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It's time to give up on breeder reactors

Since the dawn of the nuclear age, nuclear energy advocates have dreamed of a reactor that could produce more fuel than it used. More than 60 years and $100 billion later, that vision remains as far from reality as ever.

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THE POSSIBILITY OF A PLUTONIUM-FUELED NUCLEAR reactor that could produce more plutonium than it consumed (dubbed a "breeder reactor") was first raised during World War II by scientists in the U.S. atomic bomb program. They were concerned that uranium 235, the rare chain-reacting isotope that fuels today's nuclear reactors, was insufficiently abundant on Earth to support a large-scale deployment of nuclear power. Over the next 20 years, Britain, France, Germany, India, Japan, and the Soviet Union followed the United States in establishing national plutonium breeder reactor programs. (Belgium, Italy, and the Netherlands joined the French and German programs as partners.) In all of these programs, the main driver was the hope of solving the long-term energy-supply problem by deploying large numbers of nuclear power reactors.

In "Fast Breeder Reactor Programs: History and Status," a new report by the International Panel on Fissile Materials, experiences with fast breeder reactors in six countries are examined.[1] These studies make clear that the assumptions driving the pursuit of breeder reactors for the past six decades have proven to be wrong.

False assumptions. The rationale for pursuing breeder reactors was based on the following key assumptions (sometimes explicit, sometimes implicit): (1) Uranium is scarce, and high-grade deposits would quickly become depleted if light water nuclear reactors, which do not breed more fuel than they consume, were deployed on a large scale; (2) breeder reactors would quickly become economically competitive with light water reactors (the dominant reactor design used today); (3) breeder reactors could be as safe and reliable as light water reactors; and (4) the proliferation risks posed by breeders and their "closed" fuel cycle, in which plutonium would be recycled, could be managed.

These assumptions, however, all proved to be wrong.

Uranium is cheap and abundant. The Nuclear Energy Agency's *Uranium 2007: Resources, Production, and Demand* report—popularly known as the Red Book—found that known global conventional resources of uranium recoverable for less than $130 per kilogram amounted to approximately 5.5 million tons and estimated that, with further exploration, an additional 7.6 million tons would be discovered in the same cost range. (Historically, the spot price of uranium has always been less than $100 per kilogram, except for a period in the late 1970s and around 2007.)

In 2007, uranium demand for the global fleet of nuclear power reactors was 67,000 metric tons—approximately 180 tons per gigawatt of generating capacity per year. The International Atomic Energy Agency (IAEA) projects that demand for uranium could increase to between 94,000 and 122,000 tons per year by 2030 as part of an assumed global increase in nuclear energy capacity.[2] Thus, at the highest rate of consumption projected for 2030, estimated global uranium resources would last for about 100 years. But even this projection is most likely conservative.

Plausible estimates of geological abundance predict that the amount of uranium recoverable at up to $130 per kilogram is virtually certain to be far greater than the numbers reported in the Red Book. Furthermore, unlike the situation with oil- or gas-fueled power plants, the cost of uranium fuel could increase greatly without having a serious impact on the cost of nuclear power. At $130 per kilogram, the cost of uranium contributes only one-third of a penny to the cost of a kilowatt-hour, which is less than 5 percent of the cost of electricity produced by a new light water reactor.[3]

Breeder reactors are costly to build and operate. About $100 billion (in 2007 dollars) has been spent worldwide on breeder reactor research and development and on demonstration breeder reactor projects. Yet none of these efforts has produced a reactor that is economically competitive with a conventional light water reactor. The capital costs per kilowatt of generating capacity of demonstration liquid sodium-cooled fast reactors have typically been more than twice those of water cooled reactors of comparable capacity. Although it could be expected that once in production this cost ratio would decline, today few, if any, experts argue that breeder reactor capital costs could be less than 25 percent higher than that of similarly sized water cooled reactors.[4]

Detailed economic comparisons of light water and breeder reactors show that light water reactors operating on a "once-through" fuel cycle (i.e., with spent fuel stored or disposed of in a deep geological repository) would be far less expensive than plutonium breeder reactors under a wide range of assumptions.[5]

Fast neutron reactors have special safety problems. Plutonium breeder reactors require fast neutrons if they are to breed more plutonium than they consume. They therefore cannot use water as a coolant since neutrons are slowed down dramatically by collisions with the light nuclei of hydrogen in water. To date, the coolant that has been used in all demonstration breeder reactors is liquid sodium.

> If the core of a breeder reactor heats up to the point of collapse and suffers a meltdown, the fuel can assume a more critical configuration and blow itself apart in a small nuclear explosion.

Although sodium has some safety advantages, it also has serious drawbacks. The most serious: It reacts violently with water and burns if exposed to air. The steam generators used in fast reactor systems, in which molten sodium and high-pressure water are separated by thin metal pipes, have proven to be one of its most troublesome features. Any leak results in a reaction that can rupture the tubes and lead to a major sodium-water fire.

A large fraction of the liquid sodium-cooled reactors that have been built have been shut down for long periods by such fires. A notable exception is Russia's BN-600 reactor, which has had a respectable operating record despite 14 sodium fires between 1980 and 1997. The reactor continued to operate throughout that time because its steam generators were located in separate bunkers to contain sodium-water fires and an extra steam generator was included so the reactor could continue to operate while a fire-damaged steam generator was repaired. Sodium leaks from pipes into the surrounding air also have resulted in serious fires. Japan's Monju prototype fast reactor experienced a major sodium-air fire in 1995. The reactor may restart this year after 15 years of being off-line.

Sodium creates other problems as well. When it absorbs a neutron, it turns into sodium 24, a gamma-emitting radioactive isotope. Thus, the sodium that cools the core becomes intensely radioactive. To ensure that a steam generator fire does not disperse radioactive sodium, reactor designers insert an intermediate sodium loop in which heat generated from the reactor is transferred to non-radioactive sodium through a sodium-sodium heat exchanger. The non-radioactive sodium delivers heat to the steam generators that then generate electricity. The extra sodium loops and associated pumps contribute to the higher capital costs of breeder reactors.

Finally, unlike water cooled reactors that cease functioning if they lose their coolant (a vital safety feature), fast neutron reactors can actually become more reactive in cases where sodium coolant is lost. Furthermore, if the core heats up to the point of collapse and suffers a meltdown, the fuel can assume a more critical configuration and blow itself apart in a small nuclear explosion. Whether such an explosion could release enough energy to rupture reactor containment and cause a Chernobyl-scale release of radioactivity into the environment is the subject of major concern and debate. These fears convinced Germany to scrap its roughly $4 billion Kalkar demonstration fast breeder reactor and sell it for $3.3 million to an amusement park operator.[6]

Sodium cooled breeder reactors have severe reliability problems. The necessity of keeping air from coming into contact with the sodium coolant makes refueling and repairing fast reactors much more difficult and time-consuming than for water cooled reactors. The fuel has to be removed in an atmosphere free of oxygen, the sodium drained, and the entire system flushed carefully to remove residual sodium without causing an explosion. Such headaches have contributed to many fast reactors sitting idle a large fraction of the time. France's defunct Superphénix, the world's only commercial-sized breeder reactor, generated on average less than 7 percent of its capacity over its nominal operating lifetime. Japan's Monju and Britain's Dounreay prototype fast reactors and the U.S. Enrico Fermi 1 demonstration breeder reactor had similar records. Russia's BN-600 has managed to maintain a respectable capacity factor (the percent of time it runs at full power), but only because of the willingness of its operators to keep it running despite multiple sodium fires.

Fast reactors and their fuel cycles pose serious proliferation risks. All reactors make plutonium in their fuel, but breeder reactors require that this plutonium be separated from the ferociously radioactive fission products in spent fuel and reused. The separation process, so-called reprocessing, also makes the plutonium more accessible to aspiring nuclear weapon makers.

This concern is not just theoretical. India justified its reprocessing program by citing an interest in breeder reactors, but in 1974, it used its first batch of separated plutonium to carry out a "peaceful nuclear explosion." This led the United States to rethink its promotion of plutonium as the fuel of the future. France used its Phénix prototype breeder reactor, starting in the late 1970s, to make weapon-grade plutonium. Decades of plutonium separation for planned breeder reactor-based nuclear energy programs have produced approximately 250 tons of stockpiled weapons-usable plutonium, enough to make more than 30,000 nuclear bombs.[7]

The George W. Bush administration proposed a program to make reprocessing more "proliferation resistant" by leaving some neptunium, americium, and curium mixed with the plutonium. Even if this were done, however, the gamma radiation emitted by the mixture would still be one hundred times less than what the IAEA considers sufficient to protect against theft and thousands of times less than the radiation protecting plutonium when it is in spent fuel.

> The persistence of breeder programs in Russia, India, and China is testimony to the ability of their nuclear establishments to tap into national treasuries despite the fact that breeders will not be able to compete with light water reactors for the foreseeable future.

Future prospects for breeders. After six decades and the expenditure of the equivalent of about $100 billion, the promise of breeder reactors remains largely unfulfilled. Britain, Germany, and the United States have abandoned their breeder reactor development programs. Despite the arguments by France's nuclear conglomerate AREVA that fast reactors will ultimately fission the increasingly large stockpile of plutonium in France's spent fuel, the country has no operating fast reactors. Superphénix was shut down in 1996 and Phénix in 2009. No replacement breeder reactor is planned for at least a decade.

In Japan, there are plans for a new demonstration reactor by 2025 and commercialization of breeder reactors after 2050, but there is reason to doubt these projections. The Japanese government is not willing to kill its breeder program entirely, because, as in France, the breeder is still the ultimate justification for shipping spent fuel from individual reactors to a central reprocessing site. For decades, however, Tokyo has been reducing funding for its breeder program and shifting commercialization further and further into the future.

Russia and India are building demonstration breeder reactors, and China is considering buying two such reactors from Russia. The persistence of breeder programs in these countries is testimony to the ability of their nuclear establishments to tap into national treasuries despite the fact that breeders will not be able to compete with light water reactors for the foreseeable future. In India, the breeder also is justified by its ability to greatly expand the rate of India's production of weapon-grade plutonium. Successful negotiation at the U.N. Conference on Disarmament of the Fissile Material Cutoff Treaty, which would ban the production of fissile materials for weapons, could foster a new debate in India about the value of pursuing breeder reactors.

In the United States, during the Bush administration, fast reactors returned to the agenda reconfigured as "burner" reactors to fission plutonium and other transuranic isotopes (e.g., americium, neptunium, and curium) that are accumulating in U.S. spent fuel.

Theoretically, the fast neutrons in sodium cooled reactors would indeed be more effective at fissioning this material than the slow neutrons in water cooled reactors. But in 1996, a massive National Academy of Sciences assessment commissioned by the Energy Department concluded that such an effort would have high costs and marginal benefits and would take hundreds of years to greatly reduce the global inventory of transuranic isotopes. President Barack Obama and the Democratic majority in Congress share this skepticism and have proposed a new research and development program to investigate alternative strategies for managing U.S. spent fuel.

The breeder reactor dream is not dead, but it has receded far into the future. In the 1970s, breeder advocates were predicting that the world would have thousands of breeder reactors operating this decade. Today, they are predicting commercialization by approximately 2050. In the meantime, the world has to deal with the hundreds of tons of separated weapons-usable plutonium that are the legacy of the breeder dream and more being separated each year by Britain, France, India, Japan, and Russia.

In 1956, U.S. Navy Admiral Hyman Rickover summarized his experience with a sodium cooled reactor that powered early U.S. nuclear submarines by saying that such reactors are "expensive to build, complex to operate, susceptible to prolonged shutdown as a result of even minor malfunctions, and difficult and time-consuming to repair." More than 50 years later, this summary remains apt. ■

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NOTES

1. Thomas B. Cochran, Harold A. Feiveson, Walt Patterson, Gennadi Pshakin, M.V. Ramana, Mycle Schneider, Tatsujiro Suzuki, and Frank von Hippel, "Fast Breeder Reactor Programs: History and Status," International Panel on Fissile Materials (IPFM) Research Report no. 8, February 2010. Available at http://www.ipfmlibrary.org/rr08.pdf.

2. These projections were discussed in Mycle Schneider, Steve Thomas, Antony

Froggatt, and Doug Koplow, "2009 World Nuclear Industry Status Report," *Bulletin of the Atomic Scientists,* November/December 2009, vol. 65, no. 6, pp. 1–19.

3. For a full technical analysis of how much the cost of uranium factors into the cost of electricity generated at a nuclear power plant, see Massachusetts Institute of Technology, *The Future of Nuclear Power, An MIT Interdisciplinary Study* (Cambridge, MA: MIT Press, 2003), app. 5A.

4. This would be a capital cost difference on the order of $1,000 per kilowatt of generating capacity compared to a conventional reactor. With a 10 percent capital charge and a 90 percent average capacity factor (where the reactor operated 90 percent of the time), it would translate to a cost difference of about 1.3 cents per kilowatt hour.

5. Matthew Bunn, Steve Fetter, John Holdren, and Bob van der Zwaan, "The Economics of Reprocessing Versus Direct Disposal of Spent Nuclear Fuel," *Nuclear Technology* , vol. 150 (June 2005), p. 209.

6. Klaus Janberg & Frank von Hippel, "Dry-Cask Storage: How Germany Led the Way," *Bulletin of the Atomic Scientists,* September/October 2009, vol. 65, no. 5, p. 29.

7. IPFM, *Global Fissile Material Report 2009: The Path to Nuclear Disarmament.* Available at www.fissilematerials.org/ipfm/site_down/gfmr09.pdf.

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