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# Reprocessing: Mythology versus Reality

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La Hague reprocessing nuclear plant, located on the Normandy peninsula in France.

Reprocessing is the process of treating spent nuclear fuel in order to separate the various constituents, especially the theoretically potentially usable plutonium and uranium from fission products. It is sometimes called "recycling" by its promoters, though in practice only about 1 percent of the recovered material can be reused as fuel, at high cost.

Spent nuclear fuel has been piling up at reactors since the dawn of nuclear power in the United States. With no viable plan to dispose of the waste, reprocessing has become a new mantra for boosters, who point to the uranium and plutonium in the spent fuel as a treasure-trove of unused energy that we are wasting. This is a false promise, similar to the old claim that nuclear energy would be "too cheap to meter."

This article summarizes the April 2010 IEER report, *The Mythology and Messy Reality of Nuclear Fuel Reprocessing,* which serves to debunk some myths about reprocessing. We conclude with five policy recommendations.[1]

## Some History

The purpose of reprocessing is to obtain plutonium for use in nuclear power reactors or in nuclear weapons. It also recovers uranium, which can be re-enriched for use as a fuel. Uranium-238, which typically makes up more than 92 percent of spent nuclear fuel, can be turned into plutonium in breeder reactors, so called because they make ("breed") more fissile material (e.g., plutonium) than they use.

Reprocessing combined with breeder reactors found favor in the 1950s and 1960s because at that time uranium was thought to be a scarce resource. The possibility of "breeding" engendered a passionate hope among many nuclear engineers and physicists of an energy source that would last essentially forever.

The favored breeder reactor, due to its theoretical breeding efficiency, has been the sodium-cooled fast breeder reactor, so called because it uses energetic (fast) neutrons to sustain the chain reaction and liquid sodium for cooling the reactor and carrying away the heat created by nuclear fission. There was nothing theoretically wrong with the physics, but the breeder + reprocessing scheme posed too many technical, economic, and security problems, preventing its commercialization.

First, despite speculative ups and downs, uranium remained cheap overall and thus reprocessing turned out to be expensive relative to making reactor fuel from freshly mined uranium. Second, sodium-cooled breeder reactor demonstration projects have had a mixed record with some performing well and others doing badly.

The most recent breeders have been

### Breeders vs. Burners

Commercial nuclear power reactors come in two main varieties, burner reactors and breeder reactors. 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."

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EDITOR'S NOTE

# Happy birthday, IEER!

## Happy birthday, *Science for Democratic Action*!

This year, IEER turns 25 years old. IEER's newsletter, *Science for Democratic Action*, turns 20. Let's party!

We are planning a variety of virtual and internet-based ways to celebrate. Be on the lookout for invitation(s) in your email inbox!

IEER will also launch its newly redesigned website this year. It will be more user-friendly and attractive, but with the same high-quality content you've come to expect from IEER.

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among the worst-performing ones. For instance, Superphénix in France, which was shut down in 1998, was the largest breeder reactor designed to prove operation at a commercial scale. It shut down in 1998 after 14 years, averaging about 7 percent capacity factor. Monju in Japan had an accident in late 1995, eighteen months after commissioning. It remains shut despite massive efforts to restart it. Promoters are aiming at commercialization *decades* from now. Japan has a target date of 2050, which would be 100 years from the initial efforts. They are unlikely to be commercial in the near future.

Lastly, proliferation problems associated with non-military reprocessing became a big concern, especially after the Indian nuclear test in 1974, which prompted the United States to forgo commercial reprocessing.

It is worth noting 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 light water reactors to increase the use of the uranium resource because its value in that regard is marginal.

It is only recently, with the failure of the Yucca Mountain program to provide a repository, that reprocessing is being promoted as a "solution" to the problem of mounting quantities of spent fuel at more than five dozen commercial U.S. nuclear reactor sites. In this context, it is often called "recycling." Reprocessing is now explicitly being promoted as a means for greatly increasing the use of the uranium resource contained in the spent fuel.

In June 2011, the U.S. Nuclear Regulatory Commission (NRC) published a *Federal Register* notice concerning development of regulations for hypothetical future facilities engaged in the reprocessing of spent nuclear fuel. This process is likely to be problematic and contentious given that it is occurring in the wake of the Fukushi-

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# What is Reprocessing?

Reprocessing is a technology for separating fissile materials – materials that can sustain a chain reaction – 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. The technology 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.

Specifically, reprocessing treats spent nuclear fuel in order to separate the plutonium from the remaining uranium isotopes, fission products, and traces of other radionuclides including other heavy radionuclides created in the process of reactor operation. Generally, uranium is also separated from the fission products, resulting in three streams: a mix of plutonium isotopes, a mix of uranium isotopes, and fission products plus some heavy radionuclides. The table shows typical fresh and spent uranium fuel composition for light water reactors, the most common type of power reactor and the only type operating in the United States. In some reprocessing technologies, different mixes of uranium, other heavy metals and plutonium can be separated.

Chemical separation is at the center of current reprocessing technology – a technology known as the **PUREX** (for Plutonium URanium EXtraction) process. This is the one used in France, for instance, at the La Hague site in Normandy. The PUREX process separates the spent fuel into three streams – plutonium, uranium, and fission products plus trace non-fission radionuclides like neptunium.

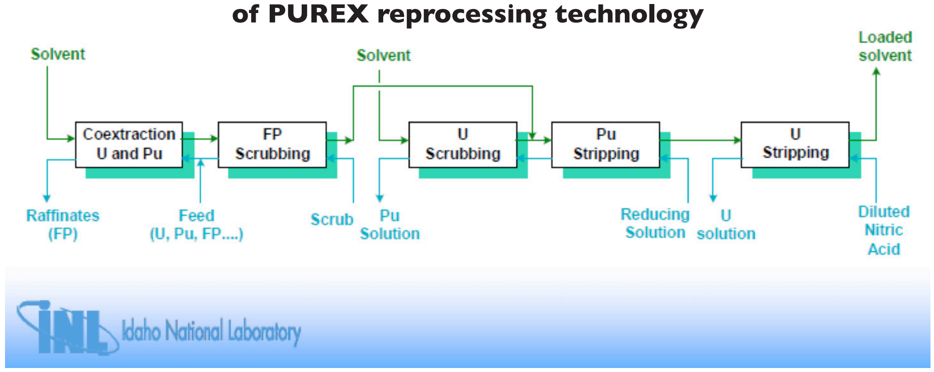
PUREX uses nitric acid to dissolve the spent fuel. Solvents are then used in successive separation steps, first to separate fission products and some other trace radionuclides from uranium and plutonium, and then uranium and plutonium from each other. Trace radionuclides are also generally separated from the uranium and plutonium streams. The figure shows the flow of materials in the PUREX separations process.

**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 |
| Fission Products | 0 | 4.62 |
| Transuranic radionuclides other than Pu isotopes | 0 | 0.095 |

Based on data from the International Atomic Energy Agency, 2007. Total fission products calculated as 100 percent minus sum of all the listed radionuclides. "Burnup" means amount of heat energy, expressed in terms of megawatt-days thermal (MWdth) per unit mass of fuel (expressed in terms of kilograms of heavy metal, which in the case of fresh uranium fuel is simply the uranium content). 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.

**Schematic of the main separations process of PUREX reprocessing technology**




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

There are other separation technologies but all are in various stages of research and development. The **UREX** (URanium EXtraction) process is an alteration of the PUREX process, the main difference being that the plutonium is not separated but rather retained in the high-level waste stream with almost all the fission products. PUREX and UREX are both aqueous (wet) separation processes.

Dry processes – variously named "pyroprocessing," "pyrometallurgical processing," "pyrochemical processing," and "electrometallurgical processing" – are characterized by electrolytic separation of elements. The basis of pyroprocessing is that, given the right set of conditions, elements are converted into charged particles called ions when well-defined voltage is applied. The reverse process can also be made to occur electrically. This allows a selective separation of groups of elements by electrolysis. This type of process was developed by Argonne National Laboratory for the Integral Fast Breeder. The Integral Fast Breeder was canceled in 1994 but development of the electrolytic process has continued, ostensibly for waste management purposes. The electrolytic process can be supplemented by further chemical separation, if desired.

For more information on separations technologies see *The Nuclear Alchemy Gamble: An Assessment of Transmutation as a Nuclear Waste Management Strategy*, by Hisham Zerriffi and Annie Makhijani, Institute for Energy and Environmental Research, August 25, 2000, on the web at http://www.ieer.org/reports/transm/report.pdf.

ma crisis, that a U.S. reprocessing plant has not been licensed in more than four decades, and that there is no foreseeable business case for reprocessing.

## Debunking the Myths

Typical arguments by reprocessing proponents include claims that more than 90 or 95 percent of spent fuel can be "recycled" for recovering the energy in it, that France has found in reprocessing an economical and technical solution to its nuclear waste problem, and that reprocessing does not lead to the proliferation of nuclear weapons.

The claims do not hold up to the facts. The French have not solved the waste problem. The proliferation, cost, and technology problems associated with reprocessing have not been solved. Using reprocessing to make fuel for new reactors would create large amounts of radioactive waste and likely involve huge additional expenses.

***Myth 1: Ninety percent of spent fuel can be "recycled." The U.S. should follow France, which "has made efficient use of recycling."*** [2]

Using more than one percent of the uranium resource in a light water reactor system is technically impossible even with reprocessing and re-enrichment.

Statements that imply that the French have somehow figured out how to use 90 percent of the uranium resource are wrong. The French use only about 0.7 percent of the original uranium resource to create fission energy – and most of that happens before any reprocessing is done. The rest – 99.3 percent of the original uranium – is mainly depleted uranium (DU). This DU is piling up as reprocessed uranium that is not being used, or is uranium left in spent fuel of various kinds (including mixed-oxide [MOX] spent fuel). This figure cannot be increased significantly even with repeated reprocessing, use of all the plutonium, and re-enrichment of the uranium so long as the fuel is used in a light water reactor system.

Figure 1 shows the flow of materials in a light water reactor plus reprocessing system. It is not hard to see that 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.

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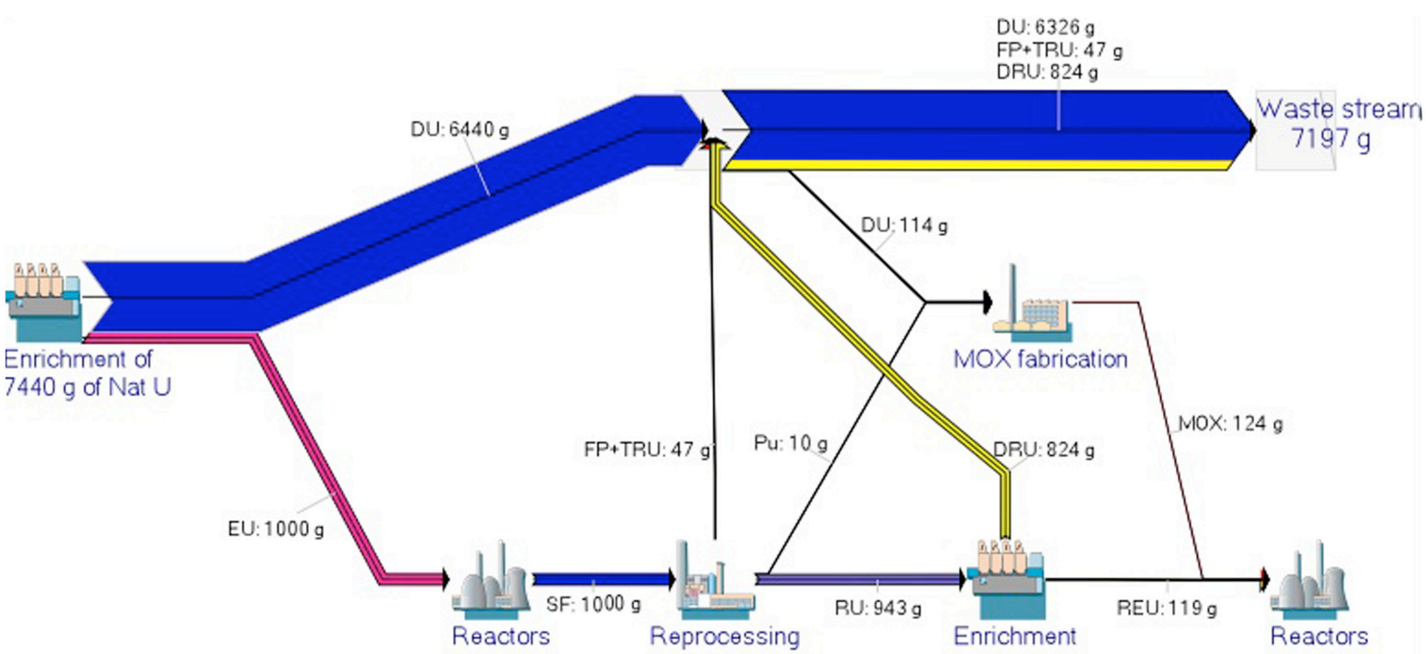
**FIGURE 1**

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




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

Yet France continues to be at the center of reprocessing myth-making. For instance, Bill Magwood, now a commissioner in the U.S. Nuclear Regulatory Commission, and Mark Ribbing of the Progressive Policy Institute, wrote as follows to President Obama in 2009:

> 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]

As shown above, any statement or implication that France is recycling 96 or 97 percent or any similar high percentage of spent fuel is wrong. Once-through fuel use without reprocessing converts about 4.7 percent of the fuel's mass into fission products – that is, just 4.7 percent of the fuel produces energy. France increases this by roughly 1 percent by reprocessing. Even if all the recovered uranium were reused, the amount of the fuel actually fissioned would be 6 percent. And repeated reprocessing and reuse presents a huge number of technical and economic difficulties. Finally, as noted above, light water reactors use less than one percent of the original uranium resources, since over 86 percent of it is depleted uranium before the fuel is made.

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. Rather, it was driven mainly by the momentum of a system that was government-owned and had already invested a great deal of money and institutional prestige in the technology. Reprocessing in France continues today due largely to two factors: 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.

***Myth 2: Reprocessing is cost-effective.***

Reprocessing costs more – not less – than nuclear fuel cycles that do not include reprocessing. This fact can be illustrated with an actual example: Reprocessing in France.

France has done commercial reprocessing about as well as it can be done. It has operated plants at full capacity and ramped up use of mixed-oxide fuel (MOX) to 20 reactors, each of which uses MOX for 30 percent of its core. MOX is a mixture of plutonium derived from reprocessing and depleted uranium. The remaining 70 percent of the reactor core is uranium oxide fuel.

Any statement or implication that France is recycling a high percentage of spent fuel is wrong.

Despite the country's operational prowess, the public in France is paying about $1.4 billion per year *extra* in fuel costs for using MOX fuel versus uranium fuel.[4] The added cost of electricity generated from MOX fuel amounts to 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.

The added costs were recognized by Electricité de France (EDF) in 1989 at the start of 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 [the La Hague reprocessing plant] be indeed transformed into UP2 800 [an upgraded La Hague reprocessing plant]. Challenging this option has no economic basis; it would also have great global repercussions that would be detrimental to the nuclear industry. [5]

France is not the only country that has recognized the economic failings of reprocessing. In 1999, a British House of Lords assessment declared that the country's plutonium – more than 100 metric tons of separated plutonium stored at Sellafield – had no economic value. Sellafield, located in northwestern England, is the site of Britain's reprocessing plant, known as THORP (THermal Oxide Reprocessing Plant). Commissioned in 1994, THORP is currently operating at partial capacity. Britain has never used any MOX fuel in a commercial power reactor.

Commercial reprocessing in the United States has a dismal economic history.

Commercial reprocessing in the United States also has a dismal economic history. The West Valley reprocessing plant near Buffalo, New York, operated only for six years before it was permanently shut down in 1972. 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 not yet complete.

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The decision to continue reprocessing in France was driven mainly by the momentum of a system that was government-owned and had already invested a great deal of money and institutional prestige in the technology.

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***Myth 3: Reprocessing reduces radioactive wastes destined for a repository.***

The truth is just the opposite. Rather than reduce radioactive wastes destined for a repository, reprocessing *increases* them, even though the volume of fission products, which are usually encapsulated in glass and known as "high-level waste," is less than that of spent fuel. But reprocessing also produces a great deal of waste that is highly contaminated with plutonium, called transuranic waste, as well as other highly radioactive waste called Greater than Class C waste that, according to current U.S. regulations, should be disposed of in a deep repository unless a special exemption is obtained.[6] French regulations also require such wastes to be disposed of in a deep repository. Transuranic (TRU) waste originating in the U.S. nuclear weapons program is being disposed of in a deep geologic repository in New Mexico, the Waste Isolation Pilot Plant (WIPP).

Rather than reduce radioactive wastes destined for a repository, reprocessing *increases* them.

Table 1 shows a comparison of radioactive waste generated over operating lifetimes of 200 nuclear light water reactors with and without reprocessing. The table's data is taken from the U.S. Department of Energy's *Draft Global Nuclear Energy Partnership Programmatic Environmental Impact Statement*.

***Myth 4: If we reprocess spent fuel, we won't need a repository.***

Reprocessing cannot obviate the need for a repository. As noted, there is a large amount of transuranic waste containing plutonium-239, with a half-life of over 24,000 years, and other long-lived radioactive materials. The high-level vitrified waste contains some very long-lived fission products, notably technetium-99 (half-life over 200,000 years), cesium-135 (half life over 2 million years) and iodine-129 (half-life over 16 million years). Hence statements, such as those by Professor Miller of the University of Missouri, that the waste remaining after the useful materials are "re-cycled" would "decay away in a few centuries"[7] are misleading at best and incorrect at worst.

Some advanced, secondary reprocessing and reactor schemes have been proposed to deal with some long-lived transuranic radionuclides. Technically this can be done in some cases; it is very difficult in others, and infeasible in yet others.[8] All of the proposed schemes add to the expense and technical problems associated with reprocessing without eliminating the problem of long-lived radionuclides. A deep geologic repository will be needed with any combination of reactor and reprocessing technologies. This has been recognized by the Blue Ribbon Commission appointed by President Obama to address the post-Yucca Mountain nuclear waste issue:

> ***...no currently available or reasonably foreseeable reactor and fuel cycle technology developments—including advances in reprocessing and recycling technologies—have the potential to fundamentally alter the waste management challenge this nation confronts over at least the next several decades, if not longer.***[9]

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**TABLE 1**

**Cumulative waste volumes for a 200 gigawatt light water reactor (LWR) system, in cubic meters**

| 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 disrcharges per year |
| Ratio with/ without reprocessing | 0.73 | 163 | 6.2 | 3.7 to 11.6 (max to max and min to min) | 7.4 | |

Waste volumes are calculated over a 50-year life-cycle. Total repository waste calculated by adding spent fuel or high-level waste volume to GTCC (Greater than Class C Waste ) volume. Data source: Table 4.8-6 (p. 4-139) in Draft Global Nuclear Energy Partnership Programmatic Environmental Impact Statement. DOE/EIS-0396. October 2008. On the Web at http://nuclear.gov/peis/Draft_PEIS/GNEP_PEIS.pdf.

***Myth 5: Reprocessing is safe and doesn't harm the environment***

Reprocessing increases a number of safety risks and environmental problems relative to once-through fuel cycles, including risks associated with storing plutonium and reprocessing-related high-level wastes, risks of severe accidents at reprocessing plants, and problems with water contamination.

Discharges have contaminated the oceans all the way to the Arctic.

For instance, France and Britain store their liquid acidic wastes from reprocessing in stainless steel tanks on site – France at its La Hague reprocessing plant on the Normandy peninsula and Britain at Sellafield on the northwestern English coast. These wastes contain almost all the fission products of the spent fuel, and it is the fission products that contain the vast majority of the radioactivity at discharge from the reactor. These tanks must be cooled constantly; loss of cooling for a few days could result in a catastrophic explosion. French high-level waste tanks lost cooling for a few hours in 1980, but fortunately cooling was restored and an accident was prevented. In April 2009 and January 2010, the tanks at the British reprocessing plant at Sellafield suffered a loss of coolant water in several tanks.

We know what can happen within days of loss of cooling. A high-level waste tank exploded in 1957 in the Soviet Union with tragic results – towns evacuated and thousands of square miles of land polluted.[10]

In 2009, the Norwegian Radiation Protection Authority prepared an estimate of the consequences for Norway of a release of 0.1 to 10 percent of the stored liquid waste at Sellafield. The Authority wrote:

> 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.[11]

The Authority only modeled cesium-137, one of several long-lived radionuclides in the wastes. Notably, strontium-90 is present in concentrations comparable to cesium-137.

Reprocessing also leads to ocean contamination off both the British and French coasts. For instance, the La Hague reprocessing plant discharges about 100 million liters of other liquid wastes into the English Channel each year. These discharges have contaminated the oceans all the way to the Arctic, drawing protests from neighboring countries, which have asked France and Britain to stop reprocessing, and by implication, to stop the discharges.[12] They have not. At La Hague, 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.

***Myth 6: Reprocessing does not increase proliferation risks.***

Proliferation concerns are associated with the PUREX process (presently the only commercial reprocessing technology) because it separates pure plutonium and puts mixed oxide (MOX) 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.

Reactor-grade plutonium and weapon-grade plutonium have different isotopic compositions, but this is not a bar to making a weapon like the one that devastated Nagasaki on August 9, 1945. The U.S. Department of Energy noted the following about reactor-grade plutonium and bombs:

> 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 l-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.[13]

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 at La Hague, enough to make 11,000 to 12,000 nuclear bombs; Britain has more than 100 metric tons at Sellafield, enough to make about 14,000 nuclear bombs.[14] Britain has been accumulating separated plutonium to an even greater extent than France mainly because it 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.

Both France and Britain started reprocessing to acquire plutonium for their weapon programs. Further, both 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.

Japan owns enough separated plutonium at home and abroad to make more 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 increas-

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ing strains in its alliance with the United States are all factors in this debate. In 2002, Ichiro Ozawa, until mid-2009 the head of the Democratic Party of Japan 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:

> 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.[15]

North Korea is the first state to use a supposedly commercial reactor and associated reprocessing plant to make nuclear bombs.

Extracting the energy in the total spent fuel from the existing fleet of U.S. reactors (assuming reactor operating lifetimes of 50 years each) would involve separating on the order of one million kilograms of plutonium. This would be enough for about 150,000 nuclear bombs.

***Myth 7: New reprocessing technologies will be proliferation resistant and solve the present problem with PUREX technologies' proliferation vulnerabilities.***

A number of reprocessing technologies and reactor schemes have been proposed to reduce the proliferation problems associated with PUREX, the one existing commercial reprocessing technology. The scheme under consideration in the United States is the so-called "Integral Fast Reactor" married with a new reprocessing technology called electrometallurgical processing (a.k.a. pyroprocessing). It is being promoted both as proliferation-resistant and as a waste management strategy.

The Integral Fast Reactor (IFR) is the familiar sodium-cooled fast breeder reactor. The term "integral" refers to the location of the reprocessing plant: the same 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. If the theory is valid, this would make the technology more proliferation resistant relative to the PUREX technology.

Electrometallurgical processing, when operated with an IFR, is designed so as to not separate pure plutonium, unlike PUREX. Rather, a mixture of actinides with some fission products is separated, making it harder to make a nuclear weapon. In theory, this also increases proliferation resistance.

However, in reality, the mix of transuranic radionuclides separated using electrometallurgical processing can be used as effectively to make a nuclear weapon as the reactor-grade plutonium separated in today's PUREX plants. For instance, it would take less than 10 kilograms of electrometallurgically separated material to make a nuclear bomb, considerably less than the amount of highly enriched uranium needed for a bomb.

Extracting the energy in the total spent fuel from the existing fleet of U.S. reactors would involve separating plutonium — enough for about 150,000 nuclear bombs.

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. (See U.S. Dept. of Energy quote on page 7.) 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. Moreover, further chemical processing of the separated actinides could result in nearly pure plutonium.

Another concern is the relative ease of hiding pyroprocessing facilities as compared to PUREX plants. The PUREX process, unlike electrometallurgical processing, consists of a huge chemical factory and thus has the proliferation advantage of being easily detectable. Electrometallurgical processing is much more compact, making it much easier to hide than a PUREX plant. This is similar to how gas centrifuges (used to enrich uranium for use in nuclear reactors or nuclear weapons) are much easier to hide than the enormous gaseous diffusion plants that were first used for enriching uranium. The Iranian example of secretly building a gas centrifuge plant provides an example of what could happen in the plutonium arena once the size of reprocessing plants is greatly reduced.

Also 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, thus defeating the purported proliferation-resistance of the technology.

At present, electrometallurgical processing is not a fully developed commercial technology. It would be very difficult for

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The mix of transuranic radionuclides separated using electrometallurgical processing can be used as effectively to make a nuclear weapon as the reactor-grade plutonium separated in today's PUREX plants.

# Dear Arjun

**Dear Arjun,**

**What is a "fast breeder"?**
**— Befuddled in Boise**

Dear Befuddled,

In the old days a people thought a "fast breeder" was a rabbit – just ask any Australian. Then the definition changed when viruses were discovered to be the cause of head colds. For instance, the "triple S" fast breeder is a virus that suddenly stuffs sinuses.

As usual, the nuclear establishment has given this term a new twist altogether. A "fast breeder" is a reactor with 'fast' neutrons – that is, a reactor that does not have to slow down the neutrons created during fission. Further, this fission sustains the chain reaction that makes ("breeds") more fuel from a non-fissile material (generally uranium-238, but some also hope thorium-232) into a fissile material (plutonium-239 or uranium-233, respectively).

The sodium-cooled "fast breeder" – the one that powerful governments have spent so much money on – has gone nowhere slowly, but has consumed money pretty fast (about $100 billion in today's dollars total).

Sincerely,
Dr. Egghead (a.k.a. Arjun Makhijani)

*P.S. Never take the first paragraph of any Dear Arjun column seriously unless you really, really want to – and then do so at your own risk.*

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

All reprocessing technologies under consideration as "proliferation resistant" are vulnerable to proliferation. This is corroborated by a Brookhaven National Laboratory review, which found that the differences in proliferation potential among the various advanced reprocessing technologies "are not very significant" except in the case of a set of technologies that separate a mixture of plutonium and neptunium, and in that case the difference with PUREX is "small."[16]

The Brookhaven paper also concluded that, once a state had mastered reprocessing technology, the time required to separate pure plutonium "ranges from a few days to a few weeks." This would present huge challenges to timely detection of diversion and to verifying stocks.

It is impossible to determine either the costs or security consequences of a system in which so much fissile material is being separated each year. 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 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 shortfall in production was apparently not detected at the time of production but had to be retrospectively investigated. The government and the International Atomic Energy Agency (IAEA) concluded that none had been diverted. Half of it was apparently never produced and 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.

All reprocessing technologies under consideration as "proliferation resistant" are vulnerable to proliferation.

An example from the military sector is also instructive, since it provides one more illustration of the difficulty of keeping track of fissile material, especially in nuclear waste generated during material processing. Los Alamos National Laboratory, arguably the crown jewel of the U.S. nuclear weapons research establishment, has two different sets of estimates for plutonium in waste, one maintained by Department of Energy headquarters and the other by waste management at the site and the Environmental Protection Agency. The values do not match.

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, and they might both be wrong. And there the matter has stood since 2006.[17] 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.

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 satisfactory level of materials accounting. Whether this can be done technically, how much it would cost, and whether it is po-

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litically feasible given current proliferation trends have not even begun to be seriously discussed.

Despite the hope of many that reprocessing can be restricted to a small number of states, it is a strategy that is unlikely to be acceptable to the very states that may have the desire to develop commercial nuclear technology. For instance, South Korea has recently expressed a desire to develop and implement reprocessing as a way to manage spent fuel. Commercial nuclear power ambitions now extend to major oil exporters in the Persian Gulf as well as Turkey, Indonesia, Egypt, Venezuela, the United Arab Emirates, Malaysia, and others.

Mohammed ElBaradei, the recently retired IAEA Director General, opined in 2008 that the new interest in nuclear power by many developing countries 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.[18]

Other than not making the plutonium in the first place, keeping it in spent fuel – where the plutonium is mixed with large amounts of uranium and highly radioactive fission products including the strong gamma-emitter cesium-137 – is by far the most proliferation-resistant approach to managing the proliferation issues arising from the back end of commercial nuclear power. No barrier to proliferation is as significant as preventing the separation of plutonium from spent fuel.

Other than not making the plutonium in the first place, keeping it in spent fuel is by far the most proliferation-resistant approach. No barrier to proliferation is as significant as preventing the separation of plutonium from spent fuel.

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 development of new technology. Restraint may not halt reprocessing development in other countries, but its pursuit in the United States will very likely encourage it elsewhere.

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## IEER RECOMMENDATIONS

**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.[19]

**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.

**3.** Energy supply R&D resources should be focused on development and deployment of renewable energy technologies and energy efficiency because breeder reactors and reprocessing are not commercial after six decades of, and enormous expenditures on, development of sodium-cooled breeder reactors.

**4.** An official analysis of issues related to reprocessing spent fuel from burner reactors would help put the public discussion in the United States on a sounder scientific footing. This should include examination of the following:

a. Official data on the present use of the natural uranium resource purchased for France's and Britain's nuclear reactors, including, specifically, the increases in fission fraction that have actually been achieved by reprocessing and recycle.

b. Official data on Greater than Class C waste equivalent expected to be generated on a life-cycle basis in France and Britain, 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.

c. 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.

d. Official analyses from the French and British governments of the mechanisms, probability, and consequences of large accidental releases of radioactivity to the atmosphere from liquid high-level waste storage in tanks.

**5.** The U.S. Nuclear Regulatory Commission should suspend development of regulations for future reprocessing facilities. The NRC should instead address real and immediate problems, such as improving existing reactor safety in the post-Fukushima world.

## Sharpen your technical skills with Dr. Egghead's *Atomic Puzzler*

# Estimate the speed of a fast neutron

Dr. Egghead's dog, Gamma, loves chasing cars, especially fast cars. Because he can best understand speed in units of miles per hour, help him grasp the speed of neutrons, both fast and slow, by answering the following questions. You might even win a prize!

**1.** What is the typical speed of a fast neutron released in fission in miles per hour? Its energy is 4 megaelectron volts.

**2.** What is the speed in miles per hour of a slow (thermal) neutron, thermalized to room temperature (20 degrees Celsius)? Thermal neutron energy is 0.0253 electron volts.

Hints:

- 1 electron volt = $1.6 \times 10^{-19}$ joules
- The energy of a particle is 0.5 times its mass times the square of its velocity.
- Mass of a neutron = $1.67 \times 10^{-27}$ kilograms

### Think you know the answer?

Send us your answers via e-mail (ieer@ieer.org), fax (1-301-270-3029), or snail mail (IEER, 6935 Laurel Ave., Suite 201, Takoma Park, Maryland, 20912, USA), postmarked by March 30, 2012. IEER will send a signed copy of *Nuclear Power Deception* and of *Carbon Free and Nuclear Free* to two people with correct answers. If there are more than two correct answers, winners will be drawn at random. People with degrees in physics or chemistry are not eligible for the prize.

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## Endnotes

1. References can be found in the report, which is on the Web at www.ieer.org/reports/reprocessing2010.pdf. A slide presentation summarizing the report can be found here: http://www.ieer.org/reports/ManagingSpentFuel-BRC-2010-slides.pdf.

2. William H. Miller. "It's Time To Recycle Used Nuclear Fuel: Proven Practice Also Lessens Stored Waste," *The Columbia (MO) Daily Tribune*, November 29, 2009. On the Web at http://www.columbiatribune.com/news/2009/nov/29/its-time-to-recycle-used-nuclear-fuel.

3. Bill Magwood and Mark Ribbing. *America's Nuclear Waste and What to Do With It*. (Memos to the New President) Washington, DC: Democratic Leadership Council, January 15, 2009. On the Web at http://www.dlc.org/ndol_ci.cfm?kaid=450020&subid=900202&contentid=254827.

4. This estimate uses the exchange rate at which the euro was issued, 1.17 dollars per euro, and is based on a 30 percent MOX core.

5. Électricité de France. *Combustible MOX: aspects techniques, économiques et stratégiques*. [Paris?]: EDF, Direction Production Transport, Service des Combustibles, November 24, 1989. Page [7]. Translation by Annie Makhijani. There is also a second plant at La Hague, known as UP3.

6. *Code of Federal Regulations. Title 10 –Energy: Chapter I – Nuclear Regulatory Commission; Part 61 – Licensing Requirements for Land Disposal of Radioactive Waste*. 1-1-11 Edition. Washington, DC: Office of the Federal Register, National Archives and Records Administration; U.S. GPO, 2011. On the Web at http://www.gpo.gov/fdsys/pkg/CFR-2011-title10-vol2/pdf/CFR-2011-title10-vol2-part61.pdf.

7. Miller, op. cit.

8. A report examining the associated technologies – including a list of long-lived radionuclides and proposals to transmute them (or not) – was published by IEER in 2000: *The Nuclear Alchemy Gamble: The Nuclear Alchemy Gamble: An Assessment of Transmutation as a Nuclear Waste Management Strategy*, August 25, 2000, on the Web at www.ieer.org/reports/transm/report.pdf. Also see Annie Makhijani and Hisham Zerriffi, "Waste Transmutation: The Nuclear Alchemy Gamble," *Science for Democratic Action*, v.8, no.3, May 2000. On the Web at www.ieer.org/sdafiles/vol_8/8-3/transm.html.

9. Blue Ribbon Commission on America's Nuclear Future. *Report to the Secretary of Energy*. Washington, DC: BRC, January 2012. Page 100. On the Web at http://brc.gov/sites/default/files/documents/brc_finalreport_jan2012.pdf. Emphasis in original.

10. International Physicians for the Prevention of Nuclear War and the Institute for Energy and Environmental Research. Plutonium, *Deadly Gold of the Nuclear Age*, Cambridge, MA: International Physicians Press, 1992. Chapter 4.

11. Norwegian Radiation Protection Authority. *Consequences in Norway of a Hypothetical Accident at Sellafield: Potential Release – Transport and Fallout*. (StrålevernRapport 2009:7) Østerås: Statens strålevern, 23 March 2009. On the Web at http://www.nrpa.no/dav/a368e9b53c.pdf. Page 5.

12. The decisions of OSPAR, the Oslo-Paris accords group, are binding on its members only if they affirm them. In 2000, 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.

13. U.S. Department of Energy. Office of Arms Control and Nonproliferation. *Nonproliferation and Arms Control Assessment of Weapons-Usable Fissile Material Storage and Excess Plutonium Disposition Alternatives*. (DOE/NN-0007) Washington DC: DOE, January 1997. Page 38.

14. We use a conservative estimate of 7 kilograms per bomb for commercial grade plutonium.

15. "Japanese nukes could counter China – politician," *Reuters*, April 6, 2002. Dateline: Tokyo.

16. R.Bari, L-Y Cheng, J. Phillips, J. Pilat, G. Rochau, I. Therios, R. Wigeland, E. Wonder, M. Zentner. *Proliferation Risk Reduction Study of Alternative Spent Fuel Processing*. To be presented at the Institute of Materials Management (INMM) 50th Annual Meeting, Tucson, Arizona, USA, July 12-16,2009. Upton, NY: Brookhaven National Laboratory, July 2009. On the Web at http://www.bnl.gov/isd/documents/70289.pdf.

17. Arjun Makhijani and Brice Smith. *Dangerous Discrepancies: Missing Weapons Plutonium in Los Alamos National Laboratory Waste Accounts*. Takoma Park, MD: Institute for Energy and Environmental Research, November 29, 2005, reissued with corrections April 21, 2006. The report plus IEER's correspondence with federal government agencies can be found at http://www.ieer.org/pu/index.html.

18. Joby Warrick, Spread of Nuclear Weapons Is Feared, *Washington Post*, May 12, 2008, p. A1. On the Web at www.washingtonpost.com/wpdyn/content/article/2008/05/11/AR2008051102212.html.

19. For more details on this recommendation please see http://www.ieer.org/reports/ManagingSpentFuel-BRC-2010-slides.pdf and http://www.ieer.org/reports/ManagingSpentFuel-BRC-2010-Summary.pdf.

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