World status of fast reactor development

by Vladimir Efimenko, Francis A. O'Hara and Hans-Juergen Laue

Fast breeder reactor development is now concentrated on the liquid metal-cooled fast breeder reactor (LMFBR). Almost a dozen countries have major development and industrialization programmes related to the commercialization of LMFBRs. In addition to these countries, some ten others are involved in the development of LMFBR components or have some fast reactor research and development activities.

Development of LMFBRs has been underway for more than 35 years. During this period, in addition to many zero power fast reactors, 19 LMFBRs have been constructed and operated. The table lists some of these plants.

Presently, ten LMFBRs are operating, five are under construction, and five are in an advanced stage of planning. In all, more than 170 reactor-years of operating experience have been accumulated.*

Large investments and considerable human resources have been devoted worldwide to the development of fast breeders to assure the necessary transition from the present thermal reactors with once-through fuel cycle.

Present nuclear power technology can only be considered as a relatively short-term energy source as presently known uranium resources will be exhausted within a period of about 50 years. However, with breeders, nuclear fission offers an almost inexhaustable source of energy, as they can utilize 60 to 70 times more of the energy contained in a unit mass of uranium. In addition, breeders will expand the volume of available uranium resources because of their ability to exploit economically lower concentration ores.

Divergent trends

The general concept of fuel breeding was first proven at experimental LMFBRs in the UK, the USSR, and the USA. More advanced LMFBRs were constructed for testing fuels, structural materials, and reactor components. In the early 1970's, three prototype reactors were put into operation in France, the UK and the USSR. They

Fast breeder reactors in operation, under construction or planned

Country	Unit name	Power (MWth/MWe)	Startup date
Operational			
USA	EBR-II	62.5/20.0	1963
USSR	BOR-60	60/12	1969
USSR	BN-350	1000/150*	1972
France	Phénix	605/270**	1973
USSR	BR-10***	10/0	1973
UK	PFR	670/250	1974
Germany, Fed. Rep.	KNK-II	58/21	1977
Japan	Joyo	100/-	1977
USSR	BN-600	1470/600	1980
USA	FFTF	400/-	1980
Under construction			
France	Superphénix I	3000/1242	1985
Germany, Fed. Rep.	SNR-300	762/327	1986
India	FBTR	42/15	1985
Italy	PEC	118/-	1989
Japan	MONJU	714/280	1991
Planned			
France	Superphénix II	3600/1500	
Germany, Fed. Rep.	SNR-2	3420/1300	
India	PFBR	1250/500	
Japan	DFBR	2550/1000	
USSR	BN-800	2100/800	
USSR	BN-1600	4200/1600	
UK	CDFR	3300/1250	

* 150 MWe + 120 000 m^3/d desalinated water.

** The design basis power level was 568/250. Good performance and precise fuel management permitted an increase in the output wihtout changing the installation.

*** Originally the BR-5 (5 MWth) which started operation in 1958.

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* *The Status of the Liquid Metal Cooled Fast Breeder Reactors,* IAEA Technical Reports Series, International Atomic Energy Agency, Vienna, Austria (to be published 1985).

have accumulated about 30 reactor-years of operational experience.

The near-commercial-size Soviet BN 600 has operated successfully for almost five years. During 1983 the load factor for this reactor was 72%, on the basis of an availability factor of 77%. Construction is expected to begin on the Soviet BN-800 shortly and it is planned to commence operation sometime after 1990.

The commercial-size Superphénix I in France is nearing completion and is scheduled to begin operation in 1985. Two more prototype reactors are under construction – SNR-300 in the Federal Republic of Germany and Monju in Japan.

However, this optimistic outlook is only one side of the picture. Presently, the commercial deployment of LMFBRs is not expected to proceed as rapidly during the 1980s and 1990s as was envisaged 10 or 15 years ago. In some countries even the construction of a smaller-size prototype fast reactor faces difficulties due to political, financial, licensing, and other problems.

In the USA, within the past year, the 380-MWe Clinch River Breeder Reactor was cancelled. This was after the initiation of site preparation, with design more than 95% complete, related research and development over 98% complete, substantial progress in component fabrication and testing, and with components (completed or on order) representing about two-thirds of the project's total procurement costs. Recent decisions have indicated that future plants would have to be constructed as a completely private enterprise with no governmental involvement.

In the Federal Republic of Germany, political enquiries as well as changes in particularly demanding safety criteria for SNR-300 have contributed to significant construction delays. Although the plant is expected to be commissioned in 1986, these delays have caused considerable cost escalation since project construction began in 1973.

In Japan, the construction of commercial fast reactors has been deferred until 2010 at the earliest. This supersedes earlier Japanese plans to deploy a series of ten commercial plants, one each year, between 1995 and 2005.

What factors are responsible for this divergence in trends and successes? To understand better the current situation, it is necessary to consider the technical features of the LMFBR, their present level, and expected trends in their development.

Current technological status

Considerable progress has been made in the last 40 years in the areas of physics, engineering, fuels and materials, resolution of safety questions, and the fuel cycle of LMFBRs. Based upon operating experience achieved, it can be said that the technology of the LMFBR clearly has been proven.

Calculational methods and nuclear data sets have been developed for core design. A vast quantity of experimental and theoretical information on neutron cross-sections needed for LMFBR physics calculations has been acquired in many countries and exchanged through international organizations, such as the IAEA and the Nuclear Energy Agency (NEA) of the Organisation for Economic Co-operation and Development. For major reactor physics and core parameters, the calculational accuracy that can be obtained is very near the accuracy considered to be required for adequate predictions.

As a result of development efforts, several optional LMFBR approaches were tested. Mixed oxide fuel and sodium coolant are considered now as preferable choices for current designs. Two principal design concepts have been broadly accepted for LMFBRs – pool-type and loop-type designs (see Figure). For both of them, significant experience has been accumulated. A detailed description of the advantages of each is beyond the scope of this article. However, the literature contains numerous arguments in favour of each.*

Optimization of core and plant design parameters, taking into account boundary conditions and properties of sodium as a coolant, result in the main features typical of prototype and commercial-size LMFBR plants. Three circuits are used in the heat transport system of both loop- and pool-type reactors: a primary-coolant circuit, containing radioactive sodium heated in the core; a secondary (or intermediate) non-radioactive sodium circuit; a tertiary water circuit producing steam for electricity generation by means of the turbine generator system.

Typically, cores have height of about one metre, and diameters of up to four metres. A blanket of fertile uranium surrounds the core. Coolant temperature at the inlet of the core is between 300° to 400°C and 500° to 550°C at the outlet. This results in higher thermal efficiency (about 40%) than for PWRs. The core usually has two fuel enrichment zones and contains 100 to 400 hexagonal fuel assemblies. There are several hundred fuel pins in each fuel sub-assembly with outer diameters of five to nine millimetres.

Extensive experience of components performance – including reactor vessels, piping, sodium pumps, intermediate heat exchangers, steam generators, refuelling equipment, and auxiliary systems – has been accumulated. One technical problem of early LMFBR development, water to sodium leaks in steam generators, plagued all three prototype plants.

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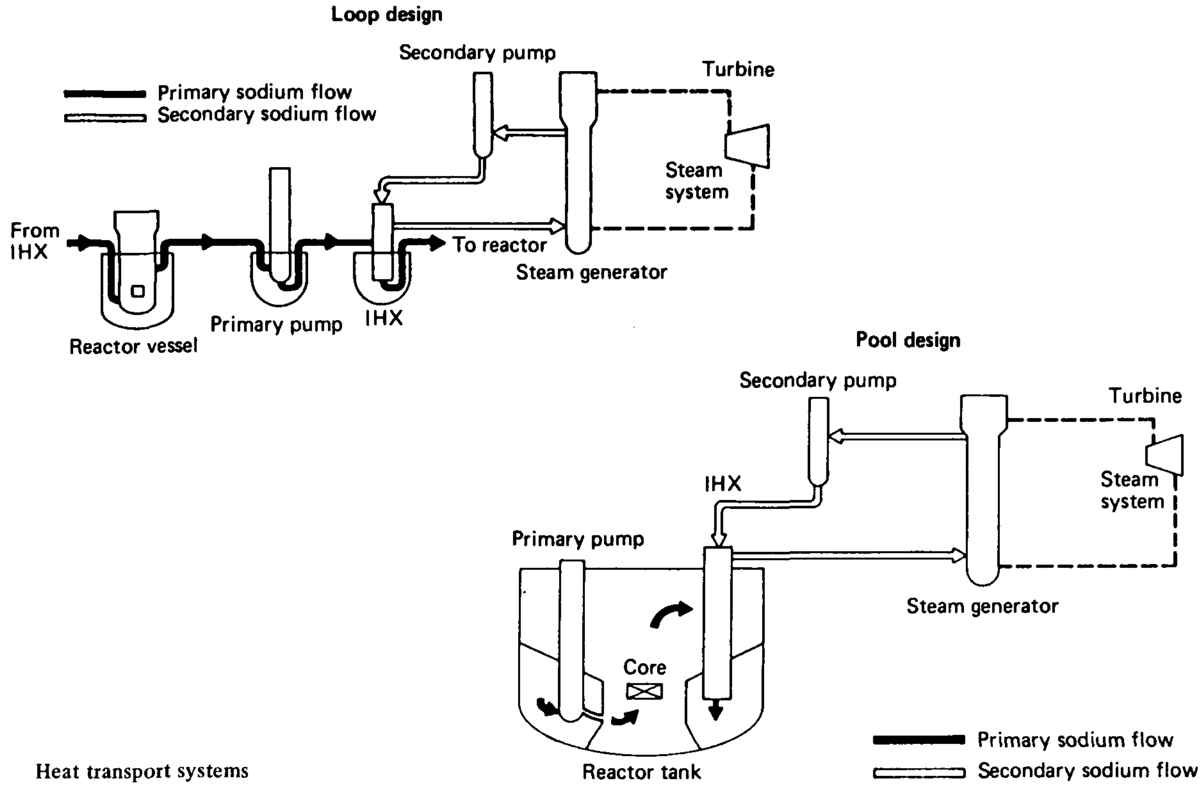
* See Rineysky, A.A., "Comparison of Technical and Economical Characteristics of NPP with Present Thermal and Fast Reactors", *Atominaya Energia*, 53 (December 1982) pp.360–67.



Heat transport systems
for the loop- and pool-type design concept.

However, improvement of steam generator design, utilization of protection devices, better understanding of leak phenomena, and great strides in developing repair procedures now ensure not only fewer leaks in steam generators, but also a more rapid restart of the plant following a leak event. Thus, at the present time, the results of LMFBR steam generator development indicate that sodium-water interaction will be minimized in future plants.

Mixed oxide fuel is now a reference design solution for almost all experimental reactors and for all prototype and demonstration reactors. It is generally employed in the form of cylindrical pellets, helium bonded to a stainless steel cladding. With this configuration and the use of austenitic stainless steel as cladding and tube wrapper materials, high fuel burnup levels have been achieved in extensive irradiation programmes.

At the prototype reactor Phénix, for instance, peak burnup levels of about 12% (more than 100 000 MW days per tonne) was reached for one (non-experimental) subassembly and a burnup level of 80 000 MW days per tonne was achieved for almost 4000 pins.* At test reactors, burnups in excess of 20% have been achieved without failure in many experimental pins. Other kinds of fuel (metal, carbide) and structural materials remain under development.

During the history of LMFBR development, there were a number of safety concerns, including rapid coolant boiling (or other cases of coolant loss) and core compaction. However, the excellent coolant properties of sodium ensure good decay-heat removal even under accident conditions. Thus, significant meltdown accidents are extremely improbable.

As a result, accident analysis focused historically on rather improbable, so-called hypothetical, accidents. A recent approach (1982–83) is based on the requirement that an LMFBR should be designed for the same level of safety (measured in risk due to accidents) as a PWR of identical power and construction date.

As a result of intensive efforts on risk analysis of the German SNR 300 it was concluded that, for the SNR-300, the frequency of severe accidents, and their consequences, are no worse than for a PWR.* This demonstrates that

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* See Benoist, E., Champeix, L., Le développement des réacteurs à neutrons rapides en France de février 1983 à février 1984, *Status of National Programmes on Fast Breeder Reactors*, TWGFR-52, International Atomic Energy Agency, Vienna (1984) pp.108–23.

* Risiko-orientierte Analyse zum SNR-300, Gesellschaft für Reaktorsicherheit, GRS-51 (1982). See also, Bayer, A., Koeberlein, K., "Risk-oriented Analysis on the German Prototype Fast Breeder Reactor SNR 300", *Nuclear Safety* 25, 1 (1984) pp.19–32.

safety levels comparable to those of PWRs are already achieved for LMFBRs.

In spite of proven technological feasibility, the commercial introduction of the LMFBR system in the energy market depends decisively on its economic prospects. High capital costs contribute significantly to the cost of electricity produced by an LMFBR. Comparison of capital costs of Soviet BN-600 (LMFBR-type) and WWER-1000 (PWR-type) reactors indicates that for the same conditions the specific capital cost is 30 to 50% higher for current LMFBRs than for PWRs.*

A major reason for this difference is the larger quantities of higher quality steels utilized for the reactor island (reactor vessel, core, primary pumps, heat exchangers, etc.) in LMFBRs designed in the 1960s and early 1970s. Now it is felt that there is considerable potential to decrease the quantity, and occasionally the quality, of metals needed for the LMFBR and, thus, reduce its capital cost.

However, there is still a significant difference that should be compensated by lower fuel cycle costs for LMFBRs. The cost of energy produced by the LMFBR is hardly influenced by the cost of natural uranium, but it is dependent on the cost of fuel reprocessing and refabrication. LMFBR fuel reprocessing has been demonstrated on pilot and semi-industrial scales, but it remains to be demonstrated on a commercial scale, with annual through-puts of at least 250 tonnes of heavy metal per year (which corresponds to 10 GWe, or seven to eight Superphénix plants).

Commercial deployment of LMFBRs depends heavily on their economics compared with that of PWRs. Due to the decrease of uranium prices in recent years and lower rates of nuclear power expansion, the time at which LMFBRs can be broadly deployed has shifted into the future by some decades, as compared to predictions made 20 years ago.

Trends in development

Initial LMFBR prototype and demonstration plants were designed or put into operation when uranium prices first began their increase or were at a high level. At that time, it was expected that the uranium price would continue climbing and LMFBRs, even with high capital costs, would eventually be able to compete with LWRs.

Now, it has been realized that it is not sufficient to rely on the rise of uranium prices to compensate for higher capital costs of LMFBRs. Considerable efforts are being made to decrease capital costs and it appears there is ample potential to do so.

First steps in this direction have been made for Soviet BN-800 and French Superphénix II. Each is considered as the first of a series, and construction of both of them is expected to commence in the near future. For both reactor designs, the power output has been increased without increasing the size and capital cost of the plants compared with those of their precursors – BN-600 and Superphénix I.

In the BN-800, major changes were made in the reactor core and the steam-water circuit without changing other parts of the plant. Increasing the core volume, decreasing the number of modules in the steam generator, and decreasing the number of turbine generators from three to one resulted in the increase of electrical power from 600 MWe to 800 MWe at the same capital cost.

In the Superphénix-II, the electrical power was increased from 1200 MWe to 1500 MWe while the total capital cost of the plant is foreseen to be even lower. This was achieved primarily by decreasing the diameter of the main reactor vessel, decreasing the length of piping of the secondary circuit, and other changes.

Ways to decrease LMFBR capital costs also are being investigated in Japan for the DFBR-1000 reactor, in the United Kingdom for CDFR, and in the United States. The objectives are to improve LMFBR economy without detriment to safety and reliability. Main directions for improvement include optimization of core design to decrease the size of the reactor vessel, optimization of the main heat transport system and overall station lay-out to decrease the dimensions of reactor and auxiliary buildings, and the use of advanced construction techniques.

Further capital cost reductions are expected in all countries developing the LMFBR. These would be achieved through plant standardization, elimination of excessive requirements, and application of innovative technology, and conceptual changes. This permits realistic expectations that modifications in the design, construction, and operation of breeder systems would reduce costs to a range of 10 to 15% higher than PWR generating costs by the early part of the next century.

Present trends in LMFBR fuel irradiation programmes also are encouraging. A target burnup of 10% of heavy atoms (approximately 100 000 MW days per tonne) has been achieved at prototype plants (Phénix, PFR) and experimental reactors (FFTF). For future reactors (for instance CDFR and Superphénix II), 15 to 20% burnup levels are envisaged.* These higher burnups

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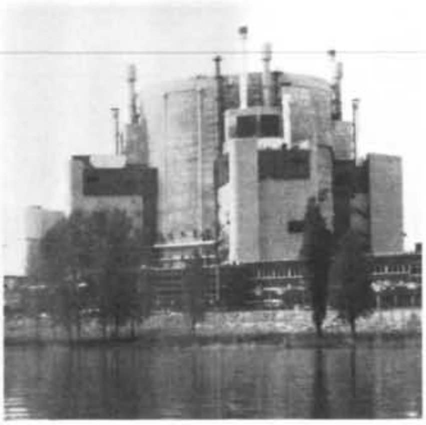
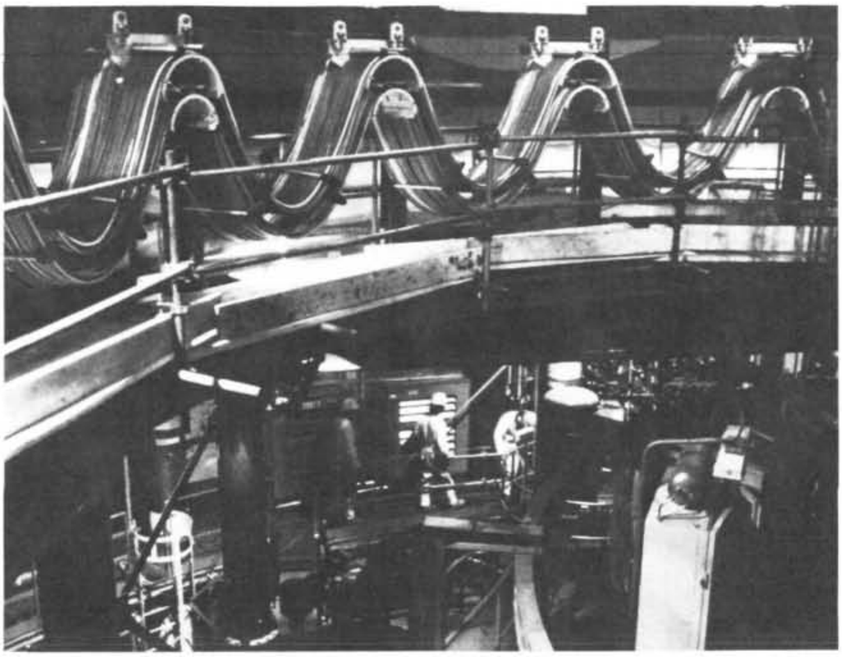
*See Rineysky, A.A., "Comparison of Technical and Economical Characteristics of NPP with Present Thermal and Fast Reactors", *Atominaya Energia,* 53 (December 1982) pp.360–67.

* See Anderson, R.G., UK Overview Paper, "IWGFR Meeting on Predictions and Experience of Core Distortion Behaviour", 1–4 October 1984, Manchester, UK, (to be published); and Bernard, A., and Van Dorsselaere, J.P., "General Presentation of the Core Mechanical Behaviour Approach in France", IWGFR Meeting on Predictions and Experience of Core Distortion Behaviour, 1–4 October 1984, Manchester, UK (to be published).





Nearing completion at Creys-Malville in France, the Superphénix fast breeder reactor is scheduled to start operation in 1985. (Photos courtesy of EDF.)

in the LMFBR will provide considerable savings due to decreasing the cost of the fuel cycle.

The accumulated experience in fuel cycle activities has provided sufficient data for realistic estimation of capital costs for reprocessing plants. Estimates made in the UK in 1983 indicate that a reprocessing plant with a capacity of 50 tonnes of heavy metal per year, sufficient to reprocess fuel from three fast reactors, would cost less than 5% of the total investment needed for the reactors and the associated complete fuel cycle.*

In spite of changes in the deployment timeframe for LMFBRs during the last 15 years, the need for their long-term application is still unquestioned. The situation regarding their technical and safety-related aspects is favourable. Considerable progress has been made in these technical realms while economics remains a major hurdle. International co-operative arrangements may hold one key to the solution of this problem, just as it has to some of the technical ones.

The market introduction of the fast breeder reactor is complicated by its long, costly development, the need for a closed fuel cycle, and the view that, with recent downturns in energy demand in the industrialized world, it may not be required for another 20 to 50 years, depending on the country.

This explains, in part, the trichotomy of attitudes ranging from overwhelming enthusiasm, through indifference to near rejection, that can be found in countries engaged in the development of fast breeder reactors.

Delays in commercial deployment of LMFBRs have shifted emphasis to the development of more economical LMFBR plant designs. More time is available now. This means that commercial LMFBR plants put into operation after the year 2000 will be more advanced, less expensive, and able to compete with LWRs at much lower uranium prices than if they would have been commercially deployed in the later 1980s or early 1990s.

A breeder without reprocessing is not a breeder. Thus, a mandatory requirement for the eventual utilization of breeder reactors is the closure of the fuel cycle. Yet the closed fuel cycle for LMFBRs, especially fuel reprocessing, still needs to be demonstrated on a commercial scale , and about 10 GWe (or seven to eight Superphénix-size plants) would have to be in operation to justify the construction of a commercial-size reprocessing plant.

However, in contrast to the technical situation, which is in hand, the availability of financing for commercial demonstration of LMFBR is not satisfactory. Definite problems are seen in long-term investments, particularly since the investment capital market seems to be oriented to a short-time return basis. This means that capital only will be available if some of the larger organizations – for example in Europe, EDF in France, CEGB in the UK, and several German utilities – pool resources to finance the facilities.

Shortage of investment capital is only one example of the incentive for consolidating efforts through international co-operation. As can be seen from the experience of Western European and countries of the Council for Mutual Economic Assistance (CMEA), considerable savings can be obtained through co-operative ventures. Joint efforts also provide a synergistic effect from the standpoint of design and permit a wider

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* Smith, R.D., "A Review of the UK Fast Reactor Programme", March 1984, in *Status of National Programmes on Fast Breeder Reactors*, TWGFR-52, International Atomic Energy Agency, Vienna (1984) pp.77–107.

Worldwide co-operation in fast reactors: Consolidating efforts

International co-operation has been a hallmark of fast breeder reactor development programmes. Perhaps in no other research and development activity has international co-operation been as successful, on a broad scale, as in the case of the LMFBR.

As early as the 1960s there was considerable international exchange of information and collaboration. To promote international co-operation and technical information exchange in the field, the IAEA established, in 1967, the International Working Group on Fast Reactors (IWGFR) to co-ordinate IAEA activities. Since that time the IAEA itself has sponsored more than 80 conferences, symposia, technical committees, and specialists' meetings in the field of fast reactors.

Co-operation ranges from open exchanges at numerous international meetings to joint projects such as SEFOR; the joint German, Belgian, and Dutch programmes; the consortium devised for Superphénix, that has lately matured into the ARGO group; and the arrangements of the Council for Mutual Economic Assistance (CMEA).

Western Europe

In 1977, France signed major agreements with the Federal Republic of Germany, associated with Belgium and the Netherlands (DeBeNe), to pool know-how on nuclear steam supply systems of LMFBRs, fuel element development, and design. The central organization for this development and for marketing commercial breeders in the future is know as SERENA, which was founded in 1978 and is the sole continental Western European company to issue licenses for future breeder plants to France, Germany, and other countries. There now seems to be the possibility of better European co-ordination and co-operation in future construction schedules of the three commercial plants in these countries.

Within this framework, the French and German R&D activities have been harmonized since 1977 by a steering committee and nine specialized working groups, accompanied by a continuous exchange of information and by common actions.

Since August 1983, an extended Western European study group for fast neutron nuclear systems has been operational. This group, known as ARGO, intends to promote the breeder reactor system so as to contribute to the security of energy supplies in Europe. Besides France, four countries initially participated in the group: Belgium, the Federal Republic of Germany, Italy, and the Netherlands. An intergovernmental memorandum of understanding (signed in Paris in January 1984), brought Britain into the European fast reactor group. The group is open to additional members.

In February 1984, Electricité de France (EDF) and the British national utility, Central Electricity Generating Board (CEGB), signed an agreement in London to work together on fast reactor power stations, with a possible share of CEGB in the Superphénix II project.

By a memorandum of understanding concluded in London on 2 March 1984, industrial companies and research organizations of Belgium, the Federal Republic of Germany, France, Great Britain, and Italy have pooled their individual activities concerning the development and construction of fast breeder reactors. Participation of partners from the Netherlands is also envisaged. The overriding objective of collaboration, as spelled out in the March memorandum, is the most efficient use of resources leading to earlier introduction of economic fast reactors.

The purpose of the comprehensive information exchange is to achieve a sequential construction programme of demonstration reactors in Europe, and to provide electrical utilities with the necessary confidence to proceed to a full commercial reactor construction programme. Each demonstration reactor would draw on experience gained from its predecessor and would lead, through a process of continuous improvement, to a commercial model on which national designs could be based. Each reactor would, in turn, provide a focus for the research, development, and design activities of all participants.

In addition, British and French organizations involved with the fuel cycle also signed in March 1984 two memoranda setting out the principles underlying co-operation in fuel fabrication and fuel reprocessing. Negotiations are under way to extend this arrangement to other countries involved in the collaboration on reactors.

Eastern Europe

Co-operation in Eastern Europe was established in 1980 when CMEA member countries signed the collaboration agreement on the development of a large power fast breeder reactor. In accordance with the R&D collaboration programme, joint investigations are carried out in the fields of reactor physics, core design, thermohydraulics, development of reactor components and instrumentation, fast reactor safety, and the fast reactor fuel cycle.

As an experimental basis for joint studies, laboratories and facilities of different countries are used. These include: critical facilities of the German Democratic Republic (GDR), Romania, and the USSR; thermohydraulic facilities of Czechoslovakia, the GDR, and the USSR; and fast breeder reactors, BOR-60 and BN-350, in the USSR.

Instrumentation for LMFBRs is being developed by scientific and research organizations of Czechoslovakia, GDR, Hungary, Poland, and the USSR, with testing in the BOR-60 and BN-350 reactors. Different designs for LMFBR steam generators, developed in Czechoslovakia, have been tested successfully at BOR-60. The design of the steam generator and its valving for the large power LMFBR is being developed jointly by specialists of Czechoslovakia and the USSR.

Equipment for fast reactor fuel reprocessing, as well as control systems and instrumentation for reprocessing plants, is being developed in Czechoslovakia, GDR, Poland, and the USSR.. As a result of joint optimization studies on fuel reprocessing, it has been concluded that an optimal capacity for such plants would be about 1500 tonnes of fuel per year. This would be sufficient to accommodate nuclear power plants with a total capacity of 40 to 50 GWe. In addition to aqueous methods of fuel reprocessing, non-aqueous reprocessing technology is being developed by specialists of Czechoslovakia and the USSR.

market for the larger number of plants necessary to demonstrate the series effects of production.

International co-operation also permits savings in fuel cycle arrangements since a given facility would have a greater number of reactors to service at an earlier date. Thus, in all these areas, international co-operation is an important trend in the future of LMFBRs.

In European countries that already have decided to harmonize their efforts, there are few doubts that several fast reactors will be on-line by the end of the century.

Referring to the previous plans, it may be seen that: Superphénix I, which is due to achieve criticality in 1985, will be operational and able to provide sufficient experience for Superphénix II, expected to be on-line by the mid 1990s. In the Federal Republic of Germany, SNR-2 may be available by the year 2000. Similarly, the UK could decide to build CDFR to be on-line by the end of the century. In the USSR, BN-600 will be followed by BN-800, early in the 1990s, as the first of a series of perhaps 20 plants. Subsequently, BN-1600 might be on-line sometime after the year 2000. Japan is expected to complete Monju around 1990 and perhaps a larger demonstration reactor by the year 2000.

All these scenarios would obviate the immediate need for commercial-sized fuel cycle facilities until sometime after the year 2000. However, it would be expected that demonstration facilities would be employed as a means of preparing for large commercial-size units.

In the longer term, after the year 2000, a series of then-proven LMFBR plants could be ordered with the consequent need for large-scale fuel reprocessing and fabrication facilities. Large-scale deployment of fast breeder reactors would thereby be available by the time liquid fossil reserves will be depleted, variously estimated to be sometime early in the 21st century. This would achieve the overall LMFBR objective of ensuring a long-term source of power for meeting world energy demand.

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