Russia a dumping ground for foreign radioactive waste and began to put clauses into its contracts that would allow it to ship high-level waste or unreprocessed spent fuel back to the country of origin. At the same time, most of Russia's former reprocessing customers had become members of the European Union (EU), and the EU has rules against transferring spent fuel to any country that cannot guarantee the same level of safety as is required in the EU. Finally, all of Russia's customers found that, like the United States, they were politically able to site and build adequate interim domestic storage for their spent fuel—either centrally or at the reactor sites.[27]

With regard to Belgium, Germany, Spain, Sweden and Switzerland, the story is different for each country. Because of domestic political opposition, Sweden decided not to have its spent fuel reprocessed after all and sold its contracts to other countries. Spain only sent spent fuel for reprocessing to France that came from its French-supplied gas-cooled reactor, which ended operations in 1990.[28] It also had a small (145 ton) reprocessing contract with the UK, equivalent to only about 1 year of discharges from its 7.5 GWe of light water reactor (LWR) capacity.[29]

Belgium, Germany, and Switzerland all have had significant quantities of spent fuel reprocessed in France,[30] and Germany and Switzerland have substantial reprocessing contracts in the UK that have not yet been completed because of the plant's poor operation and prolonged shutdown after a major pipe-break accident in 2005.[31] However, nuclear power and reprocessing became a contentious issue in all three countries. Belgium and Germany passed laws to end reprocessing and phase out nuclear power in the longer term. Switzerland's voters rejected a phase-out of nuclear power but voted for a 10-year reprocessing moratorium (2006-2016).[32]

THE CASE OF THE UK

Reprocessing in the UK started with its first-generation Magnox gas-cooled, graphite-moderated power reactors. The design of these reactors was based on the Calder Hall and Chapelcross dual-purpose reactors that produced most of the plutonium for the UK's nuclear weapons as well as electric power. The fuel of the Magnox reactors is designed for easy reprocessing and not storage. The fuel "meat" is uranium metal, which, unlike the uranium oxide used in LWR fuel, oxidizes rapidly in water, and the cladding is a magnesium alloy, which also corrodes easily in water. Although the UK could have converted to a storable fuel form after its needs for weapon plutonium were satisfied, it did not do so and all of the Magnox fuel has been reprocessed. The last Magnox reactor will be shut down in 2010, however, and the associated B-205 reprocessing plant will be decommissioned after it has reprocessed the spent fuel.

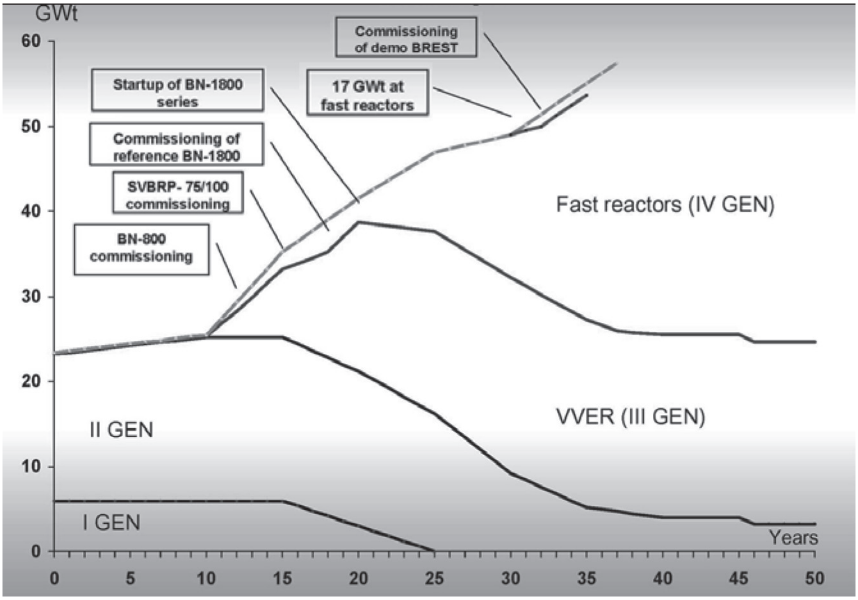
The UK has a second reprocessing plant, the THermal Oxide Reprocessing Plant (THORP), which was built primarily with prepaid contracts to reprocess foreign LWR fuel. One third of the base-load tonnage to be reprocessed in THORP is from second-generation UK Advanced Gas-cooled Reactors (AGRs) that are fueled with oxide fuel.[33] British Nuclear Fuels Limited, which operated the plant, went bankrupt when the foreign contracts were not renewed. The UK government therefore established a Nuclear Decommissioning Authority (NDA) to take over and decommission the reprocessing plant and the Magnox reactors. The NDA's first priority has been to fulfill the base-load contracts for reprocessing foreign spent fuel that paid for the construction of the plant and were to have been fulfilled by 2004, but this date keeps slipping.

The situation with regard to the UK's domestic reprocessing customers is that they have contracts under which the reprocessing plant simply takes the AGR spent fuel and can either store or reprocess it. The cheapest option, of course, would be to store the spent fuel, but the chemistry in the spent-fuel storage pools is so poorly controlled that corrosion appears to be forcing reprocessing.[34] Although NDA's 2006 strategy document discussed the option of shutting down the reprocessing plant and storing the AGR fuel,[35] the 2008 NDA plan discussed only plans to reprocess.[36] Its most recent statement, with no detail offered, is that "Thorp is currently programmed to operate until 2016."[37] In the meantime, the NDA is also beginning to grapple with the challenge of disposing of the approximately 100 tons of separated UK plutonium that will have accumulated in storage at its reprocessing plants by the time the current contracts are completed.[38]

THE CASES OF RUSSIA AND INDIA

Reprocessing in Russia and India continues to be driven by the expectation of the near-term commercialization of plutonium breeder reactors. Russia has only a small reprocessing plant, RT-1, in the Urals. It reprocesses naval and other fuels containing highly enriched uranium (HEU) to recover the HEU for blend-down to LEU for recycle into power reactors. It also reprocesses about 50 tons per year of spent fuel from Russia's first six first-generation VVER-440 LWRs. As of the end of 2007, Russia had 43.6 tons of separated plutonium stored at the RT1 reprocessing plant.[39] Russia is also storing tens of thousands of tons of spent fuel from VVER-1000 reactors and RBMK-1000 (Chernobyl-type) reactors at a never-completed reprocessing plant near Krasnoyarsk, Siberia.

Russia has ambitious plans to shift to building plutonium breeder reactors during the next decade (see Figure 12-4) as a way to conserve its uranium resources for export. It would use its separated plutonium—first excess weapon plutonium and then civilian plutonium—to start up these reactors. Whether these plans will be realized remains to be seen. As a result of the global recession, Russia's program to bring one or two light-water reactors online every year during the next decade will take longer than planned.[40]



Zero is the year 2000.[41]

Figure 12-4. Recent Plans for Russian Nuclear Power Expansion.

Because of its limited resources of high-grade uranium ore, India has, for the past 50 years, premised its plan for nuclear power on breeder reactors.[42] It is currently reprocessing the spent fuel from 3.5 GWe of unsafeguarded heavy-water reactors to provide startup plutonium for a fleet of plutonium-breeder reactors. One 0.5-GWe prototype fast breeder reactor is under construction. India's Department of Atomic Energy (DAE) projects 43 GWe of breeder capacity by 2032,[43] however an insufficient amount of plutonium would be produced to support anywhere near this rate of growth.[44] For this and other reasons, this projection is likely to continue to retreat into the future, as have all past projections of imminent breeder commercialization by DAE and its counterpart nuclear-energy R&D establishments worldwide.

THE CASE OF CHINA

China has plans underway for a huge expansion of its nuclear generating capacity from 9 GWe in 2009 to 120-160 GWe by 2030.[45] The Chinese nuclear energy establishment has been heavily influenced by that of France and emulates that of Japan. It has just completed a pilot reprocessing plant (50-100 tons/year) and is discussing with France the acquisition of reprocessing plant on the same scale as Japan's Rokkasho Reprocessing plant (800 tons/year).[46]

CONCLUSIONS

There is no debate over the fact that the economic cost of reprocessing is significantly higher than that for interim spent-fuel storage. This is why the international trend continues to move away from reprocessing.

There must therefore be special explanations for the policies of the countries that continue to reprocess—and there are. In Japan, it is the unwillingness of local governments to allow expanded onsite spent-fuel storage. In India and Russia, politically powerful nuclear establishments continue to dream of a massive buildup of plutonium breeder reactors just over the planning horizon. In France, reprocessing is sustained by sunk costs, the political power of France's nuclear conglomerate Areva and its associated nuclear union, and Areva's hopes of building $20-40 billion worth of reprocessing plants in the United States and China. In

China, the nuclear establishment is emulating France and Japan but may still decide to postpone a major commitment to reprocessing.

In the longer term, these decisions are too important to remain the province of nuclear bureaucracies. Utilities are becoming increasingly unwilling to carry the economic burden of reprocessing and governments are becoming increasingly sensitive to the security and proliferation issues. It is therefore likely that the trend will continue whereby, one-by-one, utilities that reprocess find ways to implement the less costly and less controversial option of interim spent-fuel storage.

ENDNOTES - CHAPTER 12

1. Nuclear capacities as of the end of 2008, based on the International Atomic Energy Agency's (IAEA) Power Reactor Information System, available from *www.iaea.org/programmes/a2/*.

2. A review of the history of breeder reactor commercialization efforts is forthcoming from the International Panel on Fissile Materials, available from *www.fissilematerials.org*.

3. International Panel on Fissile Materials, *Global Fissile Material Report 2008*, Chap. 1, available from *www.fissilematerials.org*.

4. *Plutonium Fuel: An Assessment*, Paris, France: Nuclear Energy Agency, OECD Publishing, September 30, 1989, Tables 9 and 11. Numbers cited are for spent fuel with a burnup of 53 Megawatt-days per kilogram of original heavy metal in the fuel and assuming that the spent LEU fuel was 10 years post discharge at the time it was reprocessed. The plutonium from the spent LEU fuel contains 50 percent Pu-239 and 15 percent Pu-241. The latter is less valuable, however, because it decays to nonchain-reacting Am-241 with a half-life of 14 years. Spent MOX fuel contains 37 percent Pu-239 and 17 percent Pu-241.

5. The fission cross-sections in the thermal neutron energy range of about 0.1 eV is about 1 barn for Pu-238, almost 1000 barns for Pu-239, less than 0.1 barns for Pu-240, several hundred barns for Pu-241, and less than 0.001 barns for Pu-242. See National Nuclear Data Center, Evaluated Nuclear Data File, available from *www.nndc.bnl.gov/exfor/endf00.jsp*.

6. See, e.g., Mycle Schneider and Yves Marignac, "Spent Fuel Reprocessing in France"; and Martin Forwood, "The Legacy of Reprocessing in the United Kingdom," International Panel on Fissile Materials, 2008, both available at *www.fissilematerials.org*.

7. "Communication Received from France Concerning Its Policies Regarding the Management of Plutonium," INFCIRC/549/Add.5/12, IAEA, October 30, 2008, available from *www.iaea.org/Publications/Documents/Infcircs/2008/infcirc549a5-12.pdf*. The IAEA assumes that 8 kg of plutonium is sufficient to make a first-generation Nagasaki-type plutonium bomb. More modern designs require less.

8. This irradiated uranium, although it contains about the same percentage of U-235 as natural uranium, is less valuable because it also contains a comparable amount of U-236 created by non-fission neutron absorption in U-235. Since U-236 absorbs neutrons without fission (i.e., is a neutron poison), it reduces the reactivity of the fuel. This effect must be offset by enriching the U-235 to higher levels than in LEU produced from natural uranium. France has re-enriched less than one-third of its reprocessed uranium. See *Management of Reprocessed Uranium: Current Status and Future Prospects*, IAEA-TECDOC-1529, IAEA, February 2007, p. 57.

9. "Spent Fuel Reprocessing in France."

10. As of the end of 2005, the spent-fuel pools at La Hague held about 8,100 tons of spent fuel and about 11,700 tons of spent fuel had been reprocessed at La Hague. See "Spent Fuel Reprocessing in France," p. 22. At a discharge rate of 1,200 tons a year from France's reactors and a contracted rate with Électricité de France for reprocessing of 850 tons/year, these totals would have climbed to about 9,000 and 14,000 tons by the end of 2008. As of the end of 2005, 543 tons of the spent fuel stored at La Hague was

French spent MOX fuel. See "Spent Fuel Reprocessing in France," Table 5. By the end of 2008, this would have increased to about 850 tons,

11. "Spent Fuel Reprocessing in France," Figure 7.

12. Matthew Bunn, Steve Fetter, John Holdren, and Bob van der Zwaan, "The economics of reprocessing versus direct disposal of spent nuclear fuel," *Nuclear Technology*, Vol. 150, June 2005, p. 209.

13. Table adapted from Frank von Hippel, "Managing Spent Fuel in the United States: The Illogic of Reprocessing," International Panel on Fissile Materials, 2007, Appendix. All scenarios discussed here assume that France's LWRs operate for an average of 45 years.

14. J. M. Charpin, B. Dessus, and R. Pellat, "Report to the Prime Minister: Economic Forecast Study of the Nuclear Power Option," 2000, p. 60, English translation available at *www.fissilematerials.org/ipfm/site_down/cha00.pdf* (CDP Report).

15. This figure is based on Figure 5 of "The economics of reprocessing versus direct disposal of spent nuclear fuel," updated by Steve Fetter through 2006 and the author through 2007 (average U.S. price) and 2008 (spot price) based on U.S. Energy Information Administration, "Average Price and Quantity for Uranium Purchased by Owners and Operators of U.S. Civilian Nuclear Power Reactors by Pricing Mechanisms and Delivery Year," and *Uranium Intelligence Weekly*, respectively.

16. "Uranium 2007: Resources, Production and Demand," OECD Nuclear Energy Agency and International Atomic Energy Agency, 2008, Table1 and Figure 8.

17. K. S. Deffeyes and I. D. MacGregor, "World Uranium Resources," *Scientific American*, January 1980, pp. 50-60; and Erich Schneider and William Sailor, "Long-term uranium supply estimates," *Nuclear Technology*, Vol. 162, June 2008, p. 379.

18. Ann MacLachlan, "EDF, Areva in tug-of-war over reprocessing price," *Nuclear Fuel*, February 25, 2008; "EDF-Areva pact ensures reprocessing, recycle," *Nuclear Fuel*, December 29, 2008.

19. According to a study funded by Areva and based on Areva proprietary data, the "overnight" cost of these plants, not including interest on the investment during construction, was about $18 billion. *Economic Assessment of Used Nuclear Fuel Management in the United States*, Boston, MA: Boston Consulting Group, 2006, Figure 8.

20. AREVA, "All about operations: La Hague," available from *www.lahague.areva-nc.com/scripts/areva-nc/publigen/content/templates/show.asp?P=50&L=EN*.

21. See also Tadahiro Katsuta and Tatsujiro Suzuki, "Japan's Spent Fuel and Plutonium Management Challenges," International Panel on Fissile Materials, 2006.

22. "Long-Term Nuclear Program Planning Committee publishes costs of nuclear fuel cycle," Citizens Nuclear Information Center, *Nuke Info,* Tokyo, Vol. 103, November/December 2004.

23. The nominal capacity of the Rokkasho plant is 800 tons per year vs. 1,000 tons/year for each of the two French reprocessing plants, UP2 and UP3. The Rokkasho plant has a design life of 40 years. As of the end of 2004, the costs incurred in its construction were 2.14 trillion yen (about $18 billion at a an exchange rate of 120 yen/$). In November 2003, the Federation of Electric Power Companies of Japan gave the total cost of the Rokkasho plant, including operations for 40 years, vitrification of the high-level waste, low-level-waste disposal, and decommissioning the plant as 11 trillion yen ($92 billion), Masako Sawai, "Japanese Nuclear Industry's Back End Costs," Citizen's Nuclear Information Center, *Nuke Info Toky*o, No 98, November 2003-February 2004. This implies an operating cost of a little less than $2 billion per year vs. AREVA's claimed cost of $1 billion a year for operating both its reprocessing plants and its MOX fuel-fabrication facility. See *Economic Assessment of Used Nuclear Fuel Management in the United States*.

24. The only way to get a cost this low is to assume that Japan has enough coal-fired capacity fueled with low-cost coal to replace the output of all its nuclear-power plants.

25. Alexei Breus, "Russian Imports of Spent Fuel from Europe to Resume by Year-End," *Nuclear Fuel*, Vol. 28, No. 8, April 14, 2003.

26. Armenia has one VVER-440, Bulgaria has two VVER-1000, the Czech Republic has 4 VVER-440s and 2 VVER-1000s, Finland has two VVER-440s, Hungary has four VVER-440s, the Slovak Republic has two VVER-1000s, and Ukraine has two VVER-440s and 13 VVER-1000s.

27. Alexei Breus and Ann MacLachlan, "Russia and Hungary sign protocol for fresh and spent fuel trade," *Nuclear Fuel*, May 10, 2004; Ann MacLachlan and Daniel Horner, "Russia drops plans for taking in foreign spent fuel, citing other priorities," *Nuclear Fuel*, July 31, 2006.

28. "The curious case of Vandellós-1," *Plutonium Investigation*, No. 16, July 1999, p. 4.

29. David Albright, Frans Berkhout, and William Walker, *Plutonium and Highly Enriched Uranium, 1996*, Oxford, UK: Oxford University Press, 1997, Table 6.4.

30. In France: Germany, 5672 metric tons; Switzerland, 766 tons; and Belgium, 672 tons. See "Spent Fuels Reprocessing in France," Figure 7.

31. Contracted in the UK: Germany, 969 tons on base-load contracts and 787 tons on post-2003 contracts; and Switzerland, 422 tons base-load contracts. See M. Forwood, *The Legacy of Reprocessing in the United Kingdom*, Research Report No. 5, Table 1, Princeton, NJ: The International Panel on Fissile Material, July 2008.

32. Bruno Pellaud, personal communication with the author, March 1, 2009.

33. *The Legacy of Reprocessing in the United Kingdom*, Table 1.

34. Martin Forwood, "Quotes from CoRWM docs Re: Problems with Management of Spent AGR Fuel," January 29, 2009.

35. *Strategy*, Cumbria, UK: Nuclear Decommissioning Authority (NDA), March 2006, p. 46.

36. *Ibid.*, Draft Business Plan 2009/2012, 2008, p. 32.

37. Pearl Marshall, "Thorp expected to soon restart normal reprocessing operations," *Nuclear Fuel*, March 9, 2009.

38. NDA, NDA Plutonium Topic Strategy: Credible Options Technical Analysis, January 30, 2009. The UK had 81.2 tons of separated UK civilian plutonium in storage at its Sellafield reprocessing site as of the end of 2007. "Communication Received from the United Kingdom of Great Britain and Northern Ireland Concerning Its Policies Regarding the Management of Plutonium," INFCIRC/549/Add.8/11, IAEA, July 2, 2008.

39. "Communication received from the Russian Federation Concerning Its Policies Regarding the Management of Plutonium," INFCIRC/549/Add.9/10, IAEA, October 30, 2008.

40. "Russian Nuclear Program Slowed on Weak Energy Demand," *Uranium Intelligence Weekly*, March 9, 2009.

41. O. Saraev, Rosatom, "Prospects of Establishing a New Technology Platform for Nuclear Industry Development in Russia," International Congress on Advances in Nuclear Power Plants, Nice, France, May 13-18, 2007.

42. H. J. Bhabha and N. B. Prasad, "A study of the contribution of atomic energy to a power programme in India," Proceedings of the Second United Nations International Conference on the Peaceful Uses of Atomic Energy, Geneva, Switzerland, 1958, pp. 89-101.

43. R. B. Grover and Subhash Chandra, Department of Atomic Energy, India, "Scenario for growth of electricity in India," *Energy Policy*, Vol. 34, 2006, p. 2834.

44. M. V. Ramana and J. Y. Suchitra, "Plutonium Accounting and the Growth of Fast Breeder Reactors," forthcoming.

45. China National Development and Reform Commission, May 2007.

46. Mark Hibbs, "CNNC favors remote site for future reprocessing plant," *Nuclear Fuel*, April 7, 2008.