By Frank N. von Hippel

RETHINKING Nuclear Fuel Recycling

Plans are afoot to reuse spent reactor fuel in the U.S. But the advantages of the scheme pale in comparison with its dangers

KEY CONCEPTS

- Spent nuclear fuel contains plutonium, which can be extracted and used in new fuel.
- To reduce the amount of long-lived radioactive waste, the U.S. Department of Energy has proposed reprocessing spent fuel in this way and then "burning" the plutonium in special reactors.
- But reprocessing is very expensive. Also, spent fuel emits lethal radiation, whereas separated plutonium can be handled easily. So reprocessing invites the possibility that terrorists might steal plutonium and construct an atom bomb.
- The author argues against reprocessing and for storing the waste in casks until an underground repository is ready.

—The Editors

Although a dozen years have elapsed since any new nuclear power reactor has come online in the U.S., there are now stirrings of a nuclear renaissance. The incentives are certainly in place: the costs of natural gas and oil have skyrocketed; the public increasingly objects to the greenhouse gas emissions from burning fossil fuels; and the federal government has offered up to $8 billion in subsidies and insurance against delays in licensing (with new laws to streamline the process) and $18.5 billion in loan guarantees. What more could the moribund nuclear power industry possibly want?

Just one thing: a place to ship its used reactor fuel. Indeed, the lack of a disposal site remains a dark cloud hanging over the entire enterprise. The projected opening of a federal waste storage repository in Yucca Mountain in Nevada (now anticipated for 2017 at the earliest) has already slipped by two decades, and the cooling pools holding spent fuel at the nation's nuclear power plants are running out of space.

Most nuclear utilities are therefore beginning to store older spent fuel on dry ground in huge casks, each typically containing 10 tons of waste. Every year a 1,000-megawatt reactor discharges enough fuel to fill two of these casks, each costing about $1 million. But that is not all the industry is doing. U.S. nuclear utilities are suing the federal government, because they would not have incurred such expenses had the U.S. Department of Energy opened the Yucca Mountain repository in 1998 as originally planned. As a result, the government is paying for the casks and associated infrastructure and operations—a bill that is running about $300 million a year.

Under pressure to start moving the fuel off the sites, the DOE has returned to an idea that it abandoned in the 1970s—to "reprocess" the spent fuel chemically, separating the different elements so that some can be reused. Vast reprocessing plants have been running in France and the U.K. for more than a decade, and Japan began to operate its own $20-billion facility in 2006. So this strategy is not without precedent. But, as I discuss below, reprocessing is an expensive and dangerous road to take.

The Element from Hell

Grasping my reasons for rejecting nuclear fuel reprocessing requires nothing more than a rudimentary understanding of the nuclear fuel cycle and a dollop of common sense. Power reactors generate heat—which makes steam to turn electricity-generating turbines—by maintaining a nuclear chain reaction that splits (or "fissions") atoms. Most of the time the fuel is uranium, artificially enriched so that 4 to 5 percent is the chain-reacting isotope uranium 235; virtually all the rest is uranium 238. At an enrichment of only 5 percent, stolen reactor fuel cannot be used to construct an illicit atom bomb.

LISA APPELBACHER (*logo*)

▲ LA HAGUE, on France's Normandy coast, hosts a large complex that reprocesses spent fuel from nuclear power plants, extracting its plutonium for fabrication into new fuel. The U.S. Department of Energy has recently proposed building a similar facility.

MARTIN BOND *Photo Researchers, Inc.*

In the reactor, some of the uranium 238 absorbs a neutron and becomes plutonium 239, which is also chain-reacting and can in principle be partially "burned" if it is extracted and properly prepared. This approach has various drawbacks, however. One is that extraction and processing cost much more than the new fuel is worth. Another is that recycling the plutonium reduces the waste problem only minimally. Most important, the separated plutonium can readily serve to make nuclear bombs if it gets into the wrong hands; as a result, much effort has to be expended to keep it secure until it is once more a part of spent fuel.

These drawbacks become strikingly clear when one examines the experiences of the nations that have embarked on reprocessing programs. In France, the world leader in reprocessing technology, the separated plutonium (chemically combined with oxygen to form plutonium dioxide) is mixed with uranium 238 (also as an oxide) to make a "mixed oxide," or MOX, fuel. After being used to generate more power, the spent MOX fuel still contains about 70 percent as much plutonium as when it was manufactured; however, the addition of highly radioactive fission products created inside a reactor makes this plutonium difficult to access and make into a bomb. The used MOX fuel is shipped back to the reprocessing facility for indefinite storage. Thus, France is, in effect, using reprocessing to move its problem with spent fuel from the reactor sites to the reprocessing plant.

Japan is following France's example. The U.K. and Russia simply store their separated civilian plutonium—about 120 tons between them as of the end of 2005, enough to make 15,000 atom bombs.

Until recently, France, Russia and the U.K. earned money by reprocessing the spent fuel of other nations, such as Japan and Germany, where domestic antinuclear activists demanded that the government either show it had a solution for dealing with spent fuel or shut down its reactors. Authorities in these nations found that sending their spent fuel abroad for reprocessing was a convenient, if costly, way to deal with their nuclear wastes—at least temporarily.

With such contracts in hand, France and the U.K. were easily able to finance new plants for carrying out reprocessing. Those agreements specified, however, that the separated plutonium and any highly radioactive waste would later go back to the country of origin. Russia has recently adopted a similar policy. Hence, governments that send spent fuel abroad need eventually to arrange storage sites for the returning radioactive waste. That reality took a while to sink in, but it has now convinced almost all nations that bought foreign reprocessing services that they might as well store their spent fuel and save the reprocessing fee of about $1 million

A NUCLEAR RENAISSANCE?

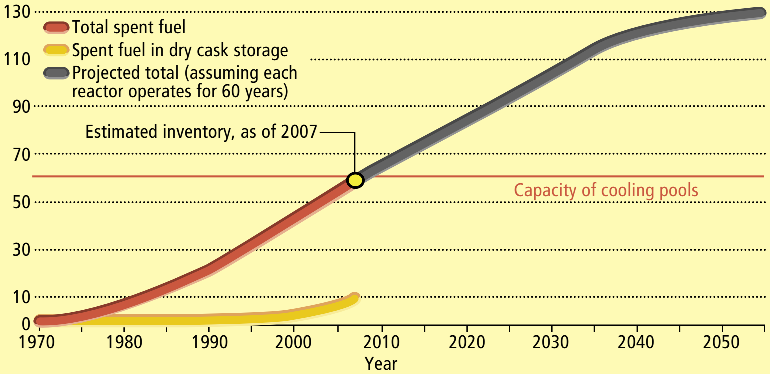
After decades of declining interest, nuclear energy is poised for a comeback, driven by:

- Rising costs of fossil fuels
- Nuclear power's lack of carbon emissions
- Generous government subsidies

[A GROWING PROBLEM]

Too Much Waste, Too Little Storage

ACCUMULATED SPENT FUEL FROM ALL U.S. NUCLEAR POWER REACTORS
(1,000 metric tons of uranium and associated reactor products)



The amount of spent fuel will rise substantially in coming decades even if no new reactors are built. Managers at nuclear power plants increasingly are forced to transfer the oldest spent fuel in their cooling pools to dry casks situated close by. Not surprisingly, the industry is pressuring the U.S. government to help find a solution to the problem.

CRITICAL POINT

The quantity of spent fuel so far accumulated by the U.S. nuclear industry (about 58,000 metric tons) now very nearly equals the capacity of the cooling pools used to hold such material at the reactor sites. By midcentury, the amount will roughly double.

per ton (10 times the cost of dry storage casks).

So France, Russia and the U.K. have lost virtually all their foreign customers. One result is that the U.K. plans to shut down its reprocessing plants within the next few years, a move that comes with a $92-billion price tag for cleaning up the site of these facilities. In 2000 France considered the option of ending reprocessing in 2010 and concluded that doing so would reduce the cost of nuclear electricity. Making such a change, though, might also engender acrimonious debates about nuclear waste—the last thing the French nuclear establishment wants in a country that has seen relatively little antinuclear activism.

Japan is even more politically locked into reprocessing: its nuclear utilities, unlike those of the U.S., have been unable to obtain permission to expand their on-site storage. Russia today has just a single reprocessing plant, with the ability to handle the spent fuel from only 15 percent of that country's nuclear reactors. The Soviets had intended to expand their reprocessing capabilities but abandoned those plans when their economy collapsed in the 1980s.

During the cold war, the U.S. operated reprocessing plants in Washington State and South Carolina to recover plutonium for nuclear weapons. More than half of the approximately 100 tons of plutonium that was separated in those efforts has been declared to be in excess of our national needs, and the DOE currently projects that disposing of it will cost more than $15 billion. The people who were working at the sites where this reprocessing took place are now primarily occupied with cleaning up the resulting mess, which is expected to cost around $100 billion.

In addition to those military operations, a small commercial reprocessing facility operated in upstate New York from 1966 to 1972. It separated 1.5 tons of plutonium before going bankrupt and becoming a joint federal-state cleanup venture, one projected to require about $5 billion of taxpayers' money.

With all the problems reprocessing entailed, one might rightly ask why it was pursued at all. Part of the answer is that for years after civilian nuclear power plants were first introduced, the U.S. Atomic Energy Commission (AEC) promoted reprocessing both domestically and abroad as essential to the future of nuclear power, because the industry was worried about running out of uranium (a concern that has since abated).

But that was before the security risks of plutonium production went from theoretical to real. In 1974 India, one of the countries that the U.S. assisted in acquiring reprocessing capabilities, used its first separated plutonium to build a nuclear weapon. At about this time, the late Theodore B. Taylor, a former U.S. nuclear weapons designer, was raising an alarm about the possibility that the planned separation and recycling of thousands of tons of plutonium every year would allow terrorists to steal enough of this material to make one or more nuclear bombs.

Separated plutonium, being only weakly radioactive, is easily carried off—whereas the plutonium in spent fuel is mixed with fission products that emit lethal gamma rays. Because of its great radioactivity, spent fuel can be transported only inside casks weighing tens of tons, and its plutonium can only be recovered with great difficulty, typically behind thick shielding using sophisticated, remotely operated equipment. So unseparated plutonium in spent fuel poses a far smaller risk of ending up in the wrong hands.

Having been awakened by India to the danger of nuclear weapons proliferation through reprocessing, the Ford administration (and later the Carter administration) reexamined the AEC's position and concluded that reprocessing was both unnecessary and uneconomic. The U.S. government therefore abandoned its plans to reprocess the spent fuel from civilian reactors and urged France and Germany to cancel contracts under which they were exporting reprocessing technology to Pakistan, South Korea and Brazil.

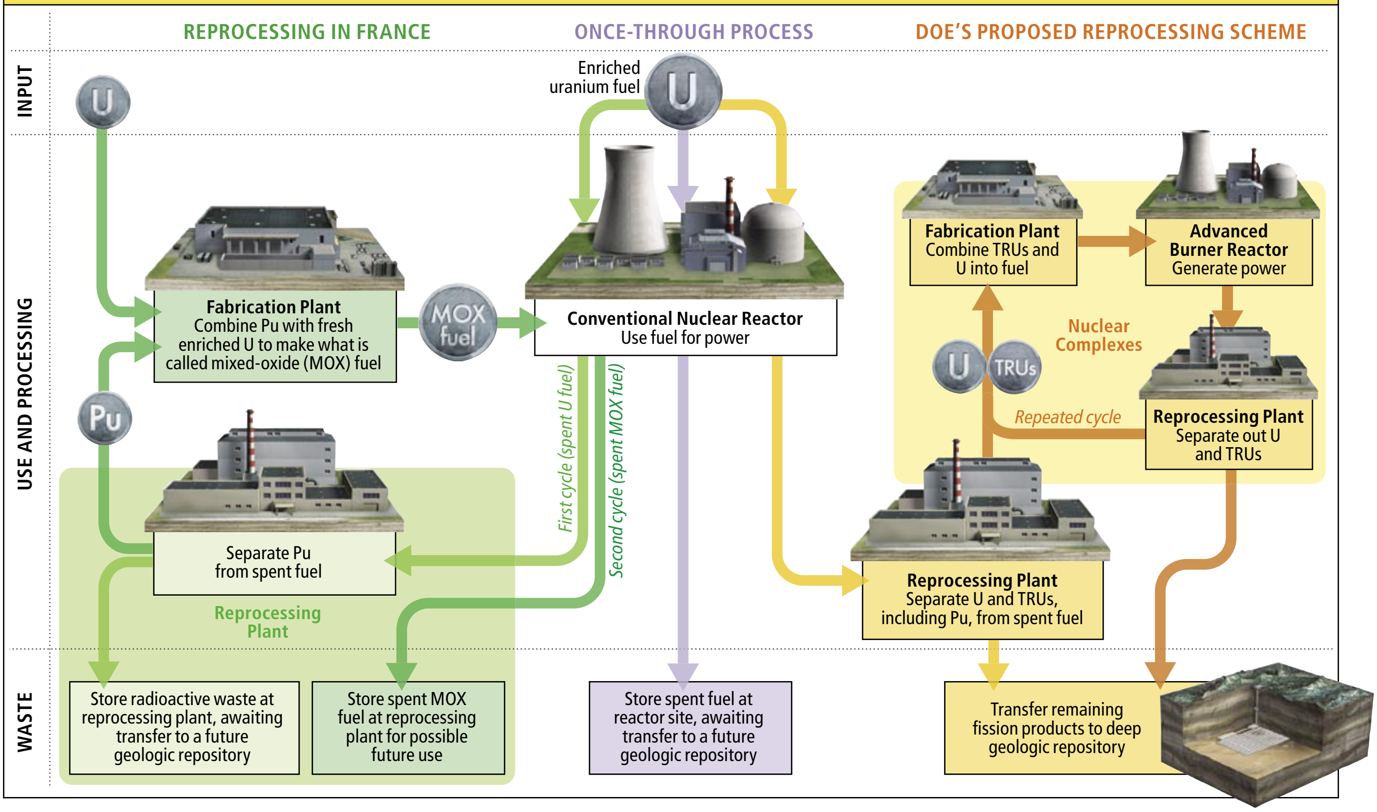
The Reagan administration later reversed the Ford-Carter position on domestic reprocessing, but the U.S. nuclear industry was no longer interested. It, too, had concluded that reprocessing

LUCY READING-IKKANDA

[BASICS]

FUEL-HANDLING OPTIONS

The nuclear power industry has a few options for managing spent reactor fuel. It can simply store the waste after fuel is used once, as the U.S. does now (*center*). Or it can reprocess the spent fuel, separating out components that can be reused. In France, plutonium (Pu) is prepared for an additional run in a reactor (*left*). Another idea, favored by the DOE, would repeatedly recycle plutonium and other elements heavier than uranium (transuranics, or TRUs) in a new kind of reactor (*right*). Reusing spent fuel seems appealing at first because it can shrink the amount of waste needing indefinite storage—but, the author notes (*box at bottom right*), the approach has serious drawbacks.



KEVIN HAND

to make use of the recovered plutonium would not be economically competitive with the existing "once-through" fueling system. Reprocessing, at least in the U.S., had reached a dead end, or so it seemed.

Rising from Nuclear Ashes

The current Bush administration has recently breathed life back into the idea of reprocessing spent nuclear fuel as part of its proposal to deploy a new generation of nuclear reactors. According to this vision, transuranics (plutonium and other similarly heavy elements extracted from conventional reactor fuel) would be recycled not once but repeatedly in the new reactors to break them down through fission into lighter elements, most of which have shorter half-lives. Consequently, the amount of nuclear waste needing to be safely stored for many millennia would be reduced [see "Smarter Use of Nuclear Waste," by William H. Hannum, Gerald E. Marsh and George S. Stanford; Scientific American, December 2005].

Some scientists view this new scheme as "technically sweet," to borrow a phrase J. Robert Oppenheimer once used to describe the design for the hydrogen bomb. But is it really so wise?

The proposal to recycle U.S. spent fuel in this way is not new. Indeed, in the mid-1990s the DOE asked the U.S. National Academy of Sciences (NAS) to carry out a study of this approach to reducing the amount of long-lived radioactive waste. The resulting massive report, *Nuclear Wastes: Technologies for Separation and Transmutation*, was very negative. The NAS panel concluded that recycling the transuranics in the first 62,000 tons of spent fuel (the amount that otherwise would have been stored in Yucca Mountain) would require "no less than $50 billion and easily could be over $100 billion"—in other words, it could well cost something like $500 for every person in the U.S. These numbers would have to be doubled to deal with the entire amount of spent fuel that existing U.S. reactors are expected to discharge during their lifetimes.

PROS & CONS

In theory, reprocessing spent fuel and recycling it in reactors reduces the quantity of uranium mined and leaves more of the waste in forms that remain radioactive for only a few centuries rather than many millennia. But in practice, this approach is problematic because it is expensive, reduces waste only marginally (unless an extremely costly and complex recycling infrastructure is built), and increases the risk that the plutonium in the spent fuel will be used to make nuclear weapons.

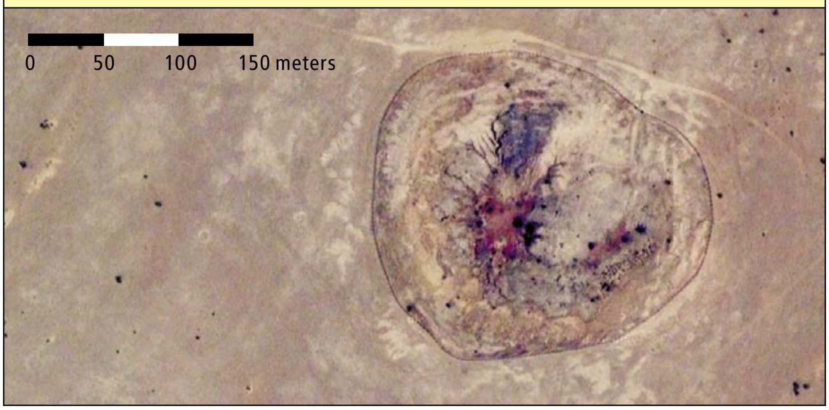
—F.N.v.H.

[A MAJOR DANGER]

Mass Destruction for the Masses?

The chief concern about reprocessing spent nuclear fuel is that by producing stores of plutonium, it might allow rogue nations or even terrorist groups to acquire atomic bombs. Because separated plutonium is only mildly radioactive, if a small amount were stolen, it could be easily handled (*above*) and carried off surreptitiously. And only a few kilograms are required for a nuclear weapon.

Before this danger was fully appreciated, the U.S. shared technology for reprocessing spent nuclear fuel with other countries but ceased doing so after India detonated a nuclear weapon built using some of its separated plutonium. Satellite imagery (*below*) reveals the crater created by India's first underground nuclear test in May 1974.



[THE AUTHOR]

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Why so expensive? Because conventional reactors could not be employed. Those use water both for cooling and for slowing down the neutrons given off when the uranium nuclei in the fuel break apart; this slowing allows the neutrons to induce other uranium 235 atoms to split, thereby sustaining a nuclear chain reaction. Feeding recycled fuel into such a reactor causes the heavier transuranics (plutonium 242, americium and curium) to accumulate. The proposed solution is a completely different type of nuclear reactor, one in which the neutrons get slowed less and are therefore able to break down these hard-to-crack atoms.

During the 1960s and 1970s the leading industrial countries, including the U.S., put the equivalent of more than 50 billion of today's dollars into efforts to commercialize such fast-neutron reactors, which are cooled by molten sodium rather than water. These devices were also called breeder reactors, because they were designed to generate more plutonium than they consumed and therefore could be much more efficient in using the energy in uranium. The expectation was that breeders would quickly replace conventional water-cooled reactors. But sodium-cooled reactors proved to be much more costly to build and troublesome to operate than expected, and most countries abandoned their efforts to commercialize them.

It is exactly this failed reactor type that the DOE now proposes to develop and deploy—but with its core reconfigured to be a net plutonium burner rather than a breeder. The U.S. would have to build between 40 and 75 1,000-megawatt reactors of this type to be able to break down transuranics at the rate they are being generated in the nation's 104 conventional reactors. If each of the new sodium-cooled reactors cost $1 billion to $2 billion more than one of its water-cooled cousins of the same capacity, the federal subsidy necessary would be anywhere from $40 billion to $150 billion, in addition to the $100 billion to $200 billion required for building and operating the recycling infrastructure. Given the U.S. budget deficit, it seems unlikely that such a program would actually be carried through.

If a full-scale reprocessing plant were constructed (as the DOE until recently was proposing to do by 2020) but the sodium-cooled reactors did not get built, virtually all the separated transuranics would simply go into indefinite storage. This awkward situation is exactly what befell the U.K., where the reprocessing program, started in the 1960s, has produced about 80 tons of separated plutonium, a legacy that will cost tens of billions of dollars to dispose of safely.

Reprocessing spent fuel and then storing the separated plutonium and radioactive waste indefinitely at the reprocessing plant is not a disposal strategy. Rather it is a strategy for disaster, because it makes the separated plutonium much more vulnerable to theft. In a 1998 report the U.K.'s Royal Society (the equivalent of the NAS), commenting on the growing stockpile of civilian plutonium in that country, warned that "the chance that the stocks of plutonium might, at some stage, be accessed for illicit weapons production is of extreme concern." In 2007 a second Royal Society report reiterated that "the status quo of continuing to stockpile a very dangerous material is not an acceptable long-term option."

Clearly, prudence demands that plutonium should not be stored at a reprocessing facility in a form that could readily be stolen. Indeed, common sense dictates that it should not be separated at all. Until a long-term repository is available, spent reactor fuel can remain at the sites of the nuclear power plants that generated it.

Would such storage be dangerous? I would argue that keeping older fuel produced by the once-through system in dry storage casks represents a

U.S. DEPARTMENT OF ENERGY (*top*); GEOEYE (*middle*); COURTESY OF FRANK N. VON HIPPEL (*bottom*) negligible addition to the existing nuclear hazard to the surrounding population. The 10 kilowatts of radioactive heat generated by the 10 tons of 20-year-old fuel packed in a dry storage cask is carried off convectively as it warms the air around it. Terrorists intent on doing harm might attempt to puncture such a cask using, say, an antitank weapon or the engine of a crashing aircraft, but under most circumstances only a small mass of radioactive fuel fragments would be scattered about a limited area. In contrast, if the coolant in the nearby reactor were cut off, its fuel would overheat and begin releasing huge quantities of vaporized fission products within minutes. And if the water were lost in a storage pool containing spent fuel, the zirconium cladding of the fuel rods would be heated up to ignition temperature within hours. Seen in this light, dry storage casks look pretty benign.

Is there enough physical room to keep them? Yes, there is plenty of space for more casks at U.S. nuclear power plants. Even the oldest operating U.S. reactors are having their licenses extended for another 20 years, and new reactors will likely be built on the same sites. So there is no reason to think that these storage areas are about to disappear. Eventually, of course, it will be necessary to remove the spent fuel and put it elsewhere, but there is no need to panic and adopt a policy of reprocessing, which would only make the situation much more dangerous and costly than it is today.

Fear and Loathing in Nevada

The long-term fate of radioactive waste in the U.S. hinges on how the current impasse over Yucca Mountain is resolved. Opinion on the site is divided. The regulatory requirements are tough: the DOE has to show that the mountain will contain the waste well enough to prevent significant off-site doses for a million years.

Demonstrating safety that far into the future is not easy, but the risks from even a badly designed repository are negligible in comparison with those from a policy that would make nuclear weapons materials more accessible. From this perspective, it is difficult to understand why the danger of local radioactive pollution 100,000 or a million years hence has generated so much more political passion in the U.S. than the continuing imminent danger from nuclear weapons.

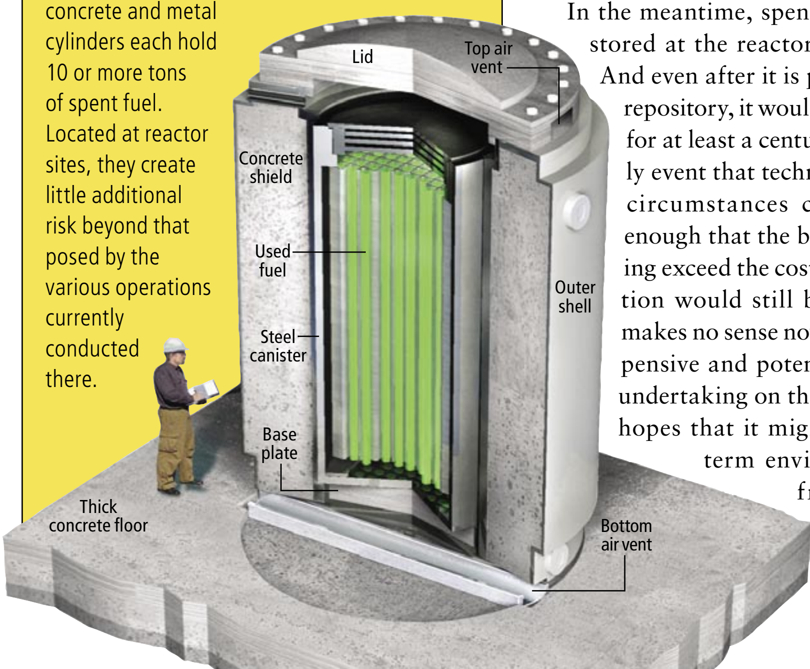
Part of the problem is the view in Nevada that the Reagan administration and Congress acted unfairly in 1987 when they cut short an objective evaluation of other candidate sites and designated Yucca Mountain as the location for the future nuclear waste repository. To overcome this perception, it may be necessary to reopen deliberations for choosing an additional site. Such a move should not be difficult. Indeed, the Nuclear Waste Policy Act of 1987 requires the secretary of energy to report to Congress by 2010 on the need for a second storage facility. Given the disastrous record of the DOE in dealing with radioactive waste, however, consideration should also be given to establishing a more specialized and less politicized agency for this purpose.

In the meantime, spent fuel can be safely stored at the reactor sites in dry casks. And even after it is placed in a geologic repository, it would remain retrievable for at least a century. So in the unlikely event that technology or economic circumstances change drastically enough that the benefits of reprocessing exceed the costs and risks, that option would still be available. But it makes no sense now to rush into an expensive and potentially catastrophic undertaking on the basis of uncertain hopes that it might reduce the long-term environmental burden from the nuclear power industry. ■

[WHAT TO DO]

A Vote for Dry Casks

Until a deep geologic repository for spent nuclear fuel opens, the author argues, the U.S. nuclear industry has a very good alternative for storing the spent fuel now accumulating in cooling pools: dry casks. These 150-ton concrete and metal cylinders each hold 10 or more tons of spent fuel. Located at reactor sites, they create little additional risk beyond that posed by the various operations currently conducted there.



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YUCCA UPDATE

Progress on the proposed U.S. nuclear repository at Yucca Mountain in Nevada remains slow. At best, its construction will not be authorized until 2011, and the project will not be completed until 2016. The U.S. nuclear industry thus will not begin storing spent fuel there until 2017—or even later, if work is delayed by scientific controversies, legal challenges or funding shortfalls.

➡ MORE TO EXPLORE

Nuclear Wastes: Technologies for Separation and Transmutation. National Academies Press, 1996.

The Future of Nuclear Power. An Interdisciplinary MIT Study, 2003. **http://web.mit.edu/nuclearpower**

Managing Spent Fuel in the United States: The Illogic of Reprocessing. Frank von Hippel in a research report of the International Panel on Fissile Materials, January 2007. **www.fissilematerials.org/ipfm/site_down/ipfmresearchreport03.pdf**