POLICY FORUM: ENERGY

Plutonium and Reprocessing of Spent Nuclear Fuel

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Historically, chemical separation or "reprocessing" technologies have been used to separate the plutonium and uranium in irradiated nuclear fuel from fission products and from other isotopes that have built up as a result of neutron absorption. Reprocessing is as old as nuclear reactors, because the first reactors were built to produce plutonium for nuclear weapons.

Plutonium can also be used as a fission fuel in civilian nuclear power reactors, and during the past three decades, U.S. policy has shifted repeatedly between encouraging plutonium recycling in power reactors and keeping it unseparated and stored in discharged "spent" fuel so as to minimize the danger of its diversion to use for nuclear weapons. The Clinton administration moved to shut down U.S. reprocessing research and development (R&D). Most recently, however, the May 2001 report of the National Energy Policy Development Group, chaired by Vice President Cheney, reopened the question by including among its recommendations that "The United States should reexamine its policies to allow for research, development, and deployment of fuel conditioning methods … that reduce waste streams and enhance proliferation resistance" (*1*). Both the proliferation and economic costs of reprocessing would probably be high, however, and the environmental benefits questionable.

Background

The fission energy released in U.S. light water–cooled reactors comes mostly from the chain-reacting isotope ^{235}U, which makes up 0.7% of natural uranium and several percent in their uranium fuel. Plutonium is produced as a result of neutron capture on ^{238}U, which makes up virtually all of the remainder of the uranium. If most of the ^{238}U could be converted to chain-reacting plutonium, which contains as much releasable fission energy per atom as ^{235}U, the energy that could be extracted from a gram of uranium could be increased about 100-fold.

During the 1960s and 1970s, the industrialized nations focused overwhelmingly on achieving this objective through the commercialization of sodium-cooled, fast-neutron reactors, which would be fueled by plutonium while breeding somewhat more plutonium from ^{238}U than they consumed. Programs were launched to reprocess spent light water–reactor fuel to recover the ~1% plutonium it contains for start-up cores for the breeder reactors.

All the economic premises on which these programs were launched turned out to be false: Sodium-cooled reactors were found to be considerably more costly and difficult to maintain than water-cooled reactors. The urgency of building much more uranium-efficient reactors was much reduced when world nuclear capacity plateaued at levels less than 1/10th those that had been projected for the year 2000 (*2*). Because the demand was much lower than expected and because of the discovery of major new deposits of high-grade uranium, the price of natural uranium fell dramatically (*3*). Finally, commercial reprocessing of light water–reactor fuel turned out to be very costly (*4*, *5*).

Portability of separated plutonium. The canister held by this worker in Russia's commercial reprocessing complex near Chelyabinsk contains 2.5 kg of plutonium dioxide powder. The material in three of these easily portable containers would suffice to make a nuclear explosive. The complex's warehouses contain over 13,000 such containers.

CREDIT: RUSSIAN MINISTRY OF ATOMIC ENERGY, 1994.

History

Reconsideration of U.S. policies to promote a world powered by plutonium-fueled reactors began in 1974, after India shocked the world by testing a nuclear explosive made with plutonium separated with reprocessing technology provided by the United States (*6*). Concern was also expressed that the projected global plutonium economy, in which millions of kilograms of plutonium would be separated out of spent fuel annually, might spawn nuclear terrorism. Less than 8 kg of plutonium is required to make a Nagasaki-type bomb (*7*–*9*).

The reassessment initiated by the Ford administration was completed by the Carter administration, which decided in 1977 against licensing for operation a newly built U.S. commercial reprocessing plant. The U.S. nuclear-energy establishment complained bitterly, and the Reagan administration reversed this policy after it came into office in 1981. By then, however, because of the adverse economics, there was no longer any industrial interest in reprocessing in the United States. In 1993, the Clinton administration reinstated U.S. opposition to reprocessing but did not reverse the Reagan administration's commitment not to interfere with plutonium-recycling programs in Western Europe and Japan (*10*).

During the 1980s and early 1990s, the United States, Germany, the United Kingdom, and France all abandoned their breeder-reactor demonstration programs. Russia and Japan still operate demonstration breeder reactors, completed in 1980 and 1993, respectively, but have not committed funding to build follow-on breeders. India is building a demonstration breeder reactor, and China is building a small experimental breeder reactor.

Tradeoffs

Commercial reprocessing continues on a large scale in Britain and France and, on a small scale, in Russia and Japan. The principal foreign customers for British and French reprocessing services have been German and Japanese utilities. Domestic political opposition to expanded at-reactor spent-fuel storage or central storage sites made shipment of spent fuel abroad for reprocessing their only alternative to shutting down their reactors. Storage of spent fuel is cheaper, safer, and more environmentally benign than reprocessing, which produces multiple types of radioactive waste that must be stored in any case, but host communities require assurances that interim spent-fuel storage will not become permanent (*11*).

Last year, the German government agreed to allow extended spent-fuel storage at reactor sites if, by mid-2005, German

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nuclear utilities end shipments of spent fuel abroad for reprocessing (*12*). Japan's utilities too are ending foreign reprocessing but are completing a ¥2.4 trillion (about US$20 billion) reprocessing plant that was committed in 1980. Because of the large number of high-paying jobs, the reprocessing plant is more acceptable to the local government than a stand-alone, interim, spent-fuel storage pool (*13*, *14*).

Given the loss of foreign customers, the continuation of the costly reprocessing of domestic spent fuel is being questioned in both Britain and France. A French government study concluded that, if France stops reprocessing in 2010, it will save 28 to 39 billion francs (US$4 to 5 billion) over the remaining lifetime of its current fleet of power reactors (*15*).

With the indefinite postponement of commercial breeder reactors, the plutonium that has been separated by commercial reprocessing has become a disposal problem. As of the end of 1999, this still-growing stockpile amounted to about 200,000 kg (the equivalent of 25,000 Nagasaki bombs) (*16*).

Some West European and Japanese utilities have launched programs to dispose of their stockpiles of separated plutonium by fabrication into mixed-oxide (MOX) uranium-plutonium fuel. This fuel can be substituted for about one-third of the low-enriched uranium fuel in most light water–reactor cores at a rate of about 400 kg plutonium/year in a 1000-megawatt (electric) reactor. There is no economic incentive for such use, however. Even when reprocessing is treated as a sunk cost, the cost of fabricating 200 tons of plutonium into MOX fuel would be billions of dollars more than the cost of the low-enriched fuel that it replaces. Britain and Russia, which together account for almost half of the world's stockpile of separated civilian plutonium, have not yet developed disposition policies. Additional disposition options are required (*17*).

The focus of U.S. Department of Energy reprocessing R&D during recent decades has been on "pyroprocessing" or electrorefining in a molten salt electrolyte as an alternative to the "PUREX" nitric acid–dissolution, organic solvent–extraction cycle used in current commercial reprocessing plants. Proponents say that, because pyroprocessing can be designed not to separate plutonium cleanly from other transuranic elements, its product could be more proliferation-resistant than the pure plutonium produced by conventional reprocessing. They also point out that it could be done at small-scale facilities. In fact, pyroprocessing R&D was a part of the U.S. Integrated Fast Reactor development program, which proposed a reprocessing and fuel-recycle plant be integrated into each reactor complex. This would result in a vast proliferation of facilities with remote processing capabilities for highly radioactive fuel, requiring only the installation of a final clean-up stage to produce separated plutonium that could be used for weapons.

It is difficult to imagine that any form of chemical reprocessing would be more proliferation-resistant in the short term than not reprocessing at all and leaving the plutonium mixed with highly radioactive fission products in the solid fuel matrix. Even 50 years after discharge, the radiation level from penetrating gamma rays a meter away from an assembly of spent light water–reactor fuel rods is 5 to 10 Sieverts/hour—enough to assure a lethal dose in less than an hour (*18*). By comparison, virtually all of the radiation from separated plutonium is short-range alpha particles (helium nuclei), which cannot even penetrate human skin. If the plutonium is stored in a sealed container to protect against the hazard of the dispersal of inhalable plutonium-oxide particles, it is easily portable (see figure on page 2397).

Proponents of reprocessing argue that burying plutonium-containing spent fuel creates an unacceptable long-term hazard, since the half-life of the most important plutonium isotope, 239Pu, is 24,000 years. Over the millennia, some of this radioactivity might find its way back to the surface environment. This has led to ambitious proposals (also mentioned favorably in the Cheney report) for chemical separation and neutron transmutation of all nonuranium, long-lived radioactive isotopes in spent fuel. However, such systems would greatly increase the cost of nuclear power. A National Academy of Sciences review concluded that "none of the dose reductions seem large enough to warrant the expense and the additional operational risk of transmutation" (*19*).

The Department of Energy has proposed that geological storage of spent fuel be kept open for possible retrieval for at least 100 years after emplacement begins (*20*). This would allow time for thorough examination of alternative approaches to final disposition while the long-term future of nuclear power is clarified.

Thus, the Cheney report's recommendation of renewed U.S. government support of reprocessing R&D reflects a 1970's vision of the near-term future of nuclear power. Today, it appears that both nonproliferation and the nuclear power establishment would be best served by focusing on the basics during the coming decades and sticking to the simple, economical "once-through" (i.e., nonreprocessing) fuel cycle.

References and Notes

1. *National Energy Policy* (The White House, May 2001), pp. 5–17; available at www.whitehouse.gov.
2. The U.S. Atomic Energy Commission projected in 1974 that, by the year 2000, U.S. nuclear-powered generating capacity would be over 1000 GWe (10^{12} Watts electric) with more than 100 GWe being added annually [*Proposed Final Environmental Statement on the Liquid Metal Fast Breeder Reactor Program* (WASH-1535, U.S. Atomic Energy Commission, Washington, DC, 1974), Fig. 11.2 to 11.23]. Today, U.S. nuclear capacity has plateaued at about 100 GWe.
3. Between January 1978 and May 2001, the unrestricted spot price of natural uranium declined from about $261 to $19 per kg in constant U.S. GDP-deflated May 2001 dollars [*Nukem Market Report* (June), p. 220 (2001)].
4. Estimated costs in constant 1992 U.S. dollars for reprocessing in a newly constructed plant increased from about $100/kg of heavy metal in the early 1970s to $2000 in the 1990s [*Nuclear Wastes: Technologies for Separations and Transmutation* (National Academy Press, Washington, DC, 1996), p. 117]. The 1990s cost corresponds to about $300/g of contained chain-reacting plutonium (plutonium-239 and plutonium-241) in 10-year-old spent fuel. Global reserves of natural uranium recoverable at costs of up to $20/g uranium-235 would last over 60 years at current rates of consumption
5. *Uranium 1999: Resources, Production and Demand* (OECD Nuclear Energy Agency and the International Atomic Energy Agency, Paris, 2000)].
6. G. Perkovich, *India's Nuclear Bomb* (Univ. of California Press, Berkeley, 1999), p. 28.
7. M. Willrich, T. B. Taylor, *Nuclear Theft* (Ballinger, Cambridge, MA, 1974). The Nagasaki bomb contained 6 kg of "weapons-grade" plutonium (containing less than 6% plutonium-240) and had a yield equivalent to 20,000 tons of TNT. Using "reactor-grade" plutonium, the probable yield would have been about 1000 tons but, with advanced designs, the yield reduction would be much smaller (*8*, *9*).
8. J. C. Mark, *Sci. Global Security* **4**, 111 (1994).
9. U.S. Department of Energy, *Nonproliferation and Arms Control Assessment of Weapons-Usable Fissile Material Storage and Excess Plutonium Disposition Alternatives* (U.S. Department of Energy, Washington, DC, 1997), p. 37.
10. White House Press Release, "Nonproliferation and Export Control Policy," 27 September 1993.
11. The cost of dry at-reactor spent-fuel storage for 40 years is about $120 or 250/kg heavy metal, depending upon whether the reactor is still operating or not [M. Bunn *et al.*, *Interim Storage of Spent Nuclear Fuel* (Managing the Atom Project, Harvard University, Cambridge, MA, and Project on Sociotechnics of Nuclear Energy, University of Tokyo, 2001)]; available at http://ksgnotes1.harvard.edu/BCSIA/Library.nsf/pubs/spentfuel, p. 14.
12. M. Hibbs, *Bull. At. Sci.* **57**(May/June), 63 (2001).
13. _____, *Nucl. Fuel* **25** (22), 5.
14. Reference in (*11*), p. 39.
15. *Economic Forecast Study of the Nuclear Option* (Planning Commission, Government of France, 2000); available at www.plan.gouv.fr/organisation/seeat/nucleaire/accueilnucleaire.html, Section 3.4.
16. Author's estimate based primarily on national declarations of stored, separated civilian plutonium to the International Atomic Energy Agency (Information Circulars 549); available at www.iaea.org/worldatom/Documents/Infcircs.
17. A. Macfarlane, F. von Hippel, J. Kang, R. Nelson, *Bull. At. Sci.* **57**(May/June), 53 (2001).
18. W. R. Lloyd, M. K. Sheaffer, W. G. Sutcliffe, *Dose Rate Estimates from Irradiated Light-Water-Reactor Fuel Assemblies in Air* (UCRL-ID-115199, Lawrence Livermore National Laboratory, Berkeley, CA, 1994).
19. National Research Council, Executive Summary, in *Nuclear Wastes: Technologies for Separation and Transmutation* (National Academy Press, Washington, DC, 1996), p. 3.
20. U.S. Department of Energy, *Draft Environmental Impact Statement for a Geologic Repository for the Disposal of Spent Nuclear Fuel and High-Level Radioactive Waste at Yucca Mountain* (YMP-0106, Yucca Mountain Project, North Las Vegas, NV, 1999); available at www.ymp.gov/documents/deis/index.htm, Section 4.2.1.