Smarter Use of

JANA BRENNING

Fast-neutron reactors could extract much more energy from recycled nuclear fuel, minimize the risks of weapons proliferation and markedly reduce the time nuclear waste must be isolated

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Despite long-standing public concern about the safety of nuclear energy, more and more people are realizing that it may be the most environmentally friendly way to generate large amounts of electricity. Several nations, including Brazil, China, Egypt, Finland, India, Japan, Pakistan, Russia, South Korea and Vietnam, are building or planning nuclear plants. But this global trend has not as yet extended to the U.S., where work on the last such facility began some 30 years ago.

If developed sensibly, nuclear power could be truly sustainable and essentially inexhaustible and could operate without contributing to climate change. In particular, a relatively new form of nuclear technology could overcome the principal drawbacks of current methods—namely, worries about reactor accidents, the potential for diversion of nuclear fuel into highly destructive weapons, the management of dangerous, long-lived radioactive waste, and the depletion of global reserves of economically available uranium. This nuclear fuel

NUCLEAR WASTE

cycle would combine two innovations: pyrometallurgical processing (a high-temperature method of recycling reactor waste into fuel) and advanced fast-neutron reactors capable of burning that fuel. With this approach, the radioactivity from the generated waste could drop to safe levels in a few hundred years, thereby eliminating the need to segregate waste for tens of thousands of years.

For neutrons to cause nuclear fission efficiently, they must be traveling either slowly or very quickly. Most existing nuclear power plants contain what are called thermal reactors, which are driven by neutrons of relatively low speed (or energy) ricocheting within their cores. Although thermal reactors generate heat and thus electricity quite efficiently, they cannot minimize the output of radioactive waste.

All reactors produce energy by splitting the nuclei of heavy-metal (high-atomic-weight) atoms, mainly uranium or elements derived from uranium. In nature, uranium occurs as a mixture of two isotopes, the easily fissionable uranium 235 (which is said to be “fissile”) and the much more stable uranium 238.

The uranium fire in an atomic reactor is both ignited and sustained by neutrons. When the nucleus of a fissile atom is hit by a neutron, especially a slow-moving one, it will most likely cleave (fission), releasing substantial amounts of energy and several other neutrons. Some of these emitted neutrons then strike other nearby fissile atoms, causing them to break apart, thus propagating a nuclear chain reaction. The resulting heat is conveyed out of the reactor, where it turns water into steam that is used to run a turbine that drives an electric generator.

Uranium 238 is not fissile; it is called “fissionable” because it sometimes splits when hit by a fast neutron. It is also said to be “fertile,” because when a uranium 238 atom absorbs a neutron without splitting, it transmutes into plutonium 239, which, like uranium 235, is fissile and can sustain a chain reaction. After about three years of service, when technicians typically remove used fuel from one of today’s reactors because of radiation-related degradation and the depletion of the uranium 235, plutonium is contributing more than half the power the plant generates.

In a thermal reactor, the neutrons, which are born fast, are slowed (or moderated) by interactions with nearby low-atomic-weight atoms, such as the hydrogen in the water that flows through reactor cores. All but two of the 440 or so commercial nuclear reactors operating are thermal, and most of them—including the 103 U.S. power reactors—employ water both to slow neutrons and to carry fission-created heat to the associated electric generators. Most of these thermal systems are what engineers call light-water reactors.

In any nuclear power plant, heavy-metal atoms are consumed as the fuel "burns." Even though the plants begin with fuel that has had its uranium 235 content enriched, most of that easily fissioned uranium is gone after about three years. When technicians remove the depleted fuel, only about one twentieth of the potentially fissionable atoms in it (uranium 235, plutonium and uranium 238) have been used up, so the so-called spent fuel still contains about 95 percent of its original energy. In addition, only about one tenth of the mined uranium ore is converted into fuel in the enrichment process (during which the concentration of uranium 235 is increased considerably), so less than a hundredth of the ore's total energy content is used to generate power in today's plants.

This fact means that the used fuel from current thermal reactors still has the potential to stoke many a nuclear fire. Because the world's uranium supply is finite and the continued growth in the numbers of thermal reactors could exhaust the available low-cost uranium reserves in a few decades, it makes little sense to discard this spent fuel or the "tailings" left over from the enrichment process.

The spent fuel consists of three classes of materials. The fission products, which make up about 5 percent of the used fuel, are the true wastes—the ashes, if you will, of the fission fire. They comprise a mélange of lighter elements created when the heavy atoms split. The mix is highly radioactive for its first several years. After a decade or so, the activity is dominated by two isotopes, cesium 137 and strontium 90. Both are soluble in water, so they must be contained very securely. In around three centuries, those isotopes' radioactivity declines by a factor of 1,000, by which point they have become virtually harmless.

Uranium makes up the bulk of the spent nuclear fuel (around 94 percent); this is unfissioned uranium that has lost most of its uranium 235 and resembles natural uranium (which is just 0.71 percent fissile uranium 235). This component is only mildly radioactive and, if separated from the fission products and the rest of the material in the spent fuel, could readily be stored safely for future use in lightly protected facilities.

The balance of the material—the truly troubling part—is the transuranic component, elements heavier than uranium. This part of the fuel is mainly a blend of plutonium isotopes, with a significant presence of americium. Although the transuranic elements make up only about 1 percent of the spent fuel, they constitute the main source of today's nuclear waste problem. The half-lives (the period in which radioactivity halves) of these atoms range up to tens of thousands of years, a feature that led U.S. government regulators to require that the planned high-level nuclear waste repository at Yucca Mountain in Nevada isolate spent fuel for over 10,000 years.

Overview/*Nuclear Recycling*

- To minimize global warming, humanity may need to generate much of its future energy using nuclear power technology, which itself releases essentially no carbon dioxide.
- Should many more of today's thermal (or slow-neutron) nuclear power plants be built, however, the world's reserves of low-cost uranium ore will be tapped out within several decades. In addition, large quantities of highly radioactive waste produced just in the U.S. will have to be stored for at least 10,000 years—much more than can be accommodated by the Yucca Mountain repository in Nevada. Worse, most of the energy that could be extracted from the original uranium ore would be socked away in that waste.
- The utilization of a new, much more efficient nuclear fuel cycle—one based on fast-neutron reactors and the recycling of spent fuel by pyrometallurgical processing—would allow vastly more of the energy in the earth's readily available uranium ore to be used to produce electricity. Such a cycle would greatly reduce the creation of long-lived reactor waste and could support nuclear power generation indefinitely.

An Outdated Strategy

EARLY NUCLEAR engineers expected that the plutonium in the spent fuel of thermal reactors would be removed and then used in fast-neutron reactors, called fast breeders because they were designed to produce more plutonium than they consume. Nuclear power pioneers also envisioned an energy economy that would involve open commerce in plutonium. Plutonium can be used to make bombs, however. As nuclear technology spread beyond the major superpowers, this potential application led to worries over uncontrolled proliferation of atomic weapons to other states or even to terrorist groups.

The Nuclear Non-Proliferation Treaty partially addressed that problem in 1968. States that desired the benefits of nuclear power technology could sign the treaty and promise not to acquire nuclear weapons, whereupon the weapons-holding nations agreed to assist the others with peaceful applications. Although a cadre of international inspectors has since monitored member adherence to the treaty, the effectiveness of that international agreement has been spotty because it lacks effective authority and enforcement means.

Nuclear-weapons designers require plutonium with a very high plutonium 239 isotopic content, whereas plutonium from commercial power plants usually contains substantial quantities of the other isotopes of plutonium, making it difficult to use in a bomb. Nevertheless, use of plutonium from spent fuel in weapons is not inconceivable. Hence, President Jimmy Carter banned civilian reprocessing of nuclear fuel in the U.S. in 1977. He reasoned that if plutonium were not recovered from spent fuel it

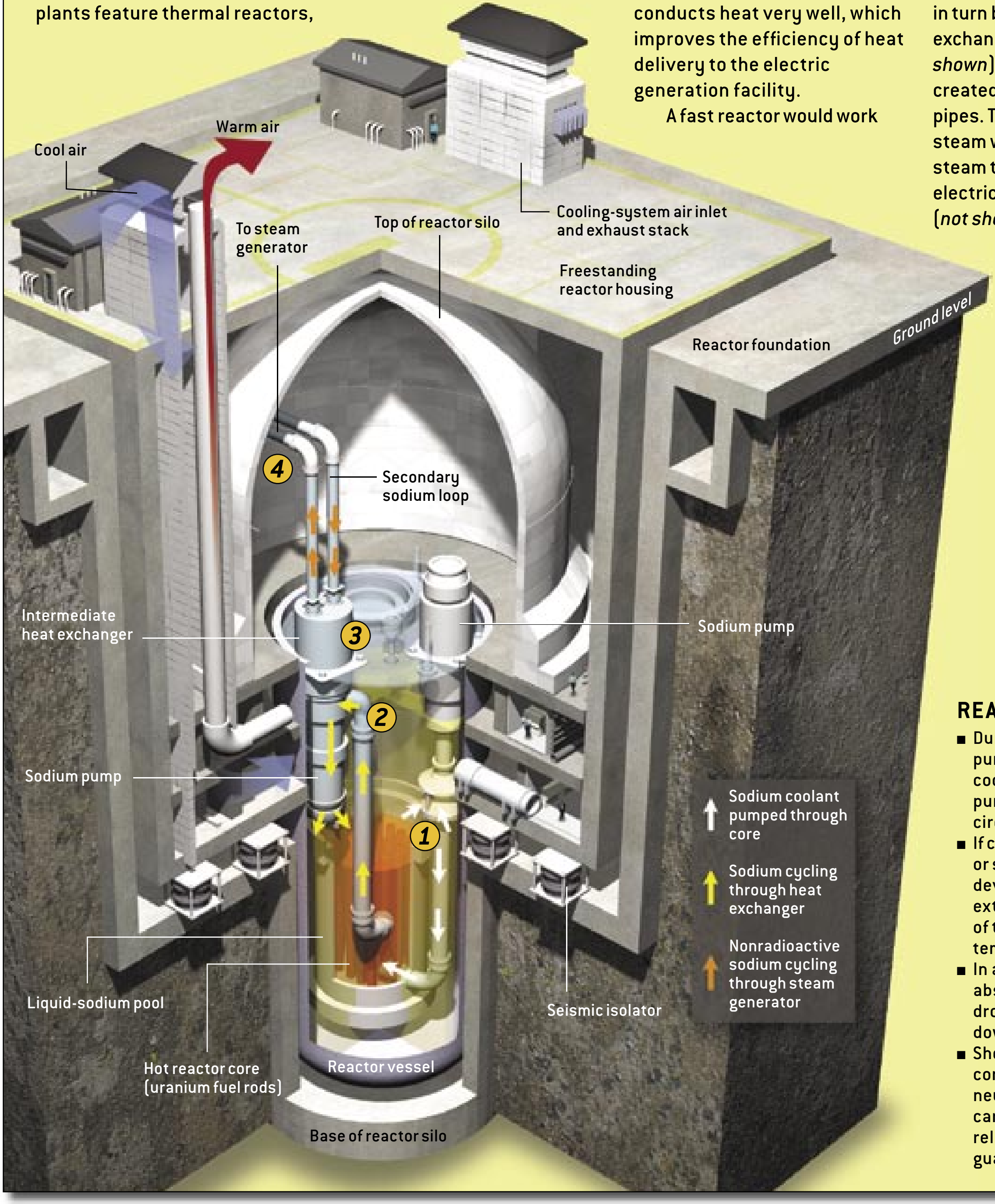
NEW TYPE OF NUCLEAR REACTOR

A safer, more sustainable nuclear power cycle could be based on the advanced liquid-metal reactor (ALMR) design developed in the 1980s by researchers at Argonne National Laboratory. Like all atomic power plants, an ALMR-based system would use nuclear chain reactions in the core to produce the heat needed to generate electricity.

Current commercial nuclear plants feature thermal reactors, which rely on relatively slow moving neutrons to propagate chain reactions in uranium and plutonium fuel. An ALMR-based system, in contrast, would use fast-moving (energetic) neutrons. This process permits all the uranium and heavier atoms to be consumed, thereby allowing vastly more of the fuel's energy to be captured. In the near term, the new reactor would burn fuel made by recycling spent fuel from thermal reactors.

In most thermal-reactor designs, water floods the core to slow (moderate) neutrons and keep it cool. The ALMR, however, employs a pool of circulating liquid sodium as the coolant (*1*). Engineers chose sodium because it does not slow down fast neutrons substantially and because it conducts heat very well, which improves the efficiency of heat delivery to the electric generation facility.

A fast reactor would work like this: Nuclear fire burning in the core would heat the radioactive liquid sodium running through it. Some of the heated sodium would be pumped into an intermediate heat exchanger (*2*), where it would transfer its thermal energy to nonradioactive liquid sodium flowing through the adjacent but separate pipes (*3*) of a secondary sodium loop. The nonradioactive sodium (*4*) would in turn bring heat to a final heat exchanger/steam generator (*not shown*), where steam would be created in adjacent water-filled pipes. The hot, high-pressure steam would then be used to turn steam turbines that would drive electricity-producing generators (*not shown*).



REACTOR SAFEGUARDS

- During operation, powerful pumps would force sodium coolant through the core. If the pumps failed, gravity would circulate the coolant.
- If coolant pumps malfunctioned or stopped, special safety devices would also permit extra neutrons to leak out of the core, lowering its temperature.
- In an emergency, six neutron-absorbing control rods would drop into the core to shut it down immediately.
- Should chain reactions continue, thousands of neutron-absorbing boron carbide balls would be released into the core, guaranteeing shutdown.

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could not be used to make bombs. Carter also wanted America to set an example for the rest of the world. France, Japan, Russia and the U.K. have not, however, followed suit, so plutonium reprocessing for use in power plants continues in a number of nations.

An Alternative Approach

When the ban was issued, "reprocessing" was synonymous with the PUREX (for *p*lutonium *u*ranium *ex*traction) method, a technique developed to meet the need for chemically pure plutonium for atomic weapons. Advanced fast-neutron reactor technology, however, permits an alternative recycling strategy that does not involve pure plutonium at any stage. Fast reactors can thus minimize the risk that spent fuel from energy production would be used for weapons production, while providing a unique ability to squeeze the maximum energy out of nuclear fuel [*see box below*]. Several such reactors have been built and used for power generation—in France, Japan, Russia, the U.K. and the U.S.—two of which are still operating [see "Next-Generation Nuclear Power," by James A. Lake, Ralph G. Bennett and John F. Kotek; Scientific American, January 2002].

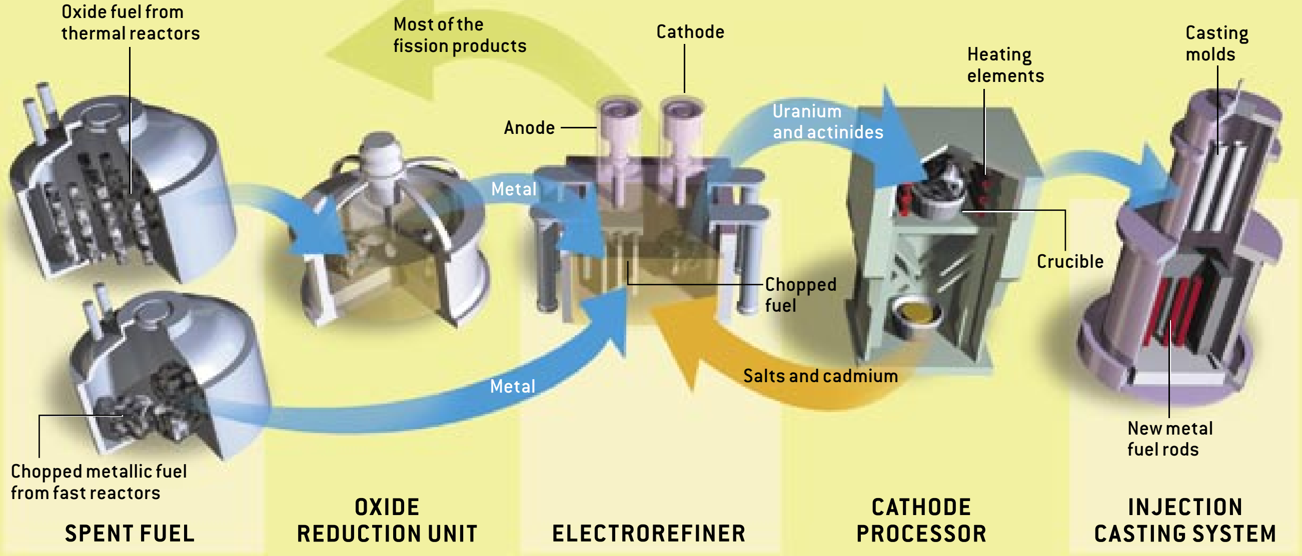
Fast reactors can extract more energy from nuclear fuel than thermal reactors do because their rapidly moving (higher-energy) neutrons cause atomic fissions more efficiently than the slow thermal neutrons do. This effectiveness stems from two phenomena. At slower speeds, many more neutrons are absorbed in nonfission reactions and are lost. Second, the higher energy of a fast neutron makes it much more likely that a fertile heavy-metal atom like uranium 238 will fission when struck. Because of this fact, not only are uranium 235 and plutonium 239 likely to fission in a fast reactor, but an appreciable fraction of the heavier transuranic atoms will do so as well.

Water cannot be employed in a fast reactor to carry the heat from the core—it would slow the fast neutrons. Hence, engineers typically use a liquid metal such as sodium as a coolant and heat transporter. Liquid metal has one big advantage over water. Water-cooled systems run at very high pressure, so that a small leak can quickly develop into a large release of steam and perhaps a serious pipe break, with rapid loss of reactor coolant. Liquid-metal systems, however, operate at atmospheric pressure, so they present vastly less potential for a major release. Nevertheless, sodium catches fire if exposed to water, so it must be managed carefully. Considerable industrial experience with handling the substance has been amassed over the years, and management methods are well developed. But sodium fires have occurred, and undoubtedly there will be more. One sodium fire began in 1995 at the Monju

NEW WAY TO REUSE NUCLEAR FUEL

The key to pyrometallurgical recycling of nuclear fuel is the electrorefining procedure. This process removes the true waste, the fission products, from the uranium, plutonium and the other actinides (heavy radioactive elements) in the spent fuel. The actinides are kept mixed with the plutonium so it cannot be used directly in weapons.

Spent fuel from today's thermal reactors (uranium and plutonium oxide) would first undergo oxide reduction to convert it to metal, whereas spent metallic uranium and plutonium fuel from fast reactors would go straight to the electrorefiner. Electrorefining resembles electroplating: spent fuel attached to an anode would be suspended in a chemical bath; then electric current would plate out uranium and other actinides on the cathode. The extracted elements would next be sent to the cathode processor to remove residual salts and cadmium from refining. Finally, the remaining uranium and actinides would be cast into fresh fuel rods, and the salts and cadmium would be recycled.



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fast reactor in Japan. It made a mess in the reactor building but never posed a threat to the integrity of the reactor, and no one was injured or irradiated. Engineers do not consider sodium's flammability to be a major problem.

Researchers at Argonne National Laboratory began developing fast-reactor technology in the 1950s. In the 1980s this research was directed toward a fast reactor (dubbed the advanced liquid-metal reactor, or ALMR), with metallic fuel cooled by a liquid metal, that was to be integrated with a high-temperature pyrometallurgical processing unit for recycling and replenishing the fuel. Nuclear engineers have also investigated several other fast-reactor concepts, some burning metallic uranium or plutonium fuels, others using oxide fuels. Coolants of liquid lead or a lead-bismuth solution have been used. Metallic fuel, as used in the ALMR, is preferable to oxide for several reasons: it has some safety advantages, it will permit faster breeding of new fuel, and it can more easily be paired with pyrometallurgical recycling.

Pyroprocessing

THE PYROMETALLURGICAL process ("pyro" for short) extracts from used fuel a mix of transuranic elements instead of pure plutonium, as in the PUREX route. It is based on electroplating—using electricity to collect, on a conducting metal electrode, metal extracted as ions from a chemical bath. Its name derives from the high temperatures to which the metals must be subjected during the procedure. Two similar approaches have been developed, one in the U.S., the other in Russia. The major difference is that the Russians process ceramic (oxide) fuel, whereas the fuel in an ALMR is metallic.

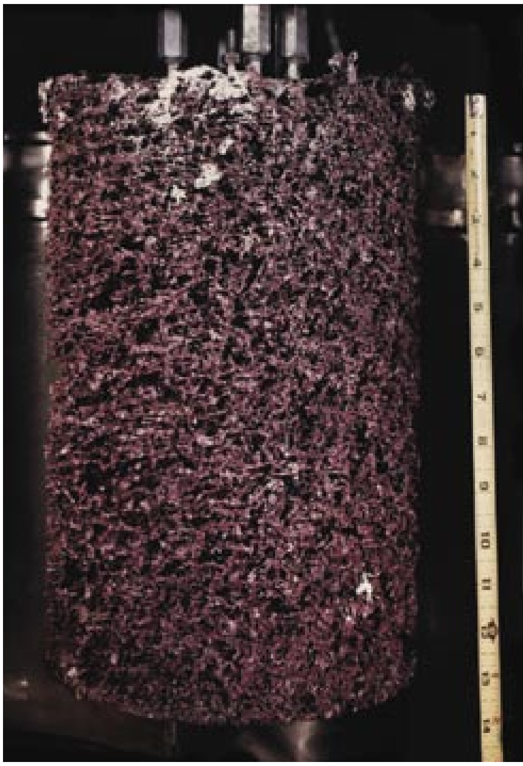
In the American pyroprocess [*see box on opposite page*], technicians dissolve spent metallic fuel in a chemical bath. Then a strong electric current selectively collects the plutonium and the other transuranic elements on an electrode, along with some of the fission products and much of the uranium. Most of the fission products and some of the uranium remain in the bath. When a full batch is amassed, operators remove the electrode. Next they scrape the accumulated materials off the electrode, melt them down, cast them into an ingot and pass the ingot to a refabrication line for conversion into fast-reactor fuel. When the bath becomes saturated with fission products, technicians clean the solvent and process the extracted fission products for permanent disposal.

Thus, unlike the current PUREX method, the pyroprocess collects virtually all the transuranic elements (including the plutonium), with considerable carryover of uranium and fission products. Only a very small portion of the transuranic component ends up in the final waste stream, which reduces the needed isolation time drastically. The combination of fission products and transuranics is unsuited for weapons or even for thermal-reactor fuel. This mixture is, however, not only tolerable but advantageous for fueling fast reactors.

Although pyrometallurgical recycling technology is not quite ready for immediate commercial use, researchers have demonstrated its basic principles. It has been successfully demonstrated on a pilot level in operating power plants, both in the U.S. and in Russia. It has not yet functioned, however, on a full production scale.

Comparing Cycles

THE OPERATING CAPABILITIES of thermal and fast reactors are similar in some ways, but in others the differences are huge [*see box on next page*]. A 1,000-megawatt-electric thermal-reactor plant, for example, generates more than 100 tons of spent fuel a year. The annual waste output from a fast reactor with the same electrical capacity, in contrast, is a little more than a single ton of fission products, plus trace amounts of transuranics.


EXTRACTED URANIUM and actinide elements from spent thermal-reactor fuel are plated out on the cathode of an electrorefiner during the pyroprocessing procedure. After further processing, the metallic fuel can be burned in fast-neutron reactors.

ARGONNE NATIONAL LABORATORY

Waste management using the ALMR cycle would be greatly simplified. Because the fast-reactor waste would contain no significant quantity of long-lived transuranics, its radiation would decay to the level of the ore from which it came in several hundred years, rather than tens of thousands.

If fast reactors were used exclusively,

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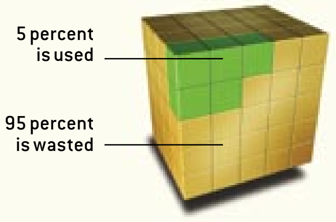
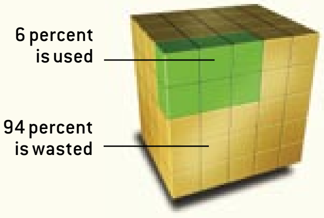
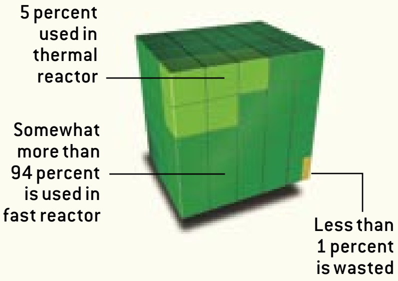
COMPARING THREE NUCLEAR FUEL CYCLES

Three major approaches to burning nuclear fuel and handling its wastes can be employed; some of their features are noted below.

ONCE-THROUGH ROUTE	PLUTONIUM RECYCLING	FULL RECYCLING
Fuel is burned in thermal reactors and is not reprocessed; occurs in the U.S.	Fuel is burned in thermal reactors, after which plutonium is extracted using what is called PUREX processing; occurs in other developed nations	Recycled fuel prepared by pyrometallurgical processing would be burned in advanced fast-neutron reactors; prototype technology
FUEL UTILIZATION		
 Initial fuel supply		
Uses about 5 percent of energy in thermal-reactor fuel and less than 1 percent of energy in uranium ore (the original source of fuel) Cannot burn depleted uranium (that part removed when the ore is enriched) or uranium in spent fuel	Uses about 6 percent of energy in original reactor fuel and less than 1 percent of energy in uranium ore Cannot burn depleted uranium or uranium in spent fuel	Can recover more than 99 percent of energy in spent thermal-reactor fuel After spent thermal-reactor fuel runs out, can burn depleted uranium to recover more than 99 percent of the rest of the energy in uranium ore
REQUIRED FACILITIES AND OPERATIONS		
Red: requires rigorous physical safeguards	Orange: needs only moderate physical safeguards	Blue: potential risks for future generations
Uranium mines Fuel enrichment to concentrate fissile uranium Fuel fabrication Power plants Interim waste storage (until waste can be permanently disposed of) Permanent storage able to securely segregate waste for 10,000 years (Needs no plutonium handling or waste processing operations)	Uranium mines Fuel enrichment Plutonium blending (mixing) Off-site fuel fabrication Off-site PUREX reprocessing Power plants Interim waste storage Off-site waste processing Permanent storage able to securely segregate waste for 10,000 years	On-site fuel fabrication On-site pyrometallurgical processing (prompt recycling of spent fuel) Power plants On-site waste processing Storage able to segregate waste for less than 500 years (No mining needed for centuries; no uranium enrichment needed, ever)
PLUTONIUM FATE		
Increasing inventories of plutonium in used fuel Excess weapons-grade plutonium degraded only slowly by mixing into fresh fuel	Increasing inventories of plutonium in used fuel and available for economic trade Excess weapons-grade plutonium degraded only slowly by mixing into fresh fuel	Inventories eventually shrink to only what is in use in reactors and in recycling Existing excess weapons-grade plutonium can be degraded rapidly Plutonium in the fuel is too impure for diversion to weapons
TYPES OF WASTE		
Energy-rich used fuel isolated in containers and underground storage facility Waste is radioactive enough to be defined as "self-protected" for a few hundred years against most groups wanting to obtain plutonium 239 for building nuclear weapons	Energy-rich, highly stable glassy waste Waste is radioactive enough to be defined as "self-protected" for a few hundred years against most groups wanting to obtain plutonium 239 for building nuclear weapons	Tailored waste forms that would only have to remain intact for 500 years, after which material would no longer be hazardous Lacking plutonium, waste would not be useful for making weapons

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transportation of highly radioactive materials would occur only under two circumstances—when the fission product waste was shipped to Yucca Mountain or an alternative site for disposal and when start-up fuel was shipped to a new reactor. Commerce in plutonium would be effectively eliminated.

Some people are advocating that the U.S. embark on an extensive program of PUREX processing of reactor fuel, making mixed oxides of uranium and plutonium for cycling back into thermal reactors. Although the mixed oxide (MOX) method is currently being used for spoiling excess weapons plutonium so that it cannot be employed in bombs—a good idea—we think that it would be a mistake to deploy the much larger PUREX infrastructure that would be required to process civilian fuel. The resource gains would be modest, whereas the long-term waste problem would remain, and the entire effort would delay for only a short time the need for efficient fast reactors.

The fast-reactor system with pyroprocessing is remarkably versatile. It could be a net consumer or net producer of plutonium, or it could be run in a break-even mode. Operated as a net producer, the system could provide start-up materials for other fast-reactor power plants. As a net consumer, it could use up excess plutonium and weapons materials. If a break-even mode were chosen, the only additional fuel a nuclear plant would need would be a periodic infusion of depleted uranium (uranium from which most of the fissile uranium 235 has been removed) to replace the heavy-metal atoms that have undergone fission.

Business studies have indicated that this technology could be economically competitive with existing nuclear power technologies [see the Dubberly paper in "More to Explore," on this page]. Certainly pyrometallurgical recycling will be dramatically less expensive than PUREX reprocessing, but in truth, the economic viability of the system cannot be known until it is demonstrated.

The overall economics of any energy source depend not only on direct costs but also on what economists call "externalities," the hard-to-quantify costs of outside effects resulting from using the technology. When we burn coal or oil to make electricity, for example, our society accepts the detrimental health effects and the environmental costs they entail. Thus, external costs in effect subsidize fossil-fuel power generation, either directly or via indirect effects on the society as a whole. Even though they are difficult to reckon, economic comparisons that do not take externalities into account are unrealistic and misleading.

Coupling Reactor Types

IF ADVANCED FAST REACTORS come into use, they will at first burn spent thermal-reactor fuel that has been recycled using pyroprocessing. That waste, which is now "temporarily" stored on site, would be transported to plants that could process it into three output streams. The first, highly radioactive, stream would contain most of the fission products, along with unavoidable traces of transuranic elements. It would be transformed into a physically stable form—perhaps a glasslike substance—and then shipped to Yucca Mountain or some other permanent disposal site.

The second stream would capture virtually all the transuranics, together with some uranium and fission products. It would be converted to a metallic fast-reactor fuel and then transferred to ALMR-type reactors.

The third stream, amounting to about 92 percent of the spent thermal-reactor fuel, would contain the bulk of the uranium, now in a depleted state. It could be stashed away for future use as fast-reactor fuel.

Such a scenario cannot be realized overnight, of course. If we were to begin today, the first of the fast reactors might come online in about 15 years. Notably, that schedule is reasonably compatible with the planned timetable for shipment of spent thermal-reactor fuel to Yucca Mountain. It could instead be sent for recycling into fast-reactor fuel.

As today's thermal reactors reach the end of their lifetimes, they could be replaced by fast reactors. Should that occur, there would be no need to mine any more uranium ore for centuries and no further requirement, ever, for uranium enrichment. For the very long term, recycling the fuel of fast reactors would be so efficient that currently available uranium supplies could last indefinitely.

Both India and China have recently announced that they plan to extend their energy resources by deploying fast reactors. We understand that their first fast reactors will use oxide or carbide fuel rather than metal—a less than optimum path, chosen presumably because the PUREX reprocessing technology is mature, whereas pyroprocessing has not yet been commercially demonstrated.

It is not too soon for the U.S. to complete the basic development of the fast-reactor/pyroprocessing system for metallic fuel. For the foreseeable future, the hard truth is this: only nuclear power can satisfy humanity's long-term energy needs while preserving the environment. For large-scale, sustainable nuclear energy production to continue, the supply of nuclear fuel must last a long time. That means that the nuclear power cycle must have the characteristics of the ALMR and pyroprocessing. The time seems right to take this new course toward sensible energy development.

MORE TO EXPLORE

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