



3 Managing Spent Fuel in the United States: The Illogic of Reprocessing

Frank von Hippel

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The Illogic of Reprocessing**

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About the IPFM

The International Panel on Fissile Materials (IPFM) was founded in January 2006. It is an independent group of arms-control and nonproliferation experts from both nuclear weapon and non-nuclear weapon states.

The mission of IPFM is to analyze the technical basis for practical and achievable policy initiatives to secure, consolidate, and reduce stockpiles of highly enriched uranium and plutonium. These fissile materials are the key ingredients in nuclear weapons, and their control is critical to nuclear weapons disarmament, to halting the proliferation of nuclear weapons, and to ensuring that terrorists do not acquire nuclear weapons. IPFM research and reports are shared with international organizations, national governments and nongovernmental groups.

The Panel is co-chaired by Professor José Goldemberg of the University of São Paulo, Brazil and Professor Frank von Hippel of Princeton University. Its founding members include nuclear experts from fifteen countries: Brazil, China, Germany, India, Japan, the Netherlands, Mexico, Norway, Pakistan, South Korea, Russia, South Africa, Sweden, the United Kingdom and the United States.

Princeton University's Program on Science and Global Security provides administrative and research support for IPFM.

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Summary

Since 1982, it has been U.S. policy, for nonproliferation and cost reasons, not to reprocess spent power-reactor fuel. Instead, the Department of Energy (DOE) is to take spent power reactor fuel from U.S. nuclear utilities and place it in an underground federal geological repository. The first U.S. repository is being developed under Yucca Mountain, Nevada. Originally, it was expected to begin taking fuel in 1998. However, project management problems and determined opposition by the State of Nevada are expected to delay its opening for at least two decades.

U.S. nuclear utilities, therefore, have been pressing the DOE to establish one or more centralized interim storage facilities for their accumulating spent fuel. They insist that a “nuclear renaissance,” i.e., investments in new nuclear power plants, will not take place in the U.S. until the federal government demonstrates that it is able to remove the spent fuel from the reactor sites. U.S. state governments resist hosting interim spent fuel storage, however, out of concern that the Yucca Mountain repository may never be licensed, and that interim storage could become permanent.

In Japan, a similar situation ultimately resulted in Japan first shipping its spent fuel to France and the United Kingdom to be reprocessed and then building a \$20 billion domestic reprocessing plant to which spent fuel is now being shipped. In 2006, the U.S. Department of Energy similarly proposed reprocessing as a “solution” to the U.S. spent fuel problem.

Reprocessing of light-water-reactor fuel is being conducted on a large scale in France and in the United Kingdom. Much of the spent fuel that has been reprocessed has been foreign, notably from Germany and Japan, but since France and the United Kingdom require that the radioactive waste from reprocessing be returned to the country of origin, the need for interim radioactive waste storage in their customer countries was only postponed. In Japan, as part of its agreement to host Japan’s domestic reprocessing plant, Amori Prefecture has also agreed to accept, for interim storage, the reprocessing waste returning from Europe to Japan. Germany and most European countries, other than France, have decided not to reprocess domestically, but rather store their spent fuel until a geological repository can be sited. France plans to continue reprocessing most of its domestic spent fuel and, like Japan, is storing the resulting radioactive waste at its reprocessing site in La Hague. The United Kingdom is abandoning reprocessing altogether.

The construction of plants to reprocess light-water-reactor spent fuel was originally justified in the 1970s as a way to obtain plutonium to start up liquid-sodium-cooled plutonium-breeder reactors that, in theory, could extract one hundred times more energy than current generation reactors from a ton of natural uranium. Breeder reactors were expected to be dominant by the year 2000. The transition to breeder reactors did not occur, however, because their capital costs, and those of reprocessing plants, were much higher than had been projected and because global nuclear generating capacity has grown to only a few percent of the level that was projected in the 1970s. This, along with the

discovery of huge deposits of high-grade uranium ore in Australia and Canada, has postponed, for at least a century, concerns about shortages of low-cost uranium. Today, where plutonium is being recycled, it is being recycled as fuel for the light-water reactors (LWRs) from which it was extracted. Even with the cost of the reprocessing ignored as a “sunk cost,” plutonium fuel is generally more costly than conventional low-enriched uranium fuel.

Worldwide, about half of the plutonium being separated is simply being stockpiled at the reprocessing plants along with the associated high-level waste from reprocessing. In effect, those sites are interim spent-fuel storage sites – except that much of the spent fuel is being stored in separated form. As of 2005, the global stockpile of separated civilian plutonium had grown to 250 tons – sufficient to make more than 30,000 nuclear weapons.

The DOE does not plan to recycle in existing light water reactors the plutonium that would, according to its proposal, be separated from U.S. spent fuel. Instead, it proposes that the federal government subsidize the construction of tens of sodium-cooled fast-neutron “burner” reactors – basically, except for changes in their core design, the same sodium-cooled reactors that could not compete economically as plutonium breeder reactors. Plutonium – and, in the future, other less abundant transuranic elements extracted from spent light-water reactor fuel – would be recycled repeatedly through these reactors until, except for process losses, they were fissioned. The principal advantage claimed from doing this would be less long-lived waste per ton of spent fuel and that the residue from more spent fuel could be stored in the Yucca Mountain repository before a second repository would be required. Such a program would be enormously costly, however. The extra cost to deal with just the spent fuel that has already accumulated in the United States was estimated in 1996 by a U.S. National Academy of Sciences study as “likely to be no less than \$50 billion and easily could be over \$100 billion.” U.S. nuclear utilities have made clear that these extra costs would have to be funded by the federal government. It is quite possible that the program would stop -- as previous efforts to commercialize sodium-cooled reactors have -- after only one or two “demonstration” reactors have been built. In this case, the reprocessing plant would simply become an interim storage site for the reprocessed spent fuel – as has happened in the United Kingdom and Russia after their breeder-reactor commercialization programs failed.

The French nuclear combine, Areva, has proposed that it would be less costly to adopt the French approach with a third-generation combined reprocessing and plutonium-fuel fabrication plant in the United States. This would involve recycling the plutonium once in light-water reactors. The resulting spent “mixed-oxide” fuel, which would still contain two thirds as much plutonium as was used to fabricate it, would then remain indefinitely in interim storage at the reprocessing plant. Thus, once again, the reprocessing plant would serve as a costly type of interim spent-fuel storage.

U.S. Government policy turned against reprocessing after India, in 1974, used the first plutonium recovered by its U.S.-assisted reprocessing program to make a nuclear explosion. Reprocessing makes plutonium accessible to would-be nuclear-weapon

makers – national or sub-national – because it eliminates the protection provided by the lethal gamma radiation emitted by the fission products with which the plutonium is mixed in spent fuel.

In early 2006, the DOE originally proposed, as a more “proliferation-resistant” alternative to traditional reprocessing, to keep the reprocessed plutonium mixed with some or all of the minor transuranic elements in the spent fuel. Some of these elements are much more radioactive than the plutonium, but the radiation field that would surround the mix would be one thousand times less intense than the IAEA considers necessary to provide significant “self protection.”

Recently, because of unresolved technical difficulties with fabricating fuel containing some of the minor transuranics, the DOE has sought “expressions of interest” from industry in building a reprocessing plant that would differ from conventional reprocessing only in that it would leave some of the uranium mixed with the plutonium. Pure plutonium could be separated out from this mixture in an unshielded glove box.

In fact, the Bush Administration does not argue that any of the variants of reprocessing proposed by the DOE are proliferation resistant enough to be deployed in states of proliferation concern. It has therefore proposed a “Global Nuclear Energy Partnership” in which the weapon states and Japan would provide reprocessing services for other non-weapon states. This proposal has already backfired in stimulating a revival of interest in France in exporting reprocessing technology and in South Korea in acquiring its own national reprocessing capabilities. A similar Bush Administration proposal to confine enrichment to states that already have full-scale commercial enrichment plants has similarly stimulated a revival of interest in enrichment in half a dozen non-weapon states.

In comparison, the U.S. policy, which is in effect, that “we don’t reprocess and you don’t need to either,” has been much more successful. During the 30-year period it has been in force, no non-weapon state has initiated commercial reprocessing and seven countries have abandoned their interest in civilian reprocessing. In Belgium, Germany, and Italy domestic developments were more important than U.S. policy. In Argentina, Brazil, South Korea and Taiwan, however, countries that were interested in developing a nuclear-weapon option, U.S. pressure played a key role. Today, Japan is the only non-weapon state that engages in commercial reprocessing.

The principal alternative to reprocessing, until U.S. spent fuel can be shipped to Yucca Mountain or some other centralized storage, is simply to keep older spent fuel in dry storage on the reactor sites. There is ample space inside the security fence at all U.S. power-reactor sites to store all the spent fuel that will be discharged, even if the reactor licenses are extended to allow them to operate until they are sixty years old. At an operating reactor site, the incremental safety and security risk from dry stored fuel is negligible relative to the danger from the fuel in the reactor core and the recently discharged fuel in the spent fuel pool.

I. Introduction

In 2006, in response to Congressional pressure to start moving spent fuel off U.S. power-reactor sites, the Department of Energy proposed U.S. Government-funded reprocessing of the fuel and recycling of the recovered plutonium and minor transuranic elements. If carried through, this proposal would reverse a nonproliferation policy established by the Ford and Carter Administrations after India, in 1974, used the first plutonium it extracted as part of a U.S.-supported reprocessing program, to make a nuclear explosion. U.S. policy became to oppose reprocessing where it was not already established and not to reprocess domestically.¹ Four years later, in 1981, the Reagan Administration reversed the ban on domestic reprocessing.² By that time, however, U.S. utilities had learned that reprocessing would be very costly and were unwilling to pay for it.³

The Nuclear Waste Policy Act of 1982 therefore established that, in exchange for revenue from a tax of 0.1 cent per nuclear-generated kilowatt-hour of electricity, starting in 1998, the U.S. Department of Energy would take spent power reactor fuel from U.S. nuclear utilities and place it in an underground federal geological repository.⁴ In 1987, Congress decided to site the first such repository under Yucca Mountain, Nevada.⁵ Project management problems and determined opposition by the State of Nevada, however, have delayed the licensing process. Currently, the Department of Energy expects to receive a license for the Yucca Mountain repository in 2017 at the earliest.⁶ U.S. utilities therefore have been suing the DOE for the costs of building on-site dry-cask storage for the spent fuel that would have been shipped to Yucca Mountain on the originally contracted schedule. The Department of Energy has informed Congress that the cost of settling these lawsuits is likely to climb to \$0.5 billion per year of delay in licensing the Yucca Mountain repository.⁷ The DOE has refused to share the basis for this estimate because of the lawsuits. The incremental cost for additional storage capacity, after the nuclear power plants have paid for the infrastructure for dry-cask storage (most have already) probably will be somewhat less.⁸ In any case, the costs would be about the same if the DOE had to pay for off-site storage.

Even if the Yucca Mountain repository had been licensed on time, however, the DOE would have faced another problem. When Congress selected Yucca Mountain to be the site of the first U.S. geological spent-fuel repository, it limited the quantity of commercial spent fuel that could be stored there to 63,000 tons until a second repository is in operation.⁹ U.S. nuclear power plants will have discharged about 63,000 tons of spent fuel by the end of 2008. The DOE is therefore faced with the challenge of siting a second repository at a time when it has not yet succeeded in licensing the first one. The Bush Administration has submitted legislation that would remove the 63,000-ton legislated limit. It is believed that the physical capacity of Yucca Mountain is great enough to hold the lifetime output of the current generation of U.S. power reactors and perhaps several times that amount (see below).

Because of the delay in the availability of the Yucca Mountain repository, in 2005, Congress asked the DOE to develop a plan for centralized interim storage and reprocessing of U.S. spent fuel. In May 2006, the DOE responded with a plan for a

“Global Nuclear Energy Partnership” (GNEP) as a part of which the DOE would build reprocessing plants and subsidize the construction of tens of fast-neutron reactors to fission the recovered plutonium and other transuranic elements. The DOE argues that, if the transuranics are fissioned, and the 30-year half-life fission products that generate most of the heat in the resulting waste are stored on the surface for some hundreds of years, then residues from much more spent fuel could be stored in Yucca Mountain.

The DOE’s Argonne National Laboratory, which provides technical support for the DOE’s research and development program on advanced reprocessing technologies, envisioned GNEP as limited for many years to an R&D program, because the technology for recycling the minor transuranics, americium and curium is not in hand. Paul Lisowski, DOE’s Deputy Program Manager for GNEP has described transuranic recycle as a “major technical risk area for GNEP.”¹⁰ Under Congressional pressure to move more quickly, however, the DOE issued a request to industry for “Expressions of Interest” in constructing a conventional reprocessing plant and a demonstration fast-neutron reactor as soon as possible. The most likely contractor for construction of the reprocessing plant, the French nuclear conglomerate Areva, advises the United States to defer recycling anything other than plutonium and to build a larger-capacity version of France’s reprocessing and plutonium recycle infrastructure. Specifically, it proposes that the plutonium in recently discharged U.S. spent fuel be recycled once in light-water reactors and then resulting spent “mixed-oxide” (MOX) fuel be stored at the reprocessing plant until the advent of fast-neutron “burner” reactors.¹¹

The U.S. House of Representatives insisted, however, that a “first test of any site’s willingness to host such a facility is its willingness to receive into interim storage spent fuel in dry casks...Resolution of the spent fuel problem cannot wait for the many years required for...GNEP [which] will not be ready to begin large-scale recycling of commercial spent fuel until the end of the next decade, and the Yucca Mountain repository will not open until roughly the same time. Such delays are acceptable only if accompanied by interim storage beginning *this decade*” [emphasis added].¹²

Thus the revived interest in the United States in reprocessing is very much entangled in the perceived urgency of starting to move spent fuel off of reactor sites.

The report that follows describes the history of interest in civilian reprocessing, past experience with reprocessing costs, estimates of its likely costs in the United States with and without transmutation of the recovered transuranic elements, and the debate over the relative “proliferation resistance” of alternative fuel cycles. It concludes that a much less costly and proliferation resistant alternative to reprocessing and transuranic recycle would be continued on-site storage of U.S. spent fuel until either Yucca Mountain or some other off-site location is available.

II. Historical Background

Fuel reprocessing was invented during World War II as a way to recover plutonium for nuclear weapons from irradiated reactor fuel. From the 1950s through the 1970s, however, it was expected to play an essential role in civilian nuclear power as well.

The original rationale for reprocessing

This expectation was based on the belief that deposits of high-grade uranium ore were too scarce to support nuclear power on a large scale based on a “once-through” fuel cycle. The once-through fuel cycle, as realized with the dominant light-water reactor (LWR) today, involves the production of low-enriched uranium containing about 4 percent U-235, which is then irradiated until most of the U-235 and about 2 percent of the U-238 have been fissioned, and then is stored indefinitely (see Figure 1).

This fuel cycle uses most of the fission energy stored in the rare chain-reacting uranium isotope, U-235, which makes up 0.7 percent of natural uranium. Atom for atom, however, the U-238 atoms, which make up virtually all of the remaining 99.3 percent of natural uranium, contain as much potential fission energy. If it were possible to fission the U-238, the amount of energy releasable from a kilogram of natural uranium therefore would be increased about one hundred fold.

Plutonium breeder reactors. A month after the first reactor went critical under the stands of the University of Chicago’s football stadium, Leo Szilard, who first conceived of the possibility of a nuclear chain reaction, invented a reactor that could efficiently tap the energy in U-238 by turning it into chain-reacting plutonium. In a sodium-cooled reactor, a chain reaction in plutonium would be sustained by “fast” neutrons that had not been slowed down as much by collisions with the sodium coolant as neutrons are in collisions with the light hydrogen atoms in the cooling water of conventional reactors. Plutonium fissions by fast neutrons produce enough neutrons so that it is possible on average to convert more than one U-238 atom into plutonium per plutonium atom destroyed.¹³ Such reactors are called plutonium “breeder” reactors. Alternatively, they can be thought of as U-238 burner reactors.

Being able to exploit the energy stored in the nucleus of U-238 would make it possible to mine ores containing about one percent as much natural uranium as could be economically mined for the energy in U-235 alone. Indeed, even the 3 grams of uranium in a ton of average crustal rock, if fissioned completely, would release almost ten times as much energy as is contained in a ton of coal.¹⁴ The nuclear-energy pioneers therefore talked of breeder reactors making it possible to “burn the rocks” and thereby create a source of fission energy that could power humanity for a million years.

The growth of global nuclear-power capacity slowed dramatically in the 1980s, however, (see Figure 2) and huge deposits of rich uranium ore were discovered in Australia,

Canada and elsewhere. As a result, the long-term trend of natural-uranium costs has been down rather than up (see Figure 3). Concerns about uranium shortages linger on today in arguments that nuclear power based on a “once-through,” low-enriched uranium fuel cycle is not “sustainable.” But such concerns about the inadequacy of the world’s uranium resources have shifted to far beyond 2050.¹⁵ In any case, depleted uranium and spent fuel can be stored so as to be available in the event that it becomes cost-effective to “mine” them for the energy in their uranium-238.

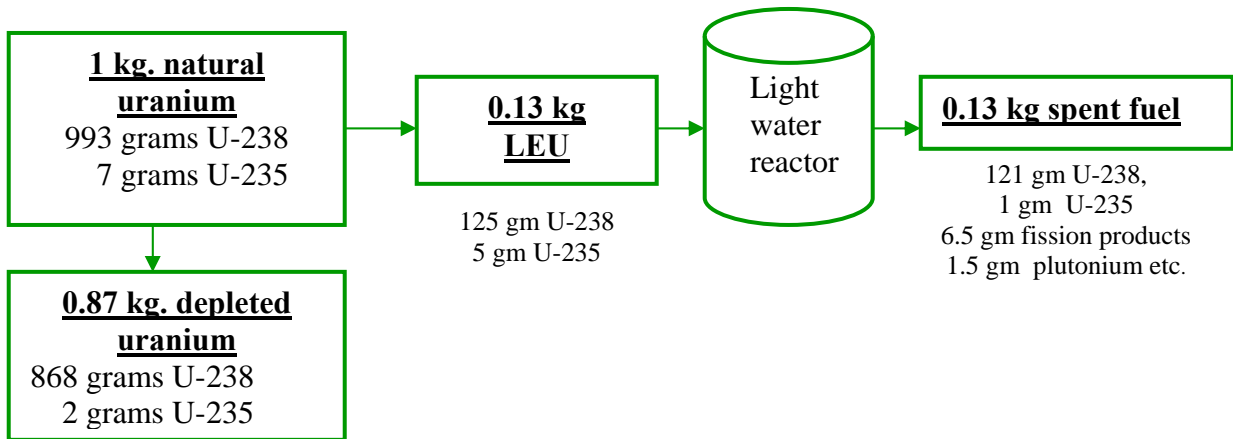


Figure 1. The once-through fuel cycle fissions less than one percent of the atoms in natural uranium, but it is less costly and more proliferation resistant than fuel cycles involving reprocessing. If, in the future, reprocessing becomes economical and otherwise acceptable, the uranium that is not fissioned in the once-through fuel cycle will still be available in the depleted uranium and spent fuel.¹⁶

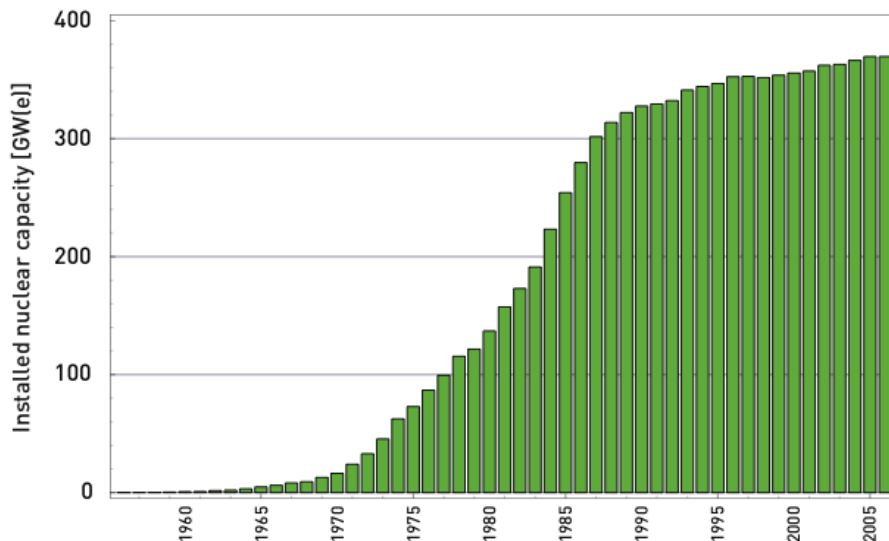


Figure 2. Global nuclear generating capacity grew rapidly in the 1970s, leading to concerns that the supply of natural uranium might not be able to keep up with the increasing demand, but growth slowed in the 1980s as a result of the high capital costs of nuclear-power plants, the slowing growth in overall demand for electric power and the Chernobyl nuclear accident of 1986.¹⁷

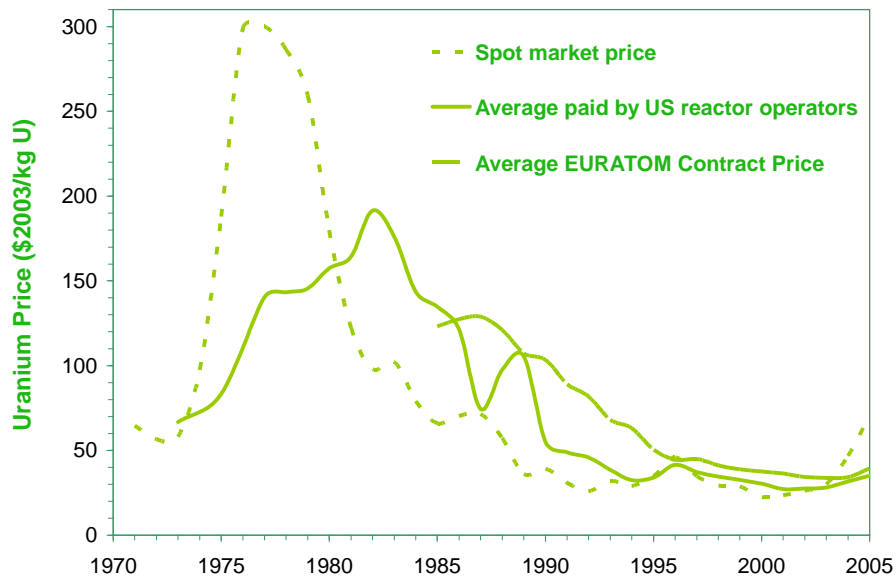


Figure 3. Average and spot uranium prices in constant 2003 dollars, 1971-2005.¹⁸

At the same time, the differences between the capital and operating costs of water and sodium-cooled reactors have remained discouragingly large. Many experimental and demonstration breeder reactors have been built around the world but none has been a commercial success.¹⁹

Because of its compact core, Admiral Rickover, the father of the U.S. nuclear navy, had a sodium-cooled reactor built for the second U.S. nuclear submarine, the *Seawolf*. After sea trials in 1957, however, he had the reactor replaced by a pressurized water reactor. His summary of his experience with the sodium-cooled reactor pretty aptly characterizes the problems that have been subsequently experienced in attempts to commercialize sodium-cooled breeder reactors. These reactors are “expensive to build, complex to operate, susceptible to prolonged shutdown as a result of even minor malfunctions, and difficult and time-consuming to repair.”²⁰

In anticipation of a need for large quantities of separated plutonium to provide startup cores for the breeder reactors, however, commercial reprocessing of spent light-water reactor fuel was launched in the 1960s. Spent light-water reactor (LWR) fuel contains about one percent plutonium. Civilian pilot and full-scale reprocessing plants have been built in eight countries.²¹

Growing stockpiles of separated civilian plutonium. In the absence of significant breeder-reactor capacity, some countries – notably France and Germany – have been recycling their separated plutonium back into LWR fuel. The cost of fabricating mixed-oxide (MOX) plutonium-uranium fuel for light water reactors has been greater, however, than the value of the low-enriched uranium fuel that has been saved.²² As a result, there is no commercial demand for plutonium as a fuel and large stockpiles have accumulated at the reprocessing plants, along with the fission-product waste from which the plutonium

was separated. The United Kingdom and Russia have stockpiled all the plutonium that they have been separating from their own spent fuel (and, in Russia's case, also from the spent fuel that Eastern and Central European utilities have been shipping to Russia for reprocessing). Japan's separated plutonium has accumulated at the French and U.K. reprocessing plants because local government opposition in Japan has delayed its plutonium recycle program for a decade.²³

Based on declarations of civilian plutonium stocks to the IAEA, the global stock of separated civilian plutonium has been growing by an average of ten tons per year since 1996 and was about 250 metric tons as of the end of 2005 (see Table 1). This stockpile is approximately the same size as the global stockpile of plutonium that was produced for weapons during the Cold War. About 100 tons of Russian, U.S. and U.K. weapon plutonium have been declared excess, increasing the global stockpile of excess separated plutonium still further.

As an energy resource, the world stockpile of separated civilian plutonium is not huge. It could fuel the world's fleet of power reactors for less than a year. In terms of weapon equivalents, however, it *is* huge. Using the IAEA's 8-kg weapon equivalent, the 320 tons of civilian and excess weapons plutonium could be converted into 40,000 first-generation (Nagasaki-type) nuclear weapons. In 1998, a Royal Society report observed that the possibility that the United Kingdom's very large stockpile of separated civilian plutonium "might, at some stage, be accessed for illicit weapons production is of extreme concern."²⁴ If this is a concern in the United Kingdom, it should be a concern in any country with significant quantities of separated plutonium.

**Table 1. Global stocks of separated civilian and excess military plutonium²⁵
(metric tons)**

Country	Civilian Stocks (end of 2005)	Military Stocks Declared Excess
Belgium	3.3 (2004) (+0.4 tons in France)	--
China	0	0
France	81 (30 tons foreign owned)	0
Germany	12.5 (+ 15 tons in France & U.K.)	--
India	5.4	0
Japan	5.9 (+38 tons in France & U.K.)	--
Russia	41	34-50
Switzerland	Up to 2 tons in France & U.K.	0
U.K.	105 (27 foreign owned) (+ 0.9 tons abroad)	4.4
U.S.	0	45
TOTALS	≈250 tons	83-100

Why reprocessing persists

The United Kingdom plans to end its reprocessing by 2012.²⁶ But France continues, Japan put a big new reprocessing plant into operation in 2006, and the Bush Administration has proposed that the United States launch a domestic reprocessing program. Why, in the face of adverse economics, does civilian reprocessing persist?

NIMBY pressures. Reprocessing continued in Western Europe and Japan in the 1980s and 1990s in part because of a combination of local political pressures to do something about the problem of spent fuel accumulating at power-reactor sites and not-in-my-backyard (NIMBY) political opposition elsewhere to geological repositories or central interim storage facilities for spent fuel. Reprocessing provided an interim destination for the spent fuel.

German and Japanese nuclear utilities largely financed the French and British multi-billion-dollar commercial reprocessing facilities.²⁷ Their respite was only temporary, however, because the reprocessing contracts provided that the solidified fission-product waste would be shipped back to the countries of origin. Germany's anti-nuclear movement finally succeeded in persuading the SPD-Green coalition government to stop reprocessing and eventually phase out nuclear power in Germany and, in exchange, agreed to accept the construction of dry-cask interim spent-fuel storage at the reactor sites until the site of a geological repository could be settled.²⁸

Japan's nuclear utilities went down a different route. They persuaded the rural Amori Prefecture to store, for 50 years, the radioactive waste being returned from Europe as part of an agreement in which the prefecture accepted a large reprocessing plant in return for receiving large payments from a central fund. Japan's nuclear utilities now are shipping their spent fuel to the Rokkasho reprocessing plant. The separated plutonium and high-level waste will be stored there. The high level waste, at least, will stay there until a geological repository can be opened – hopefully within the promised 50 years. The plutonium will be added to Japan's existing forty-ton stockpile of separated plutonium that is eventually to be recycled in MOX fuel.²⁹

The Bush Administration's reprocessing proposal. U.S. nuclear utilities too have been unable to ship their accumulating spent fuel off their reactor sites. As noted above, the reason is delays in the licensing of the DOE's proposed geological repository under Yucca Mountain, Nevada. U.S. utilities therefore have been suing the DOE for the costs of building additional on-site dry-cask storage.

In 2005, in order to stop these accumulating lawsuits, the U.S. Congress asked the DOE to develop a plan for centralized interim storage and reprocessing of U.S. spent fuel.³⁰ In May 2006, the DOE responded with a plan for a "Global Nuclear Energy Partnership" (GNEP). This plan envisioned building reprocessing plants that would separate spent light-water-reactor fuel into four streams: uranium, plutonium mixed with the other transuranic elements (neptunium, americium and curium); the 30-year-half-life fission

products, strontium-90 and cesium-137; and other fission products. This is the so-called UREX+ fuel cycle (see Figure 4).

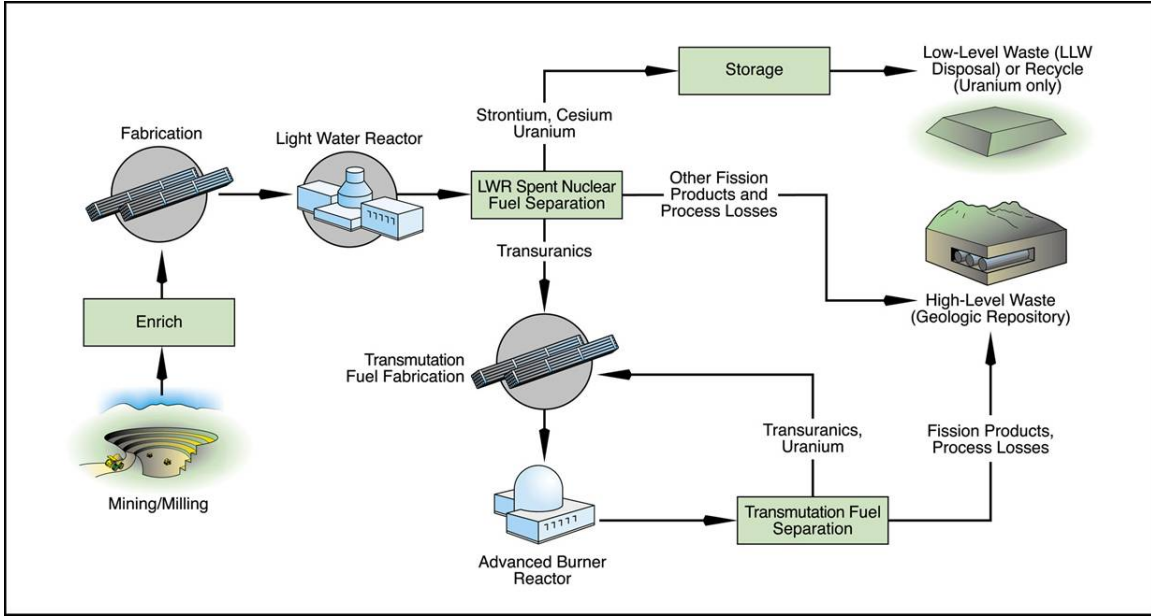


Figure 4. The Department of Energy’s May 2006 proposal for reprocessing U.S. spent fuel and fissioning the transuranics. The reprocessing plant (designated here as “LWR Spent Nuclear Fuel Separation”) would be built as soon as possible. The reactors shown here as “Advanced Burner Reactors” would be fast-neutron reactors. Only one would be built at the same time as the reprocessing plant. Others would be built on an unspecified time schedule. After reprocessing, the 30-year half-life isotopes, cesium-137 and strontium-90, which dominate the radiological hazard until they decay away, would be placed in interim surface storage for some hundreds of years. This raises the question as to why the unprocessed spent fuel should not remain in interim storage until fast-neutron reactors actually are built in significant numbers.³¹

The transuranic elements would be recycled in a hypothetical future generation of fast-neutron “burner” reactors until – except for losses to various waste streams – the transuranics were fissioned. The designs of the burner reactors would be adapted from the sodium-cooled reactors that previously were to be commercialized as plutonium-breeder reactors, only with the plutonium breeding uranium blankets around their cores removed. The uranium would be stored or disposed of as waste. The strontium-90 and cesium-137 would be placed into interim surface storage for some hundreds of years – presumably at the reprocessing plant. Only the residual wastes after the separation of these three streams would be placed in the Yucca Mt. repository.

By removing in each cycle, 99 percent of the strontium-90 and cesium-137, and of the transuranic elements, the main sources of radioactive decay heat in the spent fuel on century and millennial scales respectively, the long-term temperature increase of the rock around the disposal tunnels under Yucca Mountain per ton of spent fuel would be decreased about 20-fold. The residue from 20 times as much spent fuel therefore could be emplaced in the Mountain before a new repository would have to be sited.³² The political resistance to the siting of the Yucca Mt. repository has been so fierce that this is considered by the DOE to be a major long-term advantage of the proposed UREX+ fuel cycle and a prerequisite for nuclear power to have a long-term future in the United States.

The current limit on the capacity of Yucca Mt., however, is not physical but *legislated*. When Congress selected Yucca Mt. as the nation's first geological radioactive waste repository, it wished to reassure Nevada that it would not have to carry this burden alone. As already noted, it therefore limited the quantity of commercial spent fuel or reprocessing waste that can be stored there to 63,000 tons "until such a time as a second repository is in operation." This amount of spent fuel will have been discharged by U.S. reactors by 2008. Hence the dire warnings of the necessity to site repositories in additional states. In order to deal with this problem, the Bush Administration has proposed to lift the legislated limit on the amount of spent fuel that can be stored in Yucca Mt.³³

The federal government has not come to its own conclusion about what the *physical* capacity of Yucca Mt. might be. Using federal studies made as part of the licensing process for the repository, however, the utility industry's Electrical Power Research Institute estimates that there is enough capacity in the surveyed areas of Yucca Mountain to store 260,000 -570,000 tons of spent fuel – and perhaps more. This is two to five times as much as the current generation of U.S. power reactors are expected to discharge over their lifetimes.³⁴

Because of the delay in licensing the repository and the utility lawsuits, however, the Congressional Appropriations Subcommittees that fund the Department of Energy have been pressing the DOE to begin moving spent fuel off power reactor sites. In part at least in response to this pressure, on August 7, 2006, the DOE announced that it was considering building a 2000-3000 ton per year spent-fuel reprocessing plant based on the existing technology being used in France, and a 2000 MWt (thermal) sodium-cooled fast-neutron reactor of the pool-type design used for France's failed Superphénix reactor. The reprocessing plant would be modified so that some of the uranium in the spent fuel would remain mixed with the plutonium. In this way, the Department of Energy would honor its commitment to make reprocessing more "proliferation resistant." Plutonium can be separated out of such a mixture very much more easily, however, than from spent fuel (see Section IV). The fast reactor would be fueled initially by "conventional fast reactor fuel," i.e. a mix of plutonium and uranium.³⁵ In January 2007, the DOE announced that it planned to lay the basis for a decision by the Secretary of Energy to launch this program "no later than June 2008," i.e. before President Bush leaves office.³⁶

Reprocessing 2000-3000 tons of light-water-reactor spent fuel would separate 24-36 tons of plutonium per year.³⁷ By comparison, France's failed 3000 MWt Superphenix, even operating on a once-through fuel cycle, would have annually irradiated only about 2 tons of plutonium.³⁸ In effect, unless the DOE adopts the French strategy of recycling MOX in LWRs, its reprocessing initiative would, for the foreseeable future, transform almost all spent fuel shipped from U.S. nuclear-power-reactor sites into separated plutonium and high-level waste stored at a reprocessing site. The compelling reason for the DOE initiative, therefore, appears to be, as in Japan, to provide an alternative destination for spent fuel until a geological radioactive waste repository becomes available.

The DOE's reprocessing proposals are controversial both because of their cost and their impact on U.S. nonproliferation policy. We discuss these issues in the next two sections.

III. Reprocessing and Recycle Costs

We consider the costs for two scenarios:

1. The U.S. Department of Energy's (DOE's) May 2006 scenario in which all of the transuranics in U.S. light-water spent fuel would be separated and fissioned in fast-neutron reactors in order to increase the number of reactor-years of radioactive waste that can be accommodated in Yucca Mountain. Although the DOE has never mentioned it in connection with its current proposal, these costs were examined in depth in a massive National Academy of Sciences study that was commissioned by the DOE in the early 1990s and published in 1996.³⁹
2. The cost and benefits of doing what is done in France, which is to reprocess spent LWR fuel, mix the separated plutonium with depleted uranium to make mixed oxide (MOX) fuel for LWRs, and then store the spent MOX fuel. Areva, the French nuclear conglomerate, has launched a major effort to convince the DOE to follow this route, including by funding a study that claims that reprocessing would not be much more costly in the United States than building a second geological repository for spent fuel.⁴⁰

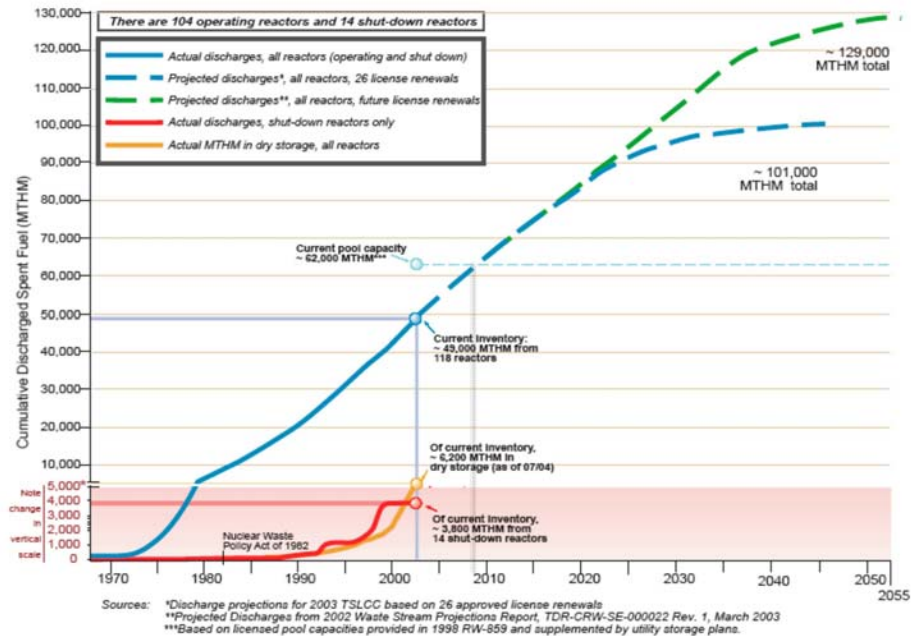


Figure 5. Projections of the total amount of spent fuel to be discharged by the current generation of U.S. power reactors depend upon what fraction of the reactors have their licenses extended to 60 years.⁴¹

The 1996 Study by the U.S. National Academy of Sciences

The 1996 U.S. National Academy of Sciences study estimated the extra cost of a separations and transmutation program for the first 62,000 tons of U.S. spent fuel, relative to the cost of simply storing the spent fuel in a repository, as “likely to be no less than \$50 billion and easily could be over \$100 billion”(1996\$).⁴² For the estimated lifetime discharges of the current generation of U.S. light water reactors (101,000 to 129,000 tons, see Figure 5), this cost would be approximately double.

Currently, U.S. nuclear utilities are paying into the DOE’s Nuclear Waste Fund 0.1 cents per kilowatt-hour in exchange for the DOE taking responsibility for disposing of their spent fuel. Assuming that the average amount of fission energy released in the first 62,000 tons of U.S. spent fuel was 40,000 megawatt-days per ton, and taking the heat-to-electric energy conversion efficiency of an average nuclear power plant to be one third, this would translate into about \$20 billion. Even including interest, this fund would not be able to cover both the estimated \$50 billion cost of the Yucca Mt. repository and a \$100 billion separations and transmutation program.⁴³ Spokesmen for the nuclear utilities have made clear that they will not pay for the extra costs of a reprocessing plant or fast-neutron reactors.⁴⁴ It is conceivable that the U.S. Congress might fund the launch (although perhaps not the completion) of a federally funded reprocessing plant costing tens of billions of dollars, but it seems unlikely that it would provide a subsidy of on the order of a billion dollars each for the construction of 40-75 fast-neutron reactors to fission the transuranics being produced by 100 GWe of low-enriched-uranium-fueled light water reactors.⁴⁵

The great cost of the DOE’s proposed program and the fact that it proposes to store the most dangerous isotopes in the spent fuel⁴⁶ on the surface for hundreds of years may eventually increase the appeal of interim storage without reprocessing.

The Areva study of the cost of recycling separated plutonium in MOX

In July 2006, the Boston Consulting Group published a report, *Economic Assessment of Used Nuclear Fuel Management in the United States*. The report was commissioned by the French nuclear combine, Areva, and is based on proprietary data and analysis provided by Areva. The report will therefore be referred to below as the “Areva study.”

The report proposes that Areva build for the U.S. Government both a spent-fuel reprocessing plant with a 2500 ton per year capacity and a mixed-oxide (MOX) fuel fabrication plant to recycle the separated plutonium back into light-water-reactor fuel. It argues that the cost would approximately equal the savings from the United States being able to delay a second repository by 50 years.⁴⁷ Given the similarities of this proposal to the DOE’s request, two weeks later, for expressions of interest in building a reprocessing plant with a capacity of 2000 – 3000 tons a year, it is worth examining the Areva report’s analysis. Below, we examine the basis of its central conclusions that:

1. Areva could build and operate a reprocessing plant and MOX fuel fabrication plant much more cheaply for the U.S. Government than it did in France; and
2. French-style reprocessing and plutonium recycle would postpone the need of a second U.S. repository.

Finally, we will summarize the results of a French Government analysis of the net costs of plutonium recycle in France.

Lower costs in the U.S. than in France? The Areva study asserted that reprocessing and MOX fuel-fabrication plants could be built in the United States more cheaply than the corresponding smaller-capacity facilities it built in France.⁴⁸ The capital cost of the French complex was revealed to be about \$18 billion in 2006 dollars, not including interest charges during construction. The study also asserted that the plants could be operated for about \$0.9 billion per year – about one third the operating cost shown for the smaller complex in France.



Figure 6. France's spent-fuel reprocessing complex on La Hague in northern France. Its plutonium fuel fabrication facility is in southern France, requiring regular long-distance truck shipments of separated plutonium.⁴⁹

Thus far, however, the DOE-Areva combination has resulted in much *higher* costs in the United States than in France. The DOE has contracted with Areva to build a MOX fuel fabrication plant to deal with 34 tons of excess U.S. weapon plutonium at a rate of 3.5

tons per year.⁵⁰ Measured in terms of MOX fuel tonnage, this is about one fifth the capacity of the plant that would be required to take the output of 2500 ton/year reprocessing plant.⁵¹ The original estimated cost of the DOE's MOX-fuel facility presented to Congress in 2002 was \$1 billion. By July 2005, three years later, the estimated cost had ballooned to \$3.5 billion and the project was 2.5 years behind schedule.⁵² Such cost overruns and delays are typical for U.S. Department of Energy projects.⁵³

Would French-style reprocessing postpone the need for a second repository? For the non-reprocessing alternative to its proposal, the Areva study assumed that the physical capacity of Yucca Mt. is 120,000 tons of spent LEU fuel. As indicated above, the capacity is likely to be much larger. Using Areva's assumption, however, at the current rate of discharge of spent fuel by U.S. power reactors, (about 2000 metric tons of heavy-metal content per year) the Yucca Mt. repository would be fully subscribed by 2040. Fuel discharged later could not be loaded into a repository until it had cooled for 25 years, i.e. till 2065, but the Areva study assumed that, already in the year 2030, the United States would have to start spending \$0.4 billion a year on a \$45-50 billion second repository.⁵⁴

Americium-241 (Am-241), which forms from the decay of 14-year half-life plutonium-241, dominates the heat output of LEU spent fuel during the period from 100 years to 2,000 years after discharge. In Areva's proposal, the Am-241 would go into the high-level reprocessing waste and be emplaced in Yucca Mt.

To minimize the buildup of Am-241 in the spent fuel and thereby the amount of Am-241 in the high level waste, the Areva study assumes that, after the reprocessing plant is completed, spent fuel would be reprocessed within three years. This would reduce the heat load from the associated high-level waste to the point where the waste from 230,000 tons of spent fuel could be stored in Yucca Mountain plus 50,000 tons of unprocessed pre-2003 spent fuel – more than doubling the amount of spent fuel that could be dealt with before a second repository would have to be established.⁵⁵

The Areva study is able to postpone the need of a second U.S. repository beyond the study's time horizon, however, only because it assumes that the spent MOX fuel would remain indefinitely in interim storage at the reprocessing plant. There would be no delay in the need for a second repository had it been assumed that the MOX spent fuel too would be emplaced in Yucca Mt. Although reprocessing and plutonium recycle consolidates the plutonium from roughly eight tons of spent LEU fuel into one ton of fresh MOX fuel, the total amount of plutonium in the spent MOX fuel is still two thirds as great as in the original eight tons of low-enriched uranium spent fuel. Furthermore, because of a shift toward a hotter mix of plutonium and other transuranics, the amount of heat that the ton of MOX spent fuel would deliver into the mountain during the first crucial two thousand years would be almost exactly the same as would have been delivered by the eight tons of spent LEU fuel. This is why the Areva study states that “[D]isposal of MOX [in a geological repository] is not considered to be a viable option.”⁵⁶ Indeed, the French Government has concluded that spent MOX fuel would

have to be stored from 150 years to “centuries” before it cooled enough to be emplaced in a geological repository.⁵⁷

A complete cost analysis would have dealt with cost of an alternative way of disposing of the spent MOX fuel. The Department of Energy proposes that the plutonium should be recycled repeatedly in fast-neutron reactors until it is completely fissioned. If this were done after one recycle in LWRs had reduced the amount of plutonium by one third, only 23-44 GWe of fast reactor capacity would be required to fission the plutonium left in the once-recycled LWR MOX fuel.⁵⁸ This is down from the 40-75 GWe calculated above for the DOE’s scenario, in which the plutonium is fed directly into sodium-cooled burner reactors. But the cost would still be huge. The Areva report assumes that sodium-cooled reactors would cost 20 percent more per unit of generating capacity than LWRs.⁵⁹ The only *full-sized* sodium-cooled ever built, France’s *Superphénix*, cost about three times as much as a light-water reactor of the same capacity.⁶⁰ In series production, the cost could come down. LWRs are estimated to cost \$2 billion per GWe. The extra capital cost for buying sodium-cooled reactors therefore would be \$9-18 billion if Areva’s 20% estimate were true and \$46-90 billion if the cost of a breeder were twice that of an LWR. Tens of billions more would be required for the infrastructure to fabricate and reprocess the sodium-cooled reactor fuel.

The French Government’s estimate of the cost of reprocessing in France. The Areva study did not reveal the cost of reprocessing and plutonium recycle in France but these costs were published in a study done by the French Government in 2000. This study also estimated the costs of alternative fuel cycles for France’s current fleet of power reactors.

Shown in the Appendix are the results for four scenarios: three treated in the French Government report and one extrapolated from the results of those calculations:

1. One hundred percent of the low-enriched uranium (LEU) spent fuel discharged from France’s LWRs in a 45-year average operational lifetime would be reprocessed (the extrapolated scenario). The separated plutonium would be recycled in MOX fuel *once* – i.e. spent MOX fuel would not be reprocessed within the time frame of the study.
2. About two thirds of the LEU fuel would be reprocessed and the plutonium recycled once (the current plan).
3. Reprocessing would end in 2010. This would amount to reprocessing 27% of the spent LEU fuel expected to be discharged in the reactors’ lifetimes.
4. A retrospective scenario in which France was assumed not to have built its reprocessing and plutonium recycle infrastructure but instead would have deposited its spent fuel directly in an underground repository as is current U.S. policy.

The cost estimates are summarized in Table 2. It will be seen from comparing the 100-percent-reprocessing with the no-reprocessing scenarios that reprocessing all of the LEU fuel would double the cost of the back end of France’s fuel cycle. The net increase is 80 percent when the savings in natural uranium and enrichment associated with the use of the MOX fuel are taken into account.

Table 2. Spent-fuel disposal costs in four scenarios for the French Fuel Cycle⁶¹
(Billions of 2006 \$, 58,000 tons of spent fuel)

	Percentage of Spent LEU Fuel Reprocessed			
	100% (Derived scenario)	67%	27% (Reprocessing ends in 2010)	No Reprocessing
Back end costs	84	74	61	41
Front end cost savings from plutonium recycle	-10	-8	-2	0
Net costs	74	66	59	41

IV. Attempts to Mitigate the Impact on U.S. Nonproliferation Policy

Following India's 1974 nuclear explosion, which used civilian plutonium separated with U.S.-provided technology, the United States reversed its policy of encouraging reprocessing and plutonium recycle worldwide. U.S. policy became, in effect, "We don't reprocess and you don't need to either." Since 1977, when Japan put its Tokai-mura pilot plant into operation, no non-weapon state has begun civilian reprocessing. During that same period, Argentina, Belgium, Brazil, Germany and Italy shut down their pilot reprocessing plants and South Korea and Taiwan abandoned their laboratory-scale reprocessing research. Japan remains the only non-weapon state that reprocesses. In Europe, countries have abandoned reprocessing primarily as a result of anti-nuclear movements and the high cost of reprocessing. Outside Europe and Japan, however, U.S. anti-reprocessing policy has played a key role in stopping programs that were covers for countries that were interested in following India's example and using a civilian reprocessing program as a cover for developing a nuclear-weapon option.

The Bush Administration has responded in two ways to concerns that a new U.S. reprocessing initiative would undermine this very successful nonproliferation policy:

1. The Department of Energy is developing reprocessing technologies that do not separate out pure plutonium.
2. The Bush Administration has proposed that reprocessing and uranium enrichment be confined to "countries that already have substantial, well-established fuel cycles."⁶²

"Proliferation resistant" fuel cycles – the saga of UREX+

The reprocessing technology currently used worldwide has the acronym PUREX for Plutonium and URanium EXtraction. It was originally developed by the U.S. to extract pure plutonium for the U.S. nuclear-weapons program.⁶³ It is therefore difficult to claim that this technology is proliferation resistant and the U.S. Department of Energy has not done so.

In fact, the revival of U.S. interest in reprocessing was launched by the 2001 report of Vice President Cheney's National Energy Policy Development Group, which recommended that

"the United States should reexamine its policies to allow for research, development and deployment of fuel conditioning methods (such as pyroprocessing) that reduce waste streams and enhance proliferation resistance."⁶⁴

Pyroprocessing is a reprocessing technology developed by Argonne National Laboratory (ANL) for recycling the metal fuel used in its Experimental Breeder Reactor II.

Another reprocessing technology would be required, however, to separate transuranics from the uranium-oxide fuel used in light water reactors. For this purpose, ANL proposed what it called UREX+, named to denote the fact that pure uranium is extracted. The transuranics are extracted in various combinations in different variants of UREX+. In fact, a series of versions of UREX+ have been proposed.

Plutonium plus neptunium. The first version of UREX+ proposed by Argonne (UREX+2)⁶⁵ would keep the plutonium mixed with neptunium.⁶⁶ There is, however, typically only about 8 percent as much neptunium as plutonium in spent fuel. Furthermore, neptunium is less radioactive than plutonium and is as good a weapons material as the U-235 used in the Hiroshima bomb. At best, the effect of leaving the neptunium mixed with the plutonium would be to dilute the plutonium slightly. The mix could be used directly to make weapons or the plutonium could be extracted in the same type of glove box that would be used to handle pure plutonium.

Unseparated transuranics (UREX+1a). The second iteration of UREX is the GNEP fuel cycle proposed by DOE in May 2006 (see Figure 2.4). It would leave all the transuranics unseparated as shown. Plutonium would still constitute more than 80 percent of the mix. The mix would be about one hundred times more radioactive than pure plutonium but would still produce only about 0.1 percent of the intensity of penetrating radiation that would be required to make it “self-protecting” by the IAEA’s standard (see Figure 7).⁶⁷ Enough plutonium for a few bombs could be separated in a glove box without the workers receiving a large radiation dose. For an industrial-scale operation in which workers were exposed to this material year around, however, shielding and remote handling would be required to keep down occupational radiation doses. This is why “addition of minor [transuranics] or fission products to recycled plutonium will increase significantly the costs of fuel fabrication and transportation.”⁶⁸

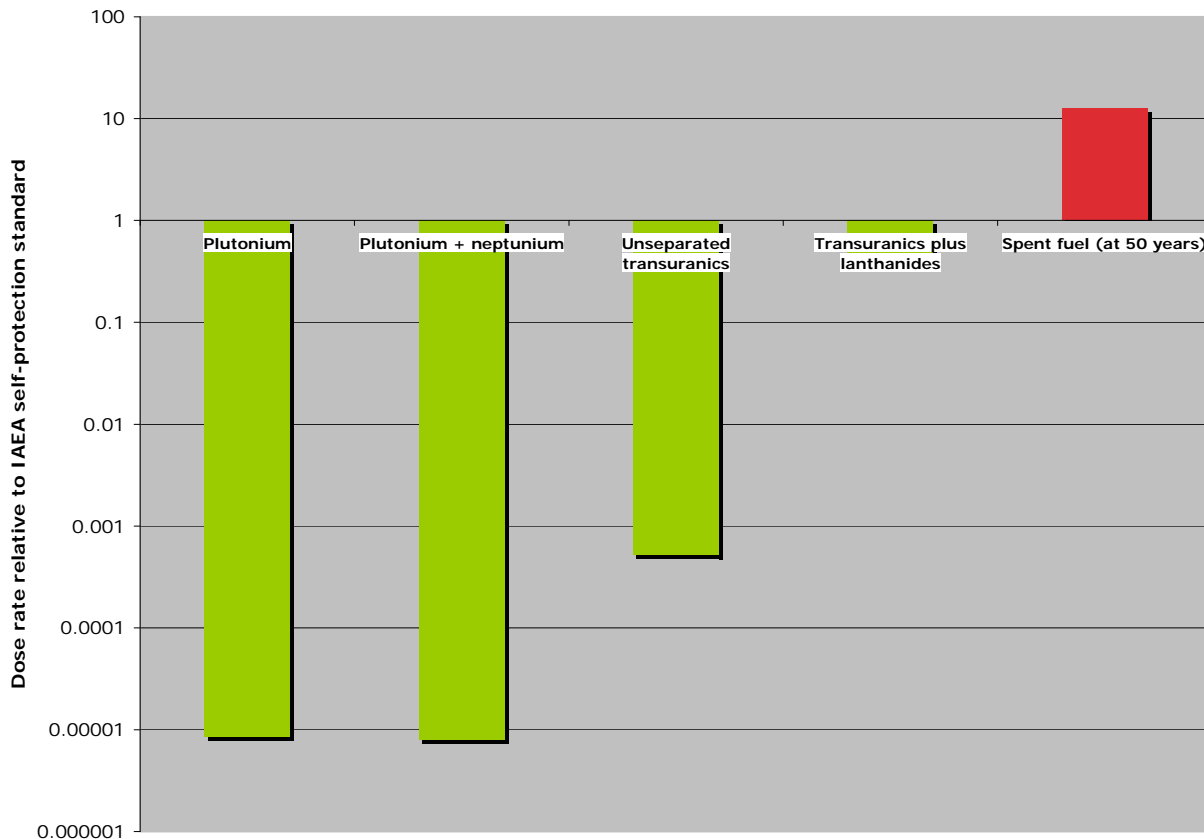


Figure 7. Factors by which dose rates from 1-kg spheres of transuranic metal produced by various versions of UREX+ fall short of the IAEA threshold for self protection (1 Sievert or 100 rems per hour at one meter). For example, the dose rate from unseparated transuranics is about 0.001 or one thousandth of the self-protection standard.⁶⁹

Unseparated transuranics mixed with lanthanide fission products (UREX+1). Argonne responded to criticisms of the lack of proliferation resistance of UREX+1a by proposing yet another variant in which one class of fission products, the lanthanides, would remain mixed with the transuranics until the mix was transported to a sodium-cooled “burner reactor” site (see Figure 8). Although still not meeting the IAEA’s self-protection standard, the gamma-radiation level from the mix would be higher than for the other UREX+ fuel cycles considered earlier. It would be highest for material separated from recently discharged spent fuel, since the longest-lived significant lanthanide, Europium-154, has a half-life of only 8.8 years. At the burner-reactor sites, the lanthanides would be stripped out in a final stage of reprocessing and the transuranic fuel would be fabricated. Thus each burner reactor site would have its own final-stage reprocessing and fuel-fabrication plant. This would compound the problem of the high cost of the separations and transmutation approach. Indeed, the complexity of this proposal approaches that of a Rube Goldberg cartoon.⁷⁰

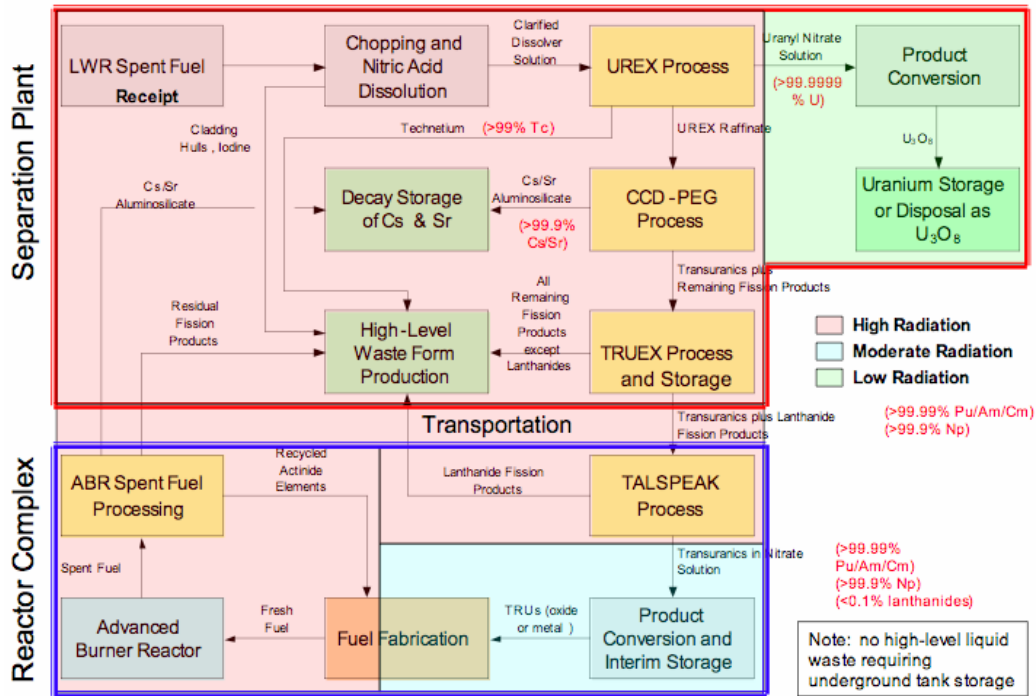


Figure 8. The version of UREX+ proposed by Argonne National Laboratory in March 2006. The top left box describes the various stages of the reprocessing plant and includes provisions for surface storage for hundreds of years of the two most hazardous fission products, cesium-137 and strontium-90, both of which have half-lives of about 30 years. The box at the bottom describes one of many proposed “burner-reactor” complexes. Each site would have a facility to carry out the final stage of the UREX+ reprocessing (TALSPÉAK). It would also have a fuel-fabrication facility and a spent-fuel reprocessing facility for the burner reactors. The enormous number of fuel processing facilities in this proposal would make it much more costly even than the separations and transmutation arrangements analyzed in the 1996 National Academies study.⁷¹

Safeguards problems.⁷² The IAEA has been unable to reduce statistical measurement uncertainties below about one percent for traditional PUREX reprocessing, which produces pure plutonium. To prevent frequent false alarms, a one-percent measurement uncertainty requires raising the alarm threshold to about three percent.⁷³ Three percent of the 24 tons of plutonium discharged annually by U.S. power reactors would amount to 760 kilograms, enough for about one hundred Nagasaki bombs.

Unfortunately, the Argonne proposals to make reprocessing more “proliferation resistant” by adding radioactive materials to the plutonium also would make it more difficult for both national and international monitors to detect plutonium diversion.

Plutonium is ordinarily detected and measured by the penetrating radiation that it emits. It fissions spontaneously at a low rate, emitting neutrons (about half a million per kilogram per second for reactor-grade plutonium). The neutrons can be detected through substantial shielding. Leaving plutonium mixed with other transuranics makes neutron measurements much less useful, however. The Curium-244 in spent fuel, in particular, emits one hundred times as many neutrons.⁷⁴ As a result, an uncertainty of only *one percent* in the Curium-244 would mask the loss in neutron signal due to the removal of *all* the plutonium.

All the plutonium isotopes also emit characteristic gamma rays. These gamma rays are much less penetrating than the neutrons, however. Large corrections must therefore be made for shielding and self-shielding of the fissile material. For this reason, gamma measurements are almost useless for quantitative assays of bulk inhomogeneous mixtures.

Back to MOX. Most recently, after learning that UREX+ was still very much in the conceptual stage and that techniques for fabricating fuel containing americium and curium had not yet been developed, the DOE decided to explore the possibility of starting with a slight modification of a PUREX plant. In its August 2006 “request for expressions of interest,” it specified only that the reprocessing plant “products are not pure plutonium.”⁷⁵ This was only a few weeks after Areva had proposed COEX, a variant of PUREX in which the plutonium would not be fully separated from the uranium.⁷⁶ Of course, once again, the plutonium could be easily separated from the COEX mix in a glove box.

Proposal to restrict reprocessing to the nuclear-weapon states plus Japan

Despite its R&D initiatives to make reprocessing more “proliferation resistant,” the Department of Energy has never suggested that the improvement could be great enough for reprocessing to be acceptable in states of proliferation concern. Indeed, in its May 2006 presentation of its GNEP proposal, the DOE included the Bush Administration’s February 11, 2004 proposal to deny enrichment and reprocessing technologies “to any state that does not already possess full-scale, functioning enrichment and reprocessing plants,” and instead to offer such states reliable access to low-enriched uranium and reprocessing services.⁷⁷

The idea that other countries can be permanently barred from acquiring enrichment and reprocessing plants has not gained international acceptance, however. An international panel of experts convened by the IAEA found that “there is a consistent opposition by many [non-nuclear weapons states] to accept additional restrictions on their development of peaceful nuclear technology without equivalent progress on disarmament.”⁷⁸

This issue is currently joined primarily with regard to the assertion by non-weapon states of their rights to have national uranium-enrichment plants. Since the Bush Administration’s 2004 proposed ban on additional countries acquiring enrichment plants, six non-possessing countries have expressed increased interest in acquiring them.⁷⁹ The U.S. GNEP proposal has, however, already revived interest in reprocessing in South Korea⁸⁰ and Areva has floated the idea of exporting the plant that it is designing for the American market to a number of non-weapon states that do not currently reprocess.⁸¹

France, the United Kingdom and Russia already have been providing reprocessing services to foreign countries but France and the United Kingdom have lost virtually all of their foreign customers. Russia has kept a few because, unlike France and the United

Kingdom, it has been willing to keep the plutonium and radioactive waste it recovers from its foreign customers' spent fuel.

In effect, Russia has been providing permanent storage for foreign spent fuel – although with the fuel separated into three components: uranium, plutonium and high-level waste. Under these conditions, its customers have been happy for Russia to take their spent fuel, whether it reprocesses it or not. Indeed, while Russia has been reprocessing the spent fuel from first-generation East European VVER-440 reactors at its Mayak facility in the Urals, it has been storing the spent fuel from second- generation Soviet-designed VVER-1000 reactors in a second closed nuclear city, Zheleznogorsk, Siberia.

V. The Alternative: Dry-Cask Spent-Fuel Storage

In the first two sections of this paper, we discussed how pressure from U.S. nuclear utilities on the Department of Energy to remove spent fuel from their reactor sites and the unwillingness of U.S. state governments to host off-site interim storage has stimulated DOE interest in federally-funded reprocessing and recycle of transuranics. In sections III and IV, we discussed the huge costs of such a program and the weaknesses of proposals to make reprocessing “proliferation resistant.” In this section, we discuss whether, considering the alternatives, interim storage of unprocessed spent fuel on the power-reactor sites may after all be the least bad solution.

First of all, it is important to understand that the costs that the federal government is paying the utilities for continuing to store the spent fuel on site is small in comparison to the costs of reprocessing. As discussed in section I, the Department of Energy estimates that the costs will grow to \$0.5 billion per year. We estimated the cost to be somewhat lower. Either cost is small, however, in comparison to a reprocessing program. Secretary of Energy Bodman has asked for an R&D budget ramping up to \$0.8-0.9 billion per year in 2009 just to *assess* the cost of the GNEP program.⁸² The French Government’s figures for the extra cost of PUREX reprocessing LWR fuel and recycling the recovered plutonium once correspond to about \$1 billion per year in the United States and the National Academy of Science’s estimate of the cost of a program involving sodium-cooled transuranic burner reactors was \$1.6 to 3.2+ billion per year (1996 \$).⁸³

Secondly, it must be understood that interim storage of spent fuel would cost approximately the same if the federal government took possession of the spent fuel and moved it to a centralized storage site. The largest contribution to the cost of dry-cask storage is the storage casks. There would be economies of scale in the monitoring and maintenance costs at the centralized site but these costs are quite modest for decentralized storage at sites with operating power plants because the casks require little maintenance and are stored within the plant’s guarded perimeter. Any cost savings associated with centralized storage are likely to be offset by the fact that the infrastructure costs for dry-cask storage at the reactor sites will have already been paid for. There would also be the extra cost of transporting the spent fuel to the centralized storage site and then to Yucca Mountain or some other repository rather than transporting the spent fuel directly from the plant.⁸⁴

Sometimes it is argued that continued storage of spent fuel at reactor sites creates a hazard. The amount of radioactivity that could be released from dry-cask storage is very small, however, in comparison to the potential releases from fuel in the reactor core or in a spent-fuel storage pool at operating reactor sites. The fuel in an operating reactor generates heat at a rate of about 30 kilowatts per kilogram. In a spent-fuel pool, a week after reactor shutdown, the fuel generates about 100 watts per kilogram. Loss of cooling water would result in the fuel in a reactor core heating up to combustion temperature within minutes. Recently discharged spent fuel in a pool would heat up to such temperatures within hours after a loss of water. Ten-year-old spent fuel generates about

two watts of heat per kilogram and can be stored in dry casks passively cooled by air passing slowly over the outside surface of the canisters.⁸⁵ Air warmed by the radioactive decay heat rises and is replaced by cooler air. Even an attack with an anti-tank missile that breached a cask would release only a relatively small amount of radioactivity.⁸⁶



Figure 9. Dry cask storage of spent fuel. Two casks typically contain the equivalent of a year's spent fuel discharges from a 1000 MWe nuclear power plant. Comparison of the simplicity of interim spent fuel storage with the complexity of the huge reprocessing complex shown in Figure 6 makes it easier to understand the relatively low cost of interim storage.⁸⁷

Why then are nuclear utilities in the United States pressing so hard for the government to begin moving the spent fuel off site? Perhaps one reason is that, in the 1970s, many nuclear-power opponents argued that there should be no further commitment to nuclear power until arrangements for ultimate disposal for spent fuel are in place. In 1976, in California, this became state law:

“no [new] nuclear fission thermal power plant...shall be permitted land use in the state...until both of the following conditions have been met:

“(a) The [California Energy] commission finds that there has been developed and that the United States through its authorized agency [the Nuclear Regulatory Commission] has approved and there exists a demonstrated technology or means for the disposal of high-level nuclear waste...”⁸⁸

The California law cannot be satisfied, however, by the mere movement of spent fuel to a centralized storage site or to a reprocessing plant. The only way to satisfy it is through the licensing of a geological repository under Yucca Mountain or elsewhere.⁸⁹

Also, the position of the nuclear-power critics has evolved. In response to the Bush Administration's reprocessing proposal, many groups that are critical of how nuclear power has been implemented in the United States have decided that they would prefer on-site dry-cask storage to reprocessing.⁹⁰

On the other side of the debate, the Nuclear Energy Institute, which speaks for U.S. nuclear utilities, while acknowledging that the subsidies in the Energy Policy Act of 2005 for the first new nuclear power plants ordered since 1974 "clearly stimulated interest among electric utilities in constructing new nuclear power plants," insist that "[t]his increased interest requires [that] the federal government must meet its contractual responsibility to accept, transport and dispose of used nuclear fuel through a comprehensive radioactive waste management program, including continued progress toward a federal used fuel repository."⁹¹ Similarly, John Rowe, the President of Exelon, which manages 20 percent of U.S. nuclear capacity, has stated famously with regard to the urgency of licensing a federal waste repository, "We have to be able to look the public in the eye and say, 'If we build a plant, here's where the waste will go.' If we can't answer that question honestly to our neighbors, then we're playing politics too high for us to be playing."⁹²

Note, however, that there is no requirement for reprocessing in the above statements of the nuclear-utility position. This suggests that the utilities might be willing to live with continued interim on-site storage as long as there is progress toward siting a repository.

The newly elected Senate Majority Leader, Harry Reid, who represents the State of Nevada, is, however, a dedicated opponent to the completion of the Yucca Mountain repository.⁹³ His proposed alternative is "The Spent Nuclear Fuel On-site Storage Act of 2005," which would have the Department of Energy take over responsibility for spent-fuel stored in dry casks at nuclear power plants to allow time for "a safe scientifically-based solution to be developed."⁹⁴

VI. Conclusions

The U.S. Government's current interest in a federally-funded reprocessing program appears to be driven in significant part by an interest in finding a location to which it could ship the older spent fuel accumulating on power reactor sites. Shipments were to have begun to the Yucca Mountain geological repository in 1998 but the licensing of that repository has been delayed repeatedly and is now projected for 2017 at the earliest. If the federal government began to ship spent fuel to a reprocessing site, that would help it limit lawsuits by U.S. nuclear utilities that are seeking federal government reimbursement for their costs for prolonged on-site storage of spent fuel. The reprocessing option would be 4-8 times more costly, however, than on-site dry-cask storage for up to 50 years.⁹⁵

At operating reactors, the incremental safety and security risk from such dry-cask storage of older fuel is negligible relative to the dangers from the fuel in the reactor core and the recently discharged hot fuel in the spent fuel pool.⁹⁶

The nuclear-weapon proliferation costs of the United States unnecessarily embracing reprocessing as a necessary part of its nuclear fuel cycle cannot be quantified but could be severe.

Endnotes

¹ President Ford, “Statement on Nuclear Policy,” 28 October 1976: “I have concluded that the reprocessing and recycling of plutonium should not proceed unless there is sound reason to conclude that the world community can effectively overcome the associated risks of proliferation.” President Carter, “Nuclear Power Policy,” 7 April 1977: “[W]e will defer, indefinitely the commercial reprocessing and recycling of the plutonium produced in the U.S. nuclear power programs. From our own experience, we have concluded that a viable and economic nuclear power program can be sustained without such reprocessing and recycling,” www.nci.org/new/pu-repro/carter77a/index.htm.

² President Reagan, “Statement Announcing a Series of Policy Initiatives on Nuclear Energy,” 8 October 1981: “I am lifting the indefinite ban which previous administrations placed on commercial reprocessing activities in the United States,” www.reagan.utexas.edu/archives/speeches/1981/100881b.htm.

³ The first and only U.S. commercial reprocessing plant that operated was the Nuclear Fuel Services plant, at West Valley, New York. Between 1966 and 1972, about 640 tons of spent fuel was reprocessed there for a price of \$33 per kilogram of heavy metal (HM) content, i.e. a total revenue of \$21 million. The cost of satisfying new regulatory requirements and making major necessary plant modifications were estimated in 1976 at \$600 million, which would have raised the reprocessing costs on new contracts to \$350/kgHM (one third the price that the French reprocessing company, Cogema, was charging at the time). U.S. utilities were unwilling to make additional contracts at the increased price, so the owner abandoned the plant and it became a \$4.5-billion federal cleanup site, *Nuclear Waste: Agreement Among Agencies Responsible for the West Valley Site is Critically Needed*, GAO-01-314, 2001 and Pierre Saverot, personal communication, January 5, 2007.

⁴ *Nuclear Waste Policy Act of 1982*, Section 302, a5B.

⁵ *Nuclear Waste Policy Act*, Section 160.

⁶ Statement of Edward Sproat, III, Director, Office of Civilian Radioactive Waste Management, U.S. Department of Energy to the Subcommittee on Energy and Air Quality of the House Committee on Energy and Commerce, 13 September 2006.

⁷ U.S. House of Representatives Appropriations Committee, *Report on the Energy and Water Development Appropriations Bill, 2006*, Report 109-86, 18 May 2005, p. 125.

⁸ There are 65 sites in the United States with operating power reactors. By 2011, 51 are expected to have dry storage, 57 by 2013, and 64 by 2017. Eight sites which no longer have operating reactors also have dry storage facilities, *Safety and Security of Commercial Spent Nuclear Fuel Storage*, National Academies Press, 2006 pp. 20-24; *Going the Distance? The Safe Transport of Spent Nuclear Fuel and High-Level Radioactive Waste in the United States*, National Academies Press, 2006, Table 5.2. By the time centralized storage could be established, therefore, almost all U.S. reactor sites will have installed dry storage systems and the avoided costs would be the additional costs associated with capacity expansion. The cost for such expansion as approximately \$110,000 per metric ton of uranium originally in the spent fuel, based on the published certificate of need, filed 18 January 2005, by Xcel Energy with the Minnesota Public Utility Commission for a dry cask storage facility near the reactor building of its Monticello reactor. [The total estimated cost for this facility (p. 3-40) is \$55 million, of which \$2 million was for regulatory processes, \$12 million for engineering and design, \$4 million for plant upgrades (presumably to provide for transport of the spent fuel casks from the spent fuel pool to the storage site), \$3.5 million for construction of the site for the dry cask storage, \$26 million for 30 canisters and pre-fabricated storage modules, each of which will hold 61 fuel assemblies (approximately 10 tons of fuel), and \$7.5 million for canister loading. The last two items, totaling \$33.5 million, or about \$0.11 million per ton, are the incremental costs.] The annual cost for

operating and maintaining such a storage site is about \$1 million per year at a site with operating reactors (Pierre Saverot, industry consultant, personal communication, 29 October 2006) and about \$3.4 million per year at sites with shutdown reactors. [The latter number is an average of the \$4.4 million per year (\$1.9 million for staffing and security, \$0.6 million for NRC and state fees, \$1.65 million in insurance and taxes, and \$0.27 million for “other” costs) declared in the 15 October 2002 *Update of Site-Specific Decommissioning Costs* for the Maine Yankee nuclear power plant, Table 7-1 and the \$2.4 million per year (\$1.34 million for staffing and security, \$0.33 million for NRC and state fees, and \$0.7 million for insurance and taxes) declared by Pacific Gas and Electric in its July 27, 2004 response to a U.S. Nuclear Regulatory Commission request for supplemental Humboldt Bay Independent Spent Fuel Storage Installation financial information.] U.S. reactors discharge about 2000 metric tons of spent fuel per year, *Safety and Security of Commercial Spent Nuclear Fuel Storage, op. cit.*, p. 20. At \$0.11 million/ton, the annual incremental capital cost of dry cask storage for this amount of spent fuel would be about \$220 million/year. At \$1 million/year for 65 sites with operating reactors and \$3.4 million/year at eight sites with shut down reactors, the cost of operating and maintaining the sites would be about \$90 million/year. Overall, therefore, the cost estimate would be about \$310 million/year. The Department of Energy estimate may be higher in part because the DOE is being forced to pay infrastructure costs at the reactor sites as well as the incremental costs estimated here.

⁹ Section 114d of the *Nuclear Waste Policy Act* prohibits “the emplacement in the first repository of a quantity of spent fuel in excess of 70,000 metric tons of heavy metal or a quantity of solidified high-level radioactive waste resulting from the reprocessing of such a quantity of spent fuel until such time as a second repository is in operation.” The radioactive waste associated primarily with the production of U.S. plutonium is assumed to reduce the limit for civilian spent fuel to 63,000 tons.

¹⁰ Paul Lisowski, Deputy Program Manager, GNEP, presentation to the National Academies Nuclear and Radiation Studies Board, November 29, 2006, www.ncsl.org/programs/enviro/cleanup/NAS1106.htm.

¹¹ The findings of the Boston Consulting Group study, *Economic Assessment of Used Nuclear Fuel Management in the United States*, July 2006, which was commissioned by Areva, will be discussed below.

¹² House report on the *Energy and Water Development Appropriations Bill, 2007*, Report 109-474, 19 May 2006, pp. 64-65.

¹³ Leo Szilard, "Memorandum on the Production of 94 [the atomic number of plutonium] and the Production of Power by the Means of the Fast Neutron Reaction," sent to A.H. Compton, 8 January 1943, cited in Bernard T. Feld, and Gertrud Weiss Szilard, eds., *The Collected Works of Leo Szilard: Scientific Papers*, MIT Press, 1972, p. 178. The idea of this route to releasing the energy of U-238 first occurred to Szilard in May 1940 when he received a letter from Louis Turner, a Princeton physicist, who suggested that a new chain-reacting isotope might be formed as a result of neutron capture on U-238, William Lanouette, *Genius in the Shadows: The Biography of Leo Szilard, the Man Behind the Bomb*, Scribners, 1992, pp. 219-220.

¹⁴ If fully fissioned, 3 grams of uranium would release about 3 megawatt-days of heat or 260×10^9 joules. The combustion energy of a ton of coal is about 30×10^9 joules.

¹⁵ *The Future of Nuclear Power*, MIT, 2003.

¹⁶ Based on *Plutonium Fuel: An Assessment* (OECD, 1989), Table 9.

¹⁷ International Atomic Energy Agency, *Power Reactor Information System (PRIS) Database*, updated 5 January 2006, www.iaea.org.

¹⁸ Matthew Bunn, Steve Fetter, John Holdren and Bob van der Zwaan, “The Economics of Reprocessing Versus Direct Disposal of Spent Nuclear Fuel,” *Nuclear Technology* 150, June 2005, p. 209, updated by

Steve Fetter. The price of uranium on the spot market has increased further since 2005, to about \$150/kg in November 2006, *Nukem Market Report*, December 2006. This appears to be due to the closure of many mines during the period of low prices and has stimulated renewed interest in uranium mining. The spot market price peak therefore is likely to be as transient as the peak in the late 1970s, "Uranium Glowing," *Economist*, 19 August 2006, p. 53.

¹⁹ A list of 11 shutdown and 8 operational fast-neutron reactors as of 1995 is given in David Albright, Frans Berkhout and William Walker, *Plutonium and Highly Enriched Uranium 1996*, Oxford University Press, 1997, p. 196. Since that time, two more reactors (Kazakhstan's BN-350 and France's Superphénix) have been shut down permanently, one (Japan's Monju) has been shut down for more than a decade by a sodium fire, and France's Phénix is scheduled to be shutdown. Russia's BN-600 has been kept on line with an average capacity factor of about 74 percent since 1980 but has had 15 sodium fires in 23 years, N.N. Oshkanov, M.V. Bakanov, and O.A. Potapov, "Experience in Operating the BN-600 Unit at the Belyiyar Nuclear Power Plant," *Atomic Energy*, Vol. 96, No. 5, 2004, p. 315. Three new sodium-cooled reactors are being built in: China (25 MWe), India (500 MWe), and Russia (800 MWe).

²⁰ Richard C. Hewlett and Francis Duncan, *Nuclear Navy 1946-1962*, University of Chicago Press, 1974, p. 274. I would like to thank Thomas B. Cochran for bringing this quotation to my attention.

²¹ Belgium, France, Germany, India, Japan, Russia, U.K., U.S., *Plutonium and Highly Enriched Uranium 1996*, *op. cit.*, p. 156. China has recently completed but not yet operated a pilot reprocessing plant.

²² "The Economics of Reprocessing Versus Direct Disposal of Spent Nuclear Fuel," *op. cit.*

²³ Shaun Burnie and Aileen Mioko Smith, "Japan's Nuclear Twilight Zone," *Bulletin of the Atomic Scientists*, May/June 2001, p. 58.

²⁴ *Management of Separated Plutonium*, London, The Royal Society, 1998, Summary.

²⁵ This is an update of Table 2.A in *Global Fissile Material Report 2006*, www.fissilematerials.org.

²⁶ "Sellafield Shutdown Ends the Nuclear Dream," *The Guardian*, 26 August 2003; "Huge Radioactive Leak Closes THORP Nuclear Plant," *The Guardian*, 9 May 2005.

²⁷ The German utilities began to build their own domestic reprocessing plant but encountered massive public opposition and found also that it would be cheaper to accept offers to invest in the French and British plants. An excellent history of this episode has been written by Pierre Saverot, *History of the Wackersdorf Reprocessing Plant Project* JAI Corporation, JAI-557, 2003.

²⁸ Mark Hibbs, "German At-Reactor Storage Deal May Scuttle Gorleben, Ahaus," *Nuclear Fuel* 8 February 1999; and Ann MacLachlan, "Cogema Says German Phase-Out Pact 'No Surprise,' Doesn't Change Situation," *Nuclear Fuel*, 26 June 2000.

²⁹ Tadahiro Katsuta and Tatsujiro Suzuki, *Japan's Spent Fuel and Plutonium Management Challenges*, International Panel on Fissile Materials, 2006.

³⁰ *Conference Report on the Energy and Water Appropriations Act for Fiscal Year 2006*, Report 109-275, "Nuclear Energy Programs," pp. 141-142 and "Nuclear Waste Disposal," pp. 156-157.

³¹ *Report to Congress: Spent Nuclear Fuel Recycling Program Plan*, U.S. Department of Energy, May 2006, Figure 3.

³² Ronald Wigeland, Theodore Bauer, Thomas Fanning and Edgar Morris, "Separations and Transmutation Criteria to Improve Utilization of a Geological Repository" *Nuclear Technology*, April 2006, p. 95.

- ³³ Proposed “Nuclear Fuel Management and Disposal Act,” submitted to the Congress, 5 April 2006.
- ³⁴ J. Kessler, *Room at the Mountain: Analysis of the Maximum Disposal Capacity for Commercial Spent Fuel in a Yucca Mountain Repository*, Electric Power Research Institute, Report 1013523, May 2006.
- ³⁵ Office of Nuclear Energy, Department of Energy, “Notice of Request for Expressions of Interest in a Consolidated Fuel Treatment Center to Support the Global Nuclear Energy Partnership,” and “Notice of Request for Expressions of Interest in an Advanced Burner Reactor to Support the Global Nuclear Energy Partnership,” *Federal Register*, 71, #151, 7 August 2006, pp. 44673-44679.
- ³⁶ *Global Nuclear Energy Partnership Strategic Plan*, U.S. Department of Energy, GNEP-167312, January 2007, p. 9; “Department of Energy: Notice of Intent to Prepare a Programmatic Environmental Impact Statement for the Global Nuclear Energy Partnership,” *Federal Register* 72, No. 2, Jan. 4, 2007, pp. 331-6.
- ³⁷ Assuming a burn up (fission energy release) of 50 MWt-days per kilogram of uranium in the fuel. Fuel discharged in the 1970s had lower burn up and the plutonium-241 has decayed into americium-241. Its plutonium content is therefore about 0.8 percent, *Plutonium Fuel: An Assessment*, OECD, 1989, Table 9.
- ³⁸ See e.g. *International Fuel Cycle Evaluation: Fast Breeders*, International Atomic Energy Agency, INFCE/PC/5, 1980, p. 2.
- ³⁹ *Nuclear Wastes: Technologies for Separations and Transmutation*, National Academies Press, 1996.
- ⁴⁰ Boston Consulting Group, *Economic Assessment of Used Nuclear Fuel Management in the United States*, July 2006.
- ⁴¹ *2002 Waste Stream Projection Report*, TDR-CRW-SE-000022, Rev. 1, DOE, 2003.
- ⁴² *Nuclear Wastes: Technologies for Separations and Transmutation*, op. cit., p. 7.
- ⁴³ See *Nuclear Waste Fund Fee Adequacy: An Assessment*, Department of Energy, DOE/RW-0534, May 2001.
- ⁴⁴ See, for example, the testimony of David J. Modeen, Vice President and Chief Nuclear Officer, Electric Power Research Institute, before the Energy Subcommittee of the Science Committee, U.S. House of Representatives, 6 April 2006.
- ⁴⁵ The number of fast-neutron reactors that would be required depends upon their net destruction rate of transuranics. Assuming a 40% thermal-to-electric conversion efficiency, a 1000 MWe fast-neutron reactor operating at a 90-percent capacity factor would fission approximately 0.8 tons of transuranics per year. If the reactor did not create new transuranics at the same time, fissioning the 24 tons of transuranics in the spent fuel discharged annually by 100 GWe of U.S. LWRs, would require 30 such reactors. Even with their uranium blankets removed, however, fast-neutron reactors, as currently conceived, would produce transuranics. The National Academy of Sciences’ report discussed the tradeoffs in reducing this conversion ratio below unity as follows: “With reduced fissile breeding and reduced heavy metal inventory, the burner designs also result in increased reactivity swing over a fuel cycle. This then requires larger control rod worths and hence entails potentially larger positive reactivity insertions [if those rods are withdrawn] and degraded performance in transient overpower events. As the breeding ratio decreases, there is less reactivity insertion resulting from sodium voiding in a power excursion. However, with decreasing breeding ratio, less negative reactivity is available from Doppler broadening of the neutron absorption resonances that occurs when the fuel is heated in a power excursion. Based on these considerations, GE concludes that a TRU burner with a breeding ratio of 0.6 and a core height of 0.76 m is the lowest possible breeding ratio configuration that would have acceptable safety features,” *Nuclear Wastes: Technologies for Separations and Transmutation*, op. cit. pp. 205-6. For a conversion ratio of 0.6, 75 GWe of burner-reactor capacity would be required. Fast-neutron reactor advocates at Argonne National Lab argue, however, that a

conversion ratio as low as 0.25 can be achieved safely with added control rods and twice-annual refueling, J. E. Cahalan, M. A. Smith, R. N. Hill, and F. E. Dunn, "Physics and Safety Studies of a Low Conversion Ratio Sodium Cooled Fast Reactor," *Proceedings of the PHYSOR 2004 Conf.*, American Nuclear Society, Chicago, April 2004. For a 0.25 conversion ratio, 40 GWe of burner-reactor capacity would be required.

⁴⁶ The long-term evacuation caused by the Chernobyl accident is primarily due to land contamination by cesium-137, "Exposures and Effects of the Chernobyl Accident," *Sources and Effects of Ionizing Radiation*, United Nations Scientific Committee on the Effects of Atomic Radiation, U.N., 2000, Annex J.

⁴⁷ *Economic Assessment of Used Nuclear Fuel Management in the United States, op. cit.*

⁴⁸ The maximum amount of spent fuel that Areva has reprocessed in its reprocessing complex in one year was 1650 tons in 1996, between 1996 and 2004, it reprocessed an average of about 1300 tons per year, Mycle Schneider, personal communication, 1 March 2006. Areva's Melox plant is licensed to produce up to 195 tons of MOX fuel per year. That much fuel would contain about 14 tons of power-reactor plutonium.

⁴⁹ Image courtesy of Greenpeace (image 35044).

⁵⁰ DOE-National Nuclear Security Administration, *Report to Congress: Disposition of Surplus Defense Plutonium at Savannah River*, 15 February 2002, p. 4-7.

⁵¹ MOX containing weapon-grade plutonium would contain only about 4 percent plutonium versus 7 percent for fuel containing reactor-grade plutonium.

⁵² DOE Inspector General Audit Report, *The Status of the Mixed Oxide Fuel Fabrication Plant*, 2005.

⁵³ See e.g. *Department of Energy: Opportunity to Improve Management of Major System Acquisitions*, U.S. Government Accountability Office, GAO/RCED-97-17, 1996 and *Department of Energy: Further Actions Needed to Strengthen Contract Management for Major Projects*, (GA)-05-123, 2005.

⁵⁴ *Economic Assessment of Used Nuclear Fuel Management in the United States, op. cit.*, Fig. 36.

⁵⁵ *Economic Assessment of Used Nuclear Fuel Management in the United States, op. cit.*, Appendix 5, Figure 29 and p. 31.

⁵⁶ *Economic Assessment of Used Nuclear Fuel Management in the United States, op. cit.*, Appendix 10.

⁵⁷ J.M. Charpin, B. Dessus and R. Pellat, *Report to the Prime Minister [of France]: Economic Forecast Study of the Nuclear Power Option*, 2000, p. 38 says 150 years. The June 2001 report of France's National Assessment Committee on Radioactive Waste Management Research says "centuries," Pierre Saverot, personal communication, 4 January 2007.

⁵⁸ In equilibrium, about 12 of the approximately 100 GWe of U.S. LWR capacity would be devoted to MOX recycle. This would leave 88 GWe of capacity fueled by low-enriched uranium (LEU). The basis for the fast-reactor to LEU-fueled LWR ratio is explained in a footnote to the subsection on the 1996 National Academy of Sciences study above. The Areva study mentions the option of recycling once in LWRs and then in fast reactors, but provides no basis for its estimate of the number of fast reactors required: "we assume that ~ 10-15 reactors are needed to absorb the plutonium stock" (p. 78).

⁵⁹ *Economic Assessment of Used Nuclear Fuel Management in the United States, op. cit.*, p. 78.

⁶⁰ The capital cost of the 1.2 GWe Superphénix in French Francs was FF 34.4 billion (about \$7 billion in 1996\$) according the France's public accounting tribunal, the Cour des Comptes, "Accounting Panel Pegs Superphénix [construction plus decommissioning] Cost at FF 60-Billion to 2000," *Nucleonics Week*, 17 October 1996.

- ⁶¹ J.M. Charpin, B. Dessus and R. Pellat, *Report to the Prime Minister: Economic Forecast Study of the Nuclear Power Option*, 2000. We have taken a 1999 French Franc (FF) = \$0.2 (2006).
- ⁶² *Report to Congress: Spent Nuclear Fuel Recycling Program Plan, op. cit.*, p. 10.
- ⁶³ Thomas B. Cochran, William M. Arkin, Robert S. Norris, and Milton M. Hoenig, *U.S. Nuclear Warhead Facility Profiles*, Ballinger, 1987, p. 24.
- ⁶⁴ *National Energy Policy*, White House, 2001, p. 5-17.
- ⁶⁵ We use here the nomenclature for the variants of UREX+ used by E.D. Collins in “Closing the Fuel Cycle Can Extend the Lifetime of the High-Level-Waste Repository,” American Nuclear Society, 2005 Winter Meeting, 17 November 2005, Washington, DC.
- ⁶⁶ G.F. Vandergrift, “Designing and Demonstration of the UREX+ Process Using Spent Nuclear Fuel,” presentation at the International Conference on Advances for Future Nuclear Fuel Cycles, Nîmes, France, 21-24 June 2004.
- ⁶⁷ The IAEA’s threshold for self protection is one Sievert per hour at a distance of 1 meter, “The Physical Protection of Nuclear Material and Nuclear Facilities,” INFCIRC/225, Rev.4. A dose of several Sieverts would be lethal.
- ⁶⁸ E.D. Collins, “Closing the Fuel Cycle Can Extend the Lifetime of the High-Level-Waste Repository,” *op. cit.*
- ⁶⁹ J. Kang and F. von Hippel, “Limited Proliferation Resistance Benefits from Recycling Unseparated Transuranics and Lanthanides from Light-Water Reactor Spent Fuel,” *Science & Global Security*, Vol. 13, 2005, p. 169.
- ⁷⁰ Rube Goldberg was a cartoonist who specialized in designing enormously complex systems to accomplish simple tasks, www.rube-goldberg.com/.
- ⁷¹ Phillip Finck, Deputy Associate Laboratory Director, “The Benefits of the Closed Nuclear Fuel Cycle,” Applied Science and Technology and National Security, Argonne National Laboratory, briefing to U.S. House of Representatives staff, 10 March 2006, slide 3.
- ⁷² This section was stimulated by Edwin Lyman’s report, “The Global Nuclear Energy Partnership: Will it Advance Nonproliferation or Undermine It?” *Proceedings of the Annual Meeting of the Institute for Nuclear Materials Management*, Nashville, Tennessee, 16-20 July 2006.
- ⁷³ Marvin M. Miller, “Are IAEA Safeguards on Plutonium Bulk-Handling Facilities Effective?” Nuclear Control Institute, 1990.
- ⁷⁴ Kang and von Hippel, “Limited Proliferation Resistance Benefits from Recycling Unseparated Transuranics and Lanthanides from Light-Water Reactor Spent Fuel,” *op. cit.*
- ⁷⁵ DOE, “Notice of Request for Expressions of Interest in a Consolidated Fuel Treatment Center to Support the Global Nuclear Energy Partnership,” *op. cit.*
- ⁷⁶ Boston Consulting Group, *Economic Assessment of Used Nuclear Fuel Management in the United States, op. cit.*
- ⁷⁷ The White House, “Fact Sheet: Strengthening International Efforts Against WMD Proliferation,” 11 February 2004, at www.whitehouse.gov/news/releases/2004/02/20040211-5.html.

⁷⁸ *Multilateral Approaches to the Nuclear Fuel Cycle: Expert Group Report Submitted to the Director General of the International Atomic Energy Agency*, IAEA, INFCIRC-640, 2005, pp. 102-3, 19.

⁷⁹ Argentina and Brazil have already been informed by the Bush Administration that they are exempt from the proposed stricture, U.S. State Department officials, personal communication. It seems likely that Australia and Canada will be as well. South Africa and Ukraine have also expressed an interest in national enrichment plants.

⁸⁰ Mark Hibbs, "US Has not Decided Whether GNEP Will Include ROK Pyroprocessing," *Nuclear Fuel*, 11 September 2006.

⁸¹ "Areva dual-track strategy aimed at two reprocessing plants," *Nuclear Fuel*, 3 July 2006. The countries listed as possible buyers were Japan, Germany, Canada, the Netherlands, Australia, Brazil, Argentina and South Africa.

⁸² "Energy Secretary Bodman Outlines Plans on Yucca, Nuclear Waste and Oil Security," Environment and Energy Publishing, 8 March 2006.

⁸³ The French Government's estimate was \$33 billion extra for 58,000 tons of spent fuel (see Table 2 above). The National Academy of Sciences' report, *Nuclear Wastes*, estimated an extra cost of \$50-100+ billion for 62,000 tons of spent fuel. We have converted these to annual costs by using the current U.S. spent-fuel discharge rate of 2,000 tons per year.

⁸⁴ Allison Macfarlane, "Interim Storage of Spent Fuel in the United States," *Annual Review of Energy and Environment*, Vol. 26, 2001, p. 201.

⁸⁵ Robert Alvarez, Jan Beyea, Klaus Janberg, Jungmin Kang, Ed Lyman, Allison Macfarlane, Gordon Thompson and Frank von Hippel, "Reducing the Hazards from Stored Spent Power-Reactor Fuel in the United States," *Science & Global Security*, Vol. 11, 2003, p. 1.

⁸⁶ *Safety and Security of Commercial Spent Nuclear Fuel Storage*, *op. cit.*, pp. 68-69.

⁸⁷ Picture of the spent fuel storage area of the shut down Maine Yankee nuclear power plant, www.maineyankee.com/.

⁸⁸ California Public Resources Code, para. 25524.2.

⁸⁹ California Energy Commission, *Integrated Energy Policy Report*, 2005 p. 85.

⁹⁰ As of 2 November 2006, 21 national groups and 106 local groups had signed a position statement, "Principles for Safeguarding Nuclear Waste at Reactors," www.citizen.org/documents/PrinciplesSafeguardingIrradiatedFuel.pdf. The statement indicates that the groups would require in addition that spent-fuel pools and dry-cask storage be hardened against attack and that the spent-fuel be moved to dry cask storage after five years in storage pools. Both requirements could be met at costs modest relative to reprocessing.

⁹¹ Skip Bowman, President of the Nuclear Energy Institute, testimony before the Senate Energy and Natural Resources Committee, 16 May 2006.

⁹² Cora Daniels, "Meet Mr. Nuke: John Rowe of Exelon is Staking Out a Megashare of What Could Be America's Great Atomic Revival," *Fortune*, 15 May 2006.

⁹³ "The proposed Yucca Mountain nuclear waste dump is never going to open," www.reid.senate.gov/issues/yucca.cfm, accessed 14 November 2006.

⁹⁴ www.reid.senate.gov/issues/yucca.cfm, accessed 14 November 2006.

⁹⁵ At the \$50-100+ billion estimated in the 1996 National Academy of Sciences study, reprocessing of 62,000 tons spent LWR fuel and fission of the recovered transuranics in advanced burner reactors would cost \$0.8-1.6+ million per metric ton. For comparison for a site with operating reactors and 500 tons of dry cask fuel the incremental capital cost for dry-cask storage is \$0.11 million/ton and the annual cost would be about \$0.002 million per ton-year. For a similar site with shut down reactors, the annual cost would be about \$0.009 million per ton-year. See footnote to section I for details.

⁹⁶ As of the end of 2002, less than 3,000 out of 50,000 tons of U.S. spent fuel were stored at ten U.S. sites with no operating power reactors, *Going the Distance*, National Academies Press, 2006, *op. cit.* Table 2.

Appendix

Scenarios for the French Fuel Cycle*

	Percentage of Spent LEU Fuel Reprocessed			
	67% (S6)	27% (Reprocessing Ends in 2010, S4)	100% (Derived Scenario)	No Reprocessing (S7)
Fuel cycle costs (10 ⁹ 1999 FF [2006 \$] undiscounted)				
Front end	578 [116]	602 [120]	558 [112]	611 [122]
Back end	370 [74]	307 [61]	422 [84]	203 [41]
Net	948 [190]	909 [182]	980 [196]	814 [162]
Back end cost (\$/kg)			\$1450	\$700
Back end cost (\$10 ⁻³ /kWh)			4.2	2.0
Inputs				
Natural uranium mined (10 ³ metric tons)	437	460	418	475
Separative Work (million 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 reprocessed (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

* Assuming a 45-year average life for France's LWR fleet. In all scenarios, 20.2x10¹² kilowatt hours are generated, J.M. Charpin, B. Dessus and R. Pellat, *Report to the Prime Minister: Economic Forecast Study of the Nuclear Power Option*, 2000, Tables on pp. 43, 56, 214., 215. We assumed that a 1999 French Franc (FF) = \$0.2 (2006\$).

About the Author

Frank von Hippel is co-chair of the International Panel on Fissile Material. He has a PhD in nuclear physics (1962) and is a founding co-director of Princeton's Program on Science and Global Security. In the 1980s, as chairman of the Federation of American Scientists, he partnered with Evgenyi Velikhov in advising Mikhail Gorbachev on the technical basis for steps to end the Soviet-U.S. nuclear arms race. In 1994-5, he served as Assistant Director for National Security in the White House Office of Science and Technology Policy. von Hippel and his colleagues have worked on fissile material policy issues for the past 30 years and have made contributions to: ending the U.S. program to foster the commercialization of plutonium breeder reactors, convincing President Gorbachev to embrace the idea of a Fissile Material Production Cutoff Treaty, launching the U.S.-Russian cooperative nuclear materials protection, control and accounting program, and broadening efforts to eliminate the use of high-enriched uranium in civilian reactors worldwide.

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