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Breeder Reactors in France

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Summary. France relies on nuclear power as an important part of her energy program. Anticipating problems with the availability of natural uranium before the year 2020, the French have been pursuing a three-stage program of development of breeder reactors. The third reactor in this program, the near-commercial plant Super Phenix Mark I, is expected to reach power operation in 1983. Although there are still some uncertainties, particularly about the date when the breeder will become competitive with other energy sources, the outlook is considered favorable and preliminary designs for commercial plants are under way.

In this article I will not attempt to describe in any detail the technical features of French breeders, as they have already been largely presented in the international technical press (*1-4*). Instead, I will discuss the experience gained in the French breeder program, the rationale of the program, its possible development, and the problems that remain to be solved. This discussion will also lead to some comments about breeder development in other countries, as any national program has, of course, strong connections with the international situation.

Rationale for Developing Breeders

The contribution of nuclear energy to world energy needs will be rather limited if breeders are not developed. With breeders, however, the world will have a major and almost inexhaustible source of energy, which will at least allow enough time to find and develop complementary and perhaps better energy sources.

To operate a typical, 1000-megawatt-electric light water reactor (LWR) for its 30 years of useful life, some 5000 tons of uranium are needed. The world resources of uranium that can be produced at a cost no higher than $50 a pound are estimated as 3.5×10^6 tons, which means that they are sufficient for 700 1000-MWe reactors. Conservative estimates indicate that there will be more than 700 such reactors in operation before the end of the century. Therefore we may start to have problems with the availability of natural uranium rather soon. If we are more optimistic about uranium resources or more pessimistic about the rate of construction of nuclear power plants, we can estimate that the problems will appear some years later. However, most experts agree that without breeders there will be a serious problem of uranium availability before the year 2020.

Who can guarantee that at this date there will be other sources of energy that are sufficiently abundant and compare favorably with nuclear energy (breeders) from the environmental and economic points of view? Furthermore, if we take some specific country or group of countries and consider independence from energy imports, we may make a much stronger argument for the development of breeders. Let me give as an example the situation of France.

At present, France is importing more than three-fourths of her energy. She plans to develop any national energy resource at the maximum possible rate and thus to achieve by the year 2000 a lesser, but unfortunately still very large (a little more than 50 percent), dependence on imported energy. This goal calls for energy saving and for developing solar energy at the maximum reasonable rate. But it also calls for an aggressive nuclear program: more than 40,000 MWe of nuclear capacity by 1985, more than 60,000 MWe by 1990, and some 100,000 MWe by 2000 (*5*).

Proved uranium resources with an extraction cost below $50 a pound, both in France and in some other countries where France has a controlling interest, are estimated as about 160,000 tons. This is sufficient for only 32 1000-MWe LWR's operating for 30 years—or it may produce more than 50,000 gigawatt-years if used in breeders. The latter amount of energy is in the same range as proved world oil resources.

The situation with respect to natural uranium resources is even worse if one considers the countries of the European Economic Community (EEC). All the other EEC countries together control less uranium than France, and, of course, their energy needs are far greater.

There is another problem with uranium availability. Even if there are sufficient resources in the earth (for example, if one agrees to pay much more than $50 a pound), one still has to make sure that enough uranium is actually available on an annual basis. This calls for a certain rate of discovery and mining. Up to now, the best rate of discovery worldwide has been 60,000 tons a year and the average has been around 40,000 tons a year. This must be compared with the estimate of annual needs, which are expected to be around 150,000 tons a year by the end of the century. I stressed this point 4 years ago (*6*) and I think it is still valid, even if some numbers (projection of nuclear power) have to be adjusted. Figure 1 shows estimates of the annual consumption of natural

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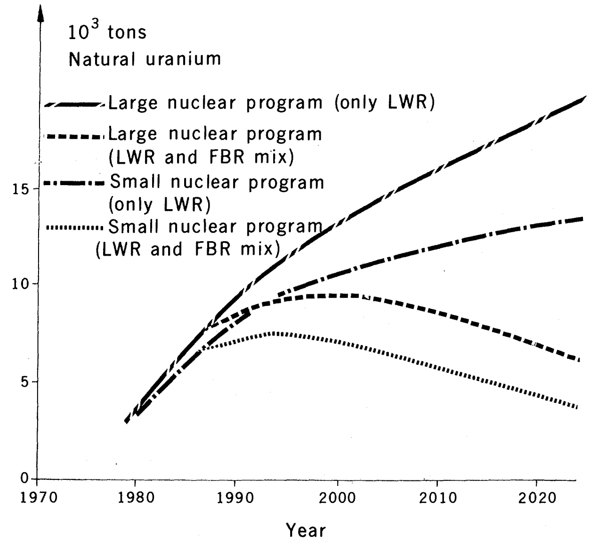


Fig. 1. French annual requirements for natural uranium.

uranium in France with and without breeders.

Recently, the International Energy Agency made two statements. One was a decreased forecast for the installation of nuclear power plants in the near future; the other stressed the need for larger nuclear programs as soon as possible. This, in my view, underlines the present uncertainties concerning the development of nuclear energy. Many difficulties, mostly related to public acceptance, indicate a downward trend. Yet it is quite possible that increasing problems and uncertainties in the total energy supply will reverse the trend and that much larger nuclear programs than the ones now anticipated will be called for even before 2000.

It is therefore prudent to admit that the estimates of both uranium reserves and nuclear generating capacity have inherent large uncertainties and that the real question for a country is, What is the relative risk (*7*) of having developed the breeder for commercial use too soon, or even unnecessarily, as compared to not having it ready when needed?

I think the answer to this question will clearly indicate the urgent need for breeders in many countries, including France. Some countries may prefer to wait until breeder technology has been developed by others and then arrange for access to this technology if they need it. The intermediate position may be to become associated with development programs in other countries.

Having outlined the reasons for developing breeders, I must now address some questions about the practicality and desirability of the breeder option. These questions are: Is breeder technology demonstrated? Will breeders produce energy at an acceptable cost? Is the environmental impact of breeders acceptable? Will the use of breeders significantly increase the risk of nuclear weapons proliferation?

After presenting the French experience with and plans for breeders, and mentioning the programs in other countries, I will discuss these questions.

Present Experience with Breeders

The development of breeders, or more precisely of liquid metal fast breeder reactors (LMFBR's), which started in France almost a quarter of a century ago, has taken place in three main steps leading to three increasingly powerful reactors: Rapsodie (20 to 40 megawatts thermal), Phenix (250 MWe), and Super Phenix Mark I (1200 MWe) (*1*, *2–4*, *8*). The design of these reactors has followed three principles: (i) making maximum use of the experience gained with one reactor in the design of the next one, thereby providing continuity in technical solutions and in the teams in charge of different reactors; (ii) aiming for economy, therefore making the unit size of the reactor and its components as large as possible; and (iii) giving the highest priority to safety and to the availability of the power plant.

Experimental reactor Rapsodie. The first major step in the French LMFBR program was the experimental reactor Rapsodie (*1*, *9*). The design was started in 1957, construction was begun in 1962, and nominal power (20 MWt) operation was reached in 1967. Subsequently, in June 1971, the power of Rapsodie was increased to 40 MWt (Fortissimo version). As Rapsodie was the first French LMFBR, it has modest characteristics: 40 MWt, no electricity production, and heat dumped to the atmosphere through sodium-air heat exchangers. The development and test of a sodium-heated steam generator was done in parallel, using nonnuclear test loops of various sizes up to 50 MWt.

In spite of these limitations and of the very early stage of the French program, many technical features of Rapsodie have been retained in the design of the larger reactors Phenix and Super Phenix. These include the choice of materials for the primary system and fuel (stainless steel and uranium and plutonium mixed oxide); general principles of fuel and core design (freestanding core, hexagonal assembly, wire spacer); temperature and specific power levels; and basic design of the main components [pumps, intermediate heat exchanger (IHX), and, at least partly, fuel-handling equipment].

From 1967 to the end of 1976, Rapsodie was operated with an average availability of 90 percent. It provided both the Commissariat à l'Energie Atomique (CEA) and certain foreign research groups with the means of performing a very large number of experiments. In May 1977, after 10 years of continuous operation followed by a 6-month period of upgrading, Rapsodie was put back into service.

Since the loading of the first Fortissimo core, 18,000 fuel pins have been irradiated to more than 65,000 megawatt-days per ton (8.1 percent of heavy atoms). Twenty experiments involving about 400 fuel pins have reached burnups up to 160,000 MWd/ton (nearly 20 percent of heavy atoms). About 20 fuel pins, some of which are similar to those used in Super Phenix, have exceeded the level of 100 lattice displacements per atom.

In summary, Rapsodie has provided extremely useful information about operating an LMFBR with high specific power, similar to that of Phenix, and is an exceptional tool for testing fuel for the next generation of LMFBR's.

I would like to mention here that the experience gained with Rapsodie is part of a much larger international experience with the first generation of LMFBR's. These include the experimental breeder reactor EBR I, the first reactor in the world to produce electricity, which began operation in Idaho in 1951; EBR II, an experimental pool-type LMFBR, which has been operating successfully since 1965 in Idaho; the Enrico Fermi Fast Breeder Reactor, running from 1965 to 1972 in Michigan; BR 5 and BOR 60, started in 1958 and 1971, respectively, and still in operation in the Soviet Union; DFR, operated from 1965 to 1976 in

Dounreay, Britain; and KNK (Kern Natrium Kraftwerk), which started operation in 1979 in West Germany.

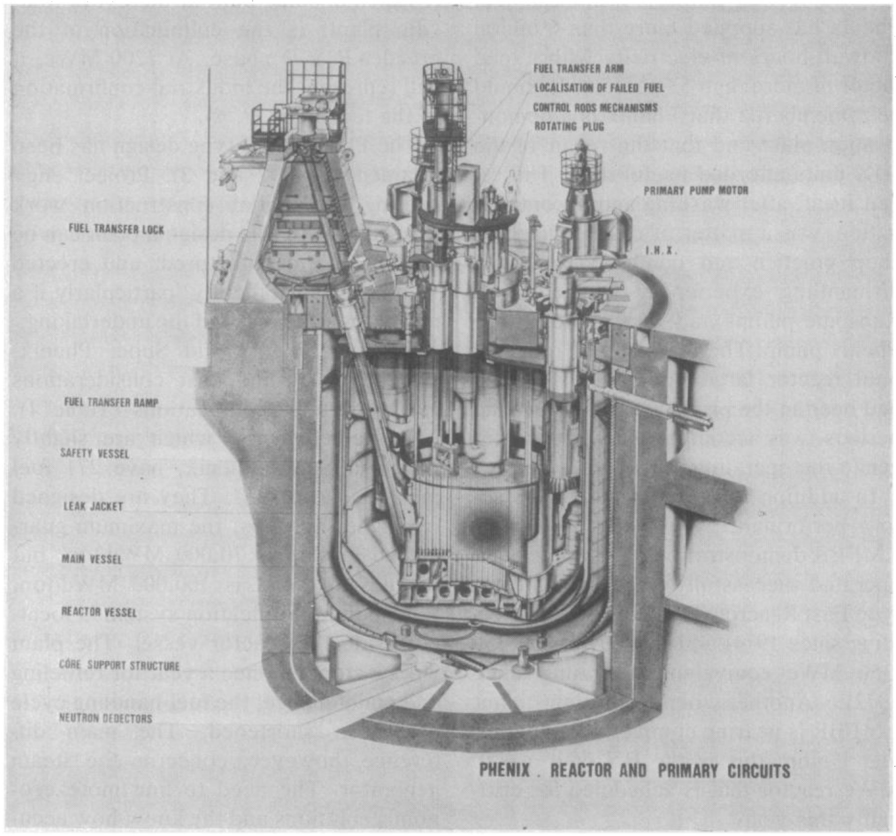
There are also other experimental reactors, some of which began operation recently and some of which are in advanced stages of construction. Among the former are Joyo in Japan (1978) and the Fast Flux Test Facility (FFTF) in Hanford, Washington, the most advanced and ambitious experimental LMFBR (400 MWt), which just reached criticality in February 1980. The latter include the PEC in Italy (130 MWt) and the FBTR Kolpakkan in India (100 MWt).

Demonstration plant Phenix. The Phenix, a 250-MWe, pool-type reactor with three secondary loops and modular steam generators, marked the second step in the French fast breeder program. Phenix design started in 1964, construction in 1968, operation in 1973, and industrial operation in July 1974 (*2, 10, 11*). Operating experience (*11–13*) acquired with Phenix has confirmed the stability and manageability of the pool-type design, originally selected for safety. The reactor proved very easy to operate with only two secondary loops in service at 66 percent of its rated electrical power.

Phenix fuel reached a maximum burnup of 72,300 MWd/ton without cladding failure. The first and so far the only fuel cladding failure (there have been some fission gas releases from pins, but they were due to microfissurization of the cladding and did not involve rupture and contact between the fuel and sodium) was detected and localized on 1 May 1979. The decision to maintain "clean" primary sodium and blanket gas led to stoppage of the reactor and replacement of the faulty subassembly (which was not a standard driver subassembly). The interruption of power production lasted 71 hours. These results remove any doubt regarding the behavior of the core elements under high neutron fluxes. Furthermore, the recorded breeding gains have slightly exceeded design figures. Thus, two basic uncertainties concerning breeder technology have been positively eliminated.

This type of reactor has a very low radioactive release rate, primarily due to the use of sodium rather than water as the coolant. During the first 2 years of normal operation of Phenix, the release rate of argon blanket gas was lower than 0.2 percent of the allowed rate, which was itself set as 1 percent of the concentration authorized by international commissions for population exposure. The average annual irradiation of power plant personnel was less than 10 millirems per person, or 0.2 percent of the allowable dose. These results, added to the fact that the gross thermodynamic efficiency of the installation is excellent (44.5 percent), show that this reactor has the least harmful effects on the environment.

After 2 years with a very good operating record (*11*) (load factor, 68 percent), this reactor was affected by mechanical problems arising from unsymmetrical sodium flow profiles on two of its six IHX's. After a period of part-time



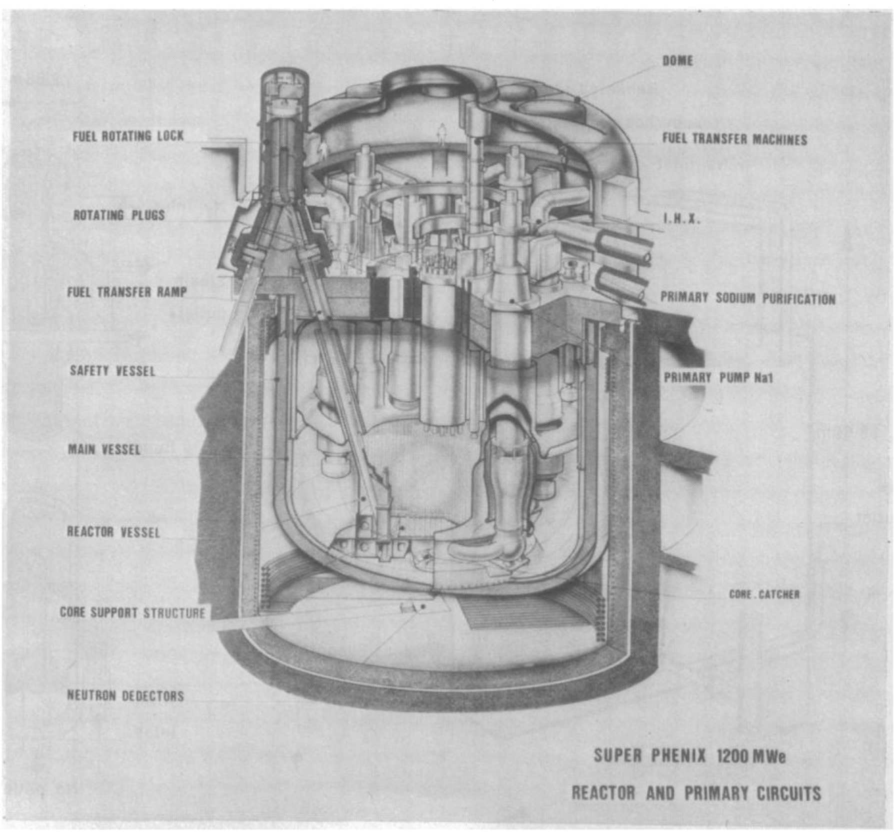


Fig. 2 (top). Reactor block of Phenix. Fig. 3 (bottom). Reactor block of Super Phenix.

operation on partial load and some redesign and modification of all six IHX's (*11*), Phenix resumed operation in April 1978 at rated power. Since then it has functioned satisfactorily, and in 1979 it achieved the very high capacity factor of 84.5 percent.

Since it was initially commissioned, Phenix has supplied more than 6 billion kilowatt-hours of electricity with a load factor of more than 53 percent. It should be remembered that Phenix is a demonstration plant and that the repair of the IHX units afforded useful data. The repair itself, after washing and decontamination, was a matter of routine machine shop practice and confirmed previous dismantling experience obtained with Rapsodie pumps and IHX's and with a Phenix pump. The removal and repair of pool reactor large components, which had been in the primary sodium for long periods, was accomplished without danger to the operating personnel.

In addition to the extremely satisfactory performance of Phenix, two other LMFBR demonstration plants have been operated successfully: the British Prototype Fast Reactor (PFR; 250 MWe, operating since 1974) and the Soviet BN 350 (350 MWe equivalent, operating since 1972). Another demonstration plant LMFBR is nearing completion in the Soviet Union; this is the BN 600, a 600-MWe reactor that is scheduled for criticality this year.

Near-commercial plant Super Phenix Mark I. Our experience with this reactor, the third stage in the French breeder program (after Rapsodie and Phenix), has so far been restricted to design, test of components, and construction. Criticality is expected in 1982 and power operation in 1983. The Super Phenix Mark I, which is being built at the Creys-Malville plant, is the culmination of the breeder R & D phase. At 1200 MWe, it will represent the industrial confirmation of the technique (*3, 4*).

The Phenix pool-type design has been retained (Figs. 2 and 3). Project engineering and initial construction work show that with this design a plant can be engineered, manufactured, and erected without major difficulty, particularly if a prototype has preceded the undertaking.

Between Phenix and Super Phenix, size increases and cost considerations led to certain modifications (Table 1). The fuel elements, which are slightly larger in Super Phenix, have 271 fuel pins instead of 217. They are designed for higher burnups; the maximum guaranteed burnup is 70,000 MWd/ton, but the design target is 100,000 MWd/ton. The sodium purification system is located inside the reactor vessel. The plant will be stopped once a year for refueling and maintenance; the fuel-handling cycle has been shortened. The main difference, however, concerns the steam generator. The need to find more economic solutions and the know-how accumulated, specifically about sodium-water reactions, have led to the replacement of the Phenix modular-type steam generators by four 750-MWt helical tube-type steam generators (Fig. 4).

The contract for Super Phenix was awarded by Nersa, the owner of the Creys-Malville plant, to Novatome-Nira in April 1977. The contract schedule provides for power operation in 1983. So far, 98 percent of the components have been ordered, with 70 supply contracts awarded to 35 different European firms. These contracts, in many cases, imply a combined effort on the part of manufacturers from several different European countries, backed by assistance from members of the Rapsodie or Phenix engineering teams.

Shop manufacturing work is progressing normally on the reactor vessels and internals; the main primary pump castings; the steam generator central tubes, on which helical coil winding has started (Fig. 5); and the roof slab, diagrid, and core support plate elements, which are positioned for assembly. Because of their very large size, certain components cannot be delivered to the site in one piece. It was thus necessary to provide special assembly facilities on the site, and a rectangular metal workshop (38 meters high and 10,000 square meters in area) was built 100 meters from the reactor building (Figs. 6 and 7).

Balance-of-plant orders have been placed by Nersa with different European firms. Civil works began toward the end

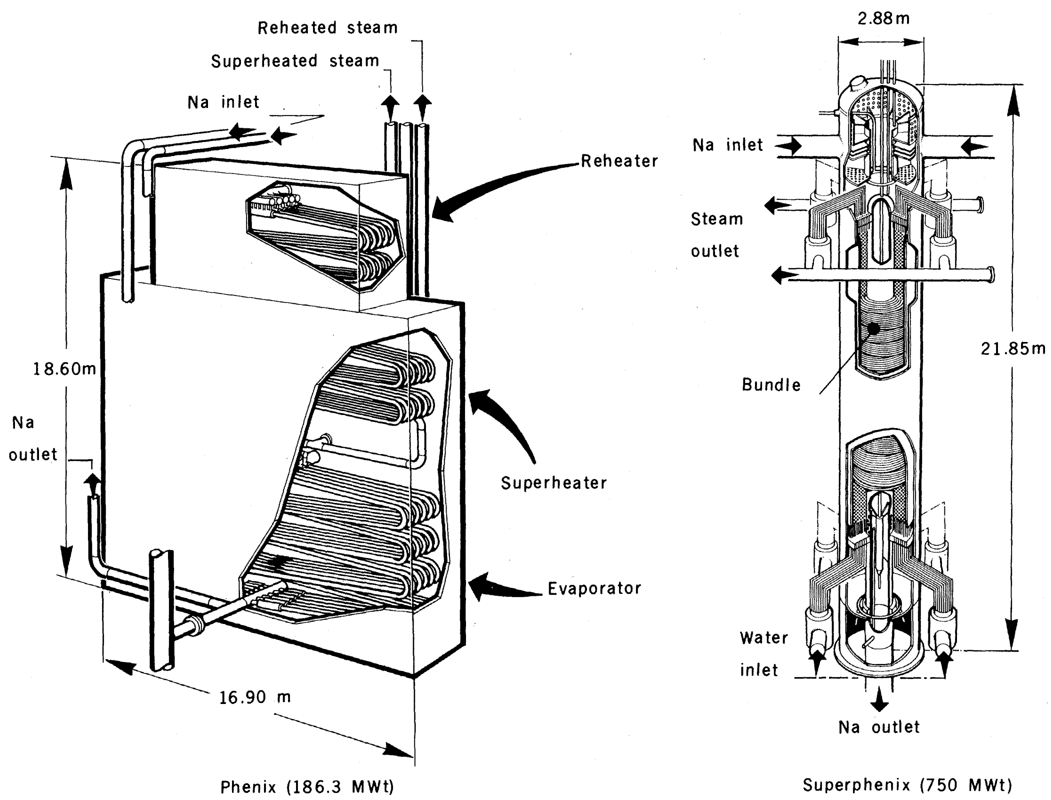


Fig. 4. Steam generators: Phenix and Super Phenix.

of 1976 and are proceeding satisfactorily. The turbogenerator set foundations are ready, the reactor buildings are progressing, and the water intake and discharge ducts are nearly finished. At present, there are more than 900 people working on the site.

In addition to these three major steps (Rapsodie, Phenix, and Super Phenix Mark I), I should mention the very large R & D effort developed in support of the reactor designs. This includes theoretical and experimental studies aimed at mastering core physics, thermohydraulics, and coolant and fuel technologies; component testing under conditions as close as possible to those encountered during reactor operation; and work on structural materials and safety.

Component testing and structural materials. Wherever possible, certain major research centers (Cadarache, Renardières, Chatou) are equipped with test rigs compatible with full- or large-scale reactor component testing (fuel-handling equipment, control rod drive mechanisms, rotating plugs, sodium pumps and valves, heat exhangers, steam generators, fuel subassemblies). This practice was extensively adopted for Rapsodie and Phenix. A new such test rig, Tripot, has just been completed at Cadarache for full-scale testing of larger plant components such as those designed for Creys-Malville. Operating statistics show that the sodium technology has thus been brought well under control and that sodium may even prove less hazardous than its water equivalent.

Component and technology R & D is backed by structural materials development programs, which supply comprehensive data on the behavior of materials in a flowing sodium environment, under irradiation and high-temperature conditions, and on the consequent evolution of their mechanical properties (fatigue, creep, swelling).

Safety R & D. International cooperation has made it possible to undertake exhaustive and costly common programs aimed at recognizing and understanding the basic phenomena that govern the physics of core behavior under grossly upset conditions. This type of research is generally performed in specially designed experimental reactors, where the behavior of different fuel elements can be observed under a wide range of accident conditions, characterized by a mismatch between the coolant flow and the power release.

An example of this type of test facility is the Cabri irradiation unit at Cadarache, which was used for several years for loss-of-flow trials. This unit was converted to a transient-overpower experimental reactor, renamed Scarabee, and reached criticality on 25 March 1977. This program was undertaken jointly by West Germany and France, which were subsequently joined by Britain and Japan.

Table 1. Comparison of Phenix and Super Phenix.

Characteristic	Phenix	Super Phenix
Gross electrical rating, megawatts	264	1,240
Thermal rating, megawatts	590	3,000
Gross efficiency, percent	44.75	41.5
Volume of core, liters	1,227	10,820
Length of fuel assemblies, meters	4.3	5.5
Number of fuel pins per assembly	217	271
Outside diameter of fuel pins, millimeters	6.6	8.65
Maximum linear power, watts per centimeter	430	450
Rate of fuel burnup, megawatt-days per ton	50,000	70,000
Maximum total neutron flux, neutrons per square centimeter per second	7.2×10^{15}	6.2×10^{15}
Breeding ratio	1.12	1.24
Nominal cladding temperature, degrees Celsius	650	620
Interval between refueling operations, months	2	12

Another important program covers sodium fires. It has yielded extremely useful results, including basic data, fire-fighting processes (high-efficiency powders and smothering devices), and computation of thermal and radiological consequences. Efforts are now being concentrated on the construction by Italy and France of the Esmeralda test rig at Cadarache, designed for the study of large-scale sodium fires, and complementary investigations are being conducted in the Fauna facility in Karlsruhe. A major effort has also been devoted to experiments on sodium-water reactions, to obtain information needed to cope with steam generator leaks and to verify the codes used for the design of the pressure relief system.

Fuel cycle experience. Since its start-up at the end of 1962, the Cadarache plutonium workshop has supplied the Rapsodie and Phenix fuel assemblies. During this period, more than 6 tons of plutonium has gone through the manufacturing lines. This workshop, after being refitted to increase its capacity to 20 tons of mixed oxide fuel per year, is now manufacturing the fuel for Super Phenix Mark I.

Since 1969, Rapsodie fuel reprocessing has taken place in a pilot plant with a capacity of 1 kilogram per day (ATI at The Hague). About 600 kg of uranium and plutonium, representing more than three cores, has been reprocessed.

An extensive development program has been initiated in the field of breeder fuel reprocessing. Work is presently focused on wet processes. A pilot plant handling 10 kg/day, located at Marcoule, has been specially equipped for the experimental reprocessing of Phenix fuel subassemblies and has been operated successfully. To adapt the reprocessing

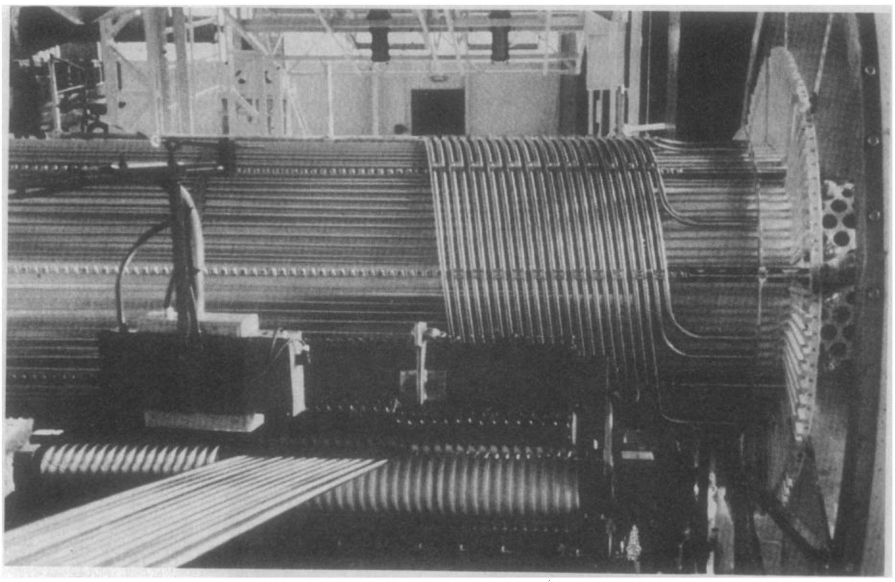


Fig. 5. Helical winding of steam tubes on the central body of a steam generator.

technique to industrial requirements and to confirm its efficiency, the CEA decided in October 1978 to extend the present Marcoule facilities by the addition of a new and larger pilot plant, known as TOR (for *traitement d'oxydes rapides*), which will be able to handle 5 tons of uranium and plutonium per year.

Besides the French experience with the fuel cycle for LMFBR's, other countries have broad experience on the pilot plant scale. In particular, the British have done considerable work on the fabrication of mixed oxide fuel and the reprocessing of enriched fuel from the DFR. The Dounreay plant was adapted to reprocessing the mixed oxide fuel of the PFR and is now being commissioned.

Future Plans for Breeder Deployment in France

In 1978, Electricité de France (EDF) commissioned and funded a study of Super Phenix Mark II. The nuclear-related portion of the plant (nuclear island) is being designed by Novatome and the balance of the plant by EDF itself, which usually performs the tasks of architect-engineer for all the power plants it builds. The preliminary design should be completed by 1980, and the final design and a firm offer (fixed price except for escalation) should be presented by Novatome and other contractors building major components (turbogenerator, electrical equipment, and so on) by 1983.

In fact, there should be two offers, one for a single power station comprising two identical units, and another for two or four identical power stations comprising two identical units each to be built on a reasonable time schedule (starting the construction of a new station every 2 years, for example). The first offer will certainly be more expensive per kilowatt installed than the second, but with a lower risk from the point of view of EDF. The decision to accept one or the other offer and the start of construction will likely take place between 1983 and 1985. Therefore the first unit may start operation around 1990.

Orders for more breeder power units will probably be placed soon after the order for the first Super Phenix Mark II. Forecasts based on utilization of only French-produced plutonium call for breeders with a capacity of 16 to 23 GWe in operation by the year 2000.

Studies of the Super Phenix Mark II have been conducted on the principle that the technical solution and physical dimensions should be as close to those of Super Phenix Mark I as possible. However, some increases in total power to 1500 MWe should be achieved by better assessing the design margin in Super Phenix Mark I and eventually suppressing some bottlenecks. In addition, it should be possible to minimize the capital cost per kilowatt by using the experience in construction and components testing gained with Phenix and Super Phenix Mark I.

How breeder development will proceed in France will depend strongly on three factors: (i) operating experience with the Phenix and Super Phenix Mark I, which is scheduled to run at full power in 1983; (ii) capital cost of the Super Phenix Mark II, which will depend on the results of the studies mentioned above and should be compared with the cost of an LWR after necessary corrections for the first-of-a-kind plant; and (iii) the cost (and certainty of the cost) of the LMFBR's fuel cycle.

Regarding the last point, besides the TOR project mentioned above, there is a plan to start operating a large reprocessing plant for fast breeder fuels in 1989. This plant is to have the capacity to process at least the fuel from the Super Phenix Mark I and two Super Phenix Mark II's. Of course, in due time there will be a need for a larger fuel fabrication plant than the one at Cadarache (20 tons of uranium and plutonium per year).

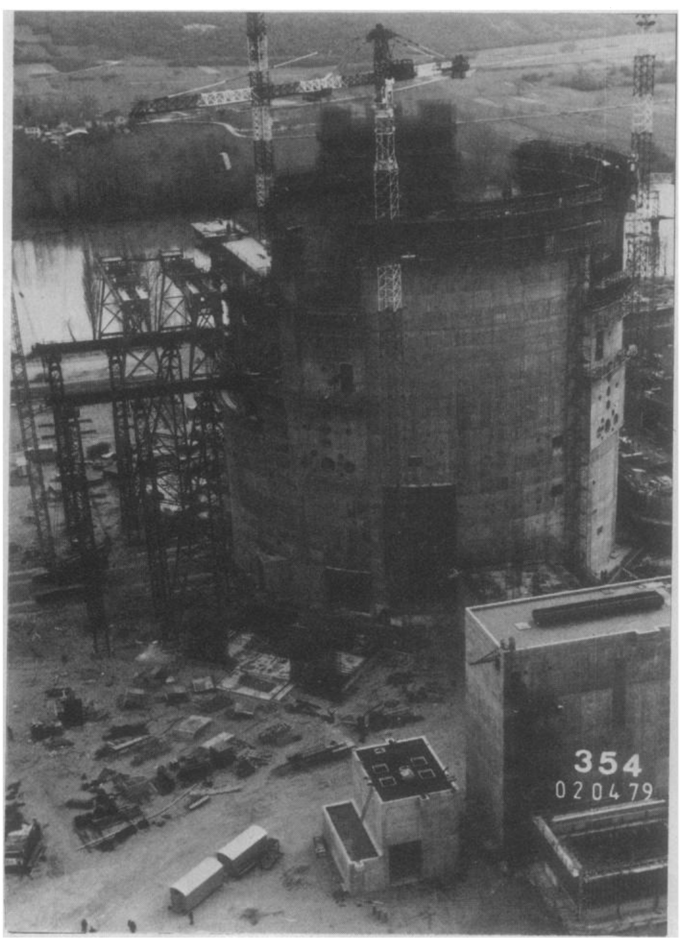


Fig. 6. Reactor building under construction at Creys-Malville.

Practicality and Desirability of Breeders

In the introduction I mentioned four questions that are often asked about breeders. I will now discuss these four questions briefly.

Demonstrated technology. The successful operation of many experimental reactors and three demonstration plants gives a first tentative answer to the question of whether breeder technology is demonstrated. In particular, the excellent performance of Phenix gives confidence to French engineers. In 1979, Phenix had an availability of 93.5 percent and a plant capacity factor of almost 84.5 percent. However, there is still the question of how representative Phenix is of commercial breeder technology. If we assume that the French commercial breeder Super Phenix Mark II will be very similar in design to Super Phenix Mark I, which seems to be a reasonable assumption, this question may be answered by comparing the design and technology of Phenix and Super Phenix Mark I.

Without going into detail, one can say

that the fuel, core, primary loops and components, fuel handling, and reactor vessels all represent a moderate extrapolation in size when going from Phenix to Super Phenix Mark I (much smaller than the extrapolation from Rapsodie to Phenix), but that essentially the same materials and technology are used. The only large extrapolation or change in technology is in the steam generators. Here the concept of once through is maintained, but the unit size (750 instead of 15.5 MWt), tube material (Incoloy 800 instead of high-alloy steels), and general configuration change drastically from Phenix to Super Phenix Mark I (Fig. 4). However, a very extensive testing program has been carried out on mock-ups of the new steam generators. This program included tests of up to three layers of full-size Incoloy 800 helical tubes for prolonged periods under normal and abnormal conditions. All the tests were successful. We therefore feel that the technology used for Super Phenix Mark I is rather well demonstrated, although there are still some uncertainties, the largest being connected with the steam generators.

Economy. If, at least for the time being, we restrict the use of breeders to electricity production, then in the vast majority of countries interested in breeders the competitors are conventional nuclear power and coal. Experience shows that in many geographic areas conventional nuclear power plants (LWR's) are already competitive with power plants burning coal. Therefore the deployment of breeders on a large scale is related to their competitiveness vis-à-vis LWR's. The economic comparison of breeders with LWR's can be considered in two parts, capital cost and fuel cycle costs, assuming that the respective operating costs of breeders and LWR's are sufficiently close that they do not significantly affect the comparison of total costs.

Some previous studies indicate that the capital cost of fully developed breeders will be 1 to 1.4 times the capital cost of LWR's (*14*). This evaluation can be updated using our recent experience with the construction of the Super Phenix Mark I. The construction cost of this reactor is now rather well known, as more than 95 percent of the contracts (fixed price except escalation) have been concluded. The cost per kilowatt is about 2.3 times the cost of building a 1300-MWe LWR in France.

However, there are some corrections that should be made to apply this comparison to a fully developed LMFBR (as developed as the LWR is at present), but one still using present (Super Phenix Mark I) technology. These corrections are for (i) one plant on site (Super Phenix) versus at least two plants (LWR), (ii) prototypical character of the Super Phenix (more studies, tests, and spare parts), (iii) prevailing commercial environment (international bidding), (iv) greater EDF expenses (architect-engineer functions) for the first of a kind rather than for a series of reactors, and (v) interest during construction, which should be comparable for an LWR and a breeder but is greater for the Super Phenix as the prototype takes longer to build.

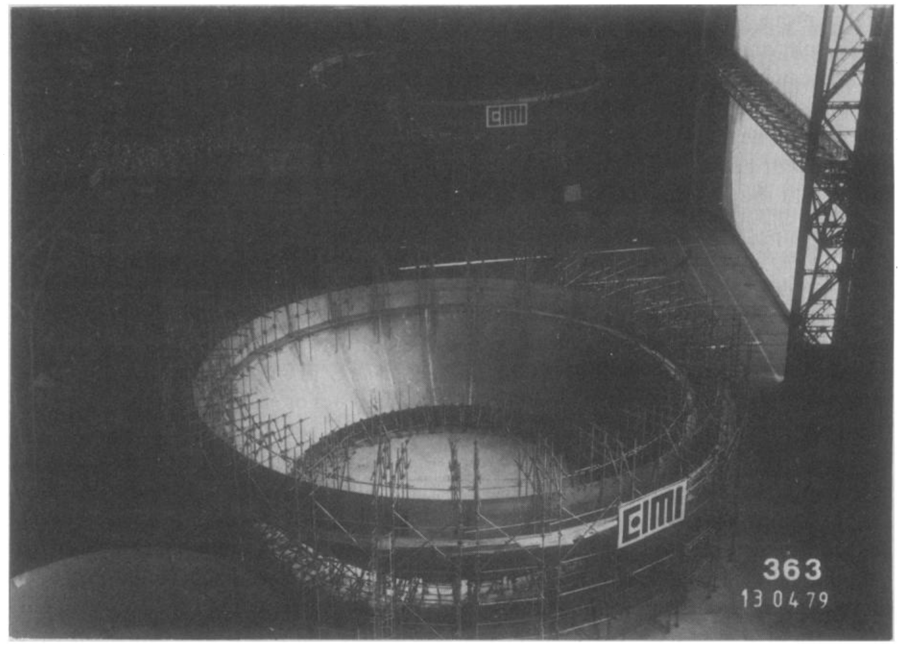


Fig. 7. Work in progress at the site workshop at Creys-Malville.

A calculation shows that the effect of each of these corrections should be to diminish the capital cost of breeders per kilowatt by a few percent (between 2 and 8 percent). The net result of these corrections is that the capital cost of a fully developed Super Phenix Mark I breeder should be 1.75 rather than 2.3 times that of an LWR.

The Novatome studies of Super Phenix Mark II indicate that progress in technology should result in some additional savings in the LMFBR's capital cost per kilowatt. For example, it seems likely that a power output of 1500 MWe could be obtained from a nuclear island with practically the same dimensions as that of Super Phenix Mark I. This alone should save about 15 percent on the capital cost per kilowatt installed. Combining this correction with those listed above leads to a predicted ratio of capital costs between breeders and LWR's of 1.3 to 1.45, which is in reasonable agreement with estimates from previous studies. The next four or six Super Phenix Mark II breeders will have a capital cost close to the highest value (1.45 times that of LWR's), but for the following fully developed series of breeders one can hope to attain a relative capital cost close to the lower bound (1.3).

In estimating fuel cycle costs for LMFBR's there are still large uncertainties, mainly in the extrapolation from present techniques to much larger plants. It is possible, however, to make a few observations.

1) There is a very good prospect that the burnups of breeder fuel will be three to four times larger than that achieved in LWR's. This means that if the fabrication and reprocessing of breeder fuel per unit weight costs three to four times more than that of LWR fuel, these operations will still cost the same per kilowatt-hour produced. The factor of 3 to 4 in fuel cycle costs for fully developed breeders may not be unreasonable.

2) The price of plutonium used in breeders is uncertain, but at least as long as breeders are not more competitive than LWR's it should not exceed the cost of reprocessing LWR fuel and storing the resulting wastes, less the cost of storing unreprocessed LWR spent fuel and the value of recovered uranium.

3) For a reasonable doubling time in breeders, one can obtain a yearly net plutonium production equivalent to 5 percent of the quantity invested in the reactor and fuel cycle initially. This means that the cost per kilowatt-hour will have to include the total cost of the plutonium invested initially divided by the number of kilowatt-hours produced per year by the reactor and multiplied by the interest

rate on money less a 5 percent allowance for the plutonium breeding.

4) Breeders may use plutonium and depleted uranium; the cost of the latter will have a negligible effect on the cost per kilowatt-hour. Therefore if one assumes that the condition of equal cost of reprocessing and fabrication is fulfilled, one will have to compare the cost of natural uranium plus enrichment with the cost of plutonium as defined above, both costs being referred to the energy produced (for example, per kilowatt-hour).

5) It is clear that in this condition, there will be a large positive margin for breeders that will increase with the price of natural uranium and in due time should compensate for the larger capital cost of breeders.

6) For the next decade, however, a more conservative assumption should be made about the cost of fabrication and reprocessing of LMFBR fuels, and the best estimates for the 1980's are that the fuel cycle of breeders should cost about the same as that of LWR's.

French estimates conclude that breeders may be competitive with LWR's in electricity production by the second half of the 1990's. These estimates assume a timely deployment of commercial breeders in France, which will lead to decreased capital and fuel cycle costs. In addition, it is assumed that the price of natural uranium will increase by 2 percent in constant money. If there is a shortage of uranium in the near future, we can expect much sharper increases in the price of natural uranium and breeders may become competitive by the first half of the 1990's.

Environmental impact and safety. I have already stressed the excellent safety performance of the Phenix during normal operation. This is due to the nature of the LMFBR, namely the choice of sodium as the coolant, and to the fact that it is not operated with failed fuel (cladding rupture). Although as a coolant it is less reactive than water with the fuel, sodium is very reactive with air or water. This necessitates the use of a tight system, which is facilitated by the fact that liquid sodium is a low-pressure fluid. A blanket gas surrounds the liquid sodium and is kept at a slight underpressure, so that if there is a leak it is inward and can be detected quickly and corrected.

The problem of wastes is also more manageable with breeders than with LWR's, as breeders can, by changing the blanket from gas to stainless steel, be used as "burners" of plutonium and transuranium elements, eliminating the storage problem for large amounts of long-lived radioactive wastes. In fact, breeders, used as burners, are the only practical way to get rid of the vast quantities of plutonium that are being and will be produced by thermal neutron reactors.

Regarding safety, there are positive and negative aspects of breeders compared to LWR's. One should not, however, draw final conclusions from general properties such as the compatibility of sodium with air and water, possibility of achieving prompt criticality by rearranging fuel or sodium voiding, low pressure of the sodium system, large thermal inertia, and high margin before boiling (typically more than a factor of 2 on nominal power for normal coolant flows). It is very difficult to give a reasonable weight to each of these properties without referring to a particular design and assessing the probabilities of different types of abnormal operation and accidents, the consequences of these eventualities, and ways to mitigate them.

A complete discussion of safety would require more space than I have available here (*15*). However, it should be kept in mind that the regulatory authorities will not allow the introduction of new technology with a lower standard of safety than the existing technology. The developers of breeders feel that they are achieving an even higher standard of safety than exists at present, as a consequence of progress in technology and stricter demands of the regulatory authorities.

Nuclear weapons proliferation. This again is too difficult and controversial an issue to be covered adequately here. However, a few remarks may be made.

1) Proliferation of nuclear weapons is possible even without the development of nuclear energy. Past experience and the opinions of many experts indicate that nuclear energy is only a minor contributor to weapons proliferation; other routes, such as enrichment technology and reactors used specifically for plutonium production, are much more likely.

2) There is no absolute technical fix that can solve the problem of nuclear weapons proliferation. What we can try to do is gain some time and hope for much better cooperation between different nations and for institutional solutions.

3) Taking into consideration these two points and the fact that it is unlikely that breeders will be deployed in many countries in the near future, the additional risks of proliferation due to breeders should not be very great.

Another way to look at this problem is to compare the additional risk due to breeders with the additional risk due to LWR deployment and the use of the once-through fuel cycle. To do this consistently one must consider in detail the technical and institutional arrangements that apply for each type of reactor and fuel cycle and also appropriate scenarios for worldwide deployment of the different types of reactors.

There is no worldwide agreement on this subject. Some consider that the risk associated with breeders is larger than that associated with LWR's and the once-through cycle; others (probably the majority of countries and experts) feel that the risks may be similar, provided adequate institutional and technical measures are taken. The latter point out that without breeders there will be a large and rapidly increasing number of "plutonium mines"—LWR spent fuel stores. These may become more and more difficult to control, and the extraction of plutonium from them will become easier as time goes on and the fuel becomes less radioactive.

Conclusion

In France the urgency of developing breeders is accepted, and the French program is going ahead steadily. There are still some uncertainties, especially about the date when the breeder will become competitive, and some problems to be solved, but we are optimistic about the final outcome.

References and Notes

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