DOI: 10.2968/065006003

Bulletin of the Atomic Scientists

Should the United States resume reprocessing? A pro and con

Last summer, 11 Harvard graduate students and postdocs went to France to investigate Areva's spent fuel reprocessing. On the trip, they debated whether the United States should reprocess as well. What resulted was the typical split that has followed this debate for decades.

Last spring, Anne Lauvergeon, the CEO of the French nuclear energy company Areva, came to Harvard University to give a talk as part of the Future of Energy seminar series sponsored by Harvard's Center for the Environment. As a result of that lecture, an invitation was extended to members of the Harvard Energy Journal Club to visit Areva's nuclear facilities in France. So last summer, 11 graduate students and postdocs spent a week touring the reprocessing plant in La Hague, the MELOX mixed-oxide fuel fabrication plant in Marcoule, and the heavy component manufacturing facility at Chalon/Saint-Marcel. None of them were nuclear technology experts; instead, they were biologists, chemists, and physicists who worked in unrelated fields. They did, however, share a common interest in energy policy and technology. Throughout the trip, they debated whether the United States should follow the French and reprocess its spent nuclear fuel, a process Washington halted 30 years ago. (Although President Ronald Reagan lifted the federal ban on reprocessing in 1981, the country still observes a de facto moratorium and discourages other countries from reprocessing.)

By the end of the trip, the group was divided. Four of them were in favor of reprocessing, and five of them were against it (with two undecided)—the typical split that has followed debates about reprocessing for decades. Here, these Harvard students and postdocs examine the case for and against reprocessing anew in a world facing climate change, the possibility of a price on carbon emissions, and a growing global population with expanding energy needs. In the first decade of the twenty-first century, is it time for the United States to take another look at reprocessing? A new generation picks up this perennial issue.—*The Editors*

The case for reprocessing

BY KATE J. DENNIS, JASON RUGOLO, LEE T. MURRAY & JUSTIN PARRELLA

The United States should reconsider reprocessing its spent nuclear fuel to obtain the highest efficiency and lowest waste. With the correct and necessary guidelines, closing the nuclear fuel cycle by allowing waste to be turned back into fuel is a viable option and should be a goal for the country.

Critics argue that the high cost of reprocessing spent fuel and fabricating mixed-oxide (MOX) fuel rods—a mixture of uranium and plutonium oxides—far outweighs the benefits. According to MIT's 2003 "Future of Nuclear Power" report, the so-called once-through fuel cycle, where spent fuel is directly deposited in geologic repositories, is four to five times less expensive than the costs associated with reprocessing. We do not argue that reprocessing is cheaper in the short-term, but that it is extremely difficult, if not impossible, to compare the short-term costs associated with reprocessing with the benefits that would occur 50–100 years hence. (A 2006 study by the Boston Consulting Group does find the long-term cost of reprocessing to be almost equivalent to once-through fuel management.) These longer-term benefits include a twofold volumetric reduction in nuclear waste, conservation of uranium resources, and a reduction in the environmental impact of uranium mining. Additionally, if the United States considers building fast reactors in the future, reprocessing becomes a necessary step to remove the plutonium that these reactors generate. Fast reactors consist of a core of fissile plutonium or highly enriched uranium surrounded by a blanket of uranium 238, which captures neutrons escaping from the core and partially transmutes into plutonium 239. The result is a reactor that produces or "breeds" a surplus of fuel. This blanket material, however, must be reprocessed to recover the generated plutonium. The development of such breeder reactors would increase the energy output for a given amount of nuclear fuel 60–100 times, according to a range of estimates, and therefore reduce consumption of natural uranium ore.

Currently, it is unclear if the United States will continue to pursue fast reactors as outlined by former President George W. Bush in the 2006 Global Nuclear Energy Partnership (GNEP), which encouraged the use of nuclear energy abroad and the restart of U.S. reprocessing. But even without GNEP, the Obama administration has continued funding the Advanced Fuel Cycle Initiative, a research project within the Energy Department that is focused on "proliferation-resistant fuel cycles and waste reduction strategies." This seems to indicate research into reprocessing will continue.

Until early 2009, the U.S. nuclear waste plan was to dispose of the country's spent fuel in a permanent geologic site at Yucca Mountain in Nevada. In the 2010 Energy budget, however, the Obama administration effectively shut down Yucca Mountain, stating its funding would be "scaled back to those costs necessary to answer inquiries from the Nuclear Regulatory Commission, while the administration devises a new strategy toward nuclear waste disposal." As a result, we are left with a dispersed, decentralized patchwork of highly radioactive waste sites (interim storage pools and dry-cask storage at nuclear power plants) with the hope that a long-term repository will be opened somewhere, sometime in the future. Otherwise, an alternative waste-disposal strategy must be established, which is no easy task.

To give an idea of what regulatory hurdles any alternate waste-disposal strategy faces, it is helpful to look back at the history of Yucca Mountain. Until recently, the repository was scheduled to open in 2017, but that date itself was delayed numerous times from 1998, the original year it was supposed to open and start accepting U.S. spent fuel. Even if the Obama administration had not ended the project, it was unclear whether Energy's Office of Civilian Radioactive Waste Management would have been able to meet the 2017 deadline, especially with political opposition from key congressional leaders. The Democratic Senate majority leader, Nevada Sen. Harry Reid, for example, is strongly opposed to Yucca Mountain; he has argued instead for on-site, dry-cask storage as a more viable solution for the country's spent nuclear fuel. Although we disagree with the long-term viability of dry-cask storage as a solution (not only does on-site, dry-cask storage create a patchwork of nuclear waste, but it also pushes long-term decision making on nuclear waste strategy to the next generation), the fact remains that even without President Barack Obama's recent cuts, congressional support for the repository site is lacking.

Cost estimates for Yucca Mountain also have risen significantly over time. Estimates to complete the project were $79.3 billion in 2008, much higher than the 1998 estimate of $11.6 billion (in 2000 dollars). Plus, it is increasingly obvious that Yucca Mountain would not have been large enough to accept all of the country's current and future nuclear waste. As of 2008, the United States had generated 58,000 tons of civilian spent fuel, and along with the 13,000 tons of government-sourced spent fuel and high-level waste, the repository's 70,000-ton capacity would have been exceeded on the day it opened. If waste continues to be generated at the rate of approximately 2,500 tons per year, another permanent geologic disposal site, or an increase in the capacity of Yucca Mountain, would have been required. If there are additional nuclear plants built in the future, this problem only will be exacerbated. Although it remains unclear if the Obama administration will support extensive nuclear power investment, Energy Secretary Steven Chu has repeatedly come out in favor of nuclear power. In addition, the 2005 Energy Policy Act provided incentives for the nuclear industry, including tax credits and up to $18.5 billion in loan guarantees for new U.S. reactors. Although we are not aware of any allocations of these funds, it again suggests that there is interest in expanding the civilian nuclear energy industry.

While it is true that high-level waste from reprocessing is hotter than non-reprocessed spent fuel, this does not completely nullify the decrease in waste volume achieved by reprocessing.

Since 1983, $10.3 billion has been spent to manage and dispose of the country's nuclear waste. That amount has been taken out of the Nuclear Waste Fund, which was established with a $0.001 per kilowatt-hour surcharge on nuclear power generating utilities. The total amount in the fund was $29.6 billion at the end of 2008. With the majority of the $10.3 billion spent developing Yucca Mountain as a repository, it is unclear how much more money will be needed before a nuclear waste storage site is decided upon, built, and opened.

Reprocessing saves valuable repository space. For long-term geologic storage, reductions in waste volume are important. But it is not just the space that the waste would physically take up that is vital, the heat output of the waste also must be taken into consideration, as does the space between waste packages necessary to prevent overheating in the repository. While it is true that high-level waste from reprocessing is hotter than non-reprocessed spent fuel, this does not completely nullify the decrease in waste volume achieved by reprocessing. The heat emitted from post-reprocessing waste decreases by approximately 70 percent during its first 30 years. In other words, such waste initially can be stored either aboveground in well-ventilated storage buildings (as Areva does), or it can be stored in geologic repositories with space between packages left empty and then filled over the years as heat output decreases.

In contrast, spent fuel rods that are directly disposed in repositories cool more slowly and require larger geologic repositories. One estimate, which appears in the book *Megawatts and Megatons* by Richard Garwin and Georges Charpak, suggests that even with the increased heat output of high-level wastes from reprocessing, the amount of space required for a geologic repository can be reduced by *one-half* if the waste is reprocessed. Overall, Garwin and Charpak argue against reprocessing but acknowledge several benefits that we believe outweigh the economic burdens, the most important being that reprocessing can effectively double the capacity of a Yucca Mountain-sized permanent repository.

Reprocessing reduces radioactivity of waste. Reprocessing also reduces the radiotoxicity of high-level waste by one-half to one-tenth when compared with direct burial, and the waste decays to the radioactivity of natural uranium in 10,000 years versus 100,000 years. With the advent of fast reactors, coupled with reprocessing, radiotoxicity of waste would be further reduced with radioactivity reaching the level of natural uranium in only 1,000 years. Given the necessity of any nuclear waste strategy's long-term viability, these reductions are significant advantages for reprocessing.

Our discussion of waste management would not be complete without acknowledging that after reprocessing spent fuel and fabricating MOX fuel rods, the spent MOX fuel rods present a unique problem when dealing with their final disposal. Spent MOX fuel has higher contents of plutonium (plutonium 238 and plutonium 241), americium, and curium than conventional low-enriched uranium (LEU) spent fuel rods, and as a result, the management of spent MOX fuel is more challenging due to cooling and criticality concerns. For interim storage, spent MOX fuel can be dispersed among LEU spent fuel resulting in no change in storage requirements. But in a geologic repository, according to a 2003 International Atomic Energy Agency report on MOX fuel technology, spent MOX fuel would need three times as much space as spent LEU fuel, or require interim storage aboveground for 150 years to reach the same thermal output and then be able to occupy the same amount of space. If we are to assume fast reactors are the long-term goal of the nuclear industry, the optimal and safest use of MOX fuel rods would be to continue recycling them in fast reactors. Yet without that option available, we must acknowledge that some of the gains made by reprocessing are lost in the storage of spent MOX fuel.

Reprocessing does not pose a proliferation threat. A frequent criticism of reprocessing is that separating pure plutonium from spent fuel creates a proliferation and theft risk. Specifically, critics say that spent nuclear fuel without reprocessing is too radioactive to be stolen easily and thus is self protecting. Therefore, some suggest, all spent fuel should remain unreprocessed. Currently, Areva, the only large-scale operator of reprocessing plants in the world, uses the PUREX technique, which separates spent fuel rods into individual streams of uranium, plutonium, and high-level fission products. Although it is true that PUREX results in a pure plutonium stream, the separated plutonium is not considered weapon-grade. Weapon-grade plutonium contains more than 93 percent plutonium 239, while reprocessed fuel contains closer to 50 percent with the remainder being oxygen and other plutonium isotopes, including approximately 15 percent plutonium 241. A nuclear explosive device that used 50 percent plutonium 239 would have an expected yield of about 1 kiloton (approximately 5 percent the power of a weapon-grade plutonium bomb). Even so, such an explosion could wipe out a handful of city blocks (in comparison, the nuclear weapon dropped on Hiroshima was 12–15 kilotons, destroying a radial area of approximately 1.6 kilometers) and is exactly why the implementation of effective security measures is paramount for safe reprocessing. According to an Areva representative, the company, along with French national security personnel, goes to great lengths to secure the transport of reactor-grade plutonium across France. In fact, during conversations with Areva we were told that if a truck were ever hijacked, "it would not get further than 100 meters." The representative was not able to further elaborate, stating that security protocol restricted his ability to clarify.

If the United States truly wants to proceed with nuclear energy as a viable, low-carbon emitting source of energy, it should pursue reprocessing in combination with the development of fast reactors.

It is reasonable to worry about the risks presented by transporting nuclear materials and plutonium separated by reprocessing, and this is exactly why we stress that the United States should use and build reprocessing and fuel fabrication facilities in a single location if it chooses to restart its domestic reprocessing program. (Areva's facilities are on opposite ends of France.) Such a combined facility, with all elements in one location, would circumvent the security concerns associated with reprocessing. The United States is currently using this design for its Savannah River Site in Aiken, South Carolina, where it plans to decommission nuclear weapons. This facility will downblend surplus weapon-grade material and use that material in the fabrication of MOX fuel rods. Although the site does not currently reprocess civilian fuel, it seems logical that any civilian program would benefit from a similarly combined facility design.

To further prevent proliferation risks, the United States should develop advanced reprocessing technologies that have been researched under GNEP and will likely continue with the Advanced Fuel Cycle Initiative. These new reprocessing techniques (COEX, UREX+, and NUEX) avoid creating a pure plutonium stream. COEX extracts plutonium and uranium together, while UREX+ and NUEX extract plutonium with some combination of highly radioactive elements that are present in spent fuel. The inclusion of such transuranic elements increases the heat output and radioactive emission rate of the produced waste, necessitating robust radioactive shielding to safely manipulate or handle the material. Such advanced reprocessing techniques coupled with combined reprocessing and fabrication facilities would provide additional layers of security to address the major proliferation concerns associated with reprocessing.

The final word. Reprocessing allows the utilization of more available energy from nuclear fuel than is currently possible in the once-through fuel cycle. Reprocessing represents a path toward decreasing the current nuclear waste burden on geologic disposal sites and on future generations. If the United States truly wants to proceed with nuclear energy as a viable, low-carbon emitting source of energy, it should pursue reprocessing in combination with the development of fast reactors. Once such a decision is made, the debate should turn to how best to develop cheaper and safer reprocessing options, rather than denying its general benefit.

The case against nuclear reprocessing

BY DAVID M. ROMPS, CHRISTOPHER D. HOLMES, KURT Z. HOUSE, BENJAMIN G. LEE & MARK T. WINKLER

In France, as in the United States and other countries, reprocessing technology was originally pursued to produce plutonium for nuclear weapons. As reprocessing plants churned out their product, the growing stockpiles of plutonium cast a doomsday pall across the globe. Therefore, it is somewhat ironic that reprocessing became part of a utopian dream to provide the world with cheap and nearly limitless energy. The concept was dubbed the "plutonium economy." In this vision, a special kind of nuclear reactor—the fast "breeder" reactor—would burn plutonium to make electricity, but it also would convert nonfissile uranium 238 into plutonium 239, thereby creating or "breeding" more fuel. Before that new fuel could be used, however, it would have to be separated from less useful radioactive material in a nuclear reprocessing plant and then formed into fuel rods in a mixed-oxide (MOX) fuel fabrication plant.

In the 1970s, France embarked on an effort to make the plutonium economy a reality. To do so, it needed a breeder reactor, a reprocessing plant, and a MOX fuel fabrication plant. For the reprocessing plant, France pressed into service its military reprocessing facility at La Hague, blurring the line between its civilian and military nuclear programs. To turn the plutonium into ceramic MOX fuel pellets, it constructed the MELOX plant at Marcoule. All that was left to build was the commercial-scale fast reactor, dubbed Superphénix. Unfortunately the reactor's construction turned out to be much more complicated than anyone imagined, and Superphénix became a notorious flop.

In the aftermath of the failure of fast reactors (not just in France, but throughout the world), the plutonium economy died. This left the French with two very expensive nuclear facilities that had lost their *raison d'être*. Although the French nuclear industry still hopes that commercial fast reactors will someday become viable, they have been forced to argue the merits of reprocessing in the current world of light water reactors fueled by low-enriched uranium.

Today's reprocessing advocates have two main arguments: It reduces hazardous waste and conserves uranium resources. Both of these justifications are seriously flawed. It is also unlikely that fast reactors will be economically competitive in the next several decades, so reprocessing will remain a technology in search of a rationale for years to come. In the nearer term, the economic costs, environmental harm, and proliferation hazards overwhelm the supposed benefits of reprocessing.

Reprocessing does not save uranium or repository space. Reprocessing proponents claim that the process dramatically reduces the volume of nuclear waste. Indeed, spent nuclear fuel contains roughly 1 percent plutonium, 4 percent high-level radioactive waste, and 95 percent uranium. After reprocessing, the highly radioactive fuel waste and fuel-rod casing material occupy only 20 percent of the original spent-fuel volume. Aboveground, where air currents can cool the high-level waste, the space savings is significant. In fact, all of France's high-level waste sits in a modestly sized building at the La Hague complex. For final geological storage, however, the high temperature of the waste is a more restrictive design consideration than the waste's volume. In order to avoid damaging the geologic repository and risk releasing radioactivity, the high-level waste must be spaced at sufficient intervals to allow for cooling. Even if the reprocessed high-level waste is allowed to cool for 100 years before final disposal, it has been estimated that the repository volume only would be cut by one-half. Whether the United States chooses Yucca Mountain or another site for geologic storage, this modest space savings does not justify the additional costs and hazards of reprocessing because reducing the volume of the repository has an almost negligible effect on the storage costs. According to a recent report from Harvard University's Project on Managing the Atom, even a fourfold decrease in the repository volume would decrease storage costs by less than 15 percent.

Even with strict monitoring at reprocessing plants, it is not feasible to account for every single gram of plutonium produced. With the large volumes of plutonium being separated and the possibilities for measurement errors or poor bookkeeping, an insider could smuggle out a bomb's worth of plutonium in several months without anyone noticing the missing plutonium.

The other major claim is that, without reprocessing, there is only enough low-cost uranium for 50 more years of nuclear power at current usage levels. Indeed, from 1965 to 2003, the Organisation for Economic Co-operation and Development's "Red Book" listed known conventional reserves of natural uranium recoverable at less than $130 per kilogram at 3–5 megatons. At the low end of this range, the current global consumption of 0.07 megatons per year would exhaust reserves in 50 years. Reserves, however, will continue to grow in the future, as they have in the past. As prices rise and extraction technology improves, extraction from difficult deposits will become more profitable, increasing the size of known reserves. For example, from 2005 to 2007, the known conventional reserves recoverable at $130 per kilogram increased by 20 percent to 5.5 megatons. Adding in "Red Book" estimates of so-far undiscovered resources brings the amount of uranium to roughly 17 megatons, which, if mined, would provide a 240-year supply.

Reprocessing is a proliferation threat. Reprocessing supporters argue that plutonium from a reprocessing plant is not weapon-grade. The term "weapon-grade" refers to plutonium that is primarily plutonium 239, with less than 6 percent plutonium 240. Plutonium 240 has a high rate of spontaneous fission, which increases the odds of prematurely igniting a fission weapon during the detonation sequence, thereby decreasing its yield. In contrast to weapon-grade plutonium, the plutonium that comes out of France's La Hague facility has about 24 percent plutonium 240. The plutonium bombs detonated during the Trinity test and over Nagasaki used super-weapon-grade plutonium to produce an explosion equivalent to 20 kilotons TNT with a 1.6-kilometer destruction radius. If the same bomb were made with plutonium from the La Hague plant, its expected yield would be around 1 kiloton of TNT equivalent. Although a 1-kiloton explosion might sound less dangerous than a 20-kiloton explosion, its likely blast radius would still be one-half to four-fifths of a kilometer, enough to level most of downtown Boston. Such a device would be 90 times more powerful than the largest conventional weapon in the U.S. arsenal and 500 times more powerful than what destroyed the Alfred P. Murrah Federal Building in Oklahoma City. So while it is true that reactor-grade plutonium is not as powerful an explosive as weapon-grade plutonium, it certainly should be considered "terrorist-grade."

In France, reprocessed plutonium is shipped the entire length of the country from La Hague on the north coast to the MELOX fuel fabrication plant in Marcoule near the south coast. To avoid uncontrolled fission, the plutonium oxide—a fine, yellow powder—is divided into small, thermos-sized canisters. Each canister contains about 2.5 kilograms of material, and only three of these provide enough to make a bomb. Every week, Areva ships dozens of these canisters from La Hague to Marcoule in shielded trucks, presenting an opportunity for theft. During our visit, we observed two such trucks on the highway guarded by four police cars. Given Areva's spin that this is non-weapon-grade plutonium, we wondered whether the police officers were aware that they were guarding enough material to destroy the downtown areas of 30 mid-sized cities.

Unfortunately, this is not the only chance someone has to steal the plutonium. Even with strict monitoring at reprocessing plants, it is not feasible to account for every single gram of plutonium produced. With the large volumes of plutonium being separated and the possibilities for measurement errors or poor bookkeeping, an insider could smuggle out a bomb's worth of plutonium in several months without anyone noticing the missing plutonium.

In addition to theft, there is the danger that reprocessing plants could be used by a host nation to initiate a nuclear weapons program. This has already happened in the case of India. The United States sold reprocessing technology to India with the understanding that it would only be used for civilian nuclear power. The plutonium product, however, was diverted for military purposes. After the detonation of an Indian bomb in 1974, the United States reversed its pro-reprocessing stance and put an end to domestic civilian reprocessing. Although reprocessing is no longer technically outlawed in the United States, a de facto ban has persisted.

In response to proliferation concerns, many reprocessing advocates recommend a new method, called COEX, for future reprocessing facilities. In contrast to the current PUREX process, which produces pure plutonium oxide, COEX would extract plutonium and uranium together to form a mixed plutonium-uranium oxide that can be directly fabricated into MOX fuel. Although this product cannot fuel bombs directly, a malicious organization could later extract the plutonium. Since none of the MOX components are highly radioactive, plutonium separation could be carried out safely in a standard chemical laboratory with existing methods. Even more worrisome, the separation process need not be efficient to obtain a large quantity of material because the COEX product is composed of 50 percent plutonium. In addition, because COEX has never been deployed on an industrial scale, the costs of developing it commercially could be massive. In combination with the unknown operating and environmental costs, COEX is a big gamble for little gain.

Although nuclear power will remain a significant source of electricity for the coming decades, spent fuel reprocessing should have no part in this future.

Reprocessing is not cost effective. In order for reprocessing to make sense economically, the price of a new MOX fuel rod must be competitive with the price of a new uranium fuel rod, which largely depends on the price of mined uranium. Several studies have concluded that the price of uranium would have to be in the range of $400–$700 per kilogram in order for reprocessed MOX to break even. But for the first half of 2009, the price of uranium oxide has hovered around $100 per kilogram. In fact, uranium prices have reached $300 per kilogram (in 2008 dollars) only twice in history—in the late 1970s during the energy crisis and briefly in the summer of 2007. In other words, uranium has never sustained a price that would make reprocessing profitable. And given the large estimated resources of uranium available at or below $130 per kilogram, it is unlikely that reprocessing will become cost competitive any time in the foreseeable future.

The high expense of reprocessing is rooted in the fact that chemically separating and processing spent nuclear fuel requires large, complex facilities that produce significant quantities of radioactive and chemical wastes. These facilities also must meet modern health and safety standards for dealing with highly toxic plutonium, which adds to the expense. In addition, these facilities produce weapons-usable plutonium and must be operated under military guard, which adds more costs to the process. At the same time, it is difficult to recoup all of these expenses when reprocessing yields so little usable product—only one MOX fuel rod is produced for every seven spent uranium fuel rods reprocessed. That means, for all of the investment and operating costs, reprocessing boosts the usable energy extracted from mined uranium only about 14 percent.

Reprocessing harms the environment. The reprocessing plants at Sellafield in Britain and La Hague in France are two of the largest anthropogenic emitters of radioactivity in the world. Both facilities intentionally discharge significant amounts of radioactive cesium, technetium, and iodine into the surrounding oceans, which show up in seafood harvested in the Irish and North seas. When it comes time to close a reprocessing plant, it requires decades to decontaminate facilities, soil, and groundwater. The United States currently spends billions of dollars each year to rehabilitate the reprocessing facilities at the Hanford site in Washington state and Britain will require similar resources to clean up Sellafield, making these among the most complicated and costly environmental cleanup projects in the world.

The final word. Contrary to the arguments given by its proponents, reprocessing is dangerous and unnecessary. Although nuclear power will remain a significant source of electricity for the coming decades, spent fuel reprocessing should have no part in this future. It is in the best interests of the United States—from the perspective of waste management, national security, economics, and environmental protection—to maintain its de facto moratorium on reprocessing and encourage other countries to follow suit. ■

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Kate J. Dennis, Christopher D. Holmes, Kurt Z. House, Jacob J. Krich, Benjamin G. Lee, Lee T. Murray, Ernst A. van Nierop, Justin Parrella, David M. Romps, Jason Rugolo & Mark T. Winkler, "Should the United States resume reprocessing? A pro and con," *The Bulletin of the Atomic Scientists*, November/December 2009, vol. 65, no. 6, pp. 30–41.

DOI: 10.2968/065006003