By Steve Fetter and
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Is U.S. Reprocessing Worth The Risk?

Nearly three decades ago, the United States swore off the reprocessing of spent nuclear fuel because it costs too much and puts separated plutonium into circulation. Now, some in Congress want to launch a massive program to reprocess the spent fuel that has accumulated at U.S. power plants.

In May, the House endorsed report language calling on the Department of Energy to prepare "an integrated spent fuel recycling plan for implementation beginning in fiscal year 2007, including… reprocessing, preparation of mixed oxide fuel, vitrification of high level waste products, and temporary process storage."[1]

Supporters, led by Rep. David Hobson (R-Ohio), chairman of the Appropriations Energy and Water Subcommittee, say the need is imminent. They point out that, in the absence of reprocessing, the amount of spent fuel discharged by U.S. power reactors will soon exceed the legislated storage capacity of the repository being built under Yucca Mountain in Nevada. Moreover, Hobson has been persuaded that the Energy Department has developed "new reprocessing technologies that have the potential to minimize the…streams of radioactive waste products and also eliminate the presence of separated plutonium."[2]

In fact, reprocessing does not eliminate the need for a repository, and there is no urgent need for additional repository capacity. Further, the new reprocessing technologies being examined by the Energy Department, if adopted, would make huge additional quantities of plutonium accessible for diversion by terrorist groups and would undercut the ability of the United States to oppose the spread of plutonium-separation technology to additional countries. Reprocessing also would be very expensive, increasing the costs of nuclear power in the United States by billions of dollars a year. Yet, the House vote took place without hearings being held. Given the high stakes involved, Congress owes the American people the opportunity for an open and informed debate on the issues involved.

Evolution of U.S. Spent Fuel Disposal Policy

Reprocessing is the generic term for the chemical processing of spent nuclear fuel. The method currently used is the PUREX (plutonium-uranium extraction) process, which was originally developed by the United States in the early 1950s to separate plutonium for nuclear weapons. The spent fuel assemblies are chopped into pieces, the fuel is dissolved in nitric acid, and organic solvents are used to separate the plutonium and uranium from the fission products (such as cesium-137 and strontium-90) and minor transuranic elements (neptunium, americium, and curium). The plutonium and uranium are then separated from each other and purified for use in fresh reactor fuel. The fission products and minor transuranics

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are mixed into glass and stored in a surface facility pending the availability of an underground repository.

Commercial reprocessing programs originated in the 1960s and 1970s when power reactor operators worldwide expected that plutonium would be needed to make start-up fuel for plutonium breeder reactors. These reactors would then fuel themselves and other reactors with the plutonium that reactors produce by transmuting the abundant non-chain-reacting uranium-238 isotope. It was believed that production of nuclear energy based on the much less abundant chain-reacting uranium-235 isotope would increase so rapidly that the world's high-grade uranium ores would quickly be depleted, making a transition to the more uranium-efficient breeder reactors economic.

This expectation, however, was wrong, as U.S. and world nuclear capacity reached a plateau at one-tenth the level that had been projected for the year 2000, huge deposits of high-grade uranium ore were discovered in Australia and Canada, and both breeder reactors and reprocessing were found to be much more costly than had been expected.

Before these errors were generally recognized, reconsideration of U.S. reprocessing policy was triggered by India's "peaceful" nuclear explosion in 1974. The Indian nuclear device had been made using plutonium extracted from spent fuel using reprocessing technology provided by the United States.

The Ford administration reacted by opposing any further export of reprocessing technology, and the Carter administration put a hold on the licensing of commercial reprocessing facilities in the United States. The Reagan administration lifted the hold on U.S. reprocessing, but by then, U.S. reactor operators had realized how costly breeder reactors and reprocessing would be and had lost interest. The only commercial reprocessing facility to operate in the United States, at West Valley, New York, had closed in 1972 after a few years of troubled operation. The site is still the location of an ongoing, multibillion-dollar, government-funded radioactive waste cleanup project. Two other commercial reprocessing plants, at Morris, Illinois, and at Barnwell, South Carolina, were built but never operated.

Given that spent fuel had become a waste and not a resource, Congress passed the Nuclear Waste Policy Act (NWPA) in 1982. In exchange for a modest tax of $0.001 per kilowatt-hour (about 2 percent of the wholesale cost of nuclear-generated electricity), the Energy Department would arrange for the disposal of spent nuclear fuel in geological repositories. In 1987, Congress specified that the first repository would be sited under Yucca Mountain. To make clear that the burden would not be Nevada's alone, however, the amount of commercial spent fuel that could be placed in Yucca Mountain was limited to 63,000 tons "until such a time as a second repository is in operation."[3] U.S. reactors will have discharged this amount of spent fuel by 2008. The NWPA requires the secretary of energy to "report to the president and to Congress on or after January 1, 2007, but not later than January 1, 2010, on the need for a second repository."[4]

Given the widespread public abhorrence of radioactive waste, neither the Energy Department nor Congress has any appetite to look for a second repository site. Nor, given recent legal reverses in the Energy Department's battle with Nevada over the licensing of the Yucca Mountain repository, do they seem interested in trying to raise the legislated limit on the amount of spent fuel that can be stored there. This has created the atmosphere of crisis that inspired Hobson to propose reprocessing spent fuel and recycling the uranium and plutonium it contains as a way out.

Yet, if the public and Congress understood the trade-offs being proposed, they would be much more frightened of the near-term dangers of nuclear terrorism and nuclear proliferation that come with plutonium separation than of the very-long-term (hundreds to thousands of centuries) danger of local, radioactive groundwater pollution that is the focus of the licensing battle over Yucca Mountain. It is important to devise the best possible long-term solution for the radioactive waste problem, but the near-term security, economic, and environmental costs of reprocessing and recycling must not be ignored.

Fortunately, there is plenty of time to look before we leap. As the American Physical Society's Panel on Public Affairs recently pointed out:

U.S. Congress

Rep. David Hobson (R-Ohio) advocates spent fuel reprocessing.

> Even though Yucca Mountain may be delayed considerably, interim storage of spent fuel in dry casks, either at current reactor sites, or in a few regional facilities, or at a single national facility, is safe and affordable for a period of at least 50 years. Further, any spent fuel that would be emplaced at Yucca Mountain would remain available for reprocessing for many decades.… There is no urgent need for the [United States] to initiate reprocessing or to develop additional national repositories.[5]

The Costs of Reprocessing and Recycling

There is widespread agreement in the United States and abroad that reprocessing and recycling is significantly more expensive than storing spent fuel in an underground repository and buying fresh low-enriched uranium (LEU) instead. This is because reprocessing itself is an expensive process and also because fabricating mixed-oxide (MOX) fuel containing the recovered plutonium mixed with depleted uranium is more expensive than buying the alternative, fresh LEU fuel.

Thus far, the only country to implement a comprehensive reprocessing and recycling program is France. However, in 2000, the French government concluded that even with the initial costs of its reprocessing and MOX fuel fabrication plants paid for, if France were to stop reprocessing in 2010, it would save $4-5 billion over the remaining life-time of its current fleet of power reactors.[6]

A study by Japan's New Nuclear Policy-Planning Council recently estimated that the total extra cost for reprocessing 32,000 tons of Japan's spent fuel (about half as much as U.S. reactors have discharged thus far) and recycling the plutonium would be about $60 billion.[7]

Three recent U.S. academic studies find that reprocessing and recycling would also be more expensive in the United States than directly disposing of spent fuel.[8] Although the estimated difference is a modest percentage of the price of electricity—about 3-5 percent—the total cost is large. For the current fleet of U.S. nuclear power plants, reprocessing spent fuel and recycling the recovered plutonium would add roughly $2 billion per year to the cost of U.S. nuclear-generated electricity. These extra costs would have to be passed along to ratepayers or to taxpayers if underwritten by the government.

It is sometimes argued that reprocessing will become economically attractive as the cost of reprocessing decreases or as nuclear power expands and uranium prices increase. At the average uranium price paid by U.S. reactor operators in 2004 ($33 per kilogram), our calculations indicate that reprocessing would have to cost less than $400 per kilogram of spent fuel in order to be competitive with direct disposal.[9] Yet, if the cost of building a new U.S. reprocessing facility were similar to those of facilities in France and the United Kingdom, the cost of reprocessing would be more than $2,000 per kilogram.[10] Even if reprocessing costs could somehow be cut in half to $1,000 per kilogram of spent fuel, the price of uranium would have to rise to nearly $400 per kilogram in order for reprocessing to be cost effective. It is extremely unlikely that world uranium prices will rise to this level in the next 50 years, even if nuclear power expands dramatically.

The PUREX process has been in use for more than five decades, and it seems unlikely that dramatic cost reductions could be achieved using this or the new more elaborate UREX+ reprocessing technology currently favored by the Energy Department. Indeed, increasingly stringent environmental and safety regulations could be expected to put upward pressures on costs. The experience at the new Rokkasho-mura reprocessing facility in Japan, where initial capital cost estimates more than tripled to about $20 billion, serves as a cautionary example.

A range of alternative chemical separation processes have been proposed over the decades. One that attracted support from the 2001 energy commission chaired by Vice President Dick Cheney is electrometallurgical processing, or "pyroprocessing." Recent official reviews have concluded, however, that such techniques are likely to be substantially more expensive than PUREX.[11] Thus, there is no reason to believe that economics will favor reprocessing.

Waste Disposal

Reprocessing and recycling, as currently practiced in France and planned in Japan, do not reduce the amount of repository area required for the disposal of radioactive wastes. The required area is determined not by the mass or volume of the wastes, which are very small in comparison to the mass and volume of the surrounding rock, but by the heat output of the wastes, which raises the temperature of that rock. Put simply, the more heat output, the more storage area that will be needed. Yet, if current reprocessing approaches are used, they would not significantly reduce the total heat output, and thus they would not significantly reduce the amount of repository area required per unit of electricity generated.[12]

Substantial reductions in repository requirements could be achieved only if all the long-lived transuranic elements in the spent fuel were separated and recycled repeatedly in reactors until they were fissioned. This separation-and-transmutation system would be even more expensive, however, than traditional reprocessing and single recycle as currently practiced in France.[13] If fast-neutron reactors or accelerators were used to transmute the long-lived radionuclides more efficiently, the cost would be even higher.[14]

No one knows how expensive a complete separation-and-transmutation system would be, because the technology has not been fully developed and demonstrated, but, in the early 1990s, the Energy Department commissioned the National Academy of Sciences (NAS) to do a thorough study of the benefits and costs of separating and fissioning the long-lived transuranic elements in spent fuel. The 1996 report found that the benefits if any would be small, while the costs would be very high. "The excess cost for an [separation and transmutation] disposal system over once-through disposal for the 62,000 [metric tons] of [light-water reactor] spent fuel [approximately the amount currently slated for Yucca Mountain] is uncertain but is likely to be no less than $50 billion and easily could be more than $100 billion if adopted by the United States."[15]

If the licenses of most U.S. reactors are extended, as seems likely, the total amount of spent fuel discharged by current reactors will be about twice as large, and the extra costs of separation and transmutation would rise proportionately from $100 billion to more than $200 billion. If new reactors are built, the extra costs would be still larger. These costs would be in addition to those of the Yucca Mountain repository, which

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would still be needed for the disposal of the fission-product wastes.

Proliferation Implications

There are two proliferation concerns associated with reprocessing. First, reprocessing increases the risk that plutonium could be stolen by terrorists. Second, countries with reprocessing plants or separated plutonium could produce nuclear weapons before an effective international response could be mobilized.

Nuclear Terrorism

Plutonium is much more difficult than highly enriched uranium to make into a nuclear explosive, but it would not be impossible for terrorists to do so.[16] Terrorists could more easily use plutonium to make potent radiological weapons. The dispersal of 10 kilograms of plutonium-oxide aerosol 32 kilometers upwind from downtown Seattle would cause hundreds to thousands of additional cancer deaths as plutonium is deadly when inhaled.[17]

The plutonium in spent fuel is relatively inaccessible to terrorists because it is mixed with fission products, some of which—notably 30-year half-life cesium-137—emit penetrating gamma rays when they decay. The radiation dose rate one meter from a 50-year-old spent fuel assembly would be high enough to deliver a fatal dose within half an hour.[18] As a result, a spent fuel assembly, which contains about 4 kilograms of plutonium, will be "self-protecting" by the standards of the International Atomic Energy Agency (IAEA) for more than 100 years. In contrast, the penetrating-radiation dose rate from separated plutonium is so low that it can be safely carried in a light airtight container.[19]

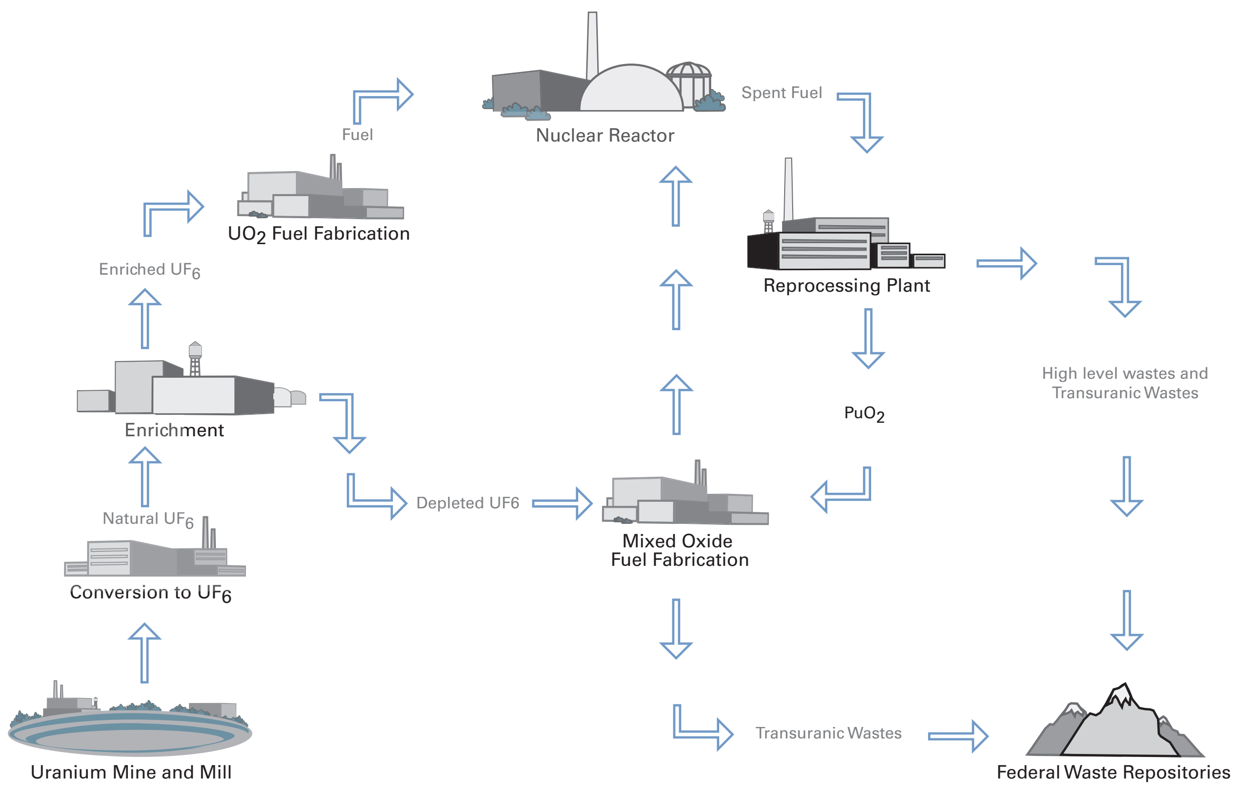
Reprocessing separates plutonium from the fission products, making it far more vulnerable to theft. Separated plutonium could be stolen from reprocessing or MOX fuel fabrication facilities or in transit between them. In addition, fresh MOX fuel could be stolen in transit or from dispersed nuclear reactor sites, and the plutonium could be separated from the uranium using straightforward chemical processes.

As already noted, the PUREX process was originally developed to separate pure plutonium for weapons. The current Bush administration therefore established an Advanced Fuel Cycle Initiative (AFCI) within the Energy Department to come up with a more "proliferation-resistant" reprocessing and recycle system in which pure plutonium would never be separated. The AFCI program has developed the UREX+ process, which would separate a mix of plutonium and neptunium. However, in a March 2005 hearing before Hobson's subcommittee, AFCI Director William Magwood volunteered that "we're not sure that it's possible to use this chemical technology to separate the plutonium, in combination with a few other things, in a fashion that will make it both proliferation resistant and economically viable."

The reason is quite obvious: neptunium is much less radioactive than plutonium and is itself a directly useable nuclear-weapon material. In fact, even if all of the other transuranic isotopes in spent fuel were separated and mixed with the

Figure 1 Recycling Plutonium

Mined uranium is transported to a mill where the uranium is separated from the ore. The uranium is then converted to UF_6, enriched, and the enriched UO_2 is then fabricated for use in nuclear reactors. Once depleted, the spent fuel can either undergo reprocessing, be stored in above-ground containment facilities or stored more permanently in federal waste repositories, such as the Yucca Mountain site.



plutonium, the gamma radiation dose rate from the mixture still would be only about 0.0001 of that from a 20-year-old spent fuel assembly and 0.001 the dose rate required to meet the IAEA's self-protection standard.[20]

National Proliferation

For a government, the possession of a reprocessing plant would provide a quick route to a nuclear-weapon capability. Every country that has embarked on commercial reprocessing has accumulated a huge stockpile of separated plutonium. Plutonium separation by the civilian reprocessing industry has gotten so far ahead of plutonium recycling that the world stockpile of separated civilian plutonium has reached 250 tons and is still growing (see table 1). Using the IAEA's conservative assumption that 8 kilograms is required to produce a first-generation nuclear bomb, this material represents more than 30,000 bomb equivalents—an enormous potential threat.

This is why the Ford and Carter administrations turned against commercial reprocessing. Given that the United States had been the leading promoter of reprocessing and plutonium breeder reactors for years, it was believed that the only way to turn other countries around would be to be able to say to them, "Reprocessing is neither necessary nor economic. We don't do it. You don't need to, either."

In the years after India's 1974 test, the United States was relatively successful in preventing or at least delaying the proliferation of reprocessing technology. France was persuaded not to complete the transfer of reprocessing plants to South Korea and Pakistan. A deal under which Germany would have transferred reprocessing and enrichment technologies to Brazil collapsed before the reprocessing technology was transferred. Further, the Nuclear Suppliers Group (NSG) was established, whose members agreed to "exercise restraint" in the transfer of reprocessing technology.

The only transfer of reprocessing technology after 1974 was to Japan, after Japan's prime minister insisted that reprocessing was a "life or death issue." Today, Japan is the only non-nuclear-armed state that has an active civilian reprocessing program. Japan's neighbors, China and South Korea, are concerned that this program would allow Japan to acquire and deploy nuclear weapons quickly if it ever decides that they are needed.

In his talk at the National Defense University on February 11, 2004, President George W. Bush called on the NSG to deny enrichment and reprocessing technologies "to any state that does not already possess full-scale, functioning enrichment and reprocessing plants." Many countries have denounced this proposal as a new form of discrimination by the nuclear-weapon states. A continued U.S. stance that reprocessing is neither necessary nor economic is likely to be more influential than a policy of "Do as I say, not as I do."

Table 1 Estimated Stocks of Separated Civilian Plutonium

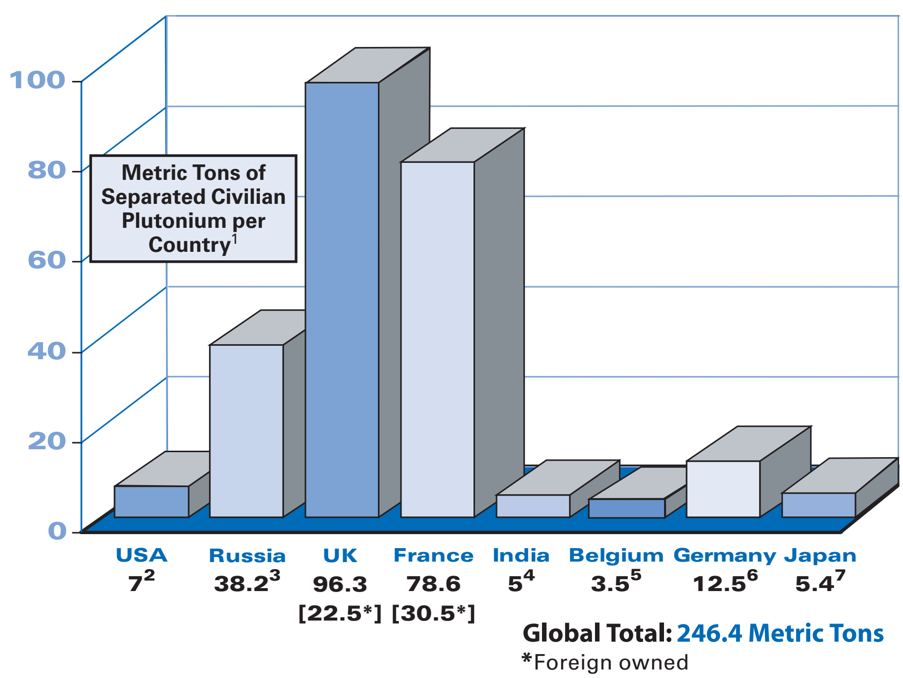


TABLE NOTES

1. Except where otherwise indicated, based on annual national declarations to the International Atomic Energy Agency (IAEA) concerning "policies regarding the management of plutonium." About 50 tons of the plutonium stored at British and French reprocessing plants belonged to other countries.
2. Not including 38 tons of weapons-grade plutonium declared excess to national security needs in 1995.
3. Not including 34 tons of weapons-grade plutonium declared excess to national security needs in 1995.
4. Estimate by M. V. Ramana, interview with author, September 6, 2004.
5. Includes foreign plutonium being processed in Belgium's mixed-oxide fuel fabrication facility. As of the end of 2003, Belgium had 0.4 tons of separated plutonium stored at France's reprocessing plant.
6. End of 2004. Germany also had approximately 15 tons of separated plutonium stored at French and British reprocessing plants.
7. End of 2003. Japan also had 35.2 tons of separated plutonium stored in French and British reprocessing plants.

The Future of Reprocessing

About 30 percent of the world's light-water power-reactor spent fuel is being reprocessed.[21] Among the nuclear-armed states, France, India, Russia, and the United Kingdom have civilian reprocessing plants, and China is designing a pilot-scale reprocessing facility. The United Kingdom's reprocessing plant, originally built with prepaid foreign reprocessing contracts, is expected to shut down by 2010 because of a lack of follow-on contracts but may shut down even earlier because of a recent accident. Russia reprocesses the fuel from first-generation domestic and East European power reactors in a plant that is old, subsidized, and has caused very serious radioactive contamination of the region.

Thus, the future of reprocessing is unclear. In France, it appears to persist because of national pride, much as the Concorde supersonic-transport program did for decades after it was clear that it was a commercial failure. Japan's reprocessing program is sustained by not-in-my-backyard (NIMBY) pressures that

Greenpeace International

Cogema's La Hague nuclear reprocessing plant, located on the western tip of the Cotentin Peninsula in Normandy, covers 740-acres.

have made interim storage of spent fuel politically difficult. The Japanese nuclear utilities responded by shipping their spent fuel to France and the United Kingdom to be reprocessed while Japan built its own reprocessing plant.[22] Japan has plans to recycle its 41 tons of already separated plutonium into reactor fuel, but these plans have thus far been set back by a decade as a result of NIMBY opposition from the local governments that host the reactors.[23] Russia's reprocessing program is a relic from the Soviet era. The purpose of India's reprocessing is to provide plutonium for its breeder-reactor development effort. That effort may be abandoned as it has been in the United States and Europe if, as a result of a July agreement between Bush and Indian Prime Minister Manmohan Singh, India gains access to the world uranium market, from which it has been excluded because it is not a party to the nuclear Nonproliferation Treaty.

U.S. power reactors annually discharge about 2,000 tons of spent fuel containing more than 20 tons of plutonium, or about as much as is being separated annually worldwide.[24] The spent fuel already discharged by U.S. reactors contains about 600 tons of plutonium. In addition to licensing and building reprocessing plants and MOX fuel fabrication facilities, a comprehensive recycling program would require that essentially all U.S. reactors be re-licensed to use MOX fuel. According to the NAS report, it would take 70 percent of U.S. nuclear capacity 30 years to dispose of just half the plutonium and other transuranic elements in 62,000 tons of spent LWR fuel—approximately what the United States will have discharged in 2008.[25] This means that disposing of the transuranics in U.S. spent fuel would far outlive the current generation of reactors.

Some of the obstacles to such a program are shown by those encountered in a similar but far less ambitious plan that the United States and Russia agreed to in 2000. According to that agreement, beginning in 2007, each country will dispose of 34 tons of excess weapon plutonium at a rate of at least two tons a year. Each plans to dispose of its plutonium by fabricating it into MOX fuel and irradiating the fuel in power reactors. The ground has not yet been broken for the proposed fuel-fabrication facilities, however, and most U.S. nuclear utilities have declined to use the plutonium fuel because of concerns about licensing problems.[26]

The difficulties that would be encountered in a more ambitious effort to fission all the transuranic elements can only be imagined. Given the history of abandoned nuclear projects, ranging from nuclear-powered aircraft to plutonium breeder reactors, it is not difficult to foresee that a multigenerational project to recycle and fission all the transuranic elements would be abandoned half completed and the country would be left with a much more costly radioactive waste and security problem, including the need to secure hundreds of additional tons of separated plutonium from theft.

Conclusion

Given the high economic and security costs of reprocessing, there should be some important reason for Congress to back—without serious consideration—such an intricate proposal, with its generations of reactors, reprocessing, and fuel fabrication plants.

The main purpose of the proposal to reprocess U.S. spent fuel seems to be to allow Congress and the administration an easy way to avoid the politically divisive problem of deciding either to expand the capacity of the Yucca Mountain repository or launching a siting process for additional or alternative geological storage.[27] Some U.S. nuclear energy advocates also believe that dealing with the spent fuel problem in a definitive manner is essential if there is to be a renaissance of nuclear power in the United States.[28] Yet, there is no technical fix for the spent fuel problem.

Fortunately, if Congress wants to deal with the problem of nuclear waste in a thoughtful way, it has time to do so. Spent fuel can be stored safely and economically for at least 50 years in dry-cask interim storage. That leaves plenty of time to clarify the future of nuclear power in the United States and to explore in an open and systematic manner the Yucca Mountain and alternative disposition options for the spent fuel discharged by the current generation of reactors. **ACT**

ENDNOTES

1. House Committee on Appropriations, *Energy and Water Development Appropriations Bill, 2006*, 109th Cong., 1st sess., 2005, H. Rep. 86.

2. *Congressional Record* (May 24, 2005): H3859.

3. *Nuclear Waste Policy Act of 1982*, sec. 114d.

4. Ibid., sec. 161.

5. Panel on Public Affairs, American Physical Society, *Nuclear Power and Proliferation Resistance: Securing Benefits, Limiting Risk*, May 2005, pp. 20, 22. The authors were among the nine authors of this report.

6. J-M. Charpin, B. Dessus, and R. Pellat, "Economic Forecast Study of the Nuclear Power Option," Paris, July 2000.

7. Based on New Nuclear Policy-Planning Council, Japan Atomic Energy Commission, "Interim Report Concerning the Nuclear Fuel Cycle Policy," November 2004.

8. Massachusetts Institute of Technology (MIT), "The Future of Nuclear Power," 2003; Matthew Bunn et al., *The Economics of Reprocessing Versus Direct Disposal of Spent Nuclear Fuel* (Cambridge, MA: Harvard University, 2003); The Economic Future of Nuclear Power (Chicago: University of Chicago, August 2004).

9. Computed using assumptions that are favorable to reprocessing, including a 50 percent reduction in base-case waste-disposal costs.

10. Assumes a plant throughput of 800 tons of spent fuel per year for 30 years; an overnight capital cost of $6 billion, repaid at interest rates appropriate for a regulated private entity with a guaranteed rate of return; annual operating costs of $560 million per year; and standard assumptions about construction time, taxes and insurance, and contingency, pre-operating, and decommissioning costs. For a government-financed facility with very low cost, the corresponding cost would be $1,350 per kilogram. For an unregulated private venture, the cost would be $3,100 per kilogram. *Economics of Reprocessing Versus Direct Disposal of Spent Nuclear Fuel*, p. 213.

11. Office of Nuclear Energy, U.S. Department of Energy, "Generation IV Roadmap: Report of the Fuel Cycle Crosscut Group," Washington, DC, March 2001; *Accelerator-Driven Systems and Fast Reactors in Advanced Nuclear Fuel Cycles: A Comparative Study*, OECD/NEA 03109, 2002.

12. With spent fuel in the Yucca Mountain repository, the temperature of the rock between the tunnels would reach its peak about 2,000 years after the spent fuel is emplaced. If the plutonium were recycled in existing power reactors, much of it would fission, but some would be converted into other transuranic isotopes that contribute more decay heat in the first few thousand years.

13. The added complexity associated with the recovery of the minor transuranics would increase reprocessing costs, and the costs of fabricating them into fuel also would be greater because some of them are more radioactive than plutonium.

14. In current-generation power reactors, the chain reaction is sustained primarily by neutrons that are slowed down by a series of collisions with the light hydrogen nuclei in the water between the fuel rods. Such "slow" neutrons are ineffective in fissioning some transuranic isotopes. This has generated a new rationale for introducing the fast-neutron reactors, which were formerly advocated for plutonium breeding. These reactors likely would be cooled by a liquid metal such as molten sodium or lead. Neutrons do not lose much energy when they collide with the heavy nuclei of these elements.

15. *Nuclear Wastes: Technologies for Separation and Transmutation* (National Academy Press, 1996), p. 7.

16. J. Carson Mark et al., "Can Terrorists Build Nuclear Weapons?" in Preventing Nuclear Terrorism, eds. Paul Leventhal and Yonah Alexander (D.C. Heath and Co., 1987), p. 55. French and Japanese reprocessing advocates have argued for decades that the "reactor-grade" plutonium in spent power-reactor fuel is not weapons usable because the fraction of the undesirable isotope Pu-240 is larger than in the weapons-grade plutonium that has been used in weapons programs. To be sure, the yield of a Nagasaki-type device would be reduced from the equivalent of 20,000 tons of TNT to as low as the equivalent of 1,000 tons of TNT because of the likelihood of premature initiation of the chain reaction by neutrons from the spontaneous fission of Pu-240, but that would still be a devastating explosion. J. Carson Mark, "Explosive Properties of Reactor-Grade Plutonium," *Science & Global Security* 4, (1993), p. 111. For countries, more modern weapon designs are insensitive to pre-initiation.

17. Steve Fetter and Frank von Hippel, "The Hazard from Plutonium Dispersal from Nuclear-Warhead Accidents," *Science & Global Security* 2 (1990), p. 21. However, the individual chance of cancer death among the large exposed population would be only on the order of 0.1 percent.

18. W. R. Lloyd, M. K. Sheaffer, and W.G. Sutcliffe, "Dose Rate Estimates from Irradiated Light-Water-Reactor Fuel Assemblies in Air," UCRL-ID-115199, 1994. The IAEA "self-protection" criterion is 1 Sievert (100 rems) per hour at 1 meter. The median dose for death within several weeks following exposure is about 5 Sieverts.

19. The primary radiological hazard from plutonium is from the alpha particles (helium nuclei) that it emits as it decays. These emissions can be blocked by a thin container but also make inhaled plutonium-oxide particles very dangerous.

20. Jungmin Kang and Frank von Hippel, "Limited Proliferation-Resistance Benefits From Recycling Unseparated Transuranics and Lanthanides From Light-Water Reactor Spent Fuel," *Science & Global Security* (forthcoming).

21. Most power reactors worldwide and in the United States are cooled by ordinary "light" water, so named to distinguish it from the "heavy water" used in a power reactor type developed by Canada. In heavy water, ordinary hydrogen is replaced by heavy deuterium, which captures fewer neutrons.

22. The local tax and job benefits from hosting a reprocessing plant are much greater than those from hosting an interim spent-fuel storage facility. This appears to have been a deciding factor for the sparsely populated and economically depressed Aomori Prefecture. The central government also has committed that no spent fuel assembly or container of vitrified high-level reprocessing waste will remain at the plant for more than 50 years.

23. In 1998, Japan expected that its first MOX fuel would be loaded into two reactors in 1999. IAEA, INFCIRC/549/Add. 1, March 31, 1998. In 2004 the two utilities involved did not expect to load the fuel before 2008. Citizens' Nuclear Information Center, "Japanese Power Companies' Pluthermal Plans: Recent Developments," May/June 2004.

24. France reprocessed about 1,050 tons of spent fuel in 2002, down from a peak of 1,650 tons of heavy metal in 1995. With the end of foreign contracts, its reprocessing rate is expected to decline further to about 850 tons per year. The average reprocessing rate at the United Kingdom's LWR spent fuel reprocessing plant between 1998 and 2002 was about 700 tons per year. Japan's reprocessing plant is scheduled to come into full operation at a capacity of 800 tons per year in 2010, the year that the British plant is scheduled to shut down. Based on its declarations of civilian plutonium stocks to the IAEA, between 1996 and 2002, Russia's reprocessing plant averages less than 200 tons per year. India's civilian reprocessing plants have a combined capacity of about 200 tons per year, but the concentration of plutonium in spent heavy-water-reactor fuel is about one-third of that in LWR fuel, which is about 1.2 percent at current burnups.

25. The NAS report estimated 18.6 GWe operating at 100 percent capacity factor with a full MOX load. *Nuclear Wastes: Technologies for Separation and Transmutation*, p. 79. We assume 1/3 core loadings and an average 80 percent capacity factor.

26. "More Reactors Needed for Disposition Under Revised Plan, DOE Says," *Nuclear Fuel*, March 4, 2002.

27. The MIT study, *The Future of Nuclear Power* proposed consideration of deep borehole storage.

28. Every order for a new power reactor in the U.S. since 1974 has been cancelled.