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THE MYTHOLOGY AND MESSY REALITY OF NUCLEAR FUEL REPROCESSING

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Arjun Makhijani
April 2010

Findings and recommendations

You had uranium in the rocks, in principle an inexhaustible source of energy – enough to keep you going for hundreds of millions of years. I got very, very excited about that because here was an embodiment of a way to save mankind. I guess I acquired a little bit of the same spirit as the Ayatollah [Khomeini] has at the moment.

Alvin Weinberg, first director of Oak Ridge National Laboratory, 1981¹

The messianic pronouncements of the 1950s about nuclear power were, in large part, based on the notion of an “inexhaustible” energy source. This required the conversion of uranium-238, which constitutes about 99.3 percent of natural uranium and is not a nuclear reactor fuel, into plutonium in special reactors called “breeder reactors”; it also needed facilities to separate that plutonium from highly radioactive waste and unused uranium (called “reprocessing”). In 1954 the Chairman of the Atomic Energy Commission, Lewis Strauss, proposed that nuclear energy would one day be “too cheap to meter.”²

In recent years, a French fever has gripped the promoters of nuclear power in the United States. Praise of its management of spent fuel by reprocessing, including its use of the extracted plutonium as fuel in its nuclear power reactors, is routine. For instance, Bill Magwood, who was appointed to the Nuclear Regulatory Commission by President Obama, wrote an open “memorandum” to him in mid-January 2009, with Mark Ribbing of the Progressive Policy Institute:

While looking to France for inspiration may or may not play well with domestic audiences, it is one of the first places to look for ideas on how to handle nuclear waste. Actually, the French...do not really think of it as waste....

...After a three-year cooling-down period, 96 percent or 97 percent of that material is potentially reusable uranium or plutonium; only the remaining 3 percent or 4 percent is genuinely useless “waste.”

France “reprocesses” that leftover uranium and plutonium into useable energy....³

Commissioner Magwood and Mark Ribbing acknowledge proliferation problems with the existing French approach but believe they will be overcome by new technology; in addition, new ways would be found to “to break waste down into stable, non-radioactive materials using ‘fast reactors.’”⁴

This has become a new mantra of nuclear waste management. Spent fuel is a treasure-trove of energy. This report shows that for existing spent fuel – the main waste problem facing the United States – the slogan belongs in the same realm of economic claims for nuclear energy that would be “too cheap to meter.”

¹ As quoted in Ford 1982 p. 25.

² For a history of early assessments and pronouncements about nuclear energy, including the quote and context of “too cheap to meter” see Makhijani and Saleska 1999.

³ Magwood and Ribbing 2009

⁴ Magwood and Ribbing 2009. “Fast reactors” refers to reactors that sustain the chain reactor with “fast” (high energy) neutrons.

Findings

1. *The reasons developing reprocessing for commercial nuclear power have been proved to be wrong.* In the early years of nuclear technology it was thought that:
 - Uranium would be scarce and expensive,
 - Sodium-cooled breeders could be developed with reasonable speed and cost.
 - The proliferation problems related to reprocessing could be overcome.
 - Costs of breeder reactors plus reprocessing would be modest.

None of these assumptions have been borne out. Neither breeder reactors nor reprocessing are commercial despite worldwide expenditures on the order of \$200 billion so far.

2. *Reprocessing as done in France does not solve the waste problem.* When high-level waste and Greater than Class C waste are considered together, the volume of waste to be disposed of in a repository is greater by about six times compared to the no-reprocessing approach that is current U.S. policy on a life-cycle basis. Low-level waste and waste shipments are also increased several fold by reprocessing. These are Department of Energy estimates comparing present U.S. once-through policy with the French “recycling” system using thermal reactors.
3. *Reprocessing involves a great deal of additional cost compared to once-through fuel uranium use.* France spends about two cents per kilowatt-hour more for electricity generated from reprocessed plutonium compared to that generated from fresh uranium fuel.
4. *Storage of liquid high-level wastes arising from present-day reprocessing technology creates a risk of catastrophic releases of radioactivity.* For instance, the Norwegian Radiation Protection Authority has estimated that a severe accident at the liquid waste storage facility in Sellafield, Britain, could result in cesium-137 contamination between 10 percent and 5,000 percent of that created in Norway by the 1986 Chernobyl nuclear reactor accident, which is the worst commercial accident to date, by far. A catastrophic release of radioactivity from a military high-level waste tank occurred in the Soviet Union in 1957.
5. *France needs a geologic repository and opposition to one has been intense there.* The French appear to dislike nuclear waste in their backyards as much as people in the United States.
6. *Using more than one percent of the uranium resource in a light water reactor system is technically impossible even with reprocessing and re-enrichment.* In light water reactor systems, almost all the uranium resource winds up as depleted uranium or in spent fuel. Even with repeated reprocessing and re-enrichment, use of the natural uranium resource cannot be increased to more than one percent in such a system. A corollary is that the use of 90 to 95 percent of the uranium resource in the spent fuel is impossible in a light water

reactor system even with reprocessing. These are technical constraints that go with the system and also apply to France's system.

7. *There has been essentially no learning curve for the sodium-cooled fast breeder reactor.* In fact, the two most recent large scale demonstration reactors, Superphénix in France and Monju in Japan, have been economic failures. Yet, to make significant use of the uranium resource, breeder reactors are required. They are not commercial today despite global expenditures on the order of \$100 billion over six decades. They are unlikely to be commercial in the near future. For instance, Japan's estimated date for commercialization of the sodium-cooled fast breeder is 2050.
8. *Proliferation risks are part of any reprocessing approach, including advanced ones like electrometallurgical processing, which is slated to be considered by the Blue Ribbon Commission.* While electrometallurgical processing reduces some proliferation risks relative to separation of pure plutonium, it also increases them in other ways. For instance, it is less difficult to conceal such a plant than with the present PUREX technology. A study by authors from a number of DOE laboratories, expressing their own conclusions, found that “only a modest improvement in reducing proliferation risk over existing PUREX technologies and these modest improvements apply primarily for non-state actors.”⁵
9. *To propose, as some have done, that most of the uranium resource value in existing spent fuel could be used is in the realm of economic mythology, like the “too cheap to meter” slogan of the 1950s.* Reprocessing plus breeder reactors are much more expensive than light water reactors today, which in turn cost more than wind-generated electricity. To use most of the uranium resource, breeder reactors would have to move to the center of U.S. electricity generation. It cannot be done using light water reactors. Even a single penny in excess generation cost per kilowatt-hour in a breeder reactor-reprocessing system would lead to an added \$8 trillion in costs if essentially all the uranium, including the uranium-238, and the plutonium in the 100,000 metric tons of spent fuel that existing U.S. reactors have generated or will generate during their licensed lifetimes is to be used as fuel. At present, the economic hurdle is far greater than a penny per kWh. Further, it would take hundreds of years to accomplish the task, involving the separation of tens of thousands of nuclear bombs worth of fissile material every year. The inspection, verification, and materials accounting problems of the adoption of the approach globally would present problems that are far greater than any concerns to date, which have been significant. It will also require storage of a significant part of the spent fuel for very long periods – likely in the hundreds of years. On-site storage is the most secure management option available today. But extending on-site storage to hundreds of years will create its own economic and security concerns. This is the principal reason that direct deep geologic disposal of spent fuel should be developed.
10. *No reprocessing program can obviate the need for a deep geologic repository.* Even complete fissioning of all actinides – an unrealistic proposition – will leave behind large amounts of very long-lived fission and activation products like iodine-129, cesium-135,

⁵ Bari et al. 2009

and chlorine-36 that will pose risks far into the future much beyond the 24,100-year half-life of plutonium-239.

Recommendations

Our main recommendations for the Blue Ribbon Commission on America's Nuclear Future appointed by Energy Secretary Steven Chu are as follows:

1. Spent fuel from existing reactors should be slated for direct deep geologic disposal without reprocessing of any kind; a suitable path for a scientifically sound program should be set forth.
2. In the interim, spent fuel should be stored on site as safely as possible – in low density configurations while in pools and in hardened storage when moved to dry casks.

Our other recommendations for the Commission are:

1. Breeder reactors and reprocessing are not commercial after six decades of development of sodium-cooled breeder reactors, and enormous expenditures. Given the long time frame for commercialization estimated even by some promoters, the proliferation risks, and the efforts already made, it does not appear to be a good investment to spend more R&D money in that direction. Rather energy supply R&D resources should be focused on development and deployment of renewable energy technologies and energy efficiency.
2. The Commission should request the French company AREVA and/or the French government to supply it with data on the present use of the natural uranium resource purchased for French nuclear reactors, including, specifically, the increases in fission fraction that have actually been achieved by reprocessing and recycle.
3. The Commission should also request official data on Greater than Class C waste equivalent expected to be generated on a life-cycle basis in France, and the total volumes and heat generation of packaged waste expected to be disposed of in a deep geologic repository, including estimates of decommissioning waste and direct disposal of MOX spent fuel.
4. The Commission should make the same requests regarding the British reprocessing program.
5. The Commission should investigate the public support or lack thereof for repository programs in France and Britain, the countries with the longest and most extensive history of commercial spent fuel reprocessing.
6. Official analyses of the mechanisms, probability, and consequences of large accidental releases of radioactivity to the atmosphere from liquid high-level waste storage in tanks should be requested from the French and British governments.

Official data from Britain and France would enable the Commission to do its own analysis of issues related to reprocessing spent fuel from burner reactors and help put the public discussion in the United States on a sounder scientific footing.

A. Introduction

Reprocessing is a technology for separating fissile materials – materials that can sustain a chain reaction⁶ – from a more complex mixture created in a nuclear reactor so that they can be used either in nuclear weapons or in nuclear power reactors. It was initially developed during the World War II Manhattan Project for obtaining the plutonium-239 to make the bomb that was used on Nagasaki on August 9, 1945. This report deals with proposals to use reprocessing as a technology to manage nuclear spent fuel from commercial nuclear power reactors and potentially also to use some of the recovered materials, including plutonium-239, as fuel.

There is only one naturally-occurring fissile material – uranium-235.⁷ It is only about 0.7 percent of natural uranium by weight, which also contains two other uranium isotopes: uranium-238 (just under 99.3 percent) and a trace of uranium-234 (about fifty parts per million). Neither uranium-234 nor uranium-238 is fissile. So, in effect, only about 0.7 percent of natural uranium consists of a material that can sustain a chain reaction and be used as a fuel in nuclear reactors.

However, it is possible to make new fissile materials by transmutation in nuclear reactors. Specifically, uranium-238, when irradiated with neutrons, transmutes into plutonium-239,⁸ which is fissile. Since neutrons are emitted in the course of a chain reaction in a reactor (and in fact are needed to keep the chain reaction going), the conditions exist in a nuclear reactor for creating new fissile materials. Hence a reactor can create *new fissile material for bombs or for reactor fuel from a non-fuel radionuclide like uranium-238, at the same time as* the reactor is consuming nuclear fissile material and producing nuclear energy. Reactors that use more fissile material than they create are called “burner reactors,” while those that make more fissile material than they use are called “breeder reactors.” The possibility for “breeding” more fuel than was consumed in the course of energy generation engendered a passionate hope among many nuclear engineers and physicists of an energy source that would last essentially forever, given the abundance of uranium-238 compared to uranium-235. Because of this potential, Alvin Weinberg, the first director of Oak Ridge National Laboratory, called it a “magical” energy source.⁹ Materials that are not fissile but can be made into fissile materials by irradiation with neutrons are called “fertile” materials. The main fertile materials that occur in nature are uranium-238 and thorium-232.¹⁰

⁶ Technically, a fissile material sustains a chain reaction with very-low or zero energy neutrons. A chain reaction occurs when a fission of a nucleus of an atom produces sufficient neutrons to trigger another fission and so on in a self-sustaining manner.

⁷ There are extremely small quantities of transuranic fissile materials created in nature (due to spontaneous fission of uranium-238 in one out of two million disintegrations). However, the concentrations and quantities are so tiny that they are of no practical interest for nuclear energy for power or weapons.

⁸ The nuclear reactions for the transmutation are as follows:

uranium-238 + neutron \rightarrow uranium-239 \rightarrow neptunium-239 + electron \rightarrow plutonium-239 + electron.

For historical reasons, electrons emitted from the nucleus are called “beta particles.”

⁹ Weinberg 1972 p.33

¹⁰ The fissile material created from thorium-232 in a nuclear reactor would be uranium-233 thus:
thorium-232 + neutron \rightarrow thorium-233 \rightarrow protactinium-233 + electron \rightarrow uranium-233 + electron. Thorium fuel cycles are briefly considered in this report, which is mainly about reprocessing existing commercial spent fuel. Electrons emitted in the process of nuclear transformations are called “beta particles.”

Commercial power reactors today do make plutonium from uranium-238 but they produce much less fuel that they consume. In other words, the breeding ratio – fuel created to fuel used – is less than one. In a breeder reactor, the breeding ratio would be more than one.

Reprocessing is needed in this scheme to separate the plutonium created in nuclear reactors from the remaining uranium isotopes, fission products, which are the radioactive fragments created in the process of liberating energy from the splitting of the nuclei of uranium-235 (or plutonium-239), and traces of other radionuclides, including other heavy radionuclides also created in the process of reactor operation. Chemical separation is at the center of current reprocessing technology. In the most common process, for instance the one used at Savannah River Site, called the PUREX process (for Plutonium URanium EXtraction), nitric acid is used to dissolve the mixture of radionuclides in the spent fuel. Solvents are then used in successive separation steps, first to separate fission products and some other trace radionuclides from uranium and plutonium and then uranium and plutonium from each other. Trace radionuclides are also generally separated from the uranium and plutonium streams. A schematic of this process is shown in Figure 1.

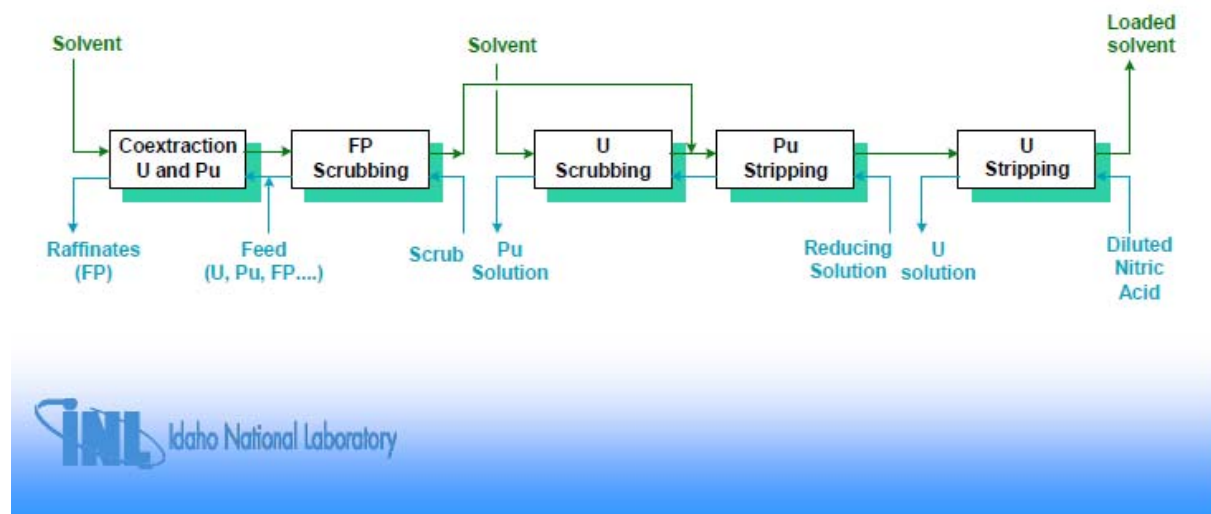


Figure 1: Schematic of the main separations process of PUREX reprocessing technology

Source: Todd 2009 Slide 22

Note: FP = fission products; U = uranium; Pu = plutonium.

1. Initial rationale for reprocessing and breeder reactors

In the context of nuclear power, reprocessing and breeder reactors first found great favor among physicists and nuclear engineers because uranium was thought to be a very scarce resource, with most of it being unusable as a fuel directly. The combination of these two technologies would, greatly increase the utilization of the uranium resource by converting non-fuel uranium-238 into plutonium-239. The favored reactor to do this is a “sodium-cooled fast breeder reactor,” so called because it uses fast (energetic) neutrons to sustain the chain reaction and liquid sodium for cooling the reactor and carrying away the heat created by nuclear fission. The reason for favoring this type of reactor was its high theoretical breeding ratio, which, in principle, would

allow a relatively rapid increase in the amount of new fuel, and hence be an efficient breeder reactor design.

There was nothing wrong with the physics underlying the rationale for breeder reactors. But the success of the scheme depended on key technical, economic, and security assumptions, which have been proved wrong, as has been pointed out in a February 2010 report by the International Panel on Fissile Materials which surveyed breeder reactors programs country-by-country:

The rationale for pursuing breeder reactors — sometimes explicit and sometimes implicit — was based on the following key assumptions:

1. Uranium is scarce and high-grade deposits would quickly become depleted if fission power were deployed on a large scale;
2. Breeder reactors would quickly become economically competitive with the light-water reactors that dominate nuclear power today;
3. Breeder reactors could be as safe and reliable as light-water reactors; and,
4. The proliferation risks posed by breeders and their “closed” fuel cycle, in which plutonium would be recycled, could be managed.

Each of these assumptions has proven to be wrong.¹¹

An earlier study by IEER also arrived at essentially the same conclusions.¹² Overall, uranium remained cheap despite speculative ups and downs along the way; reprocessing turned out to be expensive relative to making reactor fuel from freshly mined uranium; sodium-cooled breeders proved too difficult to commercialize; and proliferation problems associated with non-military reprocessing became a central concern after the Indian nuclear test in 1974. The Indian nuclear test was the main motivation that led the United States to forgo commercial reprocessing in the mid-1970s. By that time, reprocessing was also not as commercially promising as it had been in the 1950s. Further, the West Valley reprocessing plant near Buffalo, New York, operated only for six years before it was permanently shut down in 1972.¹³ We will explore these issues in more detail in this report.

It is worth noting at the outset that reprocessing and breeder reactors were *not* proposed as a solution to the problem of nuclear waste, which has so far turned out to be intractable for a host of technical, environmental, and political reasons. Reprocessing was also not proposed as an essential accompaniment to burner reactors, like the light water reactors, to increase the use of the uranium resource because its value in that regard is marginal, as we will see.

It is only recently, with the failure of the Yucca Mountain program to provide a timely repository – or indeed, any repository at all, it now appears¹⁴ – that reprocessing is now being promoted as a

¹¹ IPFM 2010 p. 5

¹² For an analysis of the failure of the breeder-reactor-reprocessing dream to develop an essentially inexhaustible energy source, see Makhijani 2001.

¹³ It became a multi-billion dollar waste management and remediation nightmare for the State of New York and the federal government. After nearly four decades, remediation is far from complete.

¹⁴ The Obama Administration has asked Congress to cut off funds for further site characterization on the grounds that the site is unsuitable. (Vogel 2009). The Obama Administration has also decided to withdraw the license

“solution” to the problem of mounting quantities of spent fuel at more than five dozen commercial nuclear reactor sites in the United States. In this context, it is often called “recycling.” It is now explicitly being promoted as a means for greatly increasing the use of the uranium resource contained in the spent fuel. This line of argument was presented succinctly in an op-ed by William H. Miller, a professor of nuclear engineering with the University of Missouri’s Nuclear Science and Engineering Institute, promoting reprocessing as a solution for the nuclear spent fuel (“used fuel”) problem is typical:¹⁵

1. “[U]sed nuclear fuel contain[s] large quantities of valuable nuclear materials that can be recycled for further use in producing electricity...
2. “[S]queezing more energy out of used fuel would be good for the nation’s economy and environment.”
3. Over 95 percent of spent fuel (or used fuel or irradiated fuel) can be “recycled” for recovering the energy in it.
4. The balance of the waste, “less than 5 percent” of the total, would “decay away in a few centuries.”
5. Reprocessing would make use of the uranium and plutonium resources in the spent fuel to reduce greenhouse gas emissions.
6. “[R]ecycling is a proven technology because at least a dozen other countries with nuclear power programs pursue it. France, in particular, has made efficient use of recycling and produces 80 percent of its electricity from nuclear power.”
7. Proliferation is not an issue:
“President Jimmy Carter banned the use of nuclear recycling on the grounds it could lead to the proliferation of nuclear weapons.
It doesn’t, and other countries know better. France and Great Britain recycle used fuel, and no plutonium has ever been diverted from French or British recycling facilities for weapons production.”

Taken together, these propositions about reprocessing imply that France has found an economical and technical solution to all but about five percent of the waste problem by “recycling” 95 percent of spent fuel (see the quote in point number 6 above and point number 3 together). Professor Miller also implies that a nuclear waste repository may not be needed at all, since the remaining waste would “decay away in a few centuries” (point 4 above). This means that it could be stored and guarded until it becomes harmless, since we know of human institutions that have lasted more than a few hundred years. A further implication is that the United States is somehow stuck in a Jimmy-Carter time warp and failed to notice the great progress that the French and British have made in “recycling” used nuclear fuel since his presidency.

Others have expressed similar opinions, including Bill Magwood,¹⁶ who headed the civilian nuclear energy development program in the Department of Energy for seven years and has been

application for Yucca Mountain “with prejudice,” which means that it “does not intend ever to refile” the application. (DOE 2010)

¹⁵ Miller 2009 p. D3. List numbers supplied by IEER.

¹⁶ Magwood and Ribbing 2009. A part of the article states: “Let’s say you were to put a batch of nuclear fuel into a reactor. After a three-year cooling-down period, 96 percent or 97 percent of that material is potentially reusable

appointed a Commissioner of the Nuclear Regulatory Commission.¹⁷ However, it should be noted that Commissioner Magwood was more careful than Professor Miller about proliferation issues related to PUREX reprocessing, which is the technology used in France.

As we shall see, conclusions such as those put forth by Professor Miller, while typical, do not hold up to the facts. The French have not solved the waste problem. Indeed, reprocessing has not and cannot solve the problem of nuclear waste in the sense implied above – that all but a few percent of the used fuel can be “recycled” efficiently and the remaining problem could be solved by storage for a few hundred years. Nor have the proliferation, cost, and technology problems associated with the so-called “recycling” been solved. Finally, converting most or all of the uranium-238 into fuel for new reactors will create large amounts of radioactive waste and likely involve huge additional expenses (Section G).

We begin with some background on the French reprocessing because, as noted above, it is a common point of reference in the present discussion in the United States about reprocessing. France has made more extensive use of reprocessing than any other country. It has supplied reprocessing services to other countries. It has had highly favorable conditions for deployment of reprocessing technologies because the two corporations that own the reprocessing plant and use the resulting plutonium fuel were 100 percent government-owned during the main period of deployment and are still about 85 percent French government-owned.¹⁸

B. Reprocessing and resource utilization in France

Reprocessing in France is continuing mainly due to the inertia of primarily-government-owned electricity generation and reprocessing corporations (EDF and AREVA respectively) and the political and economic dislocations that closing an established large industrial operation would cause in a largely rural area in Normandy that has scarcely any other industries. After it was clear that the breeder reactor program was not going to fulfill its theoretical promise any time soon, the decision to continue reprocessing in France was not about economics, technical suitability, waste management, or significantly increasing the use of the uranium resource in the fresh fuel.¹⁹ It was driven mainly by the inertia of a system that was government-owned and had already invested a great deal of money and institutional prestige in the technology.

uranium or plutonium; only the remaining 3 percent or 4 percent is genuinely useless "waste."” The article expresses some reservations about PUREX technology in regard to proliferation. Secretary of Energy Chu has expressed reservations about the French approach to reprocessing because of its proliferation implications and has advocated research on a more proliferation resistant approach. (Chu 2009 pp. 12-13) See below for further discussion.

¹⁷ NRC 2010

¹⁸ EDF 2009. The two corporations are AREVA and Electricité de France (EDF).

¹⁹ All calculations are based on four percent enriched fresh fuel made from natural uranium as the starting point, unless otherwise specified. The results would be similar with any starting enrichment for light water reactors, which are designed to use low enriched fuel (generally less than five percent U-235). Much of the description that follows is based on Makhijani 2001 and Makhijani and Makhijani 2006, unless otherwise mentioned. References may be

1. Light water reactors²⁰ and reprocessing

Uranium-238 is almost 99.3 percent of the natural uranium resource. It requires about 7.44 kilograms of natural uranium to produce one kilogram of 4 percent enriched uranium fuel, assuming 0.2 percent U-235 in the tails (depleted uranium).²¹ This means that about 86.6 percent of the natural uranium resource winds up as depleted uranium. Even if the efficiency of enrichment improved so that only 0.1 percent of U-235 remained in the tails, it would still mean that about 84 percent of the natural uranium resource would wind up as depleted uranium when it is first enriched.²²

It should also be noted that the vast majority of the uranium in the fresh fuel is still non-fissile U-238. In the case of 4 percent enriched uranium, made from natural uranium, the other 96 percent is uranium-238.²³ A small fraction (about two percent) of this gets converted into plutonium.²⁴ Some of this is fissioned in the course of reactor operation and therefore provides a portion of the energy output of the reactor. But the vast majority of uranium-238 will remain unused in burner reactors – that is, the type of reactors in use today. Table 1 shows a typical composition of 4 percent enriched fresh fuel made from natural uranium and spent fuel after it has been used to generate energy.

found in those publications. The ones associated with specific tables, quotes, and new material are provided in this report.

²⁰ Light water reactors are a specific example of “burner” reactors, which have a net consumption of fissile materials in the course of energy production from fission. Some new fissile material is created, mainly plutonium-239, but the amount of fissile material used (or burned), mainly a combination of uranium-235 and plutonium-239, is greater than the amount of fissile material residing in the irradiated material at the end of the reactor operation period. This discussion is focused on light water reactors (LWRs), and specifically on pressurized water reactors (PWRs), the design used in France. The arguments are essentially the same for boiling water reactors (BWRs). The U.S. commercial nuclear power reactor system consists entirely of PWRs and BWRs. Unless otherwise stated, the examples and figures used in this report are typical of pressurized water reactors. The exact assumptions, such as the enrichment level of the fresh fuel, make no difference to the overall conclusion about the efficiency of resource use in a light-water-reactor system with reprocessing and re-enrichment.

²¹ We use 4 percent enrichment as a typical figure. Actual enrichments in pressurized water reactors may range from 3 percent to above 4 percent. During enrichment, natural uranium is separated into two streams – the enriched stream, which is then chemically further processed to make reactor fuel, and the depleted stream, which is also called the “tails.” These tails, which consist of depleted uranium, have been accumulating at enrichment plants in the United States and elsewhere. We assume a U-235 content of about 0.2 percent in the tails (i.e., in the depleted uranium). In practice, the U-235 in the tails varies and a typical range generally considered is 0.2 to 0.3 percent. The amount of natural uranium needed to produce a kilogram of fuel will vary according to the enrichment of the fuel used and the percent of U-235 in the tails. The lower the percent of U-235 in the tails, the less natural uranium is needed for a given level of enrichment. Hence the example discussed here is a favorable practical case for maximizing resource use in a light water reactor system.

²² For simplicity, we ignore losses of uranium during milling and the series of processing steps prior to enrichment. These are small compared to the amount of depleted uranium.

²³ The fraction of U-238 is a little lower in fuel made from reprocessed and re-enriched uranium due to the buildup of other uranium isotopes, notably U-236.

²⁴ The main isotope (over 50 percent) in the separated plutonium is Pu-239, but there are also substantial amounts of higher isotopes, including Pu-240 and Pu-241. The mixture is known as reactor-grade plutonium. Pu-240 is not fissile. When used as part of MOX fuel in light water reactors some of it gets converted into Pu-241, which is fissile. Pu-240 can fission with fast neutrons and generate energy.

