European Breeders (II): The Nuclear Parts Are Not the Problem

Dounreay, Scotland. Every country that has a large program for energy research has invested heavily in an effort to perfect the technology of the breeder nuclear power station. Together, the United Kingdom, France, the Soviet Union, and the United States have spent more than $5 billion, and West Germany and Japan also have large and growing programs. The goal is to launch a new nuclear technology that will consume abundant nonfissionable uranium rather than the scarce fissionable variety, and extend the life of the resource by hundreds of years. Measured by its funding, the breeder is the world's favored bet for a long-term source of new energy.

Prototype breeders designed to produce several hundred megawatts of electricity are already being tested in the United Kingdom, France, and the Soviet Union, and the performance of the French Phenix reactor has so far been superior (*Science*, 26 December 1975). But the problems of the British and Soviet reactors may be more indicative of difficulties that must be overcome before breeders can be reliable commercial power stations.

All the programs are concentrating on a single reactor concept which employs fast neutrons, plutonium fuel, and liquid sodium coolant. The novel coolant is already causing problems because it can be corrosive. The plutonium fuel of the breeder could represent a new danger from nuclear power because it is high-grade bomb material.

Since the United States does not have a prototype breeder, and will not for almost a decade, most of the world expertise is in Europe. The Soviet BN-350 reactor first went critical in November 1972, the French Phenix reactor in August 1973, and the British Prototype Fast Reactor (PFR) in March 1974.

The British PFR, which is a 250-megawatt reactor here at Dounreay (Fig. 1), and the French Phenix, a like-sized reactor at Marcoule, are examples of the "pot" type breeder design, with the reactor core, the primary sodium pumps, and the intermediate heat exchangers all immersed in a large tank of liquid sodium. In the early 1960's the British and French adopted this design, in preference to the "loop" design favored by the Americans, because they believe it is safer. The Soviet 350-megawatt prototype is a loop type, but the Soviets are also building a 600-megawatt reactor of the pot type, named BN-600, due to be completed at Beloyarsk in the Ural Mountains in 1978. West Germany is also planning to invest in both pot and loop type experimental breeders. In the loop design, only the core is in the reactor vessel, while the pumps and heat exchangers are outside.

Judging from the performance of the European reactors, the least reliable components are the steam generators, which function as the interface between the nuclear system and a turbogenerator system (see box). Their function is simply to exchange heat between hot liquid sodium and water to produce steam. Different types have been designed for the prototype reactors, but they all consist of a number of pipes of one configuration or another inside a larger pipe or a tank. As one engineer described it, "So far the problems are all in the plumbing." The French Phenix has been run at full power for more than a year, producing more than 2 billion kilowatt-hours of electricity. But recurring steam generator problems have repeatedly shut down the British and Soviet breeders so they have produced only a miniscule amount of electricity.

It should be noted that although steam generators serve a simple function, they are large and intricate arrangements of piping that fill an entire hall. In fact the British steam generator hall takes up almost as much space as the reactor hall does and the French steam generators are larger. See for instance the PFR layout (Fig. 2).

While the French prototype steam generators have worked reliably for more than a year, a distinction must be made between steam generators that work well at a price and those cheap enough to build on a large scale. Almost everyone agrees the French design is too expensive for a commercial-sized plant. It is a simple but repetitive system in which the reactor heat is transferred to 36 identical modules. Each module is a large S-shaped pipe that carries sodium in one direction; inside the pipe is a bundle of seven tubes that carry water in the other direction. The thermal power capacity of each module is only 15 megawatts.

The British also have experience with simple, reliable, and very expensive steam

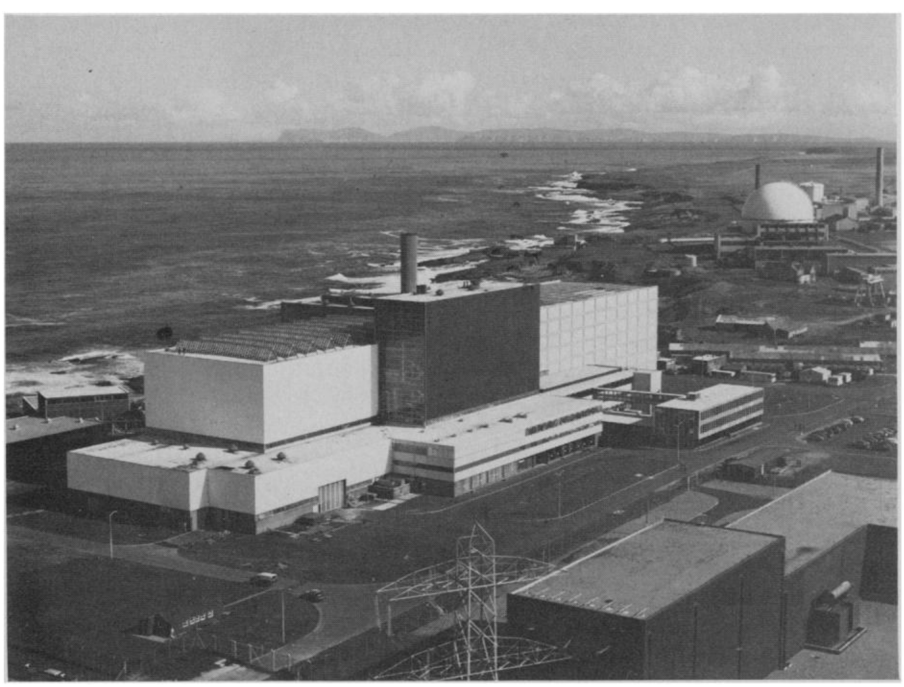

Fig. 1. British breeders on the North Sea at Dounreay, Scotland. The large building is the new 250-megawatt Prototype Fast Reactor (PFR) power station. The round shell in the background in an older 14-megawatt test breeder, the Dounreay Fast Reactor (DFR). On the horizon are the Orkney Islands.

generators. Those on a small test breeder built here at Dounreay in 1959 were devices with five tubes set in solid copper blocks that looked vaguely like cookie cutters in cross section—"positively Victorian" was the way one engineer fondly described them. They were quite reliable because two pipes would have had to fail before sodium and water could mix, but the design was inefficient for heat transfer and quite costly.

For their 250-megawatt prototype, the British designed a system with a few large complex units—the first steam generators that had inherent economies of scale and could be reasonably extrapolated to a commercial power station. The massive double-wall design of the test reactor was abandoned for a much lighter single-wall design. The thermal capacity of each steam generator was fixed at 200 megawatts.

The British breeder plant has three steam generators, each composed of three connected tanks that are 1.5 meters in diameter and 4 to 5 meters high. One unit is an evaporator, another a steam superheater, and the third a reheater. There are slight differences among the units, but in each case water or steam flows through many small tubes 2 centimeters in diameter that loop from the tank top (called a tube sheet) down into a sodium pool and out again. The only welds in the steam tubes are at the top of the tank where the tubes join the tube sheet. The level of the liquid sodium stays below the tank top, and the space in between is filled with argon.

The British are not happy to be the world's experts on steam generator leaks, but on the other hand, "We're glad it occurred with the PFR rather than with the commercial plant," says C. W. Blumfield, director of the Dounreay reactor establishment. In early 1975 an evaporator developed a leak, which was quickly detected by the hydrogen given off from sodium-water reactions. But the leak could not be found among the 80-odd tubes until it grew to 0.1 millimeter in size. After it was fixed two superheaters developed leaks. In each case the leaks were in welds between a tube and the tube sheet (a 25-centimenter-thick steel plate). The leaks did not occur below liquid sodium level, but in the gas space, where there is sodium vapor mixed with argon. The problem with these small leaks is not just that they enlarge, as sodium and water vapor penetrate from opposite sides, but that they propagate. In one superheater that has been disassembled for repairs, a large area of the tube sheet had to be cut away because the original crack expanded into a whole network that weakened the metal a considerable distance from the weld. According to Blumfield, the mechanism of propagation is not well understood, but one possible explanation is caustic stress corrosion—sodium migrates to the tip of the crack and causes corrosion, which stresses and extends the crack.

In some instances, the original leak was caused by a bad weld or an improperly seated tube. "It's partly a question of quality control," says Blumfield, "but we're sure it's not a generic issue." In the superheaters that were affected, the material is stainless steel. The evaporators are made of corrosion resistant ferritic steel (with $2\frac{1}{4}$ percent chromium).

The Soviet prototype breeder has had much more serious leaks, which mixed liquid sodium and liquid water, producing a violent reaction in its boiler tubes. The reaction built up an overpressure and caused most of the liquids in the evaporator to be expelled. The first such failure was in October 1973, and at least two more have occurred since then, putting three of the six steam generator units of the BN-350 out of commission. The failures reportedly occurred because of bad welds used to attach endcaps to tubes used in the evaporators. Five steam generator units, each consisting of two evaporators and two superheaters in parallel, are needed for full-power operation of the reactor (one unit is a spare). The large units are commercial-type designs, each rated at 200 megawatts. The steam superheaters, in particular, are similar to the British design, but the steel alloys used are lower grade and some features—such as welds below the sodium level—are not consistent with the practices of other countries. Each evaporator and superheater has more than 800 tubes in it.

The Soviet evaporator tube failures were rather dramatic events, which apparently stimulated announcements of reactor explosions and casualties, denied by the Soviets. What the sodium-water mixing did do was cause the steam generator safety system to actuate, puncturing a pressure-relief diaphragm. The sodium and water reaction products spewed into catchment tanks, ejecting all the gases up the stacks. According to one (unverified) report, the clouds of escaping gas were detected by an American satellite, furnishing the information that led to reports of a Soviet breeder reactor accident. However the reactor was not involved, and the safety systems apparently worked adequately.

The BN-350 is still not operating reliably after three years, and the Soviets are working vigorously to improve steam generator designs. They are increasing the thickness of the tubes that separate water from sodium (from 2 to 3 millimeters) and changing their welding technique. At the BN-600 the plant engineers are rapidly modifying their original steam generator design, which used much larger units than those of the BN-350, to a modular version that is becoming quite similar to the Phenix design.

The United States chose not to stress steam generator development when it decided in the early 1960's to build the Fast Flux Test Facility (FFTF), a fast reactor that will produce 400 megawatts of thermal power but no electricity. "Everybody in the world agrees that steam generators are a major problem," says George Cunningham, deputy director of the American fast breeder program. "We deliberately chose not to attack the problem until the FFTF was well under way. We have had a program, but it will not be in

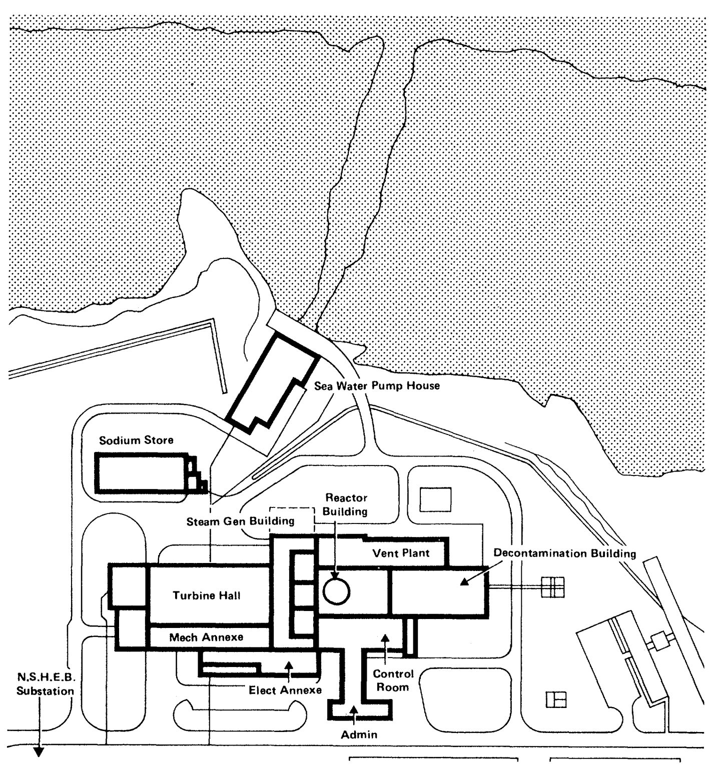

Fig. 2. Site layout of the British Prototype Fast Reactor.

depth for a while." Steam generators with a commercial-type design have been chosen for the American prototype, however, and tested at reduced scale. Full-scale steam generator units for the American prototype, rated at 100 megawatts of thermal power, will be tested at the Liquid Metal Engineering Center in the Santa Susana Mountains of California.

As a result of their experience with leaks in the steam generators of the prototype breeder, the British are designing the steam generators for their 1200-megawatt commercial fast reactor (CFR) very conservatively. The CFR design will use improved versions of the present design, with different tube-sheet details and more corrosion resistant (ferritic) steels, but no increase in size. With 16 steam generator sets (each with two units), the British are moving toward a more modular design.

Meanwhile, the French are completing the design of a commercial-sized breeder, Superphenix, and they are moving drastically away from the concept of a modular steam generator. Only four units will be used, and they will be huge: 3 meters in diameter, 28 meters high, and each rated at 750 megawatts. There will be no separation of functions. Long, helically wound tubes will carry the water through the tank only once, evaporating it at the bottom and superheating the steam as it passes out the top. The tubes will be made of a nickel alloy (Incolloy) that is more corrosion resistant than the stainless steel used for the PFR, but requires a slightly lower sodium temperature (490°C is planned). The cost per thermal megawatt will be only about half that for the Phenix steam generators, which cost $12 million for a capacity of 563 megawatts.

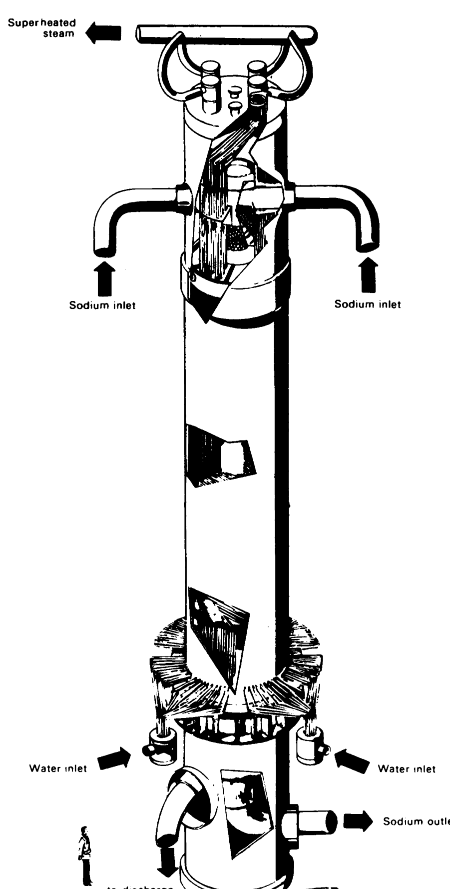

Fig. 3. Steam generator design chosen for the French 1200-megawatt breeder.

For the Superphenix steam generator a choice was made between two designs, one by Stein Industries, which made the Phenix modules, and the other by Fives-Cail Babcock company. The helical Babcock design (Fig. 3) was chosen after extensive tests of scaled-down 45-megawatt versions of both designs. It has a particularly elegant method for connecting tubes to tube sheets so that sodium and water are not on opposite sides of the same weld—instead there are sodium/air welds and steam/air welds.

"Basically I think we have a good design for Superphenix," says Marcel Robin, chief of the French steam generator development, "but we have to wait five years to see if we made too big a step." Although the Phenix had minor steam generator problems recently, when a leak in the water inlet manifold of one steam generator module caused a shutdown for two weeks in December, the French program has been remarkably free of such problems. "Our success is due to simple design, I think, and maybe more due to good inspection," says Robin. Inspection for the Phenix welding was done by a separate company, the Bureau Veritas, at a cost of 5 percent of the total steam generator cost. According to Robin, even more will be spent for the Superphenix—6 to 7 percent of the cost.

Even with their success, the French are not sanguine in thinking the steam generator problem has been solved. Robin points out that the Phenix has operated for only about 1/30 of its expected lifetime, and more problems could develop. Almost everyone, he notes, would like to use high-grade ferritic steel (which has 9 percent chromium), but the material is new enough that the standard performance codes for it have not been compiled yet. It is cheaper than Incolloy and safer against caustic-stress corrosion, but welding it will probably be more difficult. Apart from the crucial question of deciding whether the step to a 750-megawatt module is too big a jump, Robin lists the testing of ferritic steels as the most important future activity in French steam generator development.

Another factor that undoubtedly contributed to the generally high reliability of the Phenix steam generators is that the French atomic energy commission (CEA) undertook considerable full-scale testing. One module was partially tested at the 5-megawatt thermal test facility that the CEA has operated for 15 years at Grand Quevilly, and then three modules were thoroughly tested at a much larger 45-megawatt test facility built by the French national generating board (EdF) at Les Renardières specifically to assure the reliability of fast breeder prototypes. This facility was also used to test the scaled-down versions of the competing Superphenix designs.

The British facilities for steam generator tests are less ample, and no tests were done with thermal power applied. The prototype steam generator units were tested for sodium-water reactions in one rig, Super-NOAH. But a different test rig designed to ascertain how long the superheaters could run with small water leaks was not available until leaks occurred in the prototype.

The French also appear to have the more extensive facilities for testing the components inside the reactor itself. At the big laboratory in Cadarache, the CEA has six or eight large sodium experimental rigs that were used to test Phenix components (Fig. 4). A much larger building (TRIPOT) is now being constructed at a

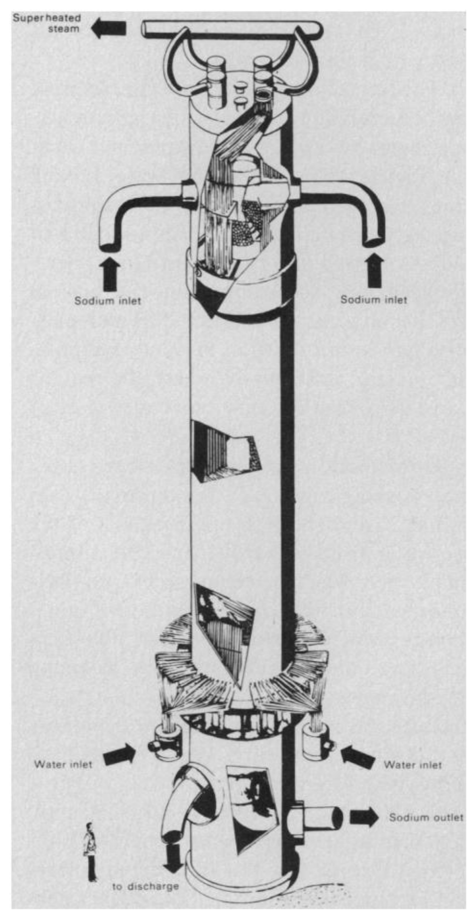

Fig. 4. The experimental sodium test rig used to check the operation of the French fuel handling ramp before it went into the Phenix reactor.

cost of $3 million to provide the same degree of extensive testing of the large components for Superphenix. Before the Phenix started up, the fuel-handling apparatus, the control rods, the intermediate heat exchangers, and even a huge ramp used to remove the fuel were all tested in liquid sodium. The primary pumps were tested in water, which duplicates many of the hydrodynamic effects of sodium.

The British appear to do less full-scale testing than the French. "We operate a sound program of development, not a program that spends money unnecessarily," says Blumfield. That sparing approach seems to have worked quite well for the design of the reactor itself, which has worked beautifully so far. The British tested the primary sodium pumps at full size in water. They also tested the general features of sodium flow in the reactor tank, including the problem of gas entrainment at the liquid surface. For their commercial reactor, however, the British will use the prototype reactor as a test facility.

One American familiar with all the major breeder problems offers the following as a helpful (if perhaps too patriotic) characterization of the national programs. The United States does extensive testing of many design variations and also of actual components before putting them in the reactor. The Soviet Union, at the other extreme of testing philosophy, prefers to build the reactor first, then see if it can be made to work. (The Soviets apparently did no testing of the steam generators for the BN-350 plant.) The French program is rated as closer to the American one in testing philosophy, and the British as closer to the Soviets.

While the French have a technology that has proved quite reliable in the Phenix, the British have a plant that is more advanced in the crucial areas of steam generator design and fuel performance.

The most important parameter of fast reactor fuel performance is the amount of "burnup" the fuel undergoes before it must be reprocessed. It may be measured by the power the fuel produces or the percentage of the fuel that undergoes fission. The British goal for the prototype reactor fuel is that it stay in the core until each ton has produced 75,000 megawatt-days of power. Of course, with its steam generator troubles, the prototype reactor has not operated nearly long enough yet to see whether the fuel will endure such a level of irradiation with a tolerably low number of fuel pin failures. This level of performance, equivalent to the burnup of 7.5 percent of the mixed oxide fuel, is not far from the performance considered adequate for a commercial reactor program by British officials, namely 10 percent. Increased burnup, however, is the best way to improve both breeder economics and doubling time—the time for the reactor to double its original inventory of fissionable material.

The French goal in designing the Phenix was a much more conservative one, a burnup of 5 percent or power production of 50,000 megawatt-days per ton. The Phenix fuel is designed to produce power for a total time of one year before it is repro-

The Way Fast Breeders Work

Fast breeders not only burn fuel in the reactor core, they also breed fuel in a "blanket" of nonfissionable ^{238}U that surrounds the core. The fuel is contained inside thousands of thin metal pins, several meters long, and many pins are held in much larger cans called subassemblies. The cans are generally hexagonal, a shape that allows them to be packed closely together standing in holders in the reactor floor. When the control rods are removed, the reactor goes critical and an intense flux of neutrons permeates everything in the core—the fuel, the fuel pin clading, and the hexagonal cans—as well as the blanket, which consists of several rows of subassemblies stacked around the core, plus some sections of uranium at the top and bottom of the fuel pins. Outside the blanket, still other subassembly cans filled with steel reflect escaping neutrons back into the core.

The fuel is burned when neutrons induce it to fission, producing more neutrons and heat. In the blanket, new fuel is bred when a neutron is captured by ^{238}U to make fissionable plutonium. The key to good breeding is to produce an abundance of neutrons, in addition to those needed to sustain the chain reaction. Light water reactors also produce plutonium, but inefficiently because neutrons emitted at high speed upon fission are slowed down by the water moderator. Fast fission produces 2.9 neutrons per fissioning nucleus, while slow fission produces only 2.4. This small differential produces the large surplus of neutrons that makes it possible for a fast reactor to produce more fuel than it consumes.

Although high-speed neutrons are effective for breeding, the nuclear cross sections (effective collision diameters) are such that the fast reactor fuel must be relatively rich in fissile material to keep the reaction going. Light water reactor fuel is typically 2 or 3 percent fissile material, but fast reactor fuel is 15 to 30 percent fissile material—either ^{235}U or plutonium.

The high-grade nature of the fuel, plus the need to limit the total amount of expensive plutonium in the core, has resulted in fast reactor designs with extremely compact cores. Closely packed fuel and high power densities are basic features, and they have largely determined the choice of sodium as a coolant.

Sodium has the good heat transfer properties needed at high power density, and it fits the nuclear requirements too because it does not slow down neutrons as water does. It also does not absorb as many neutrons as water. The physical properties also make it attractive. Sodium is in a liquid state between 98° and 880°C and so does not need to be pressurized to remain liquid at fast reactor temperatures (up to 650°C). Lack of high-pressure coolant is a safety advantage, and the high operating temperature makes breeders considerably more efficient for electricity generation than light water reactors. The result is less waste heat.

To withstand the high temperatures, the fast breeders use ceramic fuels. Specifically, the fuels are a mixture of uranium dioxide and plutonium dioxide, often called "mixed oxides." They are fabricated in the form of small pellets, about 5 millimeters in diameter, and sealed in tubes of metal clading to protect the fuel and trap gaseous fission products. Several hundred fuel pins are in each subassembly, and a flow of sodium is channeled up through each one to carry away the heat of fission.

The heat that is extracted from the core by the circulating sodium coolant is used to produce steam for a turbogenerator. But all the breeders built have been designed with a secondary sodium circuit that serves to isolate the reactor from the steam, so that no sodium-water reactions could conceivably occur within the reactor itself. It also assures that the highly radioactive sodium in the primary circuit is not involved if a leak occurs in the steam generators. Heat is transferred between the primary and secondary circuits by intermediate heat exchangers.—W.D.M.

cessed, and the fuel in one-sixth of the core is changed every two months. Thus the first load of fuel pins to be removed showed the effects of about 5,000 megawatt-days per ton, the second 10,000, and so forth. Such a system allows close monitoring of the fuel durability. By now at least one load of fuel (several thousand pins) has reached the performance goal of 50,000 megawatt-days per ton, and a significant amount of fuel (500 pins) has reached a burnup of 65,000. Thus it appears that the Phenix fuel performance goal was not only conservative, but also conservatively stated. The fuel goal for the commercial-sized Superphenix is 100,000 megawatt-days per ton.

For comparison with the American program, the average fuel burnup planned for the FFTF is 4.5 percent (8 percent peak), and the goal for the entire U.S. fuel development program—set to cover the most severe demands expected in order to make a commercial breeder design economic—is 15 percent or 150,000.

The thermal characteristics of the Phenix and PFR reactors are quite similar. The fuel pins produce about 430 watts per centimeter in each case; and the maximum sodium temperature on the fuel pin cladding (which is austenitic stainless steel for both reactors) is 650°C.

Because the Phenix and the PFR are both pot reactors, the large amount of residual heat that the fuel pins produce even after the reactor is shut down can be absorbed with only a slow rise of temperature. Not only does the 900-ton pool of sodium act as a good heat sink, but the sodium will continue to circulate by convection even if the primary pumps should fail.

Thus the pot reactors are well protected against a loss of the normal coolant systems. Both the Phenix and the PFR have ample time for standby circuits to operate in the event of an emergency shutdown. Cooling coils girding the outer shell of the reactor vessel would stabilize the Phenix's temperature, and small air-cooled loops in the intermediate heat exchangers, where convecting sodium would circulate, would remove heat from the PFR.

The pot reactor also offers a number of design advantages that are not available in the more confining reactor vessel of a loop type breeder. The French, for instance, have taken advantage of the spaciousness of the pot to install a fixed ramp, with a rotating lock at the top, for removing fuel from the reactor (Fig. 5). Both the Phenix and the PFR use retractable arms to remove fuel from the core, but not to remove it from the reactor. With the French design, a spent fuel subassembly can be pulled up the ramp, through an airlock at the top, and then lowered into a storage carousel in a sodium-filled tank in a separate but adjacent room. The design saves time and appears to be somewhat safer than alternative methods. The British plan to use such a feature in their commercial fast reactor.

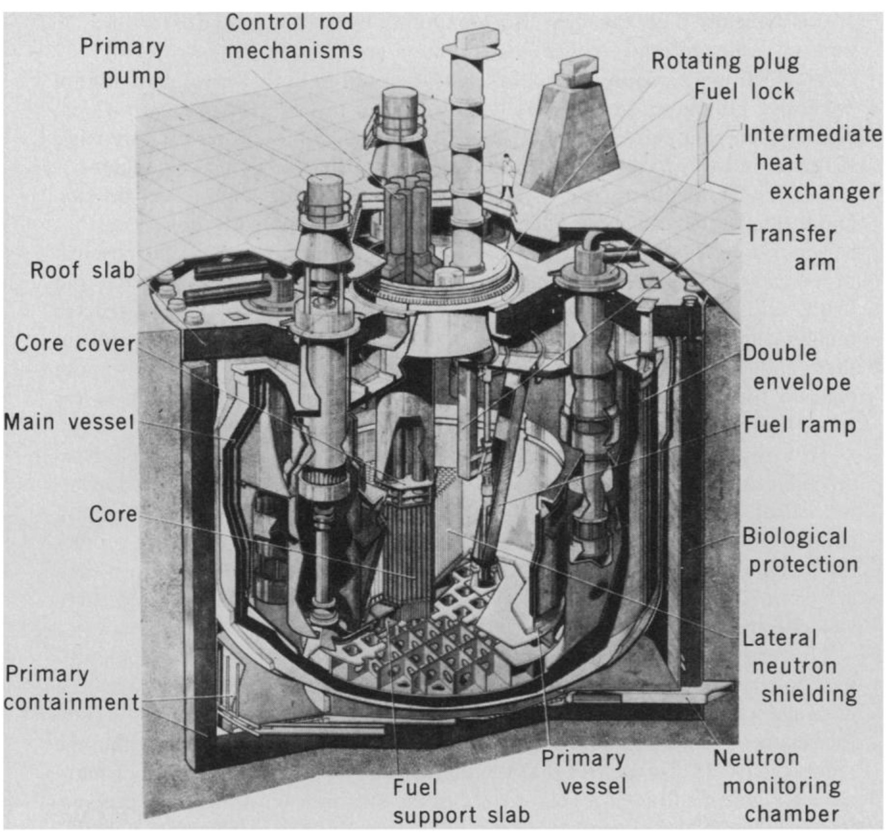

Fig. 5. The design of the reactor for the French 250-megawatt Phenix. In operation, the vessel is filled with opaque liquid sodium.

Although the Superphenix is scheduled to be completed by 1981, several years before the CFR, the two breeder designs will nevertheless be competing with each other to prove their reliability and superiority. It will most likely be to these two 1200-megawatt installations that the world will look in the 1980's to evaluate the desirability of all breeder reactors.

The British commercial reactor (CFR) will be the second reactor completed in all likelihood, and, as already noted, it will be a modular extension of the PFR design. The core will be enlarged by using 250 instead of 78 subassemblies, and the number of steam generators will be increased from 3 to 16. The doubling time of the CFR is planned to be 25 years. Assuming that the prototype problems are resolved, the biggest surprise of the commercial-sized reactor will be if it does not work well.

The Superphenix, on the other hand, will be a considerable extrapolation of the technology proved in the Phenix. It will have more advanced steam generators than any breeder plant, even in the early 1980's. The unimpressive breeding properties of the Phenix are to be considerably improved for the Superphenix—a 20-year doubling time is expected. The Superphenix design is a gamble with higher stakes—and the chance of greater winnings.

The reactors themselves are only one of the technologies that must operate in a fault-free fashion for breeder power stations to become a reality. No one can yet say for certain whether the power plants, the fuel fabrication plants, or the fuel processing plants will be the most difficult technologies to conquer. But at the present time, the reactor plants are the most advanced.

The European experience with breeders indicates that further improvements of designs and materials are needed, and other difficulties may appear later as all components are subjected to more wear. Beyond that, all the European program managers regard the subsequent task of competing with the cost of power from light water reactors as a difficult one. But the technical progress that has been made in 15 years of breeder research is impressive, and the pace of problem solving does not seem to indicate that breeder reactor development is much more difficult than the development of nonbreeding reactors.—WILLIAM D. METZ