

# The Beauty of the Nuclear Fuel Cycle

by Marjorie Mazel Hecht

It would take 2 million grams of oil or 3 million grams of coal to equal the power contained in 1 gram of uranium fuel.<sup>1</sup> Unlike oil and coal, nuclear fuel is recyclable and, in a breeder reactor, it can actually produce more fuel than is used up! For these reasons, nuclear energy is by far the best means now available to power a modern industrial economy.

Nuclear power is truly a gift to humanity, and only the propaganda of Malthusian extremists, dedicated to stopping human progress and reducing the world's population, has created public fear and skepticism.

The best way to overcome irrational fear is through knowledge. To this end, reviewed here is the process by which natural uranium ore is turned into fuel for a nuclear reactor, how it is used, and how it can be recycled, such that the reader will come to understand that there is really no such thing as nuclear "waste."

## The Nuclear Fuel Cycle

To understand the "renewability" of nuclear fission fuel, we have to look at the complete fuel cycle. At the beginning of the nuclear age, it was assumed that nations would complete the fuel cycle—including the reprocessing of spent

nuclear fuel from reactors, to get as near to 100 percent use of the uranium fuel as possible. Here we very briefly review the seven steps of this cycle. Keep in mind that the brevity of description leaves out details of the complex chemical processes, which were initiated during the Manhattan Project and are still being improved on.

**1** First, natural uranium is mined. There are enough sources of uranium worldwide for today's immediate needs, but once we begin an ambitious nuclear development program (to build 6,000 nuclear reactors in order to provide enough electricity to bring the entire world population up to a decent living standard), we would have to accelerate the development of fast breeder nuclear reactors, which produce more fuel than they consume in operation.

**2** Next, the uranium is processed and milled into uranium oxide  $U_3O_8$ , called



DOE

An overhead view of rows of centrifuge units at a U.S. enrichment plant in Piketon, Ohio.

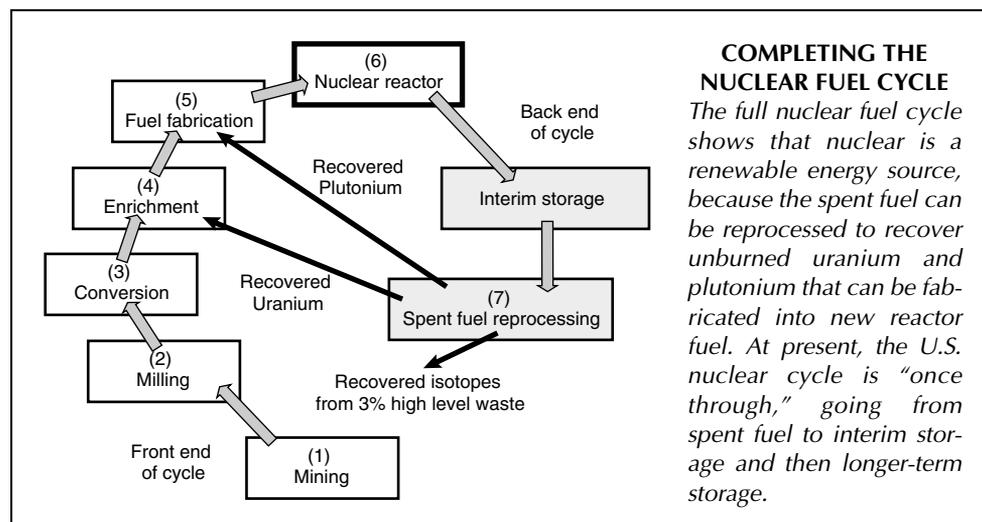
yellowcake, which is the raw material for fission fuel. Yellowcake became infamous in the political fabrication that Saddam Hussein's Iraq was trying to import yellowcake from Niger, in order to use it for bomb-making.

It is basically natural uranium ore, which is crushed and processed by leaching (with acid or carbonate) to dissolve the uranium, which can then be extracted and concentrated to 75 percent uranium, in combination with ammonium or sodium-magnesium.

**3** The concentrated uranium is then converted into uranium hexafluoride ( $UF_6$ ), which is heated into a gas form suitable for enrichment.

## Uranium Enrichment

**4** Natural uranium has one primary isotope, U-238, which is not fissionable, and a much smaller amount of U-235, which fissions. Because most uranium (99.276 percent) is U-238, the uranium fuel must go through a process of enrichment, to increase the ratio of fissionable U-235 to the non-fissionable U-238 from about 0.7 percent to 3 to 4 percent.



## COMPLETING THE NUCLEAR FUEL CYCLE

The full nuclear fuel cycle shows that nuclear is a renewable energy source, because the spent fuel can be reprocessed to recover unburned uranium and plutonium that can be fabricated into new reactor fuel. At present, the U.S. nuclear cycle is "once through," going from spent fuel to interim storage and then longer-term storage.



Frank Hoffman/DOE

*The huge Gaseous Diffusion Plant in Oak Ridge, Tenn., the first such facility in the world. The U-shaped building, constructed during the Manhattan Project, began operating in 1945. Later, the facility was expanded to produce enriched uranium for plants around the world.*

(Weapons uranium is enriched to about 93 percent U-235.)

The technology of enrichment was developed during the World War II Manhattan Project, when the object was to create highly enriched uranium (HEU) to be used in the atomic bomb. Civilian power reactors use mostly low-enriched uranium (LEU). (Canada has developed a type of reactor, the CANDU, which uses unenriched, natural uranium in combination with a heavy water moderator to produce fission.)

The gaseous diffusion method of enrichment, which is still used by the United States, was developed under the Manhattan Project. Uranium hexafluoride gas is pumped through a vast series of porous membranes—thousands of miles of them. The molecules of the lighter isotope (U-235) pass through the membrane walls slightly faster than do the heavier isotope (U-238). When extracted, the gas has an increased content of U-235, which is fed into the next membrane-sieve, and the process is repeated until the desired enrichment is reached. Because the molecular speeds of the two uranium isotopes differ by only about 0.4 percent, each diffusion operation must be repeated 1,200 times.

The Manhattan Project devised this method of gaseous diffusion with incredible speed and secrecy. It was not finished in time to produce all the uranium for the uranium bomb dropped on Japan, but it produced most of the enriched uranium for the civilian and military programs in subsequent years. Although a successful method, it required a tremendous amount of energy and a huge physical structure to house the “cascades” of separate membranes. Four power plants were built in Oak Ridge, Tenn., to power the process, producing as much electric power as the consumption of the entire Soviet Union in 1939! Almost all the power consumed in the diffusion process is used to circulate and compress the uranium gas.

Technological pessimists take note: At the time the gaseous diffusion plant was being built, scientists had not yet figured out how to make a membrane to be used in the process—but they did it in time to make it work!

The centrifuge system, used in Europe and Japan, is 10 times as energy efficient. The strong centrifugal field of a rotating cylinder sends the heavier isotope in uranium hexafluoride to the outside of the cylinder, where it can be

drawn off, while the U-235 diffuses to the inside of the cylinder. Because of the limitations of size of the centrifuge, many *thousands* of identical centrifuges, connected in a series called a cascade, are necessary to produce the required amounts of enriched uranium.

A centrifuge plant requires only about 4 percent of the power needed for a gaseous diffusion plant, and less water is needed for cooling.

Other methods of enrichment are possible—electromagnetic separation, laser isotope separation, and biological methods.

#### **Fabrication into Fuel Rods**

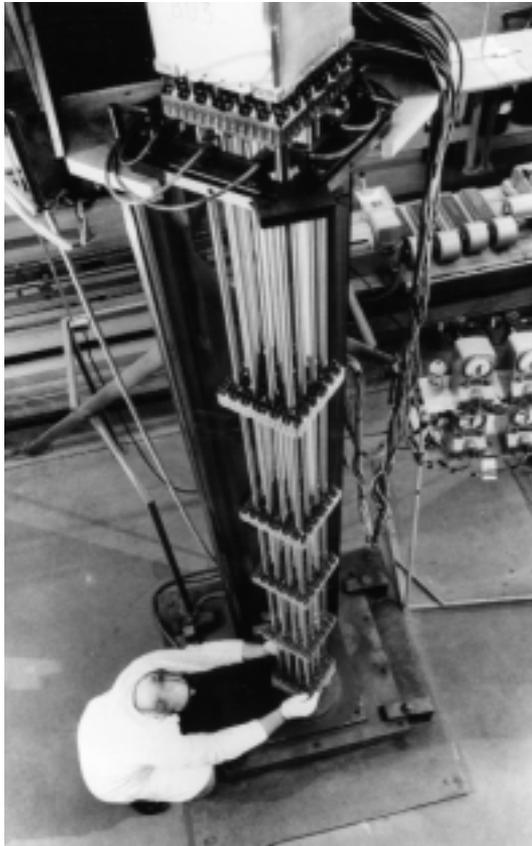
**5** Once the enriched uranium is separated from the depleted uranium, it is converted from  $UF_6$  into uranium dioxide and fabricated into uniform pellets. The pellets are loaded into long tubes made out of a zirconium alloy, which captures very few neutrons. This cladding prevents the release of fission products and also transfers the heat produced by the nuclear fission process in the fuel. The fuel is then transported to the reactor site.

Different types of reactors require different designs of fuel rods and fuel bundles. In a light water reactor, the fuel rods are inserted into the reactor to produce fission, which creates steam which turns a turbine that creates electricity.



U.S. AEC

*A cylinder of uranium hexafluoride enriched in U-235 is readied for shipment to a conversion facility, where it will be converted to uranium dioxide for use in fuel rods. The cylinder weighs 2.5 tons.*



Westinghouse Photo

*A partially completed nuclear fuel assembly. The long tubes guide the control rods in the reactor, which regulate its operation. The grids that hold the guide sheaths also align the fuel rods containing uranium pellets. When the fuel rods are inserted through the grids, parallel to the guide sheaths, the fuel assembly will be completed.*

The fuel for the next-generation high-temperature gas-cooled reactors is different: The enriched uranium is formed into tiny “pebbles” which are coated with graphite and special ceramics that serve as individual “containment buildings” for the fuel pebbles.

**6** Fuel rods are used for about four and a half years before replacement, and usually a reactor replaces about a third of its fuel at one time. The fuel is considered spent when the concentration of fissile uranium-235 becomes less than 1 percent. When removed from the reactor, the spent fuel is put into cooling pools, which shield it as its short-lived nuclides decay. Within a year, the total radioactivity level is only about 12 percent of what it was when the fuel rod came out of the reactor.

At present, the United States does not reprocess spent fuel, and so the spent fuel rods sit in cooling pools at the reactor. After the spent fuel has cooled, it is stored in dry casks, waiting—for “burial” or reprocessing.

But the spent fuel is not “waste”! It contains between 90 and 96 percent of usable uranium, that can be separated out and recycled into new fuel, and it also contains a smaller amount—about 1 percent—of plutonium, a fuel for breeder reactors.

### Reprocessing

**7** Now for the remarkable *renewability* of nuclear fuel. The spent fuel from a single 1,000-megawatt nuclear plant, operated over 40 years, is equal to the energy in 130 million barrels of oil, or 37 million tons of coal. Why bury it? Extract it and process it into new fuel. Short-sighted policy makers (discussed below) decided in the 1970s, for no good reasons, that it was preferable to prevent the full use of this potential by burying the spent fuel in a once-through cycle.

The reprocessing method that was successfully used in the United States at the

Savannah River facility in South Carolina for military purposes is just as efficient for civilian spent fuel. Spent fuel rods are processed to remove the highly radioactive fission products (3%), and separate out (partition) the fissionable U-235 (96%) and plutonium (1%).

This plutonium could be directly used as fuel for breeder reactors, which was the intention of the completed fuel cycle. It can also be used to make mixed-oxide fuel, or MOX, which some of today’s reactors are being converted to burn as fuel. (Thirty-five reactors in Europe now use MOX fuel.)

The reprocessing facilities at Savannah River were called “canyons” because they were tall, narrow buildings. The spent nuclear fuel was handled remotely by technicians who were behind protective walls. This was large-

scale industrial processing, which was entirely successful, safe, and safeguarded.

Once the uranium was separated out, it was sent to another building at Savannah River to be fabricated for weapons use. The remaining amount of highly radioactive fission products—a tiny fraction of the spent fuel—was set aside for vitrification and storage. Today, the technologies exist, or could be developed, to extract valuable medical and other isotopes from this 4 percent of high-level waste. Virtually all of the spent fuel could be made usable.

U.S. civilian spent fuel could be reprocessed in a similar fashion using the Savannah River model—or by new technologies still to be developed.<sup>2</sup> Right now, Britain, France, Russia, and India reprocess civilian spent fuel, using the Purex method (which stands for Plutonium Uranium Extraction), and Japan has a commercial reprocessing plant now in a testing start-up phase. Other nuclear nations send their spent fuel to Britain or France for reprocessing, or they store it. China reprocesses military spent fuel.

### Who Opposes Reprocessing?

Reprocessing makes the antipopulation faction very nervous, because it implies that nuclear power will continue to develop as a source of electricity, and with a cheap and clean source of power, there are no limits to growth. Malthusians and other alarmists rant about the “dangers of proliferation,” but if you poke them, what they are really concerned about is the potential for nuclear energy to expand, and population and industrial development to grow.

The overt arguments against reprocessing are mostly scare tactics: Permitting U.S. reprocessing will make it easier, they say, for “bad guys” to build bombs—or dirty bombs. This is the gist of the objection, although it may be posed at length in more academic (and tedious) language.

But this argument is one based on fear—fear that an advanced technology can never be managed properly, and fear that we will never have a world where there aren’t “bad guys” who want to bomb us. It is the opposite of the Atoms for Peace philosophy.

In fact, if one is truly worried about diversion of plutonium, why not burn it



Nuclear Materials and Equipment Corporation

In this 1964 photo, laboratory technicians work in glove-boxes to remotely fabricate plutonium fuel elements.

to produce electricity, instead of letting it accumulate in storage? And as Savannah River manager William P. Bebbington, a veteran of the Manhattan Project wrote in a landmark 1976 article on reprocessing, “Perhaps our best hope is that someday plutonium will be more valuable for power-reactor fuel than for weapons, and that the nations will then beat their bombs into fuel rods.”<sup>3</sup>

A second objection is that reprocessing is not “economical”; it is cheaper to have a “once through cycle” and discard the spent fuel. But the cost/benefit basis on which such economics are calculated is a sham. What is the cost of *not* reprocessing—in terms of lives lost and society not advancing? And what about the cost of the storage of spent fuel—not to mention the still unused U.S. storage facility at Yucca Mountain, Nevada, which has become a costly political and emotional football.

The “proliferation” argument was key in 1976 in stopping U.S. reprocessing. Fear was fed by the idea that reprocessing would make more plutonium available, which could be diverted by “rogue” nations or groups to make clandestine nuclear weapons. President Ford, the incumbent, carried out a secret study, and issued a nuclear policy statement on Oct. 28, 1976, just five days

before the election, which advocated an end to reprocessing.

Jimmy Carter, who won that election, then carried out the policy to stop U.S. reprocessing; and the next President, Ronald Reagan, sealed the lid on the fuel-cycle coffin with the idea of “privatizing” both reprocessing and breeder reactors.

The full story of how reprocessing was stopped still has to be told. But the ending of the story is clear: The United States shot itself in the foot—twice: (1) The United States stopped an important technology, which this country had pioneered, and (2) the U.S. anti-reprocessing policy did *absolutely nothing* in the rest of the world to stop other countries from developing the full nuclear fuel cycle, or desiring to.<sup>4</sup>

Interestingly, the Ford Administration’s policy in 1976, which advocated killing U.S. reprocessing for the same fallacious reasons that President Carter later elaborated, was written under the direction of Ford’s chief of staff—Dick Cheney. And one of the key reports supporting Carter’s ban on reprocessing was written by the mentor of the leading neo-cons in the Bush Administration, Albert Wohlstetter, then a consultant to the Department of Defense.

Once the political decision is taken to begin an ambitious nuclear construction



E.I. DuPont DeNemours & Co

A 1972 photo of high-level waste storage tanks in construction at DOE’s Savannah River Plant in South Carolina. The tanks are built of carbon steel, surrounded by concrete encasements 2 to 3 feet thick, set about 40 feet in the ground and then covered with dirt. Shown are the steel tanks before concrete encasement. Each tank has a capacity of from 750,000 to 1,300,000 gallons.

program, reprocessing—both Purex and new technologies—will follow.

#### Notes

1. The energy density of nuclear can be seen by comparing fission fuel to other sources. In terms of volume of fuel necessary to do the same amount of work, a tiny pellet (1.86 grams) of uranium fuel equals 1,260 gallons of oil, or 6.15 tons of coal, or 23.5 tons of dry wood. This means that nuclear is 2.2 million times more energy dense than oil, and 3 million times more energy dense than coal. Thermonuclear fusion will be even orders of magnitude more energy dense. These calculations were based on the work of Dr. Robert J. Moon in 1985.
2. The U.S. Congress in the 2005 Energy Act included \$50 million for research on new reprocessing methods.
3. “The Reprocessing of Nuclear Fuels” by William P. Bebbington, *Scientific American*, December 1976, pp. 30-41.
4. Commenting on President Carter’s 1977 policy to shut down reprocessing and the Clinch River Breeder Reactor, Bernard Goldschmidt, a prominent French nuclear scientist, who had studied with Marie Curie, wrote: “By this extraordinary and unique act of self-mutilation, an already declining American industry was to become paralyzed in two key sectors of future development, fuel reprocessing and breeder reactors, precisely the sectors in which the United States was already between 5 and 10 years behind the Soviet Union and Western Europe, in particular, France. . . .”

#### For Further Reading

Scott W. Heaberlin, *A Case for Nuclear-Generated Electricity . . . or why I think nuclear power is cool and why it is important that you think so too* (Columbus, Oh.: Battelle Press, 2004).

Alan Waltar, *Radiation and Modern Life* (Amherst, N.Y.: Prometheus Books, 2004).

See also: <http://www.world-nuclear.org/education/education.htm> on the fuel cycle.