

# EIR Science & Technology

## Breeding nuclear fuel: How the U.S. can catch up

by Marjorie Mazel Hecht

From the very first days of the Atomic Age, the idea of a nuclear breeder reactor that would produce more fission fuel than it consumed caught the imagination of scientists. Here, at last, was a feasible way to provide mankind with a virtually unlimited supply of cheap energy, by breeding fissionable fuel for nuclear power reactors (Figure 1). Just after World War II, in 1946, Los Alamos National Laboratory began operating the world's first fast breeder, Clementine, which produced 25 kilowatts-thermal energy (Figure 2). (The word "fast" refers to the high-velocity neutrons in a breeder, which have more energy than those in conventional power reactors and thus can facilitate the breeding of new fuel.) By 1951, the nation had put on-line the world's first nuclear breeder reactor to produce usable amounts of electricity—the Experimental Breeder Reactor or EBR-I—which produced 200 kilowatts-electric at its peak. Constructed by Argonne National Laboratory in Arco, Idaho, the EBR-I was followed by EBR-II, which was connected to the Idaho power grid and began producing power in 1964, reaching a full operating power level of 62.5 megawatts-thermal. Argonne has now operated EBR-II for more than 20 years, producing 1.56 billion kilowatt-hours of electricity safely and reliably, and providing the nuclear community with experimental data on advanced breeder systems.

For about 30 years, the United States led the world in the development of breeder reactor technology, carrying out the spirit of the postwar Atoms for Peace program to spread

nuclear technology internationally for the purpose of world development. Taking their cue from the United States, the other industrialized nations, in particular France, began aggressive nuclear power programs, including the development of fast breeder reactors.

But by the mid-1970s, in the devastating wake of an anti-science Carter administration that institutionalized environmentalism in this country, the United States had taken a back seat in nuclear development. Today, France is number one in breeder technology, with the 1,200-megawatt-electric Superphénix fast breeder coming on-line in Creys-Malville before the end of the 1985, culminating 20 years of French breeder development (Figure 3).

The Superphénix is the world's first commercial-size fast breeder, although there are other nations that have operating prototypes. The Soviet Union, for example, has a 600-megawatt breeder, the United Kingdom has a similar size fast reactor in Scotland, and several other countries have breeder development programs.

Constructing a commercial-size breeder reactor that can economically produce power, plus new fission fuel, is no small achievement for France, a nation that has virtually no petroleum reserves, coal deposits that are difficult to work, and no untapped hydroelectric potential. Nearly 12 million manhours have gone into the construction of the site, including 165,000 cubic meters of concrete, similar quantities of stainless steel, and 3,500 metric tons of sodium, at a cost of

approximately \$1 billion. By the year 1990, nuclear power will produce 70% of France's electrical power, so assuring a nuclear fuel supply is a top priority. As the state utility, Electricité de France put it, "When Superphénix goes into production, the event should mark the advent of a new era in nuclear power production."

Ironically, the official brochure on the Superphénix concludes that, by describing the French achievements in breeder technology, "It is our hope to thus arouse the interest of American authorities, given the close ties between France and the United States in all areas, but in particular in the nuclear industry."

### The leapfrog principle

The United States is now estimated to be 10 years behind France in breeder technology development. However, the possibility exists for the nation to quickly reverse the stagnation in this area by moving ahead to develop two more advanced breeder technologies—the Integral Fast Reactor developed in the past four years by Argonne National Laboratory and the fusion-fission hybrid, which promises even

more efficiency as a breeder. Any gear-up of the U.S. economy would demand exactly such technology development. If the nation launches a crash program to develop beam defense, for example, we would very quickly run into a severe lack of available energy to power industry. The Fusion Energy Foundation estimated, in fact, that if the spinoffs of laser technology were applied to the U.S. economy on a broad scale, within 10 years the United States would have an energy shortfall of 3 gigawatts.

Like the Superphénix, the Integral Fast Reactor or IFR is a pool-type, sodium-cooled reactor, with the additional innovation of a new metal fuel design. As Charles E. Till, associate director of Argonne for engineering research, has pointed out, the IFR is ready now to be set in motion:

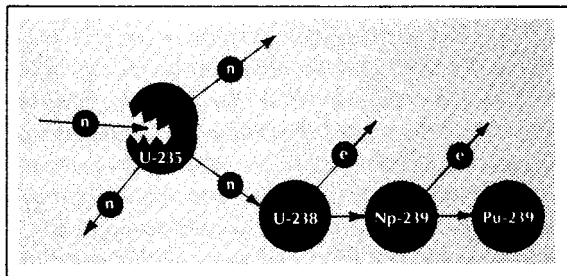
The basic features of IFR have already been demonstrated at EBR-II. Only the fuel cycle needs to be demonstrated to completely establish the practicality of the IFR concept. Most of the facilities needed to demonstrate the IFR concept already exist or can be made available at relatively low cost. The original fuel-cycle facility at EBR-II has been decontaminated and can be equipped to demonstrate the IFR fuel cycle in conjunction with EBR-II at relatively low cost. Because the process is compact, a refurbished EBR-II fuel-cycle facility would also be large enough to demonstrate the process in conjunction with a reactor much larger than EBR-II, whenever it becomes desirable to do so.

Once the fuel cycle has been demonstrated, all the pieces of the IFR concept will be in place. The nation will have available a clear means of greatly reducing its dependence on imported oil and its concern over shrinking reserves and rising prices of domestic oil and natural gas. At present consumption rates, the IFR will be able to convert known uranium reserves into the equivalent of thousands of years worth of electricity.<sup>1</sup>

The Integral Fast Reactor design overcomes some of the difficulties encountered by the previous-generation loop design liquid metal fast breeder reactor, or LMFBR, the model the U.S. Atomic Energy Commission chose to develop back in the mid-1960s. At the time, the AEC stated that it had selected the LMFBR because of "its predicted performance, existing industrial support, established base of technological experience, and proven basic feasibility." In 1975, when the Energy Research and Development Administration was created, it decided to continue the liquid metal fast breeder development as a top priority, and, in its first budget, ERDA devoted \$474 million to it—"the largest expenditure for any single civilian R&D project," according to one study of breeder economics.<sup>2</sup> A further \$10 billion was envisioned as necessary to complete the project in the year 2020. But

FIGURE 1

### The breeder process



Argonne National Laboratory

In a fission power reactor, a chain reaction of fissions of uranium-235 nuclei is set off; each nucleus splits, emitting fast neutrons in the process. These neutrons then produce new fissions. In the breeder reactor, these fast neutrons are used directly to breed new fuel from the non-fissionable uranium-238. Hit by a neutron, the U-238 gives off an electron and is transformed into neptunium-239, an unstable isotope. Np-239 then emits an electron to become plutonium-239—fuel for fission power reactors.

This process of creating new fuel also produces heat, which is used to boil water, make steam, and operate turbines by the same method a conventional power plant uses.

the optimism at the time to tackle the problem of building a U.S. commercial breeder soon dissipated under the Carter regime. The 350 megawatt-electric Clinch River Breeder Reactor was subjected to a slow death by budgetary starvation, and although now substantially physically completed, the project is effectively dead. Also dead are follow-up plans for a Commercial Demonstration Breeder Reactor on the Clinch River site.

Now, the Clinch River loop-type LMFBR technology has been superseded, although it should be stressed that had the nation pursued the Clinch River LMFBR on schedule, it would have performed as well as similar demonstration-

scale LMFBRs in Britain and the Soviet Union, and provided the United States with valuable breeder engineering and component experience. The design is more efficient thermally than the pool design, but during the past 10 years, the experience of the French and the work at Argonne have demonstrated the superiority of the pool design, in particular in terms of safety and security (Figure 4). Japan, which built a small breeder modeled on the Clinch River loop design, is now considering a switch to the pool design for its planned commercial reactor, while West Germany, Britain, and the Soviet Union are already pursuing the French Phénix pool design. Thus, at this point, a renewed com-

FIGURE 2

## The fast breeder reactor

Fast breeder reactors burn uranium fuel much more efficiently than conventional fission reactors, which burn only about 2% of the uranium in their fuel rods, producing plutonium as a waste by-product. In conventional reactors, the neutrons from the nuclear fission process are slowed down, or moderated, using water or graphite, to cooler thermal temperatures.

In the breeder reactor, the neutrons from the fission process are not moderated, but used to convert the non-fissionable uranium into new plutonium fuel.

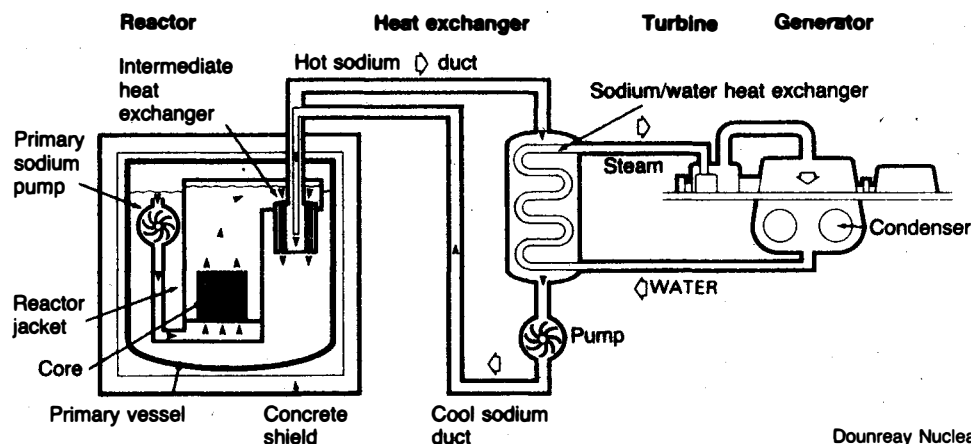
Shown here is a schematic of the Prototype Fast Reactor in Dounreay, Scotland, which began feeding 250 megawatts of power into the national power grid in 1974. The reactor is cooled by liquid sodium, a metal that melts at 98° Celsius and removes heat from the reactor core 10 times more efficiently than gas or water. Sodium is an ideal coolant because it has high thermal conductivity and low vapor pressure, which allow a reactor core with high power density and lower system pressures than a conventional nuclear plant.

The reactor vessel is located on an underground level,

suspended in a concrete vault and enclosed in an insulated jacket. The fuel and breeder assemblies, hexagonal-shaped rods, are placed on a grid at the base of the vessel.

The reactor core's inner zone consists of fuel pins that contain pellets of uranium oxide and plutonium. The outer zone consists of "blanket" pins of depleted uranium. The neutrons produced by the fission process in the inner zone are absorbed by the blanket pins and converted into plutonium. Graphite-filled steel tubes around the fuel assembly provide shielding to reduce radiation levels in the outer part of the vessel. A rotating shield on the roof of the reactor vessel is used for refueling, about every seven weeks.

There are two sodium coolant systems. In the primary system, the liquid sodium surrounds the reactor core in a pool. The primary sodium pump pumps hot sodium out of the reactor vessel to the intermediate heat exchangers. Then the primary sodium returns, much cooler, back into the pool around the reactor. The secondary coolant system is non-radioactive and completely separated from the primary sodium coolant by the reactor jacket. The secondary sodium carries the heat from the intermediate heat exchangers to the water heat exchangers, which produce steam at 1,000° F.



Dounreay Nuclear Power Development Establishment

mitment to nuclear fuel breeders means that the United States should leapfrog to more advanced breeder designs.

The fusion-fission hybrid has all the advantages of a breeder reactor, plus significant additional benefits: First, the hybrid produces 10 times more fissile fuel than a fast breeder reactor

many as 14-20 reactors; second, the hybrid would provide valuable engineering experience for fusion researchers as a bridge to pure fusion reactors; third, it could be constructed rapidly. As one scientist put it in a review of the fusion breeder in 1982, the hybrid has a unique advantage—it can be introduced at a rate that is historically unprecedented for a new technology. In fact, as he concluded his review: "We are convinced that by producing fuel for LWRs [light water reactors], fusion can have a significant impact on our energy needs in an even earlier time frame than the LMFBR, although the technology of fusion is not as developed as that of the LMFBR."<sup>3</sup>

Like the fast breeder concept, the hybrid idea has been around since the beginning of U.S. nuclear work. Reportedly, in the early days of the fusion program, the feasibility of using a fusion-fission hybrid to breed fuel is one of the main reasons that fusion research remained classified by the Atom-

ic Energy Commission until 1958. Some of the first fusion scientists were interested in the hybrid, because it seemed more possible than achieving the stringent conditions for pure fusion. And as fusion research continues to advance, the case for the fusion-fission hybrid becomes even more compelling.

### Why breed fuel?

The beauty of nuclear energy is that its fuel continuum. In other words, more than 99% of the spent fuel from nuclear power plants can be reprocessed and turned into new fuel for fission plants, leaving only a minute amount of high-level waste to be disposed of—or turned into valuable isotopic raw materials. The breeder adds another dimension to this cycle, because it can turn the non-fissionable uranium-238 into fissionable plutonium-239. Since most of the world's uranium is the U-238 variety (only 0.7% is the fissionable uranium-235 isotope), the breeder makes it possible to feed this relatively abundant non-fissionable uranium into breeders that transmute it into fuel for reactors. As Argonne National Laboratory calculated it, based on the nation's existing known uranium reserves, "the use of breeder reactors would give the nation the equivalent of about 4,500 years of oil at present [1983] consumption rates."<sup>4</sup>

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FIGURE 3

## Superphénix: world's largest breeder

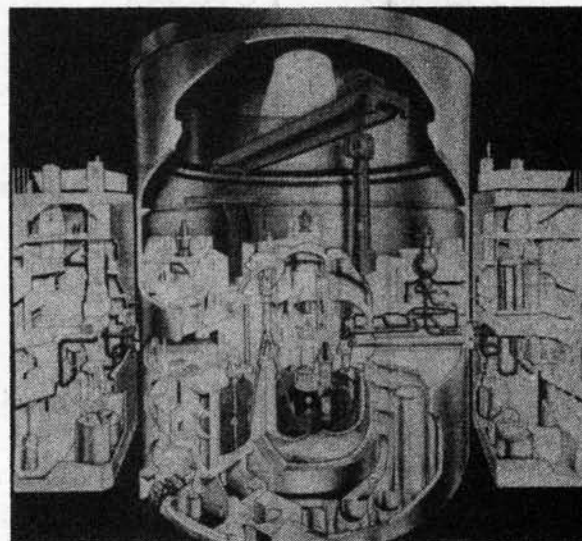
In the French Superphénix, a pool-design LMFBR soon to go on-line at Creys-Malville, near Lyon, the entirety of the primary coolant loop is near the core of the vessel, including the heat exchangers and the primary pumps. The core is comprised of 364 vertical fuel assemblies, each made up of 271 fuel pins that are 2.7 meters long with a diameter of 8.5 millimeters. The pins contain fuel pellets, about 15% of which are fissile uranium and plutonium oxides. The core has a volume of 10 cubic meters and contains about 5 tons of plutonium and 108 tons of uranium. It is surrounded by 233 fertile blanket assemblies of natural uranium or depleted uranium.

Every second, 5 tons of liquid sodium enter the core at 400° C. The sodium circulates among the fuel pins, leaving the core at a temperature of 550° C. This sodium is then pumped by four primary pumps into the four primary loops, each of which has two heat exchangers. The reactor vessel contains a total of 3,500 tons of sodium. Surrounding the main reactor vessel is a safety vessel filled with an inert gas that can contain and recover sodium in case of a leak. Outside the vessel are the secondary pumps and the device used to manipulate the fuel assemblies.

The scale of the Superphénix presented many engi-

neering firsts: The size of the vessel—21 meters in diameter weighing 350 tons—meant that it had to be constructed on-site in a shop larger than a football field. Lifting the vessel into place required hoisting it nearly 30 meters. Incredibly, this world's first commercial-size breeder was completed within 8 years from start to finish—just about half the time that it now takes the United States to put one conventional nuclear plant on-line.

Novatome



A cross-section of the Superphénix reactor.

The economics of breeder reactors is straightforward. There is a calculatable amount of high-quality uranium to be mined, processed, and enriched for use in reactors; a certain amount of spent fuel to be reprocessed and enriched for reactor use; and a certain amount of unfissionable uranium and thorium-232 that can be fed into a breeder and transmuted into fissionable nuclear fuel. The question that the nuclear community exhaustively pursued was how early would an economy require development of breeders? At what point would the large development and capital costs of breeder reactors be offset by the rise in price of increasingly scarce uranium. Thus in the early 1960s, there were cost estimates and scenarios that stretched into the mid-21st century.

At that time, before the environmentalist anti-nuclear battle lines had been drawn, the nuclear planners expected nuclear energy to be providing an increasingly significant amount of power worldwide, and breeders were seen as vital by the 1980s or 1990s at the latest, with fusion-fission hybrids necessary to make up the predicted fuel gap (Figure 5). Even taking a less optimistic growth rate for nuclear power, it was clear that hybrids would have to be introduced in time to be supplying fission fuel by about 2005.

Most analyses of power needs suffer from the cost/benefit disease. The scientists writing take a technology that practically screams for development because its benefits are so obvious and then try to justify it within the constraints of a "think small" budgetary process whose guiding philosophy is "why should we spend money today on something that won't be cost effective in the next 24 hours?" Nevertheless,

these scenarios provide the reader with some idea of when at a very conservative pace, advanced breeders and hybrids could be introduced and what they would produce.

One of the more recent published studies on the fusion breeder suggests that by 2015, the first commercial fusion breeder could provide fuel for as much as 20 gigawatt-electric of nuclear generating capacity, while six fusion breeders by the year 2030 could provide fuel for more than 120 light water reactors.<sup>5</sup> This study—whose authors include Edward Teller along with two fusion scientists from TRW and two from Lawrence Livermore National Laboratory—quite conservatively reviews the current supply of energy resources, notes the potential introduction of electric vehicles, and then states, "It is therefore prudent to ask whether nuclear power (of all varieties) can provide a major fraction (for example, approximately 50% of the U.S. electrical demand during the first half of the next century. . . ."

The authors conclude that fusion hybrids could have "a significant impact on our energy supply in an equivalent or earlier time frame than the LMFBR, even though fusion technology is less developed than LMFBR technology," and then go on to describe a feasible hybrid development scenario for the United States:

. . . Fusion technology, and thus the fusion breeder, is at least 15 years behind LMFBR development in the United States. However, fusion is mature enough to start a hybrid engineering test reactor (HETR) in the late 1980s and complete it by the mid-1990s. A

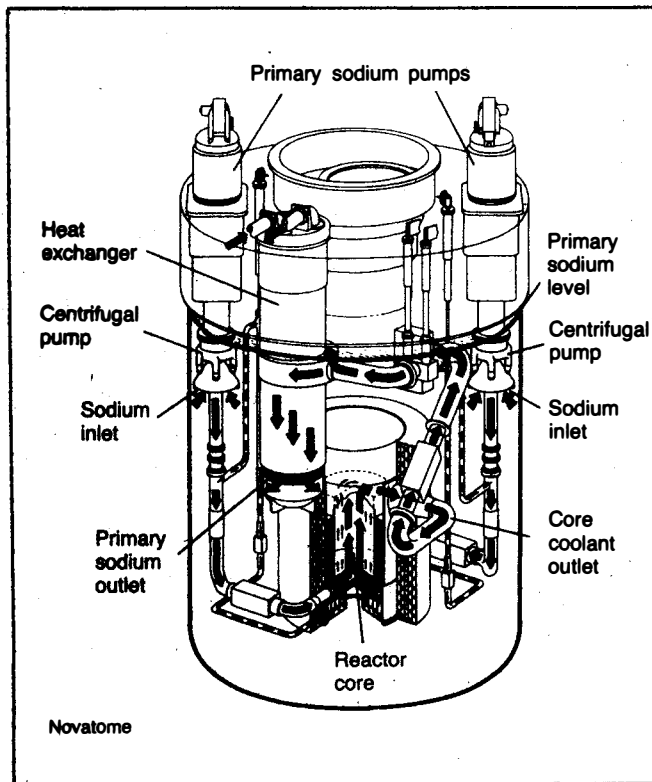


FIGURE 4

## Argonne's integral fast reactor

The Integral Fast Reactor developed by Argonne National Laboratory is pool-type reactor with several advances over the Clinch River design and the Superphénix, in particular a new fuel design and new fission fuel reprocessing system.

The IFR makes use of a new metal-alloy fuel design that is twice as efficient as the oxide fuels. The oxide fuel cores have breeding ratios of between 1.3 to 1.35, which means that they take about 20 years to double the amount of fuel initially invested in the plant. The new metal-alloy fuels have breeding ratios of 1.5 to 1.6, giving the reactor a 10-year or less doubling rate. The metal alloy also enables the reactor to run with a higher fuel density and less fissile fuel. One of the specific fuels developed by Argonne is a metal alloy of uranium, plutonium, and zirconium.

magnetic mirror fusion HETR could be used to develop nuclear technologies for a demonstration fusion breeder reactor that could begin operation shortly after 2000. The demonstration reactor would provide a near full-scale demonstration of all relevant fusion reactor and nuclear technologies and would qualify components for a commercial-scale prototype reactor. Assuming an accelerated development program, the prototype reactor could operate before 2015.<sup>6</sup>

As for the cost of the electricity produced by the fusion breeder, the fission-suppressed tandem-mirror-driven breeder that this study proposes costs three times as much as a light water reactor to build, would support 13 light water reactors, and would provide uranium-233 fuel at about \$70 per gram. While its capital costs are high, it would provide a virtually inexhaustible supply of energy at a cost less than 15 percent more than nuclear electricity costs from currently available technologies. The question of capital cost is an interesting one. For the LMFBR to produce electricity at 15% of today's nuclear prices, its capital cost would have to be less than 1.25 that of building a light water reactor. The pure fusion reactor is even more capital intensive, costing 50% more and producing electricity initially at 40% or so more than light water reactors. As the authors of this study emphasize, however, the capital costs of new advanced technology systems are initially high, but decrease as the industry becomes more experienced with these technologies.

The authors note that although the United States, with

its substantial domestic reserves of coal and uranium, potentially would not have a shortage of uranium until the year 2030, other nations are forced by their more meager resources to develop nuclear plants and breeders on a more aggressive schedule. Thus, they conclude, the United States now has a unique opportunity to pursue the development of fusion-fission hybrids as a technology for export. Ironically, the U.S. fusion research program is being aggressively cut back, rather than increased, as would be necessary to assure the development of fusion breeder technology.

## References

1. Charles E. Till, "New Breeder Reactor Design May Help Cool Discussion," *Logos*, Vol. 2, No. 3, p. 9.
2. Richard G. Richels, "R&D Under Uncertainty: A Study of the U.S. Breeder Reactor Program (New York: Garland Publishing, Inc. 1979), pp. 1-7.
3. Ralph Moir, "The Fusion Breeder," Paper prepared for The National Science Foundation Policy Workshop, March 4-5, 1982, preprint by Lawrence Livermore National Laboratory, UCRL-87290, pp. 10-15.
4. Richard R. Smith, "20 Years of Experience Shows Breeder Reactor Safe, Reliable," *Logos*, Vol. 2, No. 2, p. 10.
5. James Maniscalco, et al. "The Fusion Breeder—An Early Application of Nuclear Fusion," *Fusion Technology*, Vol. 6 (November 1984).
6. Maniscalco, et al., p. 593.

The new metal alloy fuel eliminates the problem of fuel swelling that characterized other breeder fuel designs, limiting the length of time a fuel pin can operate in the reactor core. The swelling is caused by the buildup of fission gases inside the fuel rod. If the cladding of the fuel rod ruptures, this can leak fuel into the liquid sodium, contaminating the coolant, or into the fuel pin area, where it could cause overheating.

With the metal-alloy fuel and the redesign of fuel pins to allow the fuel to expand by one-third inside the fuel rods, Argonne expects to achieve a burn-up of atoms of 14%, compared to the 1-2% of previous reactor designs. This also means that more fuel is consumed with each reloading of the reactor core, and therefore there is less of a need for reprocessing. Additionally, Argonne has studied the effects of a loss-of-coolant accident on metal-alloy fuel pins and oxide fuel pins, concluding that, because metal fuels cool faster, they allow less chance for heat to build up in the reactor core.

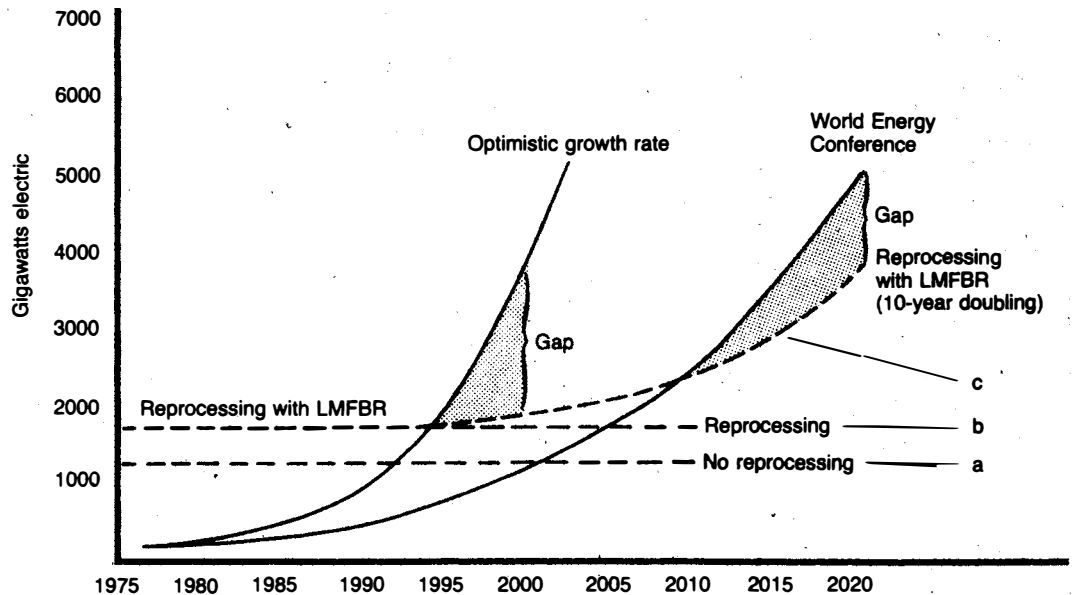
The other major advance Argonne developed concerns the process of harvesting the fuel that is bred in the breed-

er. In the past, the chemical purex method has been used, where the fission reactor waste is dissolved in water and the fissile material is chemically removed and combined with oxygen. Argonne developed a pyrometallic process in which the metal fuel is heated to 1,400° Celsius in a crucible, using metal refining techniques. This removes most of the fission reaction products, and the processed metal can then be used in a reactor. By using advanced electro-refining techniques, Argonne is now trying to solve the problem of having noble gas products remain in the new fuel. A study about to be released by the lab, proposes a pyrometallic reprocessing and fuel fabrication plant that can be constructed for as little as \$50 million.

Argonne also notes that making a compact fuel reprocessing facility an integral part of the reactor and using the new pyrometallurgical fuel reprocessing technique "eliminates the possibility of unauthorized diversion of nuclear fuel and the need to transport plutonium to and from the site." The pyrometallurgical process keeps the nuclear materials too radioactive for anyone to handle without highly specialized equipment in a sophisticated reprocessing facility.

FIGURE 5

### Projected fuel requirements for nuclear fission reactor



The solid curves represent two possible scenarios for the world growth of nuclear reactor capacity. Dotted lines represent the amounts of reactor capacity that could be fueled by a) once-through use of uranium resources, b) reprocessing spent fuel rods, c) introducing liquid metal fast breeder reactors on a fairly optimistic time-table. The shaded gaps represent the amount of capacity that would have to be fueled by fusion-fission hybrid breeder reactors. For the more rapid rate of growth in nuclear capacity, hybrids would have to be introduced in time to begin supplying fuel by about 1995; for the less rapid growth rate, about 10 years later.

FIGURE 6

## The fusion-fission hybrid

Hybrid designs have been under study for more than 30 years, and very detailed analyses exist of different fusion driver systems (tokamak, mirror, lasers) and fuel production systems (combinations of uranium, thorium, and lithium in the breeder blanket).

In the basic hybrid design a), fusion takes place in the reactor core, while new fuel is produced in a breeding blanket that contains uranium, thorium, and lithium in combination or separately. The hybrid is inherently more efficient than the fission breeder because the deuterium-tritium fusion fuel produces 14 MeV in neutron energy—about four times as many neutrons per unit of energy as a fission event. The blanket surrounding the fusion core is a fertile material, and each fusion neutron generates fast fissions in the fertile material that multiply this fusion energy 3 to 10 times and multiply the neutrons about 2 to 4 neutrons per fusion neutron. New tritium is bred by using one of these neutrons with the lithium, and the other

neutrons are used for breeding nuclear fuel.

The hybrid relaxes the stringent conditions required for pure fusion reactors, because the energy associated with the output neutrons from the fusion reactor is not used to sustain the fusion burn but to breed fuel in the blanket. Therefore, a lower fusion performance is acceptable, and it has been conservatively estimated that this performance can be reached by fusion reactors within the next 10 to 15 years. In fact, most of the hybrid plant would use conventional fission technology, with less than 10% of the plant using new fusion breeder technology. (James A. Maniscalco, et al., "The Fusion Breeder—An Early Application of Nuclear Fusion," *Fusion Technology*, Vol. 6, November 1984, p. 584.)

An additional mode of hybrid operation is the fission-suppressed blanket, which uses non-fissioning beryllium for neutron multiplication. This has safety advantages and also is able to support more nuclear reactors than the fast fission blanket mode. In the suppressed fission blanket proposed by Maniscalco, et al., a tandem mirror fusion device is used for the core with a liquid metal (lithium) coolant that flows through a two-zone blanket that is com-



FIGURE 7

## Loop versus pool-type reactors

The basic difference between the loop-type Clinch River Breeder Reactor and the pool-type Superphénix is in the design of the heat transport systems. In the loop design, the sodium coolant leaves the core and flows through an external piping loop to the heat exchanger and pump. In the pool design, the primary sodium coolant never leaves the pressure vessel; the heat exchangers and pumps are inside the vessel itself.

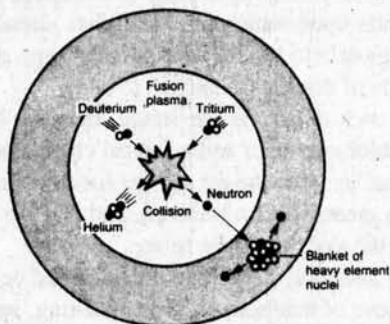
The pool-type reactor is thus larger than the loop-design reactor—74 ft. in diameter, compared to 42 ft. (Frank J. Rahn et al., *A Guide to Nuclear Power Technology*, New York: John Wiley & Sons, 1984, p. 572.) However, the increased cost from the larger size is offset by that fact that the pool-type reactor does not require any external primary sodium piping and has a smaller reactor containment building. Because there are fewer pipes, the reactor is less vulnerable to loss-of-coolant. There is also much lower neutron irradiation of the pressure vessel,

making the vessel accessible. The advantages of the loop design are that the pressure vessel does not have to support the pumps and heat exchangers, making the thermal design easier.

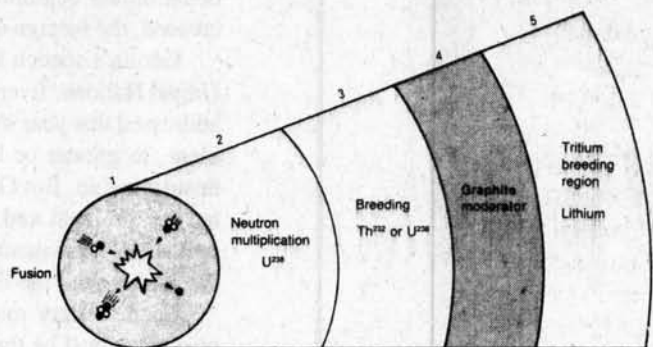
In terms of safety, the thermal inertia of the large pool of primary sodium provides a long period of time to set into motion safety systems. If there is a breakdown of the secondary steam loop, the pool design can withstand and absorb the heat from the fuel core for a much longer time. As Gilbert Labat, the chief of operation of the Superphénix put it, "If something happens, you need not have quick reflexes. You can start by smoking a cigarette and figuring out what is actually going on. You have all the time you need [about half an hour] to think twice before taking any action." (Laurent Rosenfeld, "France Takes the Nuclear Lead," *Fusion*, July-August 1984, p. 33.)

Studies at Argonne National Laboratory on the EBR-II reactor showed that even if all coolant pumps failed at the same time, the temperature differences in the system would keep the core acceptably cool by maintaining the natural convection currents in the sodium pool. Argonne also showed that the cost of construction materials for the pool reactor system would be half that for a comparable system in a conventional nuclear power plant.

posed of beryllium/thorium pebbles. The beryllium multiplies neutrons and dilutes the fertile thorium pebbles, thus suppressing fissions. The design is predicted to support 14 conventional light water reactors of 4,000 megawatts-nuclear each.



*In this simple hybrid schematic, fast neutrons enter the reactor wall where they react with the fertile material (uranium-238, thorium-232, or lithium) to form fissionable fuel (plutonium-239 or uranium-233) for fission reactors and tritium for fusion fuel.*



*A more detailed schematic of a hybrid breeder reactor, where each wedge shown is part of the circular area surrounding the core. Region (1) in which fusion occurs is surrounded by a shell of uranium (2) in which neutron multiplication occurs along with energy production from induced fission reactions. The next region (3) is entered by slowly moving neutrons, many of which are absorbed to produce fission fuel from the fertile elements embedded there. Neutrons that escape absorption in this region are partially reflected back into it by the graphite moderator (4) that surrounds it. The remaining neutrons pass through the moderator and are further slowed and then enter the next region (5) where they trigger fission of lithium to produce tritium for use as fuel in the fusion reaction.*