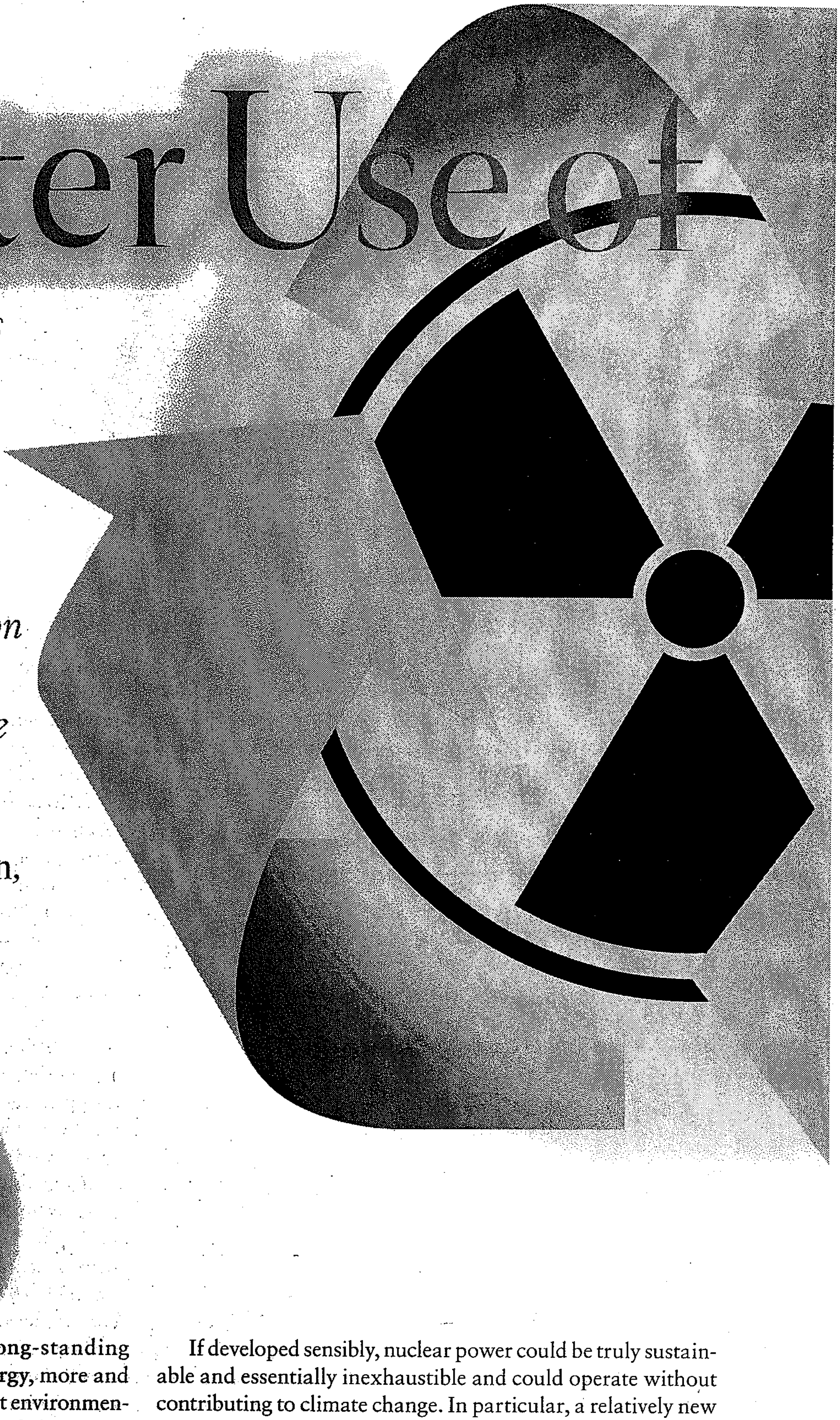
Smarter Use of



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

By William H. Hannum, Gerald E. Marsh and George S. Stanford

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

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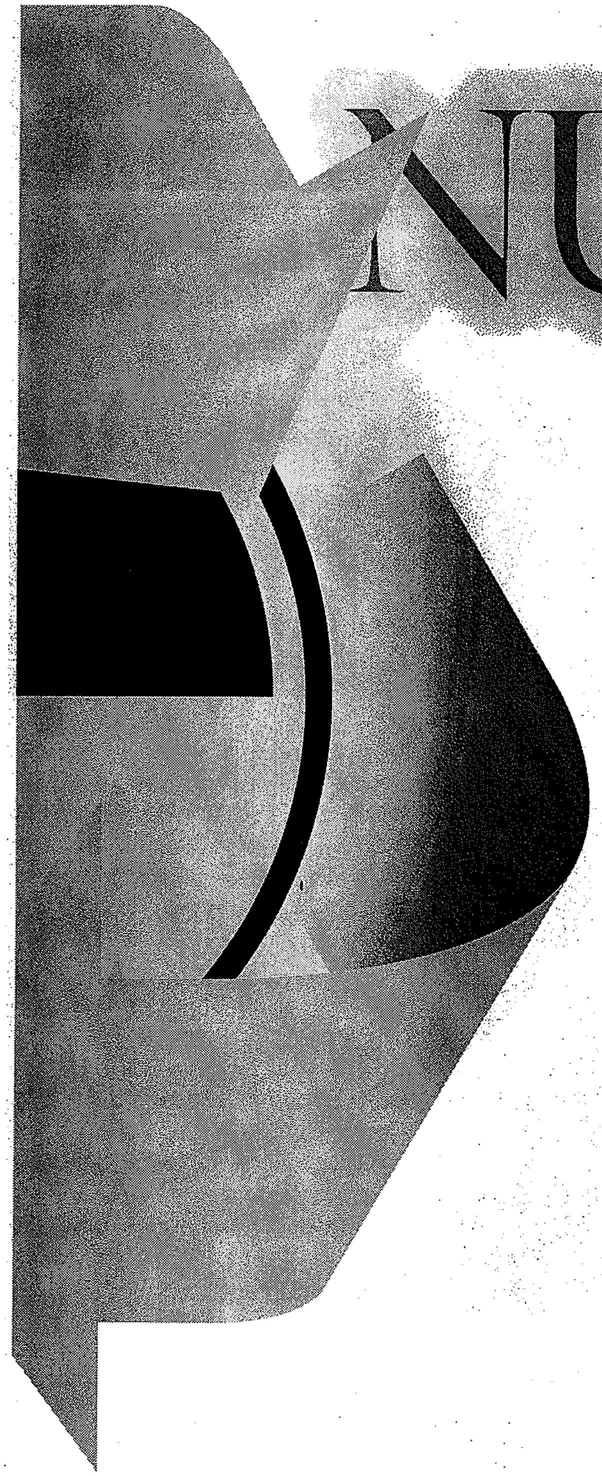

NUCLEAR WASTE

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.

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

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.