European Breeders (III): Fuels and Fuel Cycle Are Keys to Economy

Breeders are a possible way to give the world energy for hundreds of years. They are also the only hope for the nuclear industry to survive past the turn of the century, since world supplies of uranium are dwindling rapidly. But if many countries build breeders, they will introduce new problems of reactor safety and new imperatives to safeguard reactor fuel, since the plutonium fuel of breeders can be converted into weapons.

For now, breeders are something less—an advanced nuclear power concept that shows great promise of success but is not quite proved. The European research programs have already shown that prototype breeder plants can operate reliably (*Science*, 26 December 1975), but a number of problems remain to be solved before commercial-sized plants can be built (*Science*, 30 January 1976).

For a number of reasons, it appears that breeders will always be slightly more expensive to build than light water reactors. The cost of power could be less, however, because the cost of raw fuel material is practically negligible (^{238}U accumulates rapidly as a waste product of the light water reactor fuel cycle) and the cost of the steps needed to process breeder fuel is also expected to be lower. Pierre Zaleski, with the French national generating company (EdF), estimates that at a cost of $20 per pound for uranium oxide (roughly the present price), the breeder can compete with the price of power from a light water reactor if the capital cost is $100 per kilowatt higher. At $60 per pound for uranium, the breeder would have an advantage equivalent to $300 per kilowatt. Obviously, if uranium prices continue to rise, breeders will eventually become competitive.

Beyond the low cost of fuel material, another reason the breeder fuel cycle may be cheaper is that many steps in the light water reactor fuel cycle (especially costly enrichment) can be eliminated in the breeder. The only steps in the breeder fuel cycle are the reprocessing of spent fuel after it is extracted from the reactor and the fabrication of the reactor-bred plutonium into new fuel elements. The French atomic energy commission, CEA, estimates that the present fuel cycle cost is about 20 percent of the price of a kilowatt-hour of electricity, attributable equally to fabrication and reprocessing. The fuel cycle costs are hardly negligible, however, and the principal way to hold them down is to recycle the fuel as little as possible.

The French now keep their fuel in their prototype reactor until 5 percent of it has undergone fission, but if the fuel could withstand 10 percent fission (referred to as 10 percent burnup), the fuel cycle costs would be halved.

The problem with achieving high burnup is that intense bombardment by neutrons in the reactor core causes the fuel to deform, rupture, or suffer other damage. Even at 5 percent burnup, every atom in the metal parts of the fuel assemblies will be displaced 70 times before the assemblies are removed from the reactor.

Test fuels are usually discarded if they show a high rate of cracking or rupture, but one problem that cannot be eliminated is swelling. Fast neutrons produce voids in the crystal structure of metals, causing them to swell. The problem is severe for the metal cladding that surrounds the fuel, and also for the fuel itself, which is a mixture of plutonium and uranium oxides in the present breeders. It is a problem peculiar to fast breeder reactors, due to the high flux of fast neutrons. Not only do some materials swell as much as 30 percent by volume, but in many cases the swelling becomes more severe in large reactors. The flux is about 7×10^{15} cm^{-2} sec^{-1} in the prototype breeders and may be as high as 10^{16} for commercial-sized breeders.

If the fuel subassemblies swell too much, they will take up all the available space in the core and deform. Differential swelling can also occur, because of nonuniformity of the neutron flux, causing the fuel pins to bow. If two fuel pins touch, they increase the temperature of the core at that point, and in extreme circumstances the effect could propagate to other parts of the core.

The principal way a breeder designer can eliminate the problems caused by swelling is to leave more space in the core. But larger spaces between the fuel pins reduce the performance because they are filled with liquid sodium. The extra sodium slows the fast neutrons somewhat and reduces the breeding rate. Thus the swelling phenomenon, which was only discovered in the 1960's, not only makes high burnup difficult to achieve, but also adversely affects the doubling time (time to double the original inventory of fuel) of the fast reactor. A similar phenomenon called creep—the anomolous swelling of fuel pins due to pressure inside—exacerbates the problem.

Both the British and the French have tested individual pins of oxide fuel that have withstood a burnup of 17 percent, and they are investigating a broad range of oxide fuels. The French have a staff of 350 working on fuel development and the British employ about 250. The greatest achievement would be to find a cladding material that didn't swell and there are early reports of such a discovery in the United States and United Kingdom. But most observers expect that progress will be made by many small engineering improvements involving repeated trade-offs. There is undoubtedly much that can still be done with oxide fuels, but in the opinion of J. F. W. Bishop, head of fuel development in the British program, there is still some uncertainty about the burnup that can be achieved in large reactors with the present metals used in fuel assemblies.

Another possibility is a carbide fuel, which could regain much of the breeding performance lost due to swelling. Because carbide fuels would not degrade the fast neutrons as much as the oxides (there are two oxygen atoms in uranium oxide but only one carbon atom in uranium carbide), they would improve the doubling time of the reactor considerably. But the realization of carbide fuels is some time off. Britain and France each devote about $1 million per year to their study, while the United States and West Germany are doing considerably more. France is planning to load a core of carbide fuel in the 40-megawatt test breeder in 1980–1984. The British will test subassemblies of carbide fuel in their prototype reactor, but do not expect to produce significant amounts of carbide fuel before the 1990's.

Fabrication Facilities

The fuel for the French prototype breeder, Phenix, was fabricated in a large plutonium facility at the CEA laboratories at Cadarache in southeast France. Chemical processing of mixed oxide fuel is done in one building, and production of fuel pellets and their subsequent assembly into fuel pins is done in a larger building, with 18 separate sealed workrooms for plutonium handling. Many steps in the fabrication are done in glove boxes, but some, such as the sintering process in which the oxide pellets are baked to make them durable, are continuous processes. Others, such as loading the pellets into the cladding, are semiautomated. The plant is an impressive facility, with three successively lower pressure zones to guard against plutonium dispersion in case of a leak or fire and meticulous controls for movement of plutonium from one location to another to guard against the accumulation of a critical mass. The cost of the plant, including equipment, was about $12 million.

The Cadarache fabrication plant has already produced two fuel cores for the Phenix and is expanding to produce the fuel for the 1200-megawatt French breeder, Superphenix, a task that must be completed by 1981. When the expansion is complete, the plant will be capable of producing 20

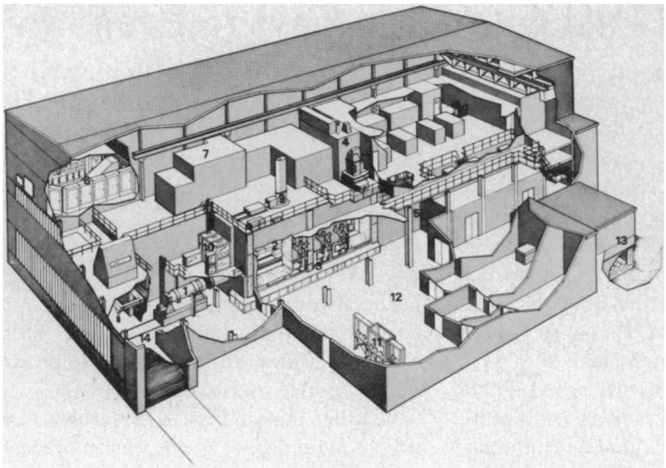

Fig. 1. The British fast reactor fuel reprocessing plant, being completed this year at Dounreay, Scotland. The prototype reprocessing factory removes newly bred plutonium from irradiated fuel rods by the solvent extraction process. Shielded flasks carrying the spent fuel (1) are emptied into the fuel assembly breakdown cave (2) where the fuel pins are chopped up with tools controlled by remote manipulators (3), then fed into the fuel dissolver cell (4). The various components of the irradiated fuel are separated in the solvent extraction cells (5), as managed from the control room (6). Other plant components are the ventilation filter unit (7), the waste removal flask (8), the laser assembly (9), the breakdown cave maintenance booth (10), and decontamination boxes (11).

tons of fast reactor oxide fuel per year. "We have enough capacity that we could supply fuel for the British, American, French, and German prototype breeders—all of them," says M. Mustelier, chief of fuel development at Cadarache.

The British facilities for fuel fabrication are at Windscale, near Manchester, and are run by an executive company, British Nuclear Fuels Limited, that was split off from the United Kingdom atomic energy agency. The British fabrication plant produced the fuel for the 250-megawatt prototype breeder, and is capable of producing between 5 and 10 tons per year.

The United States has contracted its fast reactor fuel fabrication to two companies, Kerr-McGee and Babcock & Wilcox, which are each producing a fuel core for a U.S. reactor (the Fast Flux Test Facility) that is smaller than the French prototype. Together the plants have a capacity of about 5 tons per year, but when Kerr-McGee completes its present fuel order the plant will be closed. In the near future, the Energy Research and Development Administration (ERDA) is planning to construct two large experimental fabrication facilities, but it is not clear whether they will be used for actual production. A high-performance fuel laboratory is scheduled to be built at Hanford, Washington, to demonstrate the workability of a continuous production process for oxide fuels, and another large experimental plant is planned at Los Alamos, New Mexico, that should develop carbide fuel methods. Each plant is expected to cost $60 million.

Such heavy American investments in facilities that may never be used for actual production are puzzling to the French, who have spent much less and have more production capacity to show for it. The French seem to be happy with their semi-automated fabrication plant, which—apart from a fire in 1972—has worked well for 10 years. The American plants will use continuous processes and computer-control throughout—a prospect that would make the French slightly uneasy, since they prefer to rely on human control of plutonium movement in the Cadarache plant.

On the other hand, both the French and the British breeder program managers discount the idea that the danger of illegal nuclear weapons made from stolen plutonium could be a serious reason to stop the breeder program. There is much less concern about theft than in the United States, and both countries seem to favor centralized plants for fabrication and reprocessing, although final decisions have not been made yet. What motivation there is for distributing the fuel cycle technologies to many smaller plants seems not to be fear of plutonium theft during the movement of fuel but a desire for redundancy in the fuel cycle to ensure its reliability.

Breeder Reprocessing Plants

Neither Britain nor France has experience in reprocessing except at a very small test scale, but within the next year the United Kingdom plans to begin operating a prototype reprocessing plant for fast reactor fuel at the site of the 250-megawatt prototype reactor in Dounreay, Scotland (Fig. 1). The French are just beginning to operate a large reprocessing plant designed for light water reactor fuel with a capacity of 800 tons per year. They intend to use it for some breeder fuel reprocessing also, and they have a small test plant for breeder fuel reprocessing at the same site on the English Channel at La Hague.

The British decided in 1971 to develop the reprocessing technology at the same time as the reactor technology. According to R. H. Allardice, assistant director of the Dounreay laboratories, this decision has been well substantiated by the difficulties encountered with reprocessing technologies everywhere. (One American reprocessing plant for light water reactors at Morristown, Illinois, has been a total failure, and another near Buffalo, New York, is closed for an unspecified length of time for major alterations. At present, there are none operating in the United States.)

Two major factors make reprocessing of breeder fuel more difficult than that of light water reactor fuel: increased burnup and a higher level of residual heat. At a burnup of 100,000 megawatt-days per ton, the breeder fuel will have many more "dirty" isotopes and insoluble fission products than light water reactor fuel, which only goes to about 30,000 megawatt-days per ton. The high residual heat will make the fuel difficult to process unless a considerable time is allowed for the residual radioactivity to decay. Thirty days after removal from the reactor, each fuel subassembly from the prototype breeders will still be producing 13 kilowatts of heat, and only after 180 days will the rate have fallen to 3 kilowatts.

Subassemblies have to be stored in sodium to conduct away residual heat until they have cooled, and the best duration for cooling is a matter of considerable debate. Proponents of rapidly expanding breeder networks want reprocessing to begin after 30 days, while 6 months is a better time for easy design of reprocessing plants. Most breeder plants are designed for the fuel to reside in the reactor for a year, and for short doubling times the fuel should not sit unproductively outside the reactor for as much time as it resides in the reactor.

The British fast reactor fuel reprocessing plant at Dounreay is designed for a cooling time of 180 days. By rebuilding and adding on to an older reprocessing plant used for the test reactor at Dounreay, the British were able to economize. But if the prototype reprocessing plant had been built from scratch, it would have cost $13.5 million at 1971 prices, according to Allardice. The new plant will be large enough to reprocess fuel from two 250-megawatt reactors (about 10 tons per year), and the total time for recycling of the British prototype fuel outside the reactor is to be 1 year.

In the late 1980's, the British breeder plan calls for the construction of a commercial-sized reprocessing plant large enough to handle the fuel from 10 to 15 power plants. According to Allardice, the development work for this plant will peak over the next 6 years, and present plans call for a 200-day cooling period. France is also planning to wait until the 1980's to build a commercial-sized reprocessing plant. In the same time period, the United States plans to build its first large breeder reprocessing facility, the hot pilot plant. It is projected to cost $600 million, with a capacity about as large as that of the future British and French plants, about 1 ton per day. Both British and French officials think that commercial-scale reprocessing costs are quite uncertain now. The costs of light water fuel reprocessing have escalated dramatically in the last few years, and one of the reasons is the rising cost of waste disposal.

Neither Britain nor France is spending very much money on improved methods of waste disposal, and representatives from both countries' breeder programs admit privately that more money should be devoted to the waste problem. They have small efforts to perfect the technology for sealing fission products into glass so they can be disposed of, but little effort to find improved means of permanent disposal of other wastes.

Reactor Safety Provisions

Reactor safety is of course a very immediate concern, and both Britain and France devote considerable effort to safety engineering. They do not agree, however, that all of the stringent safety measures imposed on experimental breeders by the United States—and followed to a large extent in West Germany—are necessary. The British and the French prototype breeders do not have a strong inner containment dome above the reactor or a reactor building that is reinforced to the point that it could withstand a direct airplane crash. Also, they are not designed for the moderate earthquakes that the U.S. prototype breeder is supposed to withstand, because Western Europe is not in an active seismic zone. (Whether the "pot" reactor design can withstand seismic shock as well as the "loop" design is an important and undecided question.)

The British philosophy for fast reactor safety is to build the primary reactor vessel strong enough that it can withstand any conceivable energy release from an excursion of the core. A great increase in reactivity in the core would blow upward a large mass of sodium, which would hit the reactor roof with considerable impact. Thus the British prototype was designed with a reinforced roof (which incidentally caused some problems during construction).

The French philosophy is that the reactor should be designed in such a way that large increases in reactivity of the whole core are so improbable as to be incredible. Thus, the French prototype was designed with much engineering study to assure that even if there was some melting and dispersion in the core, it would be controlled before the whole core was involved.

Unlike light water reactors, the cooling circuits of the fast breeder are not pressurized. This is the reason neither European reactor was built with external containment for a large overpressure (the U.S. prototype will be designed to sustain 0.6-atmosphere overpressure). However, the reactor buildings of the European breeders are sealed, operated below atmospheric pressure to guard against leaks of radioactivity, and are capable of withstanding 0.04-atmosphere overpressure.

There is excellent exchange of information among the safety engineers for the breeder programs in the United States and Western Europe, and the various officials seem to be moving toward agreement on the stringency of the measures needed. For the successor to the Phenix, the French are including many of the sort of features that have been incorporated into U.S. breeders, and officials at ERDA say it is possible that future U.S. breeders, after the prototype, may adopt the European view that a containment dome is not necessary. Specifically, the French Superphenix not only will have redundant control mechanisms, but a diversity of types, with three different designs, and an extra (third) shell in the primary reactor vessel design. The outer building of the Superphenix is being designed to withstand a plane crash, and French officials emphasize that nothing prevents the use of a containment dome in the design.

The crucial question for breeder safety is whether, in the event the core melted and began to rearrange itself into undesired configurations, all the fissionable material could come together again in such a way as to produce a great increase in nuclear reactivity (recriticality) and blow itself apart in a small explosion. This question of recriticality, together with the evaluation of the amount of energy it might release, depends on what presumptions are made—such as whether much of the sodium will vaporize and whether the steel at the bottom of the reactor will boil. Another safety problem, which could lead to disruption of the whole core if the reactor is not properly designed, is that in certain parts of the reactor localized boiling of the sodium tends to increase the temperature and reactivity in that area rather than to be self-correcting (the problem of the sodium void coefficient).

Differences in safety standards have been suggested as one reason why Europe is ahead of the United States in building prototype breeders. The fact that electric power production and nuclear technology development are more nationalized in Britain and France is another reason offered by spokesmen for the U.S. program. Whereas the U.S. policy is to encourage development of the technology by industry—whether at the level of large components for reactors or entire plants for fuel fabrication—the European programs can proceed much faster, it is argued, because they can undertake the whole reactor project. There is truth, of course, to both statements, but the primary advantage of the European programs appears to be strong management.

Different National Attitudes

The European national utilities, in particular, appear to have been much more active participants in breeder development than have the U.S. utilities, which many observers characterize as unenthusiastic. Rather than dragging their feet, the European utilities—CEGB in the United Kingdom and EdF in France—may have actually exerted their considerable influence to speed up breeder development. The utilities do not, however, appear to acquiesce readily to all the plans of the technical managers. The British reprocessing plant might not have been built at the same time as the prototype reactor if the CEGB had not insisted on sound evidence that the two technologies would work equally well, and the French probably would not have supported the development of two commercial-type steam generators if the EdF had not insisted on alternative designs for that trouble-plagued reactor component. Another reason the French give for their success is that they concentrate all of their research and development in one location. All the work on the components in the reactor, including testing in hot sodium, is done in Cadarache, and the work on steam generators is done at the CEA laboratories at Saclay, just outside Paris. The American program, by comparison, is spread about equally among six installations thousands of miles apart. The British program, like the French one, is very centralized, with virtually all the work, including that of the national nuclear companies, done either near Manchester or at the reactor site in Scotland.

The goal of the breeder development is to reduce power costs until breeders can compete with light water reactors. Much work is still needed to develop reliable, high-burnup fuels, and the costs of the fuel cycle technologies need to be established. But a low fuel cycle cost is one of the trump cards that breeder designers are relying on to make their capital-intensive technology competitive.

Although the Europeans are considerably ahead of the United States in proving the technical adequacy of the fast reactors, at the present time the European experience does not give many more clues to indicate how much breeder power would cost.—WILLIAM D. METZ