Perspective

Are Breeder Reactors Still Necessary?

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LEO SZILARD COINED THE WORD BREEDER DURING THE Metallurgical Project of World War II to denote a nuclear reactor in which more fissile atoms are produced than are burned. The feasibility in principle of nuclear breeding had been recognized in 1942, when the number of neutrons produced per neutron absorbed in ^{239}Pu or ^{233}U was shown to exceed two. In a plutonium breeder one of these neutrons causes fission; the remaining neutrons convert ^{238}U into ^{239}Pu. Only ^{238}U is consumed in the process, the ^{239}Pu being regenerated. Thus ^{239}Pu acts rather as a catalyst for the burning of ^{238}U; and breeders are sometimes referred to as catalytic nuclear burners.

When the breeding principle was discovered, the uranium resource of the United States was estimated at a few thousand tons. Of this, less than 1 percent is fissile ^{235}U. Thus, in the early days of nuclear energy, it was generally believed that breeders, which burned the abundant ^{238}U, would soon be necessary if nuclear fission were to become an important source of energy. Development of the breeder reactor became nuclear energy's Holy Grail.

Today the world's uranium resource, at a price of $130 or less per kilogram, is estimated to be around 6 million metric tons; if speculative resources are included, the figure rises to perhaps 24 million tons (*1*). Since a standard 1000–megawatt electric (MWe) light-water reactor (LWR) with a once-through fuel cycle at 70 percent load factor uses 150 tons of uranium per year, the 6-million-ton resource would suffice for 3×10^4 gigawatt years of electricity generated by LWR's. The world's installed nuclear capacity of about 400 gigawatts electric (GWe) (including reactors under construction) could be sustained for about 100 years on this uranium resource; or for much longer if the speculative resources, or the very extensive resource at even lower grades, are included. At concentrations below 5 to 10 parts per million, however, more energy is probably required to extract the uranium from its ore than is returned when the uranium is burned in an LWR. Only a breeder can burn the trillions of tons of uranium found in ordinary granitic rock with a comfortable positive net energy balance. The breeder must therefore be regarded as being, for all practical purposes, an inexhaustible energy source, like fusion or solar energy.

In the relatively short run, the world's supply of nuclear fuel seems to be assured even if nuclear energy is based on existing reactors, which burn less than 1 percent of the uranium. Thus the challenge raised by W. B. Lewis in his famous paper of 1963, "Breeders are not necessary" (*2*), is still relevant some 23 years later, especially since the development of breeders is a central element of the world's research and development in nuclear energy. In short, are breeders still necessary?

Proponents of breeders had always conceded that, although breeders might be necessary eventually, *when* they would be deployed depended on the cost of electricity from breeders compared to the cost of electricity from competing resources, particularly LWR's. The cost of electricity from any thermal generating plant consists of three components: capital, fuel, and operating and maintenance. In general, the fuel cycle cost of the breeder is lower and its capital cost higher than for the LWR. Moreover, the fuel cost for the breeder, because the breeder utilizes uranium so much more efficiently than does the LWR, is less sensitive to the price of uranium ore than is the fuel cost of the LWR. The fuel cycle cost in the nonrecycle LWR, in mills (1 mill = $0.001) per kilowatt-hour electric,

$$C_{NR} = 5.8 + 0.033p$$

and for the breeder is

$$C_B = 7.5 + 0.01p$$

where p is the price in dollars of a kilogram of uranium. At $130 per kilogram, $C_{NR} = 10$ mills per kilowatt-hour electric and $C_B = 8.8$ mills per kilowatt hour.

The lower fuel cycle cost for the breeder must compensate for its higher capital cost if the breeder is to compete. If the capital cost of the breeder exceeds the cost of the LWR by ΔK dollars per kilowatt electric, then, at a price p dollars per kilogram of uranium, the cost of electricity for the two systems will be equal provided that $p = 1.42\Delta K + 74$. These results depend on operating and maintenance costs being the same for breeder and nonbreeder and on the costs of the various parts of the fuel cycle as given in (*3*).

Thus, if market forces alone were operative, breeders would be deployed when p reached $130 per kilogram only if their capital cost exceeded the cost of LWR's by no more than $40 per kilowatt electric.

The designers of the earliest breeders realized that breeders would be more expensive to build than LWR's—perhaps by 25 percent. At that time, in the early 1960's, LWR's were being built for as little as $150 per kilowatt electric; thus a breeder could plausibly be expected to cost no more than $40 per kilowatt electric more than an LWR. In short, the outlook for the breeder displacing the LWR simply because it produced cheaper electricity seemed fairly good, and this became an underlying motivation for pursuing the breeder.

Today's capital cost for an LWR is around $2500 per kilowatt electric. Were the breeder to cost 25 percent more than today's LWR, that is, ΔK = $625 per kilowatt electric, then the break-even price for uranium approaches $900 per kilogram, a price at which uranium can probably be derived from seawater. At this price, the fuel cycle cost for an LWR even without recycling is around 3.5 cents per kilowatt-hour electric, which matches the fuel cost for an oil-fired power plant with oil costing around $20 per barrel. Since there are 4×10^9 tons of uranium in the sea, one could in principle base a very large world electrical system on LWR's fueled by uranium from the sea for a very long time without the cost of electricity rising out of sight. Moreover, as the price of uranium rises, recycling, which halves the uranium used in an LWR, would come into use.

If the deployment of the breeder were based solely on economics, one would have to conclude that Lewis was right: breeders are not necessary—unless their capital costs can be reduced. But before one accepts this conclusion, one must recognize that such pronouncements are based on particular economic assumptions that can change. We cannot predict what uranium from seawater will cost, let alone uranium from rocks containing a few parts per million of uranium. The fuel cycle costs upon which our conclusion rests could also change, although it would be rash to say in which direction.

As for capital costs, the SUPER-PHENIX, a 1240-MWe Liquid Metal Fast Breeder Reactor (LMFBR), was built in France for

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$2800 per kilowatt electric at present exchange rates; this is to be compared with the cost of standardized 1300-MWe LWR's that are now being built in France for $1200 per kilowatt electric. France is now designing a SUPER-PHENIX II that incorporates many simplifications. The Commissariat à l'Energie Atomique (CEA) estimates that a second-generation breeder of this type should cost around $2000 per kilowatt electric; R. Carle of the CEA suggests that future large breeders might cost as little as $1560 to $1800 per kilowatt electric (*14*).

Our experience in the United States has not been reassuring. The 400-MW Fast Flux Test Facility (FFTF) was built for $1600 per kilowatt of heat. Since no electricity is generated in FFTF, one can only estimate the equivalent capital cost per kilowatt electric had turbogenerators been installed: this comes to about $4500 per kilowatt electric in 1979 dollars, the year FFTF was completed. The expected cost of the aborted 380-MWe Clinch River Breeder was $3.6 billion. Since this was the first of a kind, the cost was very high; nevertheless, one must admit that the outlook for competitive LMFBR's in the United States remains uncertain.

In the very long run, this pessimism may be misplaced for two reasons: first, sodium-cooled breeder reactors ought to be simplified as we acquire more experience; and second, LMFBR's may last much longer than their design life of 40 years. The Experimental Breeder Reactor II, at Idaho Falls, celebrated its 20th anniversary in 1984. It now operates better than it did when it was first built and shows no evidence of corrosion. This suggests that LMFBR's, once built, might last 100 or even 150 years. (Remember that one of Newcomen's original steam engines, built in the mid-18th century, continued to operate until 1918.) Should an LMBR last longer than its amortization time, then once the plant is amortized the electricity from it will be very cheap, say around 1.5 cents per kilowatt hour. Breeders in this respect would resemble hydroelectric dams: high capital cost and low operating cost. Of course the generation that builds the dam, or the breeder—to be sure at a very high cost—is not likely to be the generation that enjoys the cheap electricity that flows once the system—dam or breeder—has been amortized.

But more than economics is involved in a decision to deploy or even to develop breeders. Most important, since a breeder burns only 1/50 as much uranium as does an LWR, a breeder-based electrical system is essentially autarkic. Neither France nor Japan has much uranium, and coal costs from 1.6 (Japan) to 2.5 (France) times as much as it does in the United States (*5*). Although these countries could depend on imported uranium to fuel their growing nuclear electrical system, which is based on LWR's, this could become very burdensome, especially as the price of uranium rises. For example, at $130 per kilogram, the annual uranium bill for France's 60-GWe nuclear system would come to about $1 billion—some 10 percent of its present bill for imported oil.

Because the breeder requires little, if any, mining of uranium, its environmental impact is much smaller, at least at the front end of the fuel cycle, than is the impact of the LWR. The roughly 300,000 tons of depleted uranium stored outside the diffusion plants, if used in breeders, could fuel our entire electric system for centuries!

Although the economics of the breeder are disappointing, at least at present, two major technical successes were recently achieved. The first was the demonstration in the French PHENIX of a positive breeding gain of 0.15 ± 0.04 in a complete breeder fuel cycle. The second was the demonstration at several laboratories of uranium and plutonium oxide fuel elements that can sustain more than 10 percent burnup of the original mixture of $^{238}U/^{239}Pu$ before the fuel has to be reconstituted, a tenfold improvement over early fuels. This means that reprocessing for an LMFBR need be little more frequent than reprocessing for an LWR with recycling. Thus, instead of the breeder cycle being dominated by a very large, closely coupled, reprocessing plant, the recycling can be decoupled from the breeder with little economic penalty.

Reducing the frequency of recycling may simplify the task of keeping track of the plutonium. One can even contemplate confining reprocessing to a few heavily safeguarded plants. In this way, the issue of proliferation, which led the Carter Administration to abjure recycling in LWR's and to view breeders rather coolly, tends to be decoupled from deployment of breeders. So long as the recycling step is safeguarded, diversion of plutonium from a breeder is not the easiest nor most likely path to making nuclear weapons.

Although one cannot claim that breeder reactors are necessary because, without them, we shall soon run out of uranium at affordable prices, one can claim that the development of breeders is as necessary as is the development of the other two inexhaustible energy sources—fusion and solar energy. On magnetic fusion, the United States is scheduled to spend some $330 million in fiscal year 1987; the direct support for solar energy is scheduled to be $72 million per year; and for breeders, about $150 million. Compared to fusion, the breeder's feasibility has already been demonstrated. Compared to solar photovoltaics, SUPER-PHENIX even now can produce electricity that costs considerably less than electricity from photovoltaics (*6*); and, unlike photovoltaics, SUPER-PHENIX produces electricity rain or shine. Thus, despite the disappointing economics of today's breeder (as well as the other inexhaustibles), at least as judged by current conceptions and technology, a prudent concern for the energy future of our grandchildren, if not our children, justifies continuing a vigorous quest for an economical, safe breeder.

REFERENCES AND NOTES

1. OECD Nuclear Energy Agency and International Atomic Energy Agency joint report, *Uranium: Resources, Production, and Demand*, Paris, France (December 1983). In making these estimates I have attributed to the Communist countries uranium resources proportional to their total land area.
2. W. B. Lewis, "Breeders are not necessary: A competing other way for nuclear power" (Report DM-69, Atomic Energy of Canada Limited, Chalk River, Ontario, 15 January 1963).
3. A. M. Weinberg, M. Alonso, J. N. Barkenbus, *The Nuclear Connection* (Paragon House, New York, 1985), p. 239.
4. *Nucleon. Week* 27 (No. 4) (23 January 1986).
5. *Inst. Gas Technol. Highlights* 14 (No. 9) (30 April 1984).
6. J. Caldwell of ARCO Solar, Inc., reported at the Institute for Resource Management Conference at Sundance, Utah, October 1984, that the present price of electricity from photovoltaics is 50 cents per kilowatt hour. At a capital cost of $2800 per kilowatt, 60 percent capacity factor, and 20 percent capital charges, I estimate electricity from SUPER-PHENIX to cost less than 15 cents per kilowatt hour.