Liquid Metal Fast Breeder Reactors

by Eduard Khodarev

1. Introduction: Why we need fast breeder reactors

A study of future energy requirements and of the potential of various energy sources (coal, oil, gas, nuclear power, hydropower and solar energy) indicates that the contribution to be made by nuclear fission, now competitive with conventional energy sources, will grow steadily over the next few decades. Whereas the amount of fuel which has to be fabricated each year for the operation of a nuclear power plant is reckoned in dozens of tonnes, coal-fired power stations generating electricity each consume in a year millions of tonnes of fuel, and the world's reserves of fossil fuel, especially coal, while vast, are not unlimited The potential capability of nuclear power in its present state of development to satisfy the world demand for electricity would depend, to a large extent, on world reserves of natural uranium and the possibility of obtaining uranium-235 as nuclear fuel at reasonable prices. The relatively small percentage of this isotope in natural uranium is however a limitation on the development of nuclear power if it were to be based solely on existing light-water reactors which, with their low conversion ratio, can not utilize more than 2% of the energy potentially available in natural uranium. Thus, the advantages of nuclear power in the long term may not be fully realized unless further sizeable reserves of natural uranium are found or until significant progress is made in more effectively utilizing uranium.

Fast breeder reactors afford an opportunity of fundamentally solving this problem in the near future They make more effective use of existing natural uranium resources (including depleted uranium from enrichment plants) and of the plutonium produced in thermal reactor fuel. They produce more plutonium than they consume, and they are capable of utilizing 60–70% of the uranium. The use of fast reactors with good breeding properties means that we can not only reduce consumption of natural uranium to a considerable extent, but we can also be more flexible in structuring an electrical power generating system to minimize costs. Considerable savings are possible compared with the use of thermal reactors alone, and the possibility exists for a country to become largely independent from an energy standpoint Ref. [1].

2. General principles of fast breeder reactors

The fission process is based on the fact that when a neutron is captured by the nucleus of an atom of fissile material, that atom splits or fissions The energy released as a result of this process is used in power reactors to produce steam, which can then be made to drive a turbine and generate electricity

There are only four heavy isotopes that effectively undergo fission, uranium-233, uranium-235, plutonium-239 and plutonium-241 Of these only uranium-235 exists in any

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quantity in nature (it constitutes about 0.7% of natural uranium) and existing power reactors are based on its use Considerable quantities of the other three fissile isotopes, however, are produced when neutrons are absorbed by certain isotopes of thorium and uranium. Materials which become fissile upon absorbing neutrons are known as "primary fuel" materials or "fertile" materials. In the case of fast breeder reactors it is uranium-238 which is the most interesting fertile material, and it is converted into the fissile isotope plutonium-239 through neutron absorption. Natural uranium contains more than 99% uranium-238, while in depleted uranium, which accumulates at plants that enrich uranium for existing nuclear power stations, the proportion is nearly 100%

When nuclei undergo fission they release more neutrons than are required to sustain the chain reaction. A characteristic feature of fast breeders is the fact that while producing energy they also produce more fissile material than they consume, and hence the name "breeder".

A liquid metal fast breeder reactor is so named because during conversion of the fertile material into fissile material use is made of high-energy ("fast") neutrons and the coolant employed is sodium, which remains in the liquid state ("liquid metal") at the prevailing high working temperatures.

In a fast breeder reactor there is fertile material (uranium-238) in the core and in the blanket around the core. The core consists of a mixture of plutonium oxide and uranium oxide. Fission takes place chiefly in the reactor core, while the conversion of uranium-238 to plutonium-239 through capture of excess neutrons occurs in both areas of the reactor.

The fuel assemblies in the blanket consist of rods filled with material of uniform composition. Those of the core consist of rods whose central sections are filled with fissile material, while the end sections contain fertile material. Hence the entire reactor core is surrounded by blanket zones. When spent fuel assemblies and blanket assemblies have been removed from the reactor, plutonium is separated from them during reprocessing and can then be used for the manufacture of fuel elements for fast breeder reactors or for nuclear power plants of some other kind.

In many respects fast breeder reactors are similar to the power reactors in operation at the present time. However, the core of a fast breeder has to be much more compact than that of a light-water reactor. Plutonium or more highly enriched uranium is used as fuel, the fuel elements are smaller in diameter, and they are clad with stainless steel instead of Zircaloy. Since water rapidly decelerates the fast-moving neutrons produced during fission to less than the energy level required for breeding, it cannot be used in fast breeders. Thus, in a fast breeder reactor we have to remove a large amount of heat from a small volume of fuel and at the same time use a coolant that does not reduce the neutron energy unacceptably.
In practice it is only certain liquid metals or pressurized helium that are suitable as coolants for fast breeder reactors. Heat transfer is better with liquid metals than with pressurized helium, but the latter does not slow the neutrons down to the same extent as do liquid metals. Small fast breeder reactor cores require high fuel density which favours the use of liquid metals as coolant in the restricted space available; large fast breeder cores for commercial-size power plants require less fuel density and in this case the available space in the core is sufficient to permit cooling by pressurized helium. Over many years however, liquid metals (i.e. mercury, sodium/potassium mixtures and sodium) have been used as coolants for the successive experimental fast breeders that have been constructed and operated throughout the world, so that experience has been accumulated in their favour.

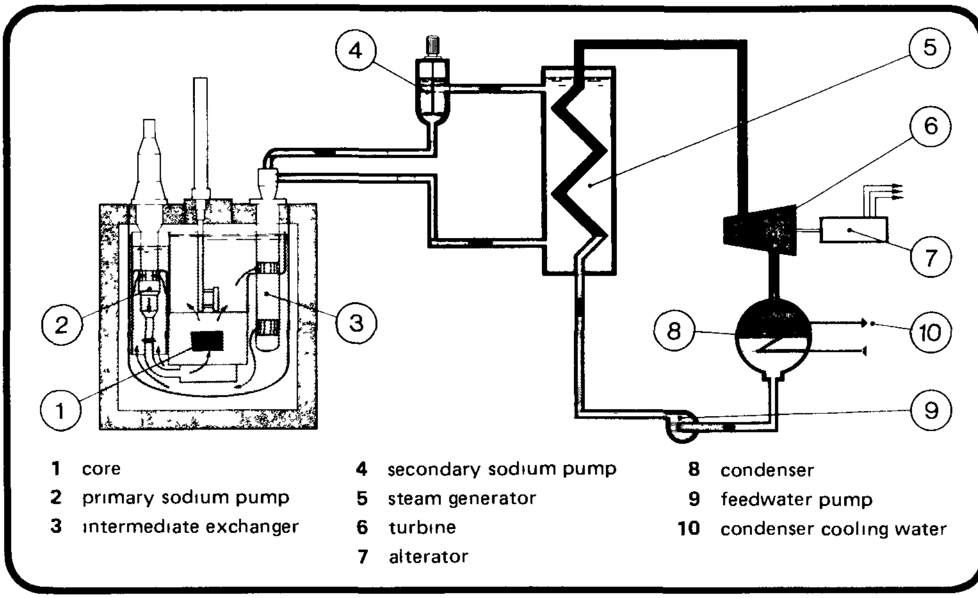
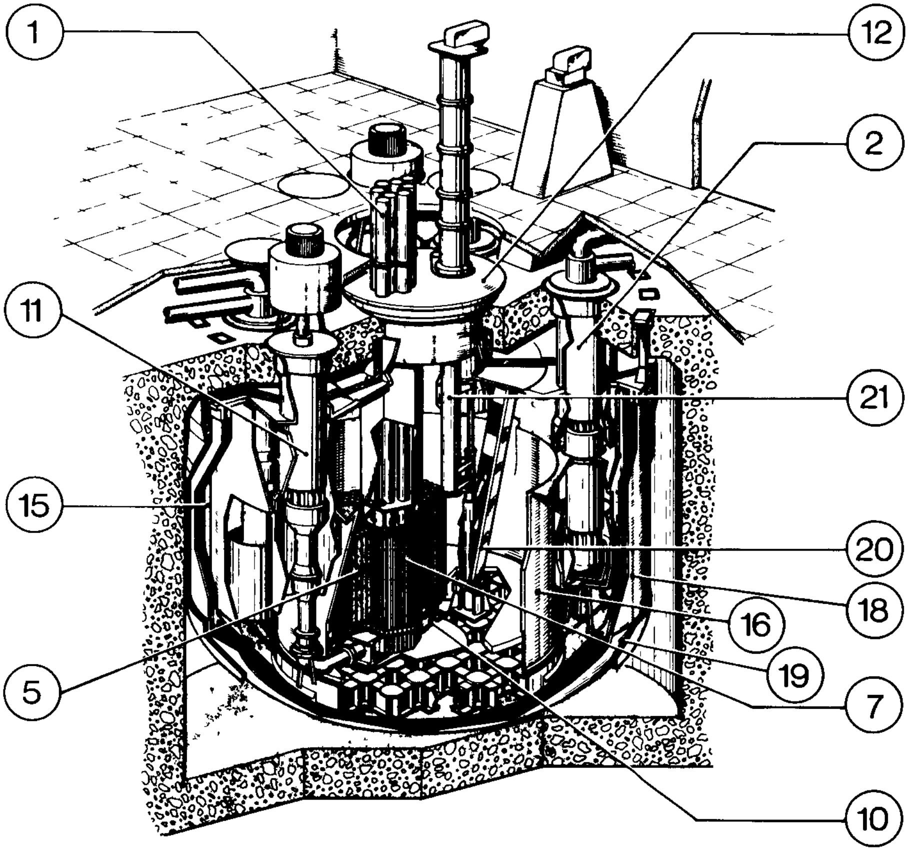


Figure 1. Schematic Diagram of Power Station with Pool-Type Fast Reactor.

Production of energy in the core of the fast breeder is intense compared with thermal reactors, and therefore the coolant must have very good heat transfer properties. For fast breeders using a liquid metal cooling system, sodium is the selected coolant since it can remove heat effectively from the compact reactor core and remains in the liquid state over a fairly broad temperature range. Sodium exhibits the best combination of required characteristics as compared with other possible coolants, namely excellent heat transfer properties, a low pumping power requirement, low system pressure requirements (one can use virtually atmospheric pressure), the ability to absorb considerable energy under emergency conditions (due to its operation well below the boiling point), a tendency to react with or dissolve (and thereby retain) many fission products that may be released into the coolant through fuel element failure, and finally, good neutronic properties. Among sodium's unfavourable characteristics are its chemical reactivity with air and water, its activation under irradiation, its optical opacity and its slight neutron decelerating and absorption properties, but these disadvantages are considered in practice to be outweighed by the merits of sodium as a coolantRef [2].

The sodium in the primary circuit (i.e. in direct contact with the core) is not used in any of the fast breeder reactor designs to produce steam. Instead, use is made of an intermediate sodium circuit (secondary circuit), which makes it possible to avoid a release of radioactive sodium in the event of a steam generator failure This necessitates the use of intermediate heat exchangers as an interface between the primary and secondary sodium circuits. The use of a secondary sodium circuit isolates the primary circuit, and hence the sodium-filled reactor, from any contact with water. But this, of course, does not make it any easier to design steam generators which are able to keep the sodium and water effectively segregated.



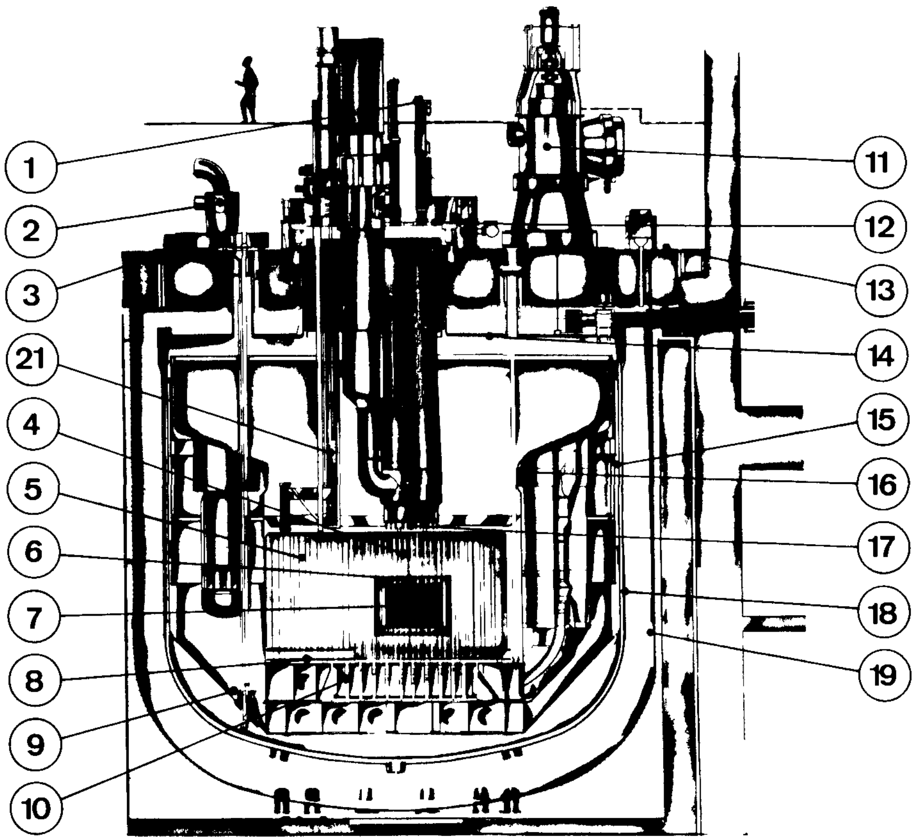
REACTOR BLOCK

1 control rod drives	**4** upper neutron shielding	**7** core
2 intermediate exchanger	**5** lateral neutron shielding	**8** lat shielding support
3 leak detector	**6** blanket	**9** conical support collar

Figure 2. Cut-Away View of a Pool-Type Fast Breeder Reactor (Phénix).

3. Main fast breeder reactor types and their design parameters

There are two basic designs for sodium-cooled fast breeders: the pool (integrated) layout and the loop type In the pool layout, the reactor vessel contains not only the core, but also a number of other components. A schematic representation of this type of reactor is shown in Fig. 1, Ref. [3]. The reactor vessel is filled with sodium at approximately atmospheric pressure and the core, refuelling machines, primary coolant pumps and intermediate heat exchangers are immersed in it. Therefore the entire primary sodium coolant circuit is located in this same vessel. This design makes it possible to reduce appreciably the amount of external piping. Figs. 2 and 3 show the French Phénix reactor as an example of this layout.



10 fuel support slab
11 primary pump
12 rotating plug
13 slab
14 roof
15 main vessel
16 primary vessel
17 core cover
18 double envelope vessel
19 primary containment
20 transfer ramp
21 transfer arm

Figure 3. Vertical Section of the Phénix Reactor.

The second type of layout, known as the loop design, is more like that of conventional light-water reactors in which the individual components of the cooling system are outside the reactor vessel and interconnected by piping, while the reactor vessel itself contains only the core and associated equipment. As an illustration of the loop design, Fig 4 shows the basic system of the Monju reactor Ref [4]. In either arrangement of the primary system the vessels containing the primary components are surrounded by guard vessels so that any rupture of the primary circuit system does not lead to a large loss of radioactive sodium.

In any fast breeder with a sodium cooling system the aim is to minimize the shutdown time required for refuelling the reactor Both in the pool and loop types of layout, use is frequently made of a rotating plug located at the top of the reactor vessel in the closure head.

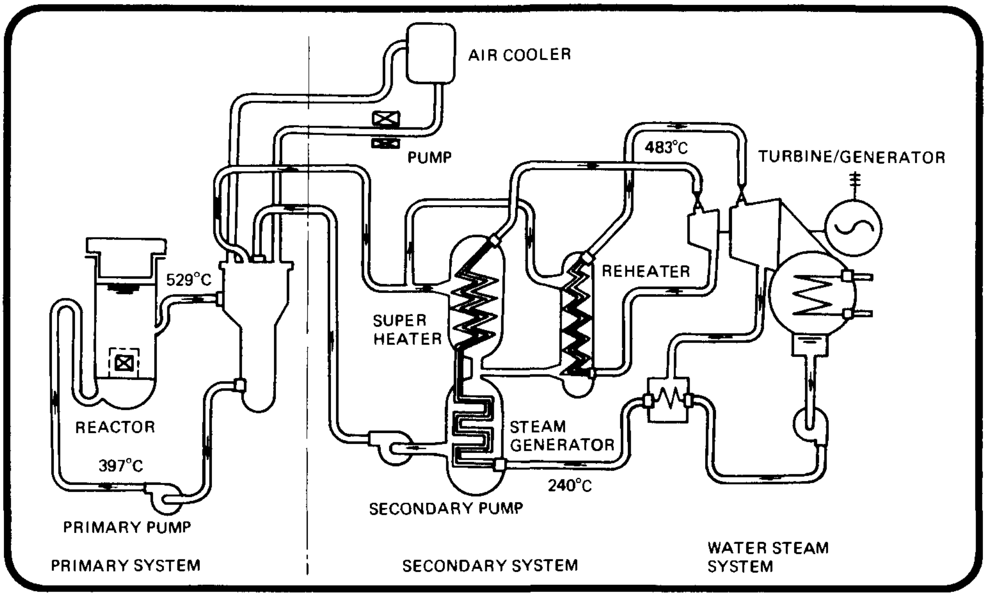


Figure 4. Schematic Diagram of the Monju Reactor.

The in-vessel fuel transfer machine is mounted on this rotating plug. The control rod drives are also mounted on this plug and are disconnected from the core before the plug is rotated. It is thus possible to transfer the fuel from the core to any point inside the reactor and vice versa using the fuel transfer machine In the pool layout, the spent fuel is normally placed in a temporary storage drum located inside the reactor vessel, in which it remains while the decay heat is removed from fission product activities. The ex-vessel fuel transfer machine is later used to transfer the spent fuel to storage outside the reactor vessel. This can be effected with the reactor in operation. In the loop design, the spent fuel is transferred directly from the core to storage facilities outside the reactor.

An important problem in the case of fast breeders is the service life of the fuel. In thermal reactors only a small percentage of the uranium atoms in the fuel fission before it is removed from the core to spent fuel storage or reprocessing. Normally, the amount of fissile material in thermal reactor fuel is not more than 4%, and since the fertile to fission conversion ratios for such reactors are small, they attain a burn-up of only 2 or 3%. At higher burn-up, there may be damage to the fuel cladding and some fuel failure. In fast breeders 15% or more of the fuel is fissile material, and since the breeding ratio exceeds unity the burn-up is not normally limited by the amount of fissile material present, but instead by the resistance to radiation damage. Typically the burn-up may attain 10–15%. Hence, whereas in existing light-water reactors the burn-up is 20 000–35 000 MW.d/t, the figure for the fast breeders now being designed is 100 000–150 000 MW.d/t The basic characteristics of the demonstration and prototype breeders in operation, or at the design stage, are shown in Table 1, Refs. [5, 6].

In many developed countries the commercial use of fast reactors in the future is seen as being of growing importance. Today there are a number of important experimental sodium-cooled fast breeders in operation, for example, Rapsodie-Fortissimo (France), KNK-II (Federal Republic of Germany), Joyo (Japan), EBR-II (USA) and BOR-60 (USSR), and larger experimental reactors are under construction, for instance, the PEC (118 MWth) in Italy and

Table I. Basic Design Characteristics of Liquid Metal Cooled Prototype and Demonstration Fast Reactors

REACTOR / PARAMETER	PHENIX (France)	SNR 300 (Germany F R)	MONJU (Japan)	PFR (UK)	CRBR (USA)	BN 350 (USSR)	BN 600 (USSR)	SUPER PHENIX I (France)	SNR 2 (Germany F R)	CDFR I (UK)	BN 1600 (USSR)
Electrical power (MWe)	250	312	300	250	350	350 (incl 200 for desalination)	600	1200	1300	1250	1600
Thermal power (MWth)	568	762	714	612	975	1000	1470	3000	3420	3230	4200
Efficiency (gross)	44 0	40 9	42 0	40 9	35 9	35	40 8	40 0	38 0	38 7	38 1
Type of layout	POOL	LOOP	LOOP	POOL	LOOP	LOOP	POOL	POOL	LOOP	POOL	POOL
No of primary coolant loops	3	3	3	3	3	6	3	4	4	6	4
No of secondary coolant loops	3	3	3	3	3	6	3	4	4	8	4
No of primary circuit pumps	3	3	3	3	3	6	3	4	4	6	4
No of intermediate heat exchangers	6	9	6	3	3	12	9	8	8	–	–
Max sodium temperature at core											
Inlet (°C)	385	377	397	394	388	300	380	395	390	370	350
Outlet (°C)	552	546	529	550	535	500	550	545	540	540	550
Steam temperature (°C)	510	495	483	513	462	435	505	487	490	486	–
Steam pressure (MPa)	16 8	16 0	12 5	12 8	10 0	4 9	14 2	21	17 2	16 0	14 2
Max sodium temperature at intermediate heat exchanger (secondary coolant)											
Inlet (°C)	343	328	325	356	344	270	320	345	340	335	310
Outlet (°C)	543	521	505	540	502	450	520	525	510	510	505

Table 1. (continued)

PARAMETER \ REACTOR	PHENIX (France)	SNR 300 (Germany, F R)	MONJU (Japan)	PFR (UK)	CRBR (USA)	BN 350 (USSR)	BN-600 (USSR)	SUPER PHENIX I (France)	SNR 2 (Germany, F R)	CDFR I (UK)	BN 1600 (USSR)
Sodium flow rate (10^3kg/s)											
Primary coolant	2 76	3 5	4 26	3 09	5 2	4 46	6 05	15 7	18 0	15 0	16 67
Secondary coolant	2 28	3 27	3 12	2 85	4 86	–	5 3	13 2	16 0	14 08	–
Feedwater temperature (°C)	246	252	240	275	232	158	240	235	250	230	–
Reactor vessel											
Internal diameter (m)	11 82	6 7	7 0	12 2	6 2	6 0	12 8	21	15 0	23 5	18 3
Internal height (m)	12 0	15 0	18 0	15 2	18 2	11 9	12 6	17 3	–	22 5	18 0
Core dimensions											
Height (m)	0 85	0 95	0 93	0 91	0 91	1 06	0 75	1 00	0 95	1 00	1 00
Volume (m^3)	1 29	2 36	2 34	1 54	2 53	2 08	2 50	10 12	12 91	6 61	8 81
No of core assemblies											
Fuel assemblies	103	205	198	78	198	226	371	364	492	342	–
Radial blanket zone assemblies	90	96	172	43	150	412	380	233	270	202	–
Length of fuel assembly (m)	4 3	3 7	4 2	3 8	4 57	3 2	3 5	5 4	–	4 3	–
Fuel material	Half PuO_2–UO_2 Half UO_2	UO_2–PuO_2	UO_2–PuO_2	UO_2–PuO_2	UO_2–PuO_2	First UO_2 Later UO_2–PuO_2	First UO_2' Later UO_2–PuO_2	UO_2–PuO_2	UO_2–PuO_2	UO_2–PuO_2	UO_2–PuO_2
Blanket material	Depleted UO_2 →										
Core volume fractions											
Fuel	0 36	0 31	0 34	0 36	–	0 46	0 45	0 34	–	–	–
Sodium	0 36	0 50	0 40	0 42	–	0 32	0 33	0 34	–	–	–
Other	0 28	0 19	0 26	0 22	–	0 22	0 22	0 32	–		–
Weight of fuel in core											
UO_2	3 8	4 2	5 2	3 1	–	7 3	8 5	30 6	–	16	–
PuO_2	0 8	1 65	1 5	0 9	–	–	–	6 31	–	4	–

Table 1. (continued)

REACTOR / PARAMETER	PHENIX (France)	SNR 300 Germany F R)	MONJU (Japan)	PFR (UK)	CRBR (USA)	BN 350 (USSR)	BN 600 (USSR)	SUPER PHENIX I (France)	SNR 2 (Germany F R)	CDFR I (UK)	BN 1600 (USSR)
No of pins per core assembly	217	166/127	169	325	217	169	127	271	271	325	–
Outside diameter of fuel pin (mm)	6 6	6 1/7 6	6 5	5 8	5 8	6 1	6 9	8 50	7 6	5 8	–
No of pins per blanket assembly	61	61	61	85	61	37	37	91	127	85	–
Outside diameter of blanket pin (mm)	13 4	11 7	11 6	13 5	13 2	14 2	14 2	15 8	11 6	13 5	–
Max linear power (kW/m)	45	38/49	35	48	48–52	44	53	45	41 5	–	–
Average core power density (kW/l)	406	290	300	380	380	430	550	285	–	–	–
Max burn up (GWd/t)	50 72 [2]	87	100	75–100	80–150	41 50 [2]	100	100		100	83
Breeding ratio	1 16	1 0	1 2	1 2	1 23	1 0 1 4 [3]	0 9 1 3 [3]	1 18	1 17–1 35	1 25	1 4[3]
Start up date											
Planned	1974	1983	1985–6	1976	–	–	1980	1983	–	–	–
Actual	1974			1977							

Notes
1 BN 600 will be fuelled initially with enriched UO_2 and subsequently with UO_2–PuO_2
2 For Phenix and BN 350 the upper figure was the planned burn up and the lower one was that actually achieved
3 For BN 350 and BN 600 the upper figure is for UO_2 fuel and the lower one for UO_2–PuO_2 fuel for BN 1600 the figure is for UO_2–PuO_2 fuel

the FFTF (400 MWth) multi-purpose experimental reactor for fuel studies being built in the United States of America.

Experience is being accumulated in the operation of the first prototype fast reactors, including the BN-350 (350 MWe) in the USSR, the Phénix (250 MWe) in France, and the PFR (250 MWe) in Great Britain. Nuclear power stations employing fast reactors, such as the SNR-300 (327 MWe) in the Federal Republic of Germany, the BN-600 (600 MWe) in the USSR, and the first full-scale demonstration fast breeder, Super-Phénix (1200 MWe) in France are being constructed There are likewise a number of other projects under development in various countries.

Evaluating the experience gained in the design, construction and operation of experimental sodium-cooled fast breeders, especially the first prototype fast reactors, we can say that the major industrial experiment to determine whether fast breeders are a sound proposition, is progressing favourably and that this type of reactor has broadly demonstrated such desirable characteristics as simplicity, stability in control, and the possibility of attaining high energy outputs and high fuel burn-up. The difficulties encountered in the initial operation of the BN-350, Phénix and PFR facilities do not reflect fundamental problems with the reactor but rather relate to certain technological shortcomings in the manufacture of some non-reactor components.

The very large volume of technological data that has been amassed and the experience acquired in designing and operating sodium-cooled fast breeder prototypes indicates that we can now go on to the next stage in developing these reactors, namely the design of electricity-producing facilities with minimum power costs and optimum breeding characteristics. All countries with extensive fast reactor programmes are planning, after their first prototype reactors, to build full-scale demonstration power reactors, following which they will start construction of a series of large power stations with outputs in the 1000–1800 MWe range. One full-scale demonstration plant – Super Phénix – is at present under construction in France. Similar plants are being developed in the Federal Republic of Germany, Great Britain and the USSR. As a result of the rapid advance of its fast reactor programme, Japan is planning to complete construction of a 300 MWe prototype reactor in the mid 1980s and then move on to a full-scale demonstration power station.

The need to introduce fast breeders as soon as possible is most evident in the case of countries that import the largest percentage of their energy supplies. Japan imports 90% of the energy it consumes, while the figure for France is 77% Countries such as these consider that the introduction of fast breeders at the earliest opportunity is vital to their energy independence.

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