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THE MYTHOLOGY AND MESSY REALITY OF NUCLEAR FUEL REPROCESSING

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Table of Contents

Acknowledgements.....	4
Findings and recommendations	5
A. Introduction.....	9
B. Reprocessing and resource utilization in France.....	13
C. Reprocessing and radioactive waste.....	18
D. Costs of reprocessing in France	22
E. Reprocessing and proliferation.....	23
F. Breeder reactors	32
G. Reprocessing and spent fuel stocks from existing U.S. reactors	37
H. References.....	42

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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 than 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.

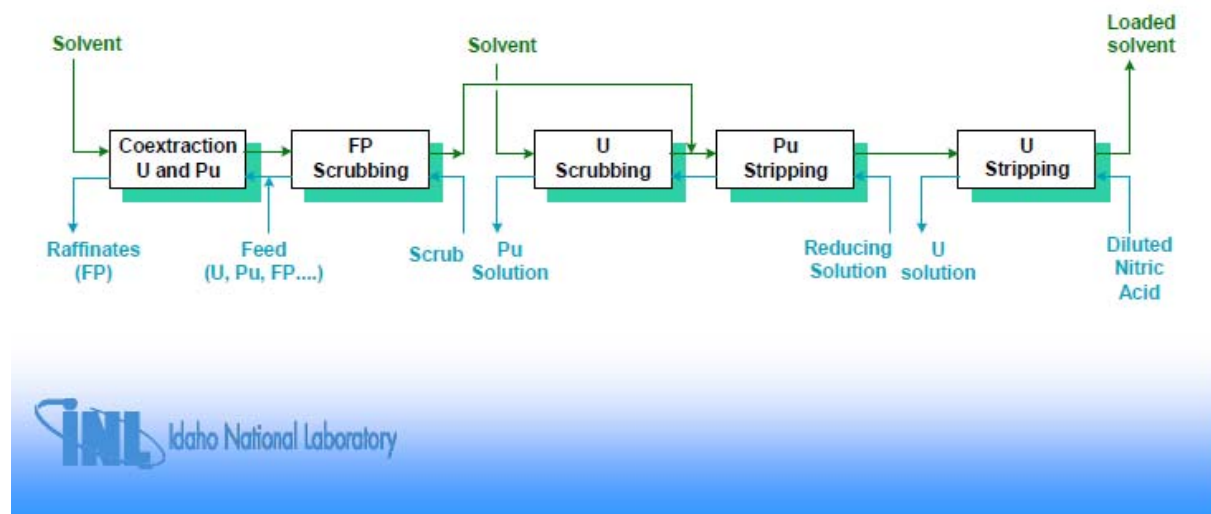


Figure 1: Schematic of the main separations process of PUREX reprocessing technology

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.

Table 1: Comparison of Isotopic Composition of Uranium in 4 Percent Enriched Fresh Fuel and in Spent Light Water Reactor Fuel, Burnup 45 MWd/kgHM, in percent

Uranium Isotope	Fresh Fuel	Spent Fuel
Trace U	~0.04	~0.02
U-235	4	0.68
U-236	0	0.52
U-238	96	93.05
Pu isotopes	0	0.99
FP	0	4.62
Non-Pu-TRU	0	0.095

Source: Spent fuel values are from IAEA-TECDOC-1535 2007, adapted from Table 27 (p. 74). The total of fission products is calculated as the 100 percent minus the sum of all the listed radionuclides. Fresh fuel values are from IAEA-TECDOC-1529 2007, Table 7.

Notes: 1. Burnup means the amount of heat energy (expressed here in terms of megawatt-days thermal (MWdth) per unit mass of fuel (expressed here in terms of kilograms of heavy metal, which in the case of fresh uranium fuel is simply the uranium content).

2. FP = fission products, non-Pu-TRU = transuranic radionuclides other than plutonium isotopes.

3. Trace U consists of U-234 for fresh fuel and mainly U-234 for spent fuel with much smaller amounts of U-232, U-233 and U-237.

Commercial reprocessing using the PUREX process, the only commercial technology at present, separates the spent fuel into three streams – (i) plutonium, (ii) uranium, and (iii) fission products, plus trace non-fission radionuclides, like neptunium.

France uses most, but not all (see below), of the separated plutonium as a mixed plutonium dioxide uranium dioxide fuel, called MOX fuel for short. It uses depleted uranium to make MOX fuel. However, of the 6.44 kilograms of depleted uranium created in the process of making fresh fuel from natural uranium, in the example we have been using, just over a tenth of a kilogram is used as a component of MOX fuel; most of that remains unused in spent MOX fuel.

France also uses a part of the uranium recovered from spent fuel as a fuel. But this uranium must be re-enriched to the requisite level. To get the same performance as fresh 4 percent fuel, the reprocessed uranium must be enriched to about 4.4 percent,²⁵ which means that about 87 percent of the recovered uranium becomes depleted uranium waste. Further, roughly 93 percent of this re-enriched fuel is also uranium-238. When this recovered and re-enriched uranium is used as fuel only a small amount of it is converted to plutonium, while most remains unused. If repeated reprocessing and re-enrichment are carried out, the pile of depleted uranium mounts rapidly, while the amount of fissile material dwindles. Further, it should be noted that the process of enriching reprocessed uranium also increases the concentration of uranium-236, which is not fissile; this reduces the usefulness of re-enriched uranium as a fuel.²⁶

²⁵ This is because of the degraded isotopic composition of the uranium. Approximate value read from the graph in IAEA-TECDOC-1529 2007 Figure 7 (p. 12).

²⁶ See, for instance, the caution of Electrabel/Synatom of Belgium in IAEA-TECDOC-1529 2007 Table 23 (p. 39). Note 2 contains a caution expressed by this company.

The flow of materials in a light water reactor scheme with reprocessing is shown in diagram in Figure 2. It corresponds to the example we have been using: an initial fuel loading of 1 kilogram of fresh (4 percent) low-enriched uranium fuel, 0.2 percent U-235 in the depleted uranium tails at the enrichment plant, and 8 percent plutonium in MOX fuel. We assume that all the recovered uranium is re-enriched.

Only one round of reprocessing and re-enrichment is shown in Figure 2. At the end of the use of the MOX fuel and re-enriched uranium fuel, only about 6 percent of the kilogram of original fresh fuel has been used to generate energy. In turn this is only about 0.8 percent of the 7.44 kilograms natural uranium resource used to make the single kilogram of 4 percent enriched uranium fuels.

Repeated reprocessing, MOX fuel use, and re-enriched reprocessing uranium fuel use does not improve the picture much. This is because most of the remaining spent fuel is left behind as depleted uranium in each round. In fact after five rounds, about 99 percent of the original uranium resource is depleted uranium. This means that the fraction of the uranium resource that can be used in a light water reactor-reprocessing-re-enrichment scheme is one percent or less. This can be raised slightly by reducing the amount of U-235 in the tails below 0.2 percent.

This is a conservative calculation, done as a simple illustration. It ignores the isotopic degradation of both the uranium and plutonium in the second and subsequent rounds of use in a reactor. Specifically, uranium-236 and uranium-234, which are not fissile isotopes and which degrade fuel performance, build up in the fuel as the reactor operates; uranium-236 increases in concentration with re-enrichment. Small amounts of uranium-232 also build up.²⁷ This isotope has a specific activity (defined as disintegrations per second per unit mass) that is 30 million times greater than natural uranium. Unlike fresh uranium fuel, it quickly generates decay products that emit strong gamma radiation, which creates higher worker radiation risks. Fuel quality requirements limit U-232 to a few parts per billion. As a result, re-enrichment becomes more complex and costly for each round of recycled uranium fuel use in a reactor. The fraction of uranium-236 and uranium-232 must be reduced by blending the enrichment feedstock with natural, un-reprocessed uranium or by blending the enriched uranium derived from reprocessed uranium with enriched uranium originating from fresh ore. Similarly, the isotopic composition of MOX fuel degrades with each round of MOX fuel use and reprocessing; this makes reprocessing even more expensive and the fuel less valuable.

As a result of the above considerations, technical and cost considerations limit the practical ability to reprocessing and re-enrich for more than one round past the first use of fresh fuel made from natural uranium.

We should also note that Figure 2 does not show the losses of the uranium resource at the uranium mill (where, typically, several percent of the uranium is discarded into tailing ponds along with almost all the radium-226 and thorium-230 in the ore) as well as in processing uranium into uranium hexafluoride form needed for enrichment are ignored here for simplicity.

²⁷ IAEA-TECDOC-1529 2007 p. 5. Uranium-233 and -237 are also formed in very small quantities and have very little radiological impact. Uranium-233 is a fissile material which gives a tiny added benefit to the reprocessed uranium. (IAEA-TECDOC-1529 2007 pp. 7-8)

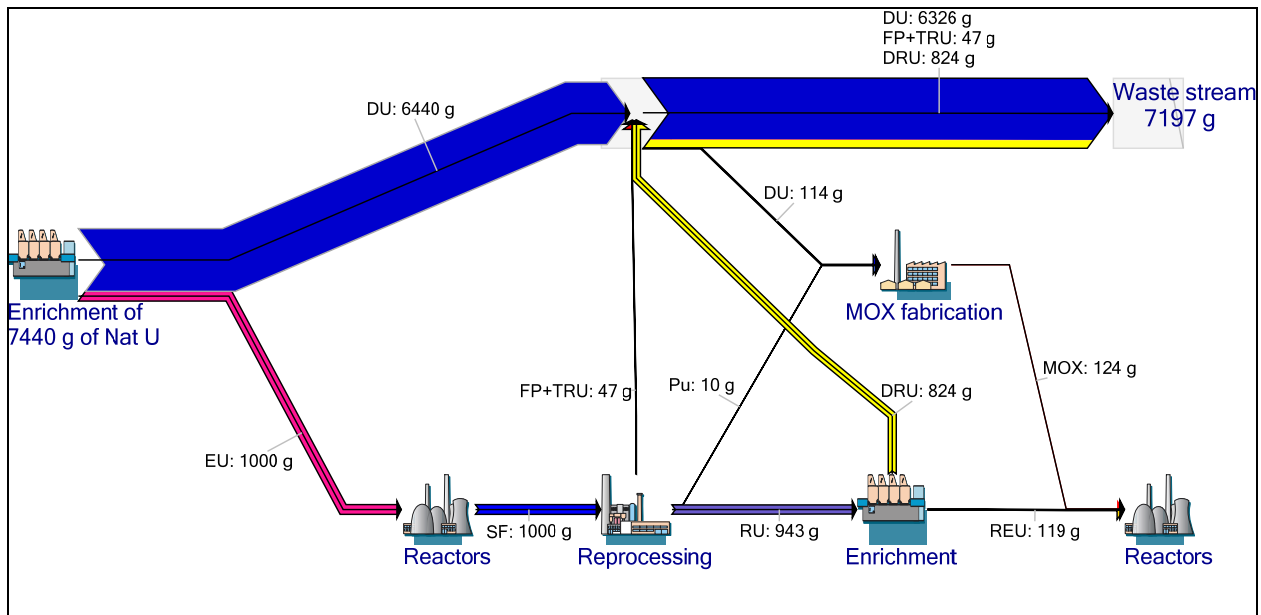


Figure 2: Fuel and Waste Streams in a Light Water Reactor System with Reprocessing and Re-Enrichment for One Kilogram of Fresh Fuel (4% Enriched)

Notes: 1. Nat U = natural uranium; DU = depleted uranium tails (0.2 percent U-235 assumed for this chart); EU = enriched uranium; Pu = plutonium from spent fuel; REU = re-enriched uranium; MOX = mixed plutonium dioxide uranium dioxide fuel; FP = fission products; SF = spent fuel; TRU = transuranic radionuclides other than plutonium isotopes; RU = uranium recovered from spent fuel; DRU = depleted recovered uranium. Pu value rounded up to nearest gram.

2. U-235 in the tails at the enrichment plant = 0.2 percent.

3. The amount of matter converted to energy (according to the famous $E = mc^2$) is very small (much less than one gram per kilogram of fuel) and is ignored in the above diagram.

Even when the initial depleted uranium is left out of the calculation (though it should not be, since it contains most of the natural uranium resource), reprocessing and repeated re-enrichment and MOX fuel use will utilize only about six percent (rounded) of the fuel originally loaded into the reactor, with about two-thirds of that occurring in the initial irradiation and most of the rest occurring in the first round of MOX fuel use. Repeated reprocessing, re-enrichment, and MOX fuel use just does not increase resource use significantly, because most of the uranium becomes part of the depleted uranium stream at each step. Finally, it should be noted that these numbers ignore uranium losses at the uranium mill and in the processing steps needed to make the uranium hexafluoride feed for the enrichment plant. The actual resource utilization based on the uranium content of the ore at the mill is, in practice significantly less than one percent. Fresh fuel plus one cycle of MOX use and re-enrichment uses only about 0.8 percent of the natural uranium resource. This is reduced to about 0.7 percent when the losses of uranium in the processing at the uranium mill and the conversion to uranium hexafluoride are taken into account.

France currently only re-uses a third of the recovered uranium. This means that France uses less than six percent the uranium resource in the original fresh fuel; about 80 percent of this is used in the first round of fresh fuel use prior to reprocessing. In other words, the expense, risk, and

pollution created by French reprocessing (see below) only marginally increases the use of the underlying uranium resource. Further, the re-enrichment is not done in France but in Russia. The depleted uranium from re-enrichment, amounting to roughly 87 percent of the reprocessed uranium by weight,²⁸ remains behind in Russia.²⁹

In sum, the French use only about 0.7 percent of the original uranium resource to create fission energy. The rest is mainly in depleted uranium at various locations, or is piling up as reprocessed uranium that is not being used, or is uranium left in spent fuel of various kinds (including MOX spent fuel). This figure cannot be increased significantly even with repeated reprocessing and re-enrichment so long as the fuel is used in a light water reactor system.

Statements that imply that the French have somehow figured out how to use 90 or 95 plus percent of the uranium resource, such as the one made by Professor Miller, quoted above, are incorrect. At best they are highly misleading because they assume a breeder reactor system (see below)..

C. Reprocessing and radioactive waste

Does reprocessing reduce radioactive wastes destined for a repository? Does it leave behind only relatively short-lived wastes that would decay away in a few hundred years, relieving the need for a deep geologic repository? What about the wastes issues created by reprocessing? We briefly take up these questions in this section.

The PUREX process is an aqueous process that uses large amounts of nitric acid and organic solvents to separate the plutonium, uranium, and fission products (plus minor actinides) into separate streams of material. The fission products contain the vast majority of the radioactivity at discharge from the reactor.³⁰ Reprocessing channels these into a liquid high-level waste stream. These liquid wastes are then mixed with molten glass and poured into metal canisters – a process called vitrification. The resulting high-level radioactive waste canisters are stored onsite. Neither France nor any other country has a deep geologic repository for high-level waste.

Almost all the heat generation in spent fuel, a major issue for repository disposal, is by the fission products in it. Whether the fission products are in spent fuel or mixed with molten glass makes almost no difference to the heat generation. Very long-term heat generation in the high-level waste (more than 1,000 years) is reduced somewhat, but the most important considerations having to do with repository space have to do with the initial heat load. That can be reduced by storing spent fuel or storing high-level vitrified waste above ground for many years before disposal in a repository.

²⁸ The exact percentage will depend on the composition of the recovered uranium and degree of enrichment. This assumes 4.4 percent enrichment, as discussed above.

²⁹ France DGEC 2009 pp. 2-3

³⁰ Murphy 1996 Figure 9 (p. 18)

A second consideration is that MOX spent fuel has even more long-lived transuranic isotopes than spent uranium fuel. This makes the long-term heat load from MOX spent fuel disposal significantly higher than uranium spent fuel. Reprocessing MOX spent fuel is a losing economic proposition. Even if it is done, the resulting wastes will be even more problematic.

A third consideration is that reprocessing, re-enrichment, and MOX fuel use do nothing to eliminate long-lived fission products. These are among the most troublesome for long-term water pollution that is likely to be associated with repositories. Iodine-129 (half-life 16 million years), cesium-135 (half-life 2.3 million years), and technetium-99 (half-life 213,000 years) are important long-lived fission products. There are also other problem radionuclides that are very long lived, like chlorine-36 and tin-126.

Some advanced, secondary reprocessing and reactor schemes have been proposed to deal with some long-lived transuranic radionuclides. This can be done in some cases; it is very difficult in others and technically infeasible in yet others. All of the proposed schemes add to the expense and technical problems associated with reprocessing without getting rid of the problem of long-lived radionuclides.³¹

Fourth, reprocessing generates waste highly contaminated with plutonium, known in the United States as “transuranic waste” or TRU waste for short, as well as other wastes known as Greater than Class C waste. All of this waste must also be disposed of in a repository, according to French regulations and are presumed to be destined for a deep geologic repository under U.S. regulations as well. TRU waste originating in the U.S. nuclear weapons program is being disposed of in a deep geologic repository in New Mexico. The Department of Energy has estimated that the combined cumulative volume of wastes destined for deep geologic disposal, including vitrified waste, is estimated to be about six times that of direct disposal of spent fuel, which is the current U.S. policy. Most of this volume consists of Greater than Class C waste,³² which can be packed more closely than either spent fuel or vitrified high-level waste. These estimates were made on a life-cycle basis for comparing the various approaches to nuclear energy generation.

There are short-term waste considerations with reprocessing as well. France stores the liquid acidic wastes containing almost all the fission products in stainless steel tanks at its La Hague reprocessing plant on the Normandy peninsula. These tanks must be cooled constantly; loss of cooling for a few days could result in a catastrophic accident. The tanks did lose cooling for a few hours in 1980, but fortunately cooling was restored and an accident was prevented.³³ More recently, in April 2009 and January 2010, the tanks at Sellafield, the site of the British reprocessing plant, suffered a loss of coolant water in several tanks.³⁴

³¹ A list of long-lived radionuclides and proposals to transmute them (or not) can be found in Makhijani and Zerriffi May 2000. A report examining the associated technologies and concerns in detail was published by IEER in 2000. See Zerriffi and Makhijani 2000.

³² DOE/EIS-0396 GNEP Draft Table 4.8-6 (p. 4-139)

³³ ACRO 2005

³⁴ For 2010: CORE 2010 and Irving 2010; for 2009: West Cumbria 2009 Section 2.2.4 and Irving 2009

A comparison of radioactive waste generated by a system of 200 nuclear light water reactors without and with reprocessing reactors over their operating lifetime as estimated by the DOE is shown in Table 2.

Table 2: Cumulative waste volumes for 200 GW Light Water Reactor (LWR) Systems, in m³

System	Spent fuel or High-level waste	GTCC waste	Total repository waste	Low-level waste	Annual radiological transports (rail plus truck)	Comments
LWR once-through	70,990	2,500	73,490	150,000 to 585,000	165,000	
LWR with reprocessing	52,000	407,000	459,000	1,740,000 to 2,175,000	1,224,000	~100 million liters of liquid radioactive waste reprocessing discharges per year (Note 2)
Ratio with/without reprocessing	0.73	163	6.2	3.7 to 11.6 (max to max and min to min)	7.4	

Source: DOE/EIS-0396 GNEP Draft Table 4.8-6 (p. 4-139)

Note: 1. Total volume to be disposed of in a repository calculated by adding spent fuel or high-level waste volume to GTCC volume. GTCC stands for Greater than Class C Waste.

2. For discussion of liquid discharges, see below.

3. Waste volume is calculated over a 50-year life-cycle.

We have used DOE estimates, since French estimates for reprocessing versus non-reprocessing systems are not readily available on a cumulative, life-cycle basis. Rather than reducing the waste problem, the French have increased the volume greatly. The heat load problem is likely to be a comparable problem if direct disposal of MOX fuel is included.³⁵ They will generate about six times the total volume of wastes to be disposed of in a repository. And the low-level waste and transport volumes are multiplied several fold.

France has faced intense opposition to its repository program and its experience has been quite similar to that in the United States. Starting with an ambitious program to characterize several sites in different geologic media, intense opposition was among the factors that reduced the program to characterizing a single site near Bure in northeastern France.³⁶ According to the calculations of ANDRA, the French nuclear waste agency, iodine-129 would be the main source of long-term dose in case of a failure of repository seals.³⁷

Reprocessing also generates large amounts of other radioactive waste. The La Hague plant discharges about 100 million liters of liquid wastes into the English Channel each year.³⁸ These

³⁵ French policy is not yet clear regarding the ultimate disposition of MOX spent fuel. At present it is being stored.

³⁶ France. Assemblée nationale 2006, Statement by Christian Bataille; Boilley 1998; and France Mission 2000

³⁷ Makhijani 2005 Slide 15

³⁸ AREVA 2009-06. The discharges of radionuclides other than tritium have declined but discharges of tritium, which dominate the radioactivity of the discharges, are about the same as a decade ago. (AREVA 2008)

discharges have contaminated the oceans all the way to the Arctic,³⁹ drawing protests from neighboring countries, which have asked France (and Britain) to stop reprocessing, and by implication, to stop the discharges.⁴⁰

Further, France does not reprocess all of its spent fuel. Currently, about 850 metric tons of the 1,200 metric tons that are discharged every year are reprocessed, leaving 350 metric tons as spent fuel. Hence, besides accumulating volumes of high-level and intermediate level waste, France had to also build spent fuel storage facilities at La Hague, which AREVA is now planning to expand. Starting in 2010 the 850 metric tons were to be increased to 1,050 metric tons per year covering all uranium spent fuel, according to a framework agreement between AREVA and EDF at the end of 2008 that would last until 2040.⁴¹ This would leave only MOX spent fuel unreprocessed, which amounts to about 150 metric tons per year.

In sum:

- France needs a deep geologic repository and it does not yet have one. Public opposition to the French repository program has been intense. For instance, research on a second repository in granite was stopped due to public opposition.
- Reprocessing has increased the volume of waste to be disposed of in a deep geologic repository (high-level waste plus Greater than Class C waste) in France, based on DOE lifecycle waste estimates. Low-level wastes and waste transports are also estimated to be greater.
- France discharges about 100 million of liters of liquid radioactive waste into the English Channel each year and has polluted the oceans all the way to the Arctic, drawing protests from neighboring governments who have asked France to stop reprocessing on this account.
- Reprocessing has created additional risks in the form of the need to store liquid high-level wastes, which need constant cooling, and of surplus separated plutonium.

Some additional comment on the last point is warranted. Loss of cooling to a liquid high-level waste storage system resulted in an explosion and a very large release of radioactivity in the Soviet Union in 1957.⁴² In 2009, the Norwegians prepared an estimate of the consequences for Norway of a release of 0.1 to 10 percent of the stored liquid waste at Sellafield, which is the British commercial (and in the past military) reprocessing site in northwestern England. It did not estimate the mechanisms or probability of such an accident. The potential for such an accident is recognized. One mechanism could be a prolonged (several-day) loss of cooling to the tanks.

³⁹ OSPAR 2000 p. 61

⁴⁰ OSPAR 2000 Decision. OSPAR, the Oslo-Paris accords group. Its decisions are binding on its members only if they affirm them. OSPAR decided by a large majority (11 of 15 members) on a non-reprocessing policy for managing spent fuel. But since France and Britain abstained, they are not obliged to implement the decision. Luxembourg, which was absent, later agreed with the OSPAR decision.

⁴¹ Dubillot 2008

⁴² IPPNW and IEER 1992

In addition to a range of source terms, the Norwegian Radiation Protection Authority also modeled releases under different meteorological conditions.

Norway received large amounts of ^{137}Cs fallout under the scenarios (an accidental release of between 0.1 – 10 % of the total HAL [Highly Active Liquors] inventory) of between 10 – 5000 kBq/m², especially along the west coast. Model simulations resulted in between 0.1 – 50 times the maximum ^{137}Cs fallout experienced in Norway after the Chernobyl accident. For the chosen weather situation, fallout started to occur over Norway only 9 hours after the hypothetical release.⁴³

The Authority only modeled a single radionuclide. The liquid radioactive wastes contain several long-lived radionuclides in significant amounts. Notably, strontium-90 is present in concentrations comparable to cesium-137.

D. Costs of reprocessing in France

Prior to the recent contract to increase reprocessing from 850 to 1,050 metric tons per year, France was spending about 800 million euros per year extra in fuel costs, compared to uranium fuel, for using MOX fuel.⁴⁴ This amounts to about 40 million euros per reactor per year using 30 percent MOX core. It is about two euro-cents per kWh for the electricity generated from this fuel. With the new contract to increase reprocessing, added costs on this basis will be about 1.2 billion euros. The exchange rate of the euro to the U.S. dollar has varied enormously since the introduction of the euro as a banking currency in 1999 and as a currency of everyday use in 2001, from just over 80 U.S. cents to the euro to about \$1.60 per euro. If we use the rate at which the euro was issued, 1.17 dollars per euro, the added costs come to about \$1.4 billion. At this exchange rate, the added cost of electricity generated from MOX fuel is about U.S. 2.3 cents per kWh, which is more than the present fuel and non-fuel operating cost of U.S. nuclear power reactors.⁴⁵ We have rounded this to a single significant figure of 2 cents per kWh in the rest of this report.

The added costs were recognized by *Électricité de France* (EDF) in 1989 at the start of the MOX fuel use, even though it did not see a justification for stopping the program on economic grounds. According to an EDF memo from the time:

In view of the commitments already made, and even though MOX is significantly less competitive than natural uranium, it appears that the reprocessing option must be maintained and that UP2 be indeed transformed into UP2 800. Challenging this option has no economic basis; it would also have great global repercussions that would be detrimental to the nuclear industry.⁴⁶

⁴³ Norwegian Radiation Protection Authority 2009 p. 5

⁴⁴ Makhijani 2001 footnote 26 and associated text. About the same added cost was estimated based on an official French report, Charpin, Dessus, and Pellat 2000 p. 56 of the pdf version (in Chapitre 1, section 3.4)

⁴⁵ NRC 2009-2010 Table 2 (p. 21) states the fuel and non-fuel operating and maintenance costs for 2007 to be \$20 per megawatt-hour, which equals 2 cents per kWh.

⁴⁶ EDF 1989 p. [7]. Translation by Annie Makhijani. The La Hague reprocessing plant UP2 was eventually upgraded and is now known as UP2-800. There is a second plant at La Hague, known as UP3

Reprocessing and MOX fuel use continues in France not because of a significantly better use of the natural uranium resource, economic advantage, or waste reduction benefits. Rather it continues despite the failure of France's breeder reactor program for which it was originally envisioned in 1974⁴⁷ because both companies involved in it are mainly government-owned and they have found it impossible to stop the program despite its many drawbacks.

1. A note on British reprocessing compared to France

It is important to note that, despite the poor economic, waste, and environmental outcome of French reprocessing (compared to once-through fuel use), France has, in the past two decades or so, done commercial reprocessing about as well as it can be done, operating plants at full capacity and ramping up MOX fuel use to 20 reactors, each of which uses MOX for 30 percent of its core.

By contrast, the corresponding British PUREX plant, called THORP (THERmal Oxide Reprocessing Plant), has been a case study in operating problems, leaks, shut-downs, and low capacity factors.⁴⁸ The plant is located at Sellafield, in northwestern England. Even as it incurs huge costs and environmental liabilities, Britain has been accumulating separated plutonium to an even greater extent than France. The surplus from the PUREX plant as well as another reprocessing plant stored at the site is in excess of 100 metric tons. A primary reason is that Britain has not used any MOX fuel in its commercial reactors; in fact, it has no practical way to use a significant amount of this plutonium in its reactors.⁴⁹ As with France, Britain's neighbors, including Ireland, have protested its radioactive discharges into the seas (the Irish Sea in this case).

E. Reprocessing and proliferation

1. PUREX process and proliferation

A simple fact should first be noted. Separated plutonium made in the course of commercial reactor operation can be used to make nuclear bombs. It has a different isotopic composition than weapon-grade plutonium and would not be the desired material for bomb making were weapon-grade material available. However, the different isotopic composition is not a bar to making weapons like the one that devastated Nagasaki on April 9, 1945.

The Department of Energy has noted the following about reactor-grade plutonium and bombs:

⁴⁷ EDF 1989 p. [1]

⁴⁸ It was commissioned in 1994 and is currently operating at partial capacity; it is slated to be shut in 2011. (World Nuclear News 2010)

⁴⁹ Further most of the separated plutonium is now so old, that it has built up a significant amount of americium-241 from the decay of plutonium-241. Such plutonium would have to be chemically processed again, involving even more expenditures, if it to be used as reactor fuel.

Designing and building an effective nuclear weapon using reactor-grade plutonium is less convenient than using weapon-grade plutonium, for several reasons....[B]ackground neutrons from Pu-240 can set off the reaction prematurely, and with reactor-grade plutonium the probability of such “pre-initiation” is large. Pre-initiation can substantially reduce the explosive yield, since the weapon may blow itself apart and thereby cut short the chain reaction that releases the energy. Nevertheless, even if pre-initiation occurs at the worst possible moment (when the material first becomes compressed enough to sustain a chain reaction), the explosive yield of even a relatively simple first-generation nuclear device would be of the order of one or a few kilotons. **While this yield is referred to as the “fizzle yield,” a 1-kiloton bomb would still have a radius of destruction roughly one-third that of the Hiroshima weapon, making it a potentially fearsome explosive. Regardless of how high the concentration of troublesome isotopes is, the yield would not be less.**⁵⁰

All countries that have commercial reprocessing at present – France, Britain, Russia, Japan, and India – have surplus stocks of separated plutonium, with the total amounting to about 250 metric tons, about the same as global military plutonium stocks. Britain and France have the largest stocks. France has about 80 metric tons of it at La Hague, enough to make 11,000 to 12,000 nuclear bombs;⁵¹ Britain has more than 100 metric tons at Sellafield, enough to make about 14,000 nuclear bombs.

While Professor Miller states that “no plutonium has ever been diverted from French or British recycling facilities for weapons production”⁵² a close examination shows that this statement is somewhat misleading as to the proliferation implications of reprocessing in these two countries. In fact, both started reprocessing to acquire plutonium for their weapon programs. Further, both France and Britain reprocess spent fuel for third countries, including Japan. While Japan has a stated policy of using separated plutonium as MOX fuel in its reactors (and, in fact, has its own reprocessing facilities as well), it has only recently used any MOX fuel in a commercial nuclear power reactor.⁵³

Japan’s stocks of commercial plutonium keep rising. At the end of 2008, Japan had 9.6 metric tons of separated plutonium either as pure plutonium or as unirradiated MOX fuel. A further 25.2 metric tons of fissile isotopes of plutonium (about 38 metric tons total plutonium) stored in other countries.⁵⁴ Japan owns enough separated plutonium at home and abroad to make more

⁵⁰ DOE 1997 p. 38. Emphasis added.

⁵¹ The amount of commercial plutonium needed to make a bomb is somewhat greater than if the isotopic composition corresponds to weapons-grade plutonium, which has about 93 or 94 percent plutonium-239. According to Kang and von Hippel 2005 it takes about a third more commercial grade plutonium to make a bomb compared to weapon-grade plutonium. Using a figure of 5 kilograms per bomb for weapon-grade plutonium, we get a figure of 6.3 kilograms per bomb for commercial grade plutonium. We use a value of 7 kilograms in this report as a conservatism. Data on stocks of commercial and military plutonium can be found at Albright and Kramer 2005 Table 2 (p. 6) and Table 3 (p. 7).

⁵² Miller 2009

⁵³ AREVA 2009-12. Britain, which has over 100 metric tons of separated plutonium in storage at Sellafield, has not used any MOX fuel in a commercial power reactor. In 1999, a British assessment declared that this plutonium had no economic value. (House of Lords 1999 pp. 63-66)

⁵⁴ IAEA 2009

than 5,000 nuclear bombs. While the matter does not get much publicity, there is an active debate in Japan whether it should develop nuclear weapons. The rise of China, the acquisition of nuclear weapons by North Korea, and the increasing strains in its alliance with the U.S. are all factors in this debate. In 2002, Ichiro Ozawa, the head of the Democratic Party of Japan until mid-2009,⁵⁵ which now rules Japan, made comments about the potential for Japan to make nuclear weapons from its commercial power assets. According to a newswire report from Reuters:⁵⁶

The leader of Japan's opposition Liberal Party, Ichiro Ozawa, said on Saturday it would be a simple matter for Japan to produce nuclear weapons and surpass the military might of China if its neighbour got "too inflated."

...

"It would be so easy for us to produce nuclear warheads. We have plutonium at nuclear power plants in Japan, enough to make several thousand such warheads," he said.

The argument about whether Japan should become a nuclear weapon state goes back at least to its consideration of the Nuclear Non-Proliferation Treaty. In 1968, a Japanese Foreign Ministry document indicated that it was a "cost-benefit" calculation as to whether Japan should rely on the United States nuclear arsenal or acquire its own. Japan has never made public the internal Foreign Ministry documents indicating that it abandoned the thinking in the 1968 document when it ratified the NPT despite public demands that it do so.⁵⁷

Given that North Korea is the first state to use a supposedly commercial reactor and associated reprocessing plant to make nuclear bombs, Professor Miller's attitude seems rather cavalier. In fact, Japan could quickly become a nuclear weapon state using its commercial separated plutonium. I discussed this with the late Herbert York, the first director of Lawrence Livermore National Laboratory, one of the two U.S. nuclear-weapon design laboratories, in 2001, in an on-the-record interview:⁵⁸

Makhijani: This wasn't a planned part of my interview, but since we are on the subject, what about if the designs of these complex weapons were available, how long would it take to recreate them?

Dr. York: If you shut everything down – eliminated the entire U.S. nuclear weapons infrastructure, but had the designs, one could recreate them in a short time, two or three years.

Makhijani: How about countries like Japan?

Dr. York: What do you think?

Makhijani: My speculation has been that Japan would take six months to become a nuclear weapons state.

⁵⁵ Wikipedia Liberal Party Japan 2009 and Wikipedia Democratic Party of Japan 2009. In 2002, Ozawa was still in the Liberal Party, which later merged with the Democratic Party of Japan.

⁵⁶ Reuters 2002

⁵⁷ Makhijani 1995

⁵⁸ York 2001

Dr. York: That's right. I say that too. They wouldn't have the very sophisticated weapons, but they could be a nuclear weapons state in six months. Almost any western European country and a few other countries could do that. Switzerland could do it [for example].

The central proliferation issue associated with reprocessing is that it results in separating a material that can be used to make bombs. Getting weapons-usable material is the main obstacle to making nuclear weapons. As regards potential proliferant states, most of the rest is mainly a matter of intentions, which as history shows in ample measure, can change.

2. Advanced reprocessing

Since the PUREX technology is a potential source of proliferation, despite sanguine statements made by some, a number of alternative reprocessing technologies and reactor schemes have been proposed. Ostensibly these would enhance the utility of reprocessing as a waste management tool and/or increase the utilization of uranium resources. As to waste management, it is generally recognized in serious technical discourse, if not always in public statements, that the PUREX process, which is the only commercial reprocessing technology at present, does not deal with minor actinides, notably americium-241 (half-life 432 years) and neptunium-237 (half-life 2.14 million years), which are created in significant amounts in reactors. The former is created as the decay product of plutonium-241 and the latter via successive neutron absorptions by uranium-235.⁵⁹

Alternative separation and transmutation technologies generally involve further separation of long-lived trace radionuclides by various chemical means and their repeated irradiation in nuclear reactors. None can eliminate long-lived radionuclides sufficiently to obviate the need for a deep geologic repository. Further, the amount of depleted uranium from commercial and military activities is now so large that it will be practically impossible to use it as a resource, given the technical, cost, and proliferation problems as well as the very long time frame and huge number of breeder reactors that would be needed. This depleted uranium has a high enough specific activity and other characteristics that it should be required to be disposed of in a deep geologic repository in a manner similar to military transuranic waste (TRU waste).⁶⁰

Sufficient quantities of long-lived wastes would remain with any reprocessing approach to require a repository, raising a question about whether these "transmutation" strategies, advertised as useful for turning long-lived into short-lived radionuclides, are waste management strategies or simply a device to get money for nuclear energy R&D.⁶¹ Consider, for instance the following

⁵⁹ Pu-239 + neutron → Pu-240 + neutron → Pu-241 → Am-241 + beta particle (electron); and U-235 + neutron → U-236 + neutron → U-237 → Np-237 + beta particle (electron)

⁶⁰ TRU waste from U.S. nuclear bomb production is being disposed of at the Waste Isolation Pilot Plant, a deep geologic repository in New Mexico. France has also designated such wastes for deep disposal, but does not have an operating repository as yet.

⁶¹ The transmutation issue is analyzed in detail in Zerriffi and Makhijani 2000.

statement by Paul Govaerts of the Belgian Nuclear Research Center, made at a transmutation conference in 1998.⁶²

Research on partitioning and transmutation is rather seductive to all of us. It requires new reprocessing techniques, new fuel developments, additional nuclear data, new reactors and irradiation facilities, new waste treatment and disposal concepts, and specific safety studies. The global nuclear scientific and engineering community is challenged by this opportunity.

...

Everybody realises however that this voyage to the promised land will pass a desert with a lot of mountains and that we are not so sure that the horizon will be as bright as one can hope.

We will only consider a single advanced reprocessing technology in this report, since it the one under consideration in the United States and since it has been promoted as “proliferation-resistant.” An analysis of various other techniques can be found in a report published by IEER in the year 2000.⁶³ We also provide an overview of the proliferation implications of advanced reprocessing technologies.

3. Electrometallurgical processing

In the United States, the alternative reprocessing and reactor scheme now favored as a waste management strategy by breeder-reactor advocates in the DOE laboratories centers on the Integral Fast Reactor (IFR). This is the familiar sodium-cooled fast breeder reactor married with a new reprocessing technology called pyroprocessing or electrometallurgical processing. This differs from the aqueous chemical process that is PUREX in that it involves electrolytic separation of the constituents of spent fuel. The term “integral” to describe the scheme refers to the location of the reprocessing plant at the same site as the reactor. The theory is that the separated fissile materials would not leave the site; hence the proliferation vulnerabilities associated with transportation of fissile material can be eliminated and accountability of the material can be increased, thereby making the technology more proliferation resistant relative to the PUREX technology. Further, unlike the PUREX process, electrometallurgical processing, when operated with an IFR, is designed so as to not separate pure plutonium. Rather, a mixture of actinides, with some fission products, is separated, making it more complex to make a nuclear weapon. In theory, this also increases proliferation resistance.

Proliferation concerns are associated with the PUREX process both because it separates pure plutonium for commercial purposes and because it puts mixed oxide fuel, from which it is not very difficult to separate out plutonium, on the roads. Further, fresh MOX fuel would have to be stored at commercial reactors; this would raise far more security concerns than low-enriched uranium, which is much more difficult to process into weapons usable material. In light of this, the following advantages are claimed for the reprocessing scheme associated with the IFR:⁶⁴

⁶² Govaerts 1998

⁶³ Zerriffi and Makhijani 2000

⁶⁴ Berkeley Nuclear no date. This is a description of the IFR system from the University of California, Department of Nuclear Engineering. Some of the specifics of reactor operation as well as two 1986 safety tests are from the

1. The reprocessing plant would be at the reactor site, making diversion of fissile material much more difficult.
2. “In the IFR, the nature of the fuel reprocessing is such that the fuel remains highly radioactive at all times.... In any event, IFR fuel is not suitable for weapons without extensive processing in very expensive facilities.”
3. A mixture of radionuclides is separated for use as a fuel, instead of only plutonium isotopes, as is the case with PUREX technology today. This would make the IFR proliferation-resistant.

In addition, Wymer et al. have pointed out that some radionuclides in the transuranic mix, like plutonium-238 and curium-242, have much higher specific activities than plutonium-239. The heat produced by the material would make it more difficult to make nuclear weapons and may make them unstable. However, a small aqueous separations “finishing” process could be added to separate the plutonium.⁶⁵

These non-proliferation merits must be seen on a relative basis. The act of separation of any material that can be used to make nuclear bombs greatly increases proliferation risks relative to once-through fuel use, in which spent fuel is stored for a time and then disposed of in a deep geologic repository. The above claims also have some technical substance, but they do not address the principal problems associated with the technology.

The mix of transuranic radionuclides separated using electrometallurgical processing can be used quite as effectively to make a nuclear weapon as the reactor-grade plutonium separated in today’s PUREX plants. Further, since neptunium-237 and americium-241, the principal non-plutonium radionuclides that would be in the separated mix of actinides, are both fissile materials, it requires just about a fourth more material to do so than with the pure plutonium that results for PUREX process separation. It takes about a third more reactor-grade plutonium to make a nuclear bomb than weapon-grade plutonium. The net result is that it would take less than 10 kilograms of electrometallurgical separated material to make a nuclear bomb. In both cases, the amount of material is considerably less than the amount of highly enriched uranium needed for a bomb. The difficulty of making nuclear bombs using a transuranic mix is generally comparable to using reactor-grade plutonium, which also contains troublesome isotopes that could cause “pre-initiation” of a nuclear weapon.⁶⁶ The material is more difficult to handle and the pit would have to be cooled to prevent excessive heating, but these problems can be overcome, for instance, by using a pre-cooled pit.⁶⁷

The actual process of making nuclear weapons can be rendered more complex if gamma-radiation-emitting fission products are in the separated fuel mix in sufficient amounts to make handling the material much more dangerous than pure reactor-grade plutonium. An inherent

operation of a pilot plant called “Experimental Breeder Reactor II” or “EBR II” at the Argonne National Laboratory – West in Idaho. The EBR II, shut down in 1994, was a 62.5 megawatt-thermal reactor. This is about 2 percent of the thermal rating of a typical commercial nuclear power plant.

⁶⁵ Wymer et al. 1992 pp. 52-54

⁶⁶ Kang and von Hippel 2005

⁶⁷ Kang and von Hippel 2005

limitation on this is that fission products interfere with the process of maintaining a chain reaction in the reactor. There only two radionuclides with high enough gamma radiation rates and long enough half-lives to make the work of using the electrometallurgical processing product much more difficult. They are:

- Cerium-144 (Ce-144); half-life 0.78 years
- Europium-154 (Eu-154); half-life 8.8 years

The other radionuclides in this group (Lanthanides) are either too short-lived (Praseodymium-144 (Pr-144)) or have radiation levels that are too weak to be effective (Samarium-147 (Sm-147)), Europium-155 (Eu-155), for instance).

Further, of the two suitable radionuclides, electrometallurgical processing separates out Eu-154 from the transuranics. This leaves only Ce-144 as an effective radiation barrier to potential fabricators of nuclear bombs. But given that the half-life of Ce-144 is only 0.78 years, the radiation level declines in a few years to levels that would not deter a determined non-state group or a state with no other fissile material.⁶⁸

Nuclear weapon states with established access to weapon-grade materials to use in nuclear bomb programs would be highly unlikely to resort either to reactor-grade plutonium from PUREX plants or to a transuranic mix from electrometallurgical processing. That is not the proliferation issue. Rather, it is the development and refinement of a technology that could provide nuclear-weapons-usable materials to states that do not now have them, and possibly also to non-state groups.

The PUREX process consists of a huge chemical factory using an aqueous process. Hence while it is cumbersome from an engineering standpoint, it has the proliferation advantage of being easily detectable. In contrast, electrometallurgical processing is much more compact. The heart of the system is the electrorefiner, which is can be as small as one meter (about 3.3 feet) in diameter.⁶⁹ This makes the electrometallurgical system much easier to hide than a PUREX process, much in the same way that gas centrifuges used for uranium enrichment are much easier to hide than the enormous gaseous diffusion plants that were first used for enriching large amounts of uranium. The Iranian example of building a large gas centrifuge plant secretly provides an example of what could happen in the plutonium arena once the size of reprocessing plants is greatly reduced.

While the U.S. proposals for the IFR have focused on the reactor and reprocessing being collocated, this is not an essential technical element of the approach. In fact, a centralized electrometallurgical installation is among the options that could be considered in the context of a plan to build many fast neutron reactors.⁷⁰ If a country or a non-state group decided to secretly build a small plant for weapons purposes, it could be done at locations that are not under safeguards. The main issue in such a case would be to procure spent fuel, which is the raw material for reprocessing systems. This is a non-trivial problem, but it should be noted that spent

⁶⁸ Kang and von Hippel 2005 pp. 174-176

⁶⁹ Chang 2007 p. 168

⁷⁰ Wymer et al. 1992

fuel is not safeguarded in the same way as separated plutonium. Indeed, spent fuel has been inadvertently lost from nuclear power reactor storage pools in the United States without being detected for many years. For instance, a bent fuel rod and a displaced fuel rod were put into a canister, which was stored in 1972 in the spent fuel pool of the Millstone 1 reactor in Connecticut. The canister could not be located in 1980. The matter came to light only when the reactor was put up for sale in 2000. The two fuel rods contained about 40 grams of plutonium. They may have been dumped into a low-level waste disposal facility or may have been in the pool at an unknown location;⁷¹ the NRC simply could not tell in 2001,⁷² 21 years after the plant operator first could not identify where the canister was in the spent fuel pool.

At present, electrometallurgical processing is not a fully developed commercial technology. It would be very difficult for proliferant states that do not now have reprocessing or uranium enrichment facilities or both to develop this technology fully. But once it is developed, it would be difficult to keep it under wraps. The know-how will spread. The lessons of gas centrifuges for enriching uranium, which were difficult to master, are also instructive. Today it is the technology that poses the most acute proliferation concerns in the commercial nuclear power system.

Other than not making the plutonium in the first place, keeping it in spent fuel, mixed with large amounts of uranium and highly radioactive fission products, including cesium-137, which is a strong gamma emitter, is by far the most proliferation-resistant approach to managing the proliferation issues arising from the back end of commercial nuclear power.

4. Overall assessment of proliferation potential of advanced reprocessing technologies

All reprocessing technologies that are under consideration as “proliferation resistant” (because they do not separate pure plutonium, among other possible features) are vulnerable to proliferation. In fact, for proliferant states that do not now have separated fissile materials, the additional barriers are not significant compared to separating plutonium from spent fuel. A review of advanced technologies and their proliferation potential was published by Brookhaven National Laboratory. Its authors, who were expressing their own views in the paper, were from several DOE laboratories, including weapons laboratories like Los Alamos National Laboratory and Sandia National Laboratory as well as the lead laboratory for nuclear power in the United States, the Idaho National Laboratory, and the laboratory that has had the lead in the development of the sodium-cooled reactor in the United States, Argonne National Laboratory.⁷³

The authors considered a number of criteria related to proliferation:

- The technical sophistication needed to handle the nuclear materials.
- Cost of the technology and time and staff required.

⁷¹ NRC 2001

⁷² Meserve 2001

⁷³ Bari et al. 2009. We note here that the paper is not oriented to a recommendation of direct disposal of spent fuel instead of reprocessing. It is directed rather towards safeguards issues in the event a decision is made to pursue reprocessing.

- Type of fissile materials involved and their suitability for making nuclear explosives.
- The ease with which safeguards can be applied and the costs and capabilities needed to implement the safeguards.
- The potential consequences of the proliferant party's actions.

They grouped various advanced reprocessing approaches into four groups (W, X, Y, Z), with electrometallurgical processing in Group W, according to their technical and material characteristics to compare each to the PUREX process. (The PUREX process is regarded as the most proliferation-prone reprocessing technology.) As discussed above, it is the one in use today. The Bari et al. paper's conclusions were that the differences among the various advanced reprocessing technologies, so far as proliferation potential is concerned, "are not very significant" except in the case of a set of technologies that separate a mixture of plutonium and neptunium. In that case the difference with PUREX is "small."⁷⁴

Moreover, once states have mastered reprocessing technology, the time required to purify material mixtures and separate pure plutonium "ranges from a few days to a few weeks."⁷⁵ Given past experience, this would present huge challenges to timely detection of diversion and verify stocks. Action to stop the program and reverse the process is complex and uncertain and would involve many risks for all parties. The overall conclusions of Bari et al. are as follows:

In sum, for a state with pre-existing PUREX or equivalent capability (or more broadly the capability to design and operate a reprocessing plant of this complexity), there is minimal additional proliferation resistance to be found by introducing Group W [which includes electrometallurgical processing], X, or Y processing technologies when considering the potential for diversion, misuse, and breakout scenarios.

In a nuclear material theft scenario involving non-state actors, Groups W, X, and Y provide some advantage over Group Z (whose product is plutonium or plutonium not separated from neptunium). These advantages arise from the additional cost, time, and technical difficulty that would be entailed in further processing by a non-state actor of any Group W, X, or Y products to obtain pure plutonium.

...

This evaluation found only a modest improvement in reducing proliferation risk over existing PUREX technologies, and these modest improvements apply primarily for non-state actors. This study reinforces the importance (1) limiting reprocessing activities to a small number of states with strong nonproliferation credentials and (2) developing effective and transparent international safeguards for any reprocessing technologies selected for use in a comprehensive program.⁷⁶

However, despite the hope of many that reprocessing can be restricted to a small number of states, this is a strategy that is unlikely to be acceptable to the very states that may have the desire to develop commercial nuclear technology with the aim of developing latent nuclear weapons capability. For instance, South Korea has recently expressed a desire to develop and implement reprocessing as a way to manage spent fuel.⁷⁷

⁷⁴ Bari et al. 2009 p. 6 of pdf

⁷⁵ Bari et al. 2009

⁷⁶ Bari et al. 2009 pp. 6-7 of pdf

⁷⁷ NTI 2010

Commercial nuclear power ambitions now extend to major oil exporters in the Persian Gulf. But a news report of an event announcing the interest makes clear that one eye is towards Iran and the other is towards Israel:

The leaders of Saudi Arabia, Bahrain, Kuwait, Oman, Qatar, and the United Arab Emirates called for a peaceful settlement of the conflict over Iran's nuclear program, and demanded that Israel, the only country in the Middle East believed to have nuclear weapons, join the nuclear Non-Proliferation Treaty.

Speaking to reporters after the summit, Foreign Minister Prince Saud Al-Faisal said the GCC states' intention to pursue civilian nuclear technology was not a "threat" to anyone. "We are announcing our intention to pursue the ownership of nuclear technology for peaceful (purposes)," he said.

"It is not a threat. It is an announcement so that there will be no misinterpretation of what we are doing. We are not doing this secretly. We are doing it openly," he said.

"We want no bombs. Our policy is to have a region free of weapons of mass destruction," the prince added. "This is why we call on Israel to renounce (nuclear weapons)." The "original sin" was from Israel as it established a nuclear reactor with the only purpose of producing nuclear weapons, Prince Saud said.⁷⁸

Mohammed ElBaradei, the just retired Director General of the International Atomic Energy Agency, stated in 2008 that the new interest in nuclear power by many developing countries, in his view, was to acquire "latent" nuclear capability:

You don't really even need to have a nuclear weapon...It's enough to buy yourself an insurance policy by developing the capability, and then sit on it. Let's not kid ourselves: Ninety percent of it [the new interest in nuclear power in developing countries] is insurance, a deterrence.⁷⁹

For the United States to resume the pursuit of commercial reprocessing could have the gravest of proliferation consequences both in terms of its example and in terms of the development of new technology. While restraint on the part of the United States in this regard may not halt reprocessing development in other countries, it is much more likely that its pursuit in the United States will encourage it elsewhere.

F. Breeder reactors

As we have seen, it is essentially impossible to use a large fraction of the underlying uranium resource for energy production without breeder reactors. Sodium-cooled fast breeder reactors (called "fast" because fission is accomplished with high-energy or "fast" neutrons) have been the

⁷⁸ Qusti 2006

⁷⁹ As quoted in Warrick 2008

ones most sought after because they have the best breeding ratio, which is the ratio of fuel produced to that consumed. In a breeder reactor, this ratio is more than one.

In a breeder reactor, depleted uranium, which is the byproduct of uranium enrichment, is put in a “blanket” around the breeder reactor core and converted into plutonium. This conversion is not part of the generation of energy from fission, which occurs in the central part of the core from MOX fuel containing a much higher percentage of plutonium than light water reactor MOX fuel. Rather the outer part of the reactor, the “blanket,” is dedicated to the purpose of converting uranium-238 into plutonium. This plutonium would be greater in quantity than that consumed in the core, resulting in a net increase in fuel, and providing the theoretical possibility of using up almost all the uranium resource.

The development and commercialization of breeder reactors, which has focused worldwide on sodium-cooled fast reactors, has been a failure, despite immense effort and expenditure. Table 3 shows the demonstration breeder reactors that have been built so far (pilot plants of less than 100 megawatts electrical are omitted). Looking at the overall record of nearly six decades of experience, there is no evidence of a significant learning curve. Some demonstration reactors have operated well; some have not.

If there were, a positive learning curve would show that the early plants functioned worse than the later ones. But this is not the case. Some early plants worked well; other did not. The same is true of the more recent ones. The first small sodium-cooled reactor, the EBR I built at the Idaho National Laboratory, had a partial meltdown. The second one built at Idaho, EBR II, operated well; its proponents wanted it to be the reactor component in an IFR scheme to be developed at INL. But the first breeder built as a commercial power plant, Fermi I near Detroit, ran into problems early on and never generated much energy. And so on, up and down it has gone over six decades.

The two most recent large demonstration reactors to be completed – Superphénix in France (by far the largest breeder reactor ever built) and Monju in Japan have among the worst performance records. Superphénix had a lifetime capacity factor of under 8 percent from grid connection in 1986 to shut down at the end of 1996 and did not operate at more than one-third capacity factor in any of those years.⁸⁰ Monju had a secondary sodium loop fire about a year-and-a-half after commissioning and remained shut as of early March 2010. Efforts are being made to repair and restart it. The restart date has been repeatedly postponed and was recently scheduled for late March 2010.⁸¹ But it did not restart by then.

⁸⁰ IAEA Super-Phénix 2009

⁸¹ Nuclear Engineering International 2010

Table 3: Capital Costs of Breeder Reactors Larger Than 100 megawatts-thermal (MWt) (Note 1)

Name and country	Capacity MWt	Capacity, MWe - Net/Gross	Grid connection dates	Capital cost million US dollars, Constant 1996	Cost per kWe, 1996 US dollars	Comments
Fermi 1, USA	300	61/65	1966-1972	403	4,030	partial meltdown, scant operation
BN350, Kazakhstan	1,000	350 equivalent	1972-1999	724	2,172	massive sodium fire, 20 to 25 percent enriched uranium fuel; electricity plus desalination
Phénix, France	560	233/250	1973-2009	395	2,116	operated reasonably well
Dounreay PFR, Britain	600	234/250	1974-1994	395	1,975	many operational problems
BN600, Russia	1,470	560/600	1980-	918	1,873	designed for 20 to 25 percent enriched uranium fuel, 14 sodium fires
FFTF, USA	400	133	1980-1993	1,397	10,478	operated reasonably well
Superphénix, France	2,900	1,200/1,242	1986-1998	6,028	4,822	operated at 7 percent average capacity factor, many operational problems
Monju, Japan	714	246/280	1995	5,134	21,571	secondary sodium fire led to closure; not yet reopened; current date for start of tests after end of March 2010; three years of tests to follow
SNR-300, Kalkar, Germany	762	254	Did not open	4,272	16,819	safety concerns led to decision not to operate
Total	8,906			19,666	7,317	

Notes: 1. Adapted from Makhijani 2001 Table 3 (pp. 22-23). This table consists of large sodium-cooled reactors that could be used as breeder reactors in theory, whether or not they were actually used as breeder reactors. For details of how estimates were made, including conversion from local currency to US dollars and adjustment from current to constant dollars, see Makhijani 2001 Table 3. Pilot plants not shown; demonstration reactors only ~100 MW electrical or more.

2. **Operating, fuel, maintenance, and decommissioning costs are not included.**

Sources: Makhijani 2001 Table 3 and the following: Phénix closing date: CEA 2009. Electric capacities from IAEA 2006, except and FFTF and SNR-300 are IEER calculations. For comments: Fermi 1: Fuller 1976 and IAEA

Fermi 2009; BN350 and BN600: IPFM 2010; Phénix: IAEA Phénix 2009; Dounreay: IAEA Dounreay 2009 and Cruickshank and Judd 2000; FFTF: Cadwallader and Petti 1999; Superphénix: IAEA Super-Phénix 2009; Monju: Miyakawa et al. 2000 and Nuclear Engineering International 2010; Kalkar: No Nukes Inforesource no date. BN350 and BN 600, IPFM 2010 p.64 and Albright, Berkhout, and Walker 1997, pp. 204-205. For sodium fires see IPFM 2010.

One problem is that liquid sodium, which is used as a coolant in all the breeder reactors, shown in Table 3, is a difficult and dangerous material. It burns on contact with air (which is what happened at Monju) and explodes on contact with water. Performance and operational requirements are very exacting. A review of sodium-cooled reactor problems in the excellent history of breeder reactors recently published by the International Panel on Fissile Materials indicates that, despite the advantage that sodium-cooled reactors can operate at low pressures, small and large problems with sodium cooling have been a common theme.⁸² Because it is necessary to keep the sodium out of contact with air and water, it is typically much more complex and difficult to fix problems with sodium-cooled reactors than with light water reactors.

It is instructive to take a brief look at the two most recent demonstration breeder reactors, the Superphénix and Monju.

A French Parliament report on Superphénix⁸³ noted that it was not the nuclear aspect of the reactor but the sodium that had been at the center of the problems. In fact, the problems, catalogued in the report caused 25 months of shutdown of the reactor.⁸⁴ It was commissioned in January 1986. The major sodium-related shutdown incidents were as follows:

- 1987: poor choice of steel caused a tank to fail and a sodium leak. The shutdown and repairs lasted 10 months.
- 1990: the primary sodium circuit became contaminated with air due to a compressor malfunction. Sodium purification took eight months, during which the reactor was shut.
- 1994: an argon gas leak into a sodium-sodium heat exchanger inside the reactor vessel cause a seven-month shut down.

The Japanese demonstration breeder was commissioned at about the time of the last Superphénix sodium leak in 1994. In December 1995 it suffered a sodium fire in the secondary cooling loop. It remains shut (as of March 2010), despite long efforts to reopen it. Even after it is restarted, it will have to be tested again – currently three years of tests are envisioned.⁸⁵ So even if it is restarted this year, the Monju reactor will have generated essentially no electricity for its first 19 years, including, reportedly, the three years of forthcoming tests.

In sum, the most recent large demonstration reactors have not done better than the early ones; indeed their performance has been worse than some early ones. The history of sodium-cooled reactors gives no realistic basis for inferring a learning curve or for the optimism expressed by proponents that the problems can be overcome systematically and at reasonable cost. For

⁸² IPFM 2010

⁸³ France. Assemblée Nationale 1998 Section II.A.3 (Des difficultés réelles de mise au point de l'installation mais aussi de son statut administrative)

⁸⁴ For comparison, the reactor fed electricity into the grid for only 53 months.

⁸⁵ Nuclear Engineering International 2010

instance, an assessment of the IFR by the University of California (Berkeley), Department of Nuclear Engineering⁸⁶ reads more like a promotional brochure than a serious assessment, such as the one produced in early 2010 by the International Panel on Fissile Materials.

It should be noted that Japan now expects to commercialize sodium-cooled reactors in the year 2050, about 80 years after the initial expected date, and about 100 years after the first sodium-cooled reactor was turned on in Idaho (EBR I, in 1951).⁸⁷

There is also the issue of cost. No large breeder reactor has been built in the last 15 years (two are under construction, one in India and one in Russia). It is difficult to estimate breeder reactor power production costs because they are not yet commercial. This can be seen both from the large variation in operating time and in cost per kW of the demonstration breeder reactors in Table 3. Nuclear costs have escalated greatly in the last decade. Breeder reactor costs are expected to be higher even in the case of commercialization:

Since breeder reactors were never built in quantity, it could be expected that, in production, this cost ratio would decline. Few if any argue today, however, that the capital costs for breeder reactors could be less than 25 percent higher than for water-cooled reactors of similar generating capacities. This would be a capital cost difference on the order of \$1000 per kilowatt of generating capacity. At a 10 percent capital charge and a 90 percent average capacity factor, this would translate to a cost difference of about 1.3 cents per kilowatt hour.⁸⁸

According to the report of the International Panel on Fissile Materials, governments belonging to the Organization for Economic Cooperation and Development (commonly referred to as the “West,” including Japan) have reported spending \$50 billion on breeders since 1974, but that this does not include most of the cost of the Superphénix. In addition, about \$12 billion of Russian expenditures are not-included.⁸⁹ When expenditures before 1974 and in other countries like India are taken into account, \$100 billion (2007 dollars) is a reasonable approximate estimate of breeder reactor development costs to date.⁹⁰ This does not include future costs of decommissioning.

In addition, tens of billions of dollars have been spent on reprocessing costs in plants that were originally conceived to support breeder reactor programs. They have no economic rationale and practically no resource rationale in a light water reactor system.⁹¹

In all, roughly \$200 billion (2007 dollars) is a reasonable range of costs to date to commercialize a plutonium economy; including breeder reactor and reprocessing costs. The system is still far

⁸⁶ Berkeley Nuclear no date.

⁸⁷ Green Action 2009, Mitsubishi 2007, and Albright, Berkhout, and Walker 1997 p. 196

⁸⁸ IPFM 2010 p. 7

⁸⁹ IPFM 2010 pp. 6-7

⁹⁰ Frank von Hippel, personal communication April 5, 2010

⁹¹ See Makhijani 2001 for a discussion of some of the excess costs of reprocessing, especially pages 26-28, including footnotes. Up 1999, a partial count of excess commercial reprocessing costs were ~\$60 billion in 1999 dollars or about \$70 billion (rounded) in 2007 dollars. There have been more excess expenses since then.

from commercial; an essential element, the sodium-cooled fast breeder reactor, is not even technologically developed enough to be consistently reliable.

G. Reprocessing and spent fuel stocks from existing U.S. reactors

As we have seen, statements that 90 or 95 percent of the material in spent fuel can be used are completely invalid without breeder reactors. In this section we will examine some of the implications of a policy that seeks to deal with existing spent fuel by trying to convert the mass of the material into fuel and using it for energy, assuming that breeder reactors will work and can be deployed on a large scale.

We start with a heuristic calculation. A 1,000-megawatt nuclear power reactor fissions about one metric ton of heavy metal per year in the course of energy generation. At present, there are over 60,000 metric tons of spent fuel in the United States. With reactor re-licensing, the total amount of spent fuel could amount to well over 100,000 metric tons by the time the reactors are retired; 95-plus percent of the content of this spent fuel is uranium or transuranic elements (mainly plutonium). We will use a round number of 100,000 metric tons⁹² of uranium and plutonium content in spent fuel that would be converted into fuel. This corresponds approximately to statements that 90 or 95 percent of existing spent fuel has “energy value” and hence should not be regarded as waste. For instance, such a scheme would appear to be the one that Dr. Miller had in mind and that NRC Commissioner Bill Magwood made explicit in his discussions of spent fuel management.⁹³

Setting aside for the moment a variety of difficult issues, including those associated with the rate of conversion of uranium-238 into plutonium, it is easy to see that it would take 100,000 reactor years (assuming 1,000 megawatt reactors) to convert the heavy metal content of spent fuel from the existing fleet of U.S. power reactors into fission products in a manner that extracts essentially all the physically possible energy value in it.

Assume a reactor operating life of 50 years, accumulating 100,000 reactor years would mean building 2,000 reactors to extract the energy in the total spent fuel from the existing fleet of reactors. This is about 20 times the size of the existing U.S. nuclear power system. It is four times the total electricity generation of the United States and seven or eight times the baseload requirements under the present centralized electricity dispatch system. If the material is consumed in a smaller number of reactors, the time to consume it would be proportionally increased. For instance, it would take 200 years to consume the material in 500 reactors.

The matter gets more complex when the time required to breed plutonium out of uranium-238 is taken into account. This is because it takes considerable time to build up the inventory of plutonium created from uranium-238 in breeder reactors to get to the point where all reactors

⁹² The estimates in this section are rounded to one significant figure and are order of magnitude values provided as heuristic calculations to illustrate the magnitude of the problem of converting most or all of the uranium in spent fuel to fuel.

⁹³ Miller 2009 and Magwood and Ribbing 2009

would be fueled with plutonium alone (mixed with depleted uranium). In the meantime a considerable amount of the fissile material requirements would consist of enriched uranium fuel. This would increase the uranium fuel requirements, in turn increasing the amount of uranium-238 to be converted into plutonium. In other words, the number of reactor-years needed to make substantially complete use of the uranium resource in existing spent fuel would be even greater than indicated by the above calculations.

Along the way the process will involve separating on the order of 100 million kilograms of plutonium, enough for more than ten million nuclear bombs. Even if it is mixed with some other materials that make making a nuclear weapon more complex, the material is usable in nuclear weapons. Worldwide, the total material that would be converted in such a process to fuel would be about three times the amounts in the United States⁹⁴ or enough for more than 30 million nuclear bombs.

These considerations lead to some basic technical and proliferation-related conclusions about a system in which 90 to 95 percent of the “energy value” of the materials in existing spent fuel is to be extracted:

- Large amounts of spent fuel will have to be stored for very long periods, extending in some cases to hundreds of years (instead of being disposed of in a repository) awaiting reprocessing.
- The process will involve making on the order of 100 million kilograms of plutonium – enough to make more than 10 million nuclear bombs from U.S. material alone.
- If the United States is able to widely deploy reprocessing and breeder reactor technologies, other countries are likely to do it as well (see below). More than 30 million nuclear-bomb-equivalent fissile materials are at issue worldwide from spent fuel from existing reactors alone.
- If the conversion of non-fissile uranium in spent fuel from existing reactors to fissile materials is carried out over say 300 years, the amount of weapon-usable material separated each year in the United States will be enough to make more than 30,000 bombs, about equal to the peak of the U.S. nuclear arsenal of the United States during the Cold War. The corresponding figure for worldwide separation will be roughly 100,000 nuclear bombs annually. It is highly questionable whether safeguarding or even accounting for so much material is a reasonable proposition.

It is impossible to determine either the costs or security consequences of a system in which so much separated fissile material is being separated each year.⁹⁵ But we can infer some things from past experience. There is, of course, the well-known case of North Korean proliferation using plutonium separated from spent fuel from a power producing reactor. But there have been

⁹⁴ This is an approximate value based on a U.S. generation fraction of about a third (31 percent of worldwide nuclear generation of electricity in 2008 – see NRC 2009-2010 p. 24). In practice the details will be different. For instance, some reactors designs, like the Canadian heavy water reactor design, CANDU, use natural rather than enriched uranium, which take a larger total uranium loading.

⁹⁵ It should be noted that while proposals for the IFR in the United States are usually in the context of a co-located reactor and reprocessing plant, co-location is not inherent in the technology. Countries may choose, for a variety of reasons, including economic, to build centralized electrometallurgical separation facilities. See Wymer et al. 1992.

issues even in the OECD countries. For instance, it took 15 years of official investigations of a Japanese plutonium discrepancy of over 200 kilograms – sufficient for about 30 nuclear bombs – at relatively small reprocessing plant in Tokai-mura. The government and the IAEA concluded that none had been diverted. Half of it was apparently never produced. The shortfall in production was apparently not detected at the time of production but had to be retrospectively investigated. Most of the rest had been discarded as waste, the investigation concluded. The Japanese discrepancy involved about 3 percent of the total plutonium separated at the plant.⁹⁶

An example from the military sector is also instructive, since it provides one more illustration of keeping track of fissile material, especially in nuclear waste generated during material processing. Los Alamos National Laboratory, arguably the crown jewel of U.S. nuclear weapons research establishment, has two sets of numbers for plutonium in waste that do not match, one maintained by Department of Energy headquarters and the other by waste management at the site and the Environmental Protection Agency. According to an IEER report, the discrepancy amounts to about 300 kilograms of weapon-grade plutonium – enough for about 60 nuclear bombs. Each agency maintains that its account is correct. But IEER has pointed out that both numbers for the same thing cannot be right, though they might both be wrong. And there the matter has stood since 2006.⁹⁷ While the cumulative amount of plutonium handled at Los Alamos is not publicly known, the discrepancy is likely to be on the order of 1 percent or more, given that most plutonium was processed into weapons at Rocky Flats in Colorado and the total plutonium production in the U.S. weapons complex was about 100 metric tons.⁹⁸

Based on these examples, discrepancies of hundreds of kilograms in a world in which annual separations, both commercial and military, have averaged on the order of 10,000 kilograms of plutonium, one can infer that inspections and verification infrastructure would have to be 100 times more effective to maintain a level of materials accounting that has never been entirely satisfactory from a proliferation standpoint, assuming the approach being advocated is implemented worldwide. Whether this can be done technically, how much it would cost, and whether it is politically feasible given current proliferation trends has not even begun to be seriously discussed.

Then there is the matter of economics. To implement the scheme of converting much or most of the material in spent fuel to usable fuel is not within economic reach at present:

- The use of MOX fuel made from reprocessed plutonium costs about two cents per kWh more than that from uranium fuel at the best operated plant in the world – that in France. In other places the numbers are even more grim.
- Breeder reactors today cost much more than light water reactors.

At the present state of development of reprocessing and breeder reactors the additional costs of converting uranium-238 recovered from spent fuel in breeder reactors into plutonium-238 would cost several cents more per kWh than once-through uranium fuel use.

⁹⁶ Hall 2003

⁹⁷ Makhijani and Smith 2006. In addition to this report, IEER's correspondence with federal government agencies and their responses can be found at <http://www.ieer.org/pu/index.html>.

⁹⁸ Total U.S. military plutonium production was disclosed in an official report in 1996. See DOE 1996.

To illustrate the utter impracticality of using this approach with anything like the present cost structure, consider the case where the added cost of electricity generation is only one cent per kWh compared to available alternatives. Since about each 1,000 MW reactor generates about 8 billion kWh per year, 100,000 reactor years would have a cumulative generation of 800 trillion kWh. For each penny per kWh added cost, the total additional cost (undiscounted constant dollars) would be \$8 trillion. This far exceeds the total value of electricity that has been and will be generated by the present fleet of reactors.⁹⁹

It is immediately evident that the scheme is economically impractical even if all proliferation and technical problems and associated costs) associated with large scale reprocessing and breeder reactors are ignored.

It should be noted that the cost of the breeder-reprocessing system will have to be brought down not only to the level of light water reactors without reprocessing, but to alternative renewable electricity sources. At present light water reactors are already generally more expensive than wind-generated electricity, even when compressed air energy storage is added to make wind energy available even when the wind does not blow.¹⁰⁰

In addition, solar technologies are maturing. Concentrating solar thermal power is broadly comparable in cost to light water reactors; solar photovoltaics are somewhat more expensive today. The costs of both are expected to decline rapidly in this decade. It is likely that both will be comparable to wind in that time.¹⁰¹

Overall, reprocessing plus breeders has a huge economic hurdle relative to light water reactor technology. Breeder reactors are not highly likely to be commercially competitive with renewable energy technologies even if the technological problems that have afflicted them are overcome.

Further, if one of the goals is to transmute long-lived fission products, minor actinides like neptunium-237 and americium-241, and long-long-lived activation products into stable or short lived elements, the approach will become even more expensive.¹⁰²

⁹⁹ We assume each 1,000 MW reactor operates at a little over 90 percent capacity factor. The existing fleet of 104 reactors generates about 800 billion kWh per year (rounded). At 5 cents per kWh wholesale at the busbar (generating station dispatch point), the annual value of electricity generated is \$40 billion. This adds up to \$2.4 trillion over 60 years, assuming license extensions of 20 years for all reactors now operating.

¹⁰⁰ It is difficult to estimate unsubsidized costs of nuclear energy in the United States at present, since Wall Street refuses to finance the plants as too risky. The California Energy Commission puts the costs of a plant coming on line in 2018 between about 17 and 34 cents per kWh (rounded), depending on plant ownership and financing compared to costs for wind-generated electricity (land-based) from 8 to 13 cents per kWh, depending on ownership structure and wind speeds at the site. See California Energy Commission 2009, Table 5, p. 18. Compressed air energy storage (CAES) would cost another 3 cents or so per kWh, making the total for dispatchable wind 11 to 16 cents per kWh. Author's estimate of CAES cost based on configuration for baseload wind by the National Renewable Energy Laboratory. (NREL 2006). The estimates of the author of this paper for electricity from unsubsidized new light water reactors are 12 to over 20 cents, if there are no delays or significant real cost escalations over the construction period.

¹⁰¹ California Energy Commission 2009 p. 6 and p. 18

¹⁰² Various transmutation technologies are discussed in Zerriffi and Makhijani 2000.

If a penny per kilowatt-hour penalty presents an insuperable hurdle to the management of existing spent fuel using reprocessing and breeders, is it even worth contemplating?

Advocating a reprocessing-breeder reactor system to extract 90 or 95 percent of the energy value in spent fuel from existing reactors does not add up to a sound policy direction from the logistical, security, or cost point of view. Given the vast amounts of fission and activation products as well as large amounts of Greater than Class C waste, sizeable repository disposal capacity will be needed even after storing the spent fuel for prolonged periods – likely to extend to hundreds of years in some cases.

A detailed consideration of the facts shows that slogans and romantic appeals to “energy value” of the resource in spent fuel and to France, such as the ones by Dr. Miller and Commissioner Magwood cited at the beginning of this report have become a parallel to the unrealistic and technically ill-founded promise of nuclear power “too cheap to meter” of the 1950s.

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