PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

Development, Operational Experience and Implications for Future Design of FBRS in Japan [and Discussion]

S. Sawai, M. Hori, A. Brandstetter, J. M. Cassels, A. D. Evans and R. S. Pease

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Development, operational experience and implications for future design of FBRs in Japan

By S. Sawai and M. Hori

Power Reactor and Nuclear Fuel Development Corporation, 1-9-13, *Akasaka*, *Minato-ku*, *Tokyo*, *Japan*

[Plate 1]

Joyo, the 100 MW_t experimental reactor, has been successfully operated since 1977, and Monju, the 280 MW_e prototype FBR, is under construction, with the first criticality planned for 1992.

To promote FBR R&D efficiently – including the demonstration FBR (DFBR) programme – a steering committee for R&D was organized in 1986 by the Japan Atomic Power Company, the Power Reactor and Nuclear Fuel Development Corporation, the Japan Atomic Energy Research Institute and the Central Research Institute of Electric Power Industry.

A design study of the DFBR is now underway to define its basic specifications by 1990.

R&D for Monju, DFBR and future commercial FBRs has been done (1) to improve key technologies developed through the Joyo and Monju programmes; (2) to develop innovative technologies to make FBRs commercial; (3) to promote FBR development in conjunction with the development of the FBR fuel cycle.

1. Introduction

Japan has few indigenous energy resources, both fossil and nuclear fuels, and the development of nuclear power has been made – especially in plutonium utilization technology – to improve Japan's energy security and ensure a stable energy supply in the future.

A fast breeder reactor (FBR) breeds more fissile material than that consumed in the reactor and is able to use uranium efficiently. Its fuel cycle system is one in which plutonium fuel is fabricated and spent fuel reprocessed.

Taking the above into account, the Japan Atomic Energy Commission showed the basic strategy of nuclear power development in the 'long-term programme for development and utilization of nuclear power' (June 1987) as follows: (1) to develop nuclear power to be a 'key energy source in Japan'; (2) to establish a plutonium utilization system, mainly consisting of an FBR and its associated fuel cycle system, for the future.

At present, an experimental FBR, Joyo (100 MW_t), has been operated satisfactorily since 1977, and a prototype FBR, Monju (280 MW_e), is being constructed on schedule, with the target of achieving its first criticality in 1992. As far as a demonstration FBR (DFBR) is concerned, its basic specifications will be defined in 1990 and its construction is expected to start in 1997.

The technology, economy and reliability required for commercial FBRs are now being improved as the stable uranium supply is anticipated in the near future and remarkable progress is also being made in light water reactors (LWRS). The FBR is expected to become commercial around 2020–30.

To commercialize FBRS, R&D is now being carried out in Japan on the basis of following principles:

(1) to improve key technologies developed through the Joyo and Monju programmes;
(2) to develop innovative technologies to make the FBR commercial;
(3) to promote FBR development in conjunction with the development of the FBR fuel cycle.

2. Development and experience in Joyo and Monju programmes

The development of the FBR in Japan was actually started in 1967 when the Power Reactor and Nuclear Fuel Development Corporation (PNC) was established (Sawai *et al.* 1987; Hori *et al.* 1987; Takahashi *et al.* 1987). Design, construction, operation and related R&D of Joyo and Monju have been done by the PNC with the cooperation of associated organizations, such as institutes, utilities, manufacturers, etc.

R&D results and operational experience in Joyo have been reflected in Monju and DFBR.

(a) *Operational experience in Joyo*

Joyo has operated for 36000 h since its first criticality in 1977. Neither fuel failure nor sodium leak has yet occurred.

Joyo has been used as a fuel and material irradiation facility and also as a test bed for components and plant systems. Table 1 shows main core parameters of Joyo with irradiation test rigs. Three kinds of special fuel test assemblies (figure 1) and an instrumented test assembly are used for fuel irradiation tests. Tests have been done for developing analytical codes and confirming system characteristics.

(i) *Tests on decay heat removal by natural convection*

To demonstrate the inherent safety of Joyo and enable the design of FBRS with inherent safety, tests on decay heat removal by natural convection were conducted under loss of electric power. The results showed the inherent safety of Joyo and agreed well with the analysis.

(ii) *Main circulating pump*

About 50 °C of peripheral temperature difference was observed in the main circulating pump. Baffle plates were installed in the inner casing to prevent natural convection of cover gas, which reduced the temperature difference to below 4 °C.

(iii) *Behaviour of corrosion products*

The radiation dose exposure of personnel during maintenance of Joyo is mainly a result of corrosion products in the primary circuits, especially ^{54}Mn and ^{60}Co. The analytical code of the corrosion products' behaviour in FBR primary circuits, PSYCHE, has been developed by the PNC and verified by data in Joyo.

(b) *Construction of Monju*

Monju was designed on the basis of experience with Joyo and R&D work. Its main design data are listed in table 2. The construction, with the cooperation of the Japan Atomic Power

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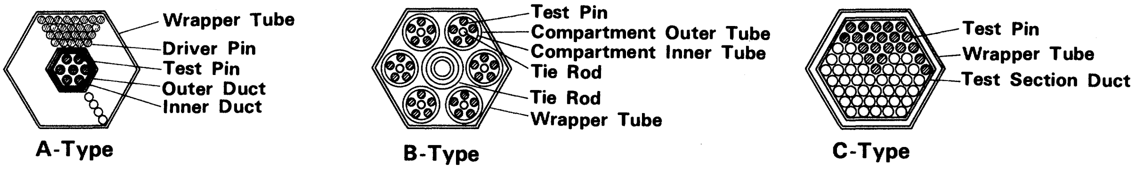

FIGURE 1. Special fuel assembly types for irradiation tests in Joyo.

TABLE 1. MAIN CORE PARAMETERS OF JOYO

reactor type		sodium cooling loop type
thermal output power/MW_t		100
fuel material		PuO_2–UO_2
core	equivalent diameter/mm	730
	height/mm	550
	volume/l	230
Pu enrichment (Pu fissile, %)		
	initial core	23
	equilibrium core	20
fuel inventory		
	core (U+Pu metal, t)	0.7
max. pin burn-up/(MW d t^{-1})		75000
cladding material		modified 316SS
cladding outside diameter/thickness (mm)		5.5/0.35
permissible cladding temperature/°C (middle of thickness)		650
neutron flux (max.)/(n cm^{-2} s)		5.1×10^{15}
neutron flux (core average)/(n cm^{-2} s)		2.8×10^{15}
power density/(kW l^{-1})		430
driver fuel assembly numbers (max.)		67
A type special fuel assembly (max.)		3
B type special fuel assembly (max.)		3
C type special fuel assembly and/or instrumented test assembly (max.)		3
material irradiation rigs		~ 10
reactor vessel (height/inside diameter, m)		10/3.6
reactor inlet/outlet sodium temperature (°C)		370/500

Company (JAPC), was started in October 1985 and at the end of May 1989 it was more than two-thirds of the way to completion (figure 2, plate 1).

The reactor site is in Tsuruga, Fukui-ken. The reactor vessel was installed in October 1988 and main circulating pumps arrived at the site in June 1989. Special attention has been paid to prevent components from being deformed and to keep components clean and dry during transportation, installation and maintenance.

Functional testing will follow the installation of components, piping, etc., and the first criticality will be achieved in October 1992.

(c) *Development of Joyo and Monju programmes*

To develop FBR key technologies, such as reactor safety, fuel and materials, components, sodium technology, etc., development facilities were and are being constructed in the Oarai Engineering Center (OEC), PNC (figure 3, plate 1). Some typical R&D in Joyo and Monju programmes are described as follows.

Table 2. Main design and performance data of Monju

reactor type		sodium cooling loop type
thermal output power/MW_t		714
electrical output power/MW_e		about 280
fuel material		PuO_2–UO_2
core	equivalent diameter/mm	1790
	height/mm	930
	volume/l	2335
Pu enrichment (Pu fissile, %)		
	initial inner core/outer core	15/20
	equilibrium inner core/outer core	16/21
fuel inventory	core (U + Pu metal, t)	5.9
	blanket (U metal, t)	17.5
max. pin burn-up/(MW d t^{-1})		98000
cladding material		modified 316SS
cladding outside diameter/thickness (mm)		6.5/0.47
permissible cladding temperature/°C (middle of thickness)		675
power density/(kW l^{-1})		283
breeding ratio		1.2
reactor inlet/outlet sodium temperature/°C		397/529
secondary sodium temperature/°C (IHX outlet/IHX inlet)		505/325
number of loops		3
pump position (primary and secondary loops)		cold leg
type of steam generator		helical coil, once-through unit type
steam pressure/(kg cm^{-2} g^{-1}) (turbine inlet)		127
steam temperature/°C (turbine inlet)		483
refuelling system		single rotating plug with fixed arm FHM
refuelling interval (month)		6

(i) *Computer-aided expert system*

Development has been made on the computer-aided expert system for Joyo operation and maintenance, supported by analytical codes and operation data. The system covers the following fields: (1) core and refuelling management; (2) operation guidance for anomalies in the plant; (3) guidance for plant maintenance.

(ii) *Components reliability database*

FREEDOM (FBR reliability evaluation database for operation and maintenance) of PNC and CREDO (centralized reliability data organization) set up in ORNL have been combined to enlarge the common database. The collaboration is now underway and data of over 2×10^9 component-hours have been stored.

(iii) *Modified* 316 *stainless steel*

316 stainless steel was selected as the fuel cladding material for Monju. The stabilizers in 316 stainless steel, such as B, P, Ti, Nb, were so settled as to improve creep strength and swelling resistance at high temperature and neutron exposure. This modified 316 stainless steel shows good characteristics (figure 4).

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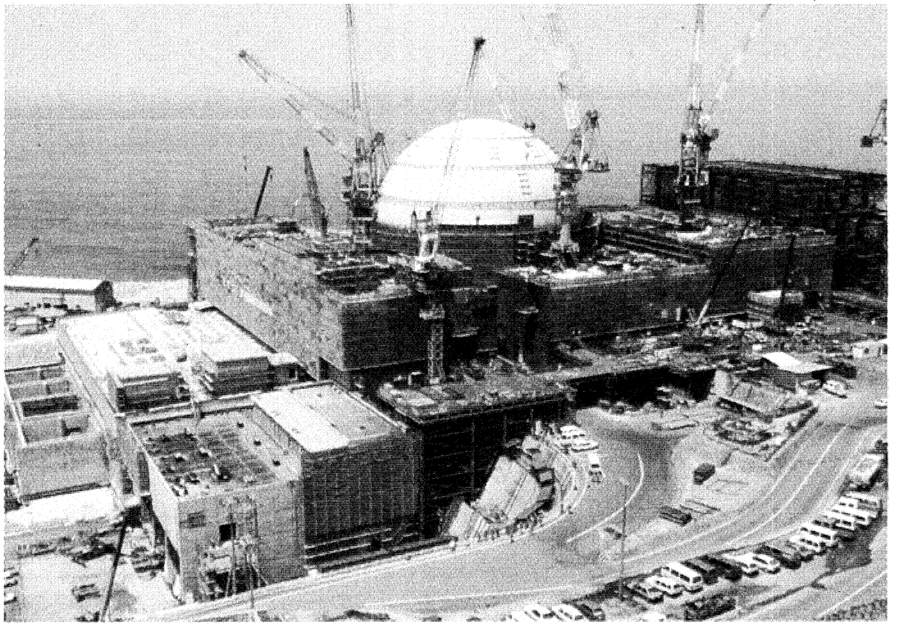

FIGURE 2. General view of Monju.

FIGURE 3. Bird's-eye view of Oarai Engineering Center.

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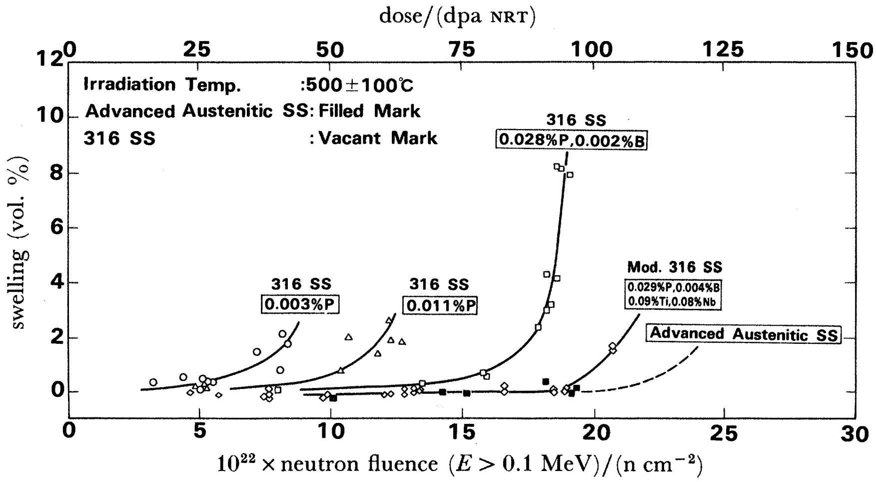

FIGURE 4. Improvement in swelling property of 316 stainless steel cladding.

(iv) *Design standards*

Standards for Monju design were established as follows: (1) safety design guide; (2) elevated temperature structural design guide (Okabayashi *et al.* 1987); (3) standards for weldments; (4) seismic design guide.

(v) *In-service inspection equipment apparatus*

In-service inspection in Monju will be conducted on the basis of technologies developed for LWRS. However, specific in-service inspection apparatus for FBRS are being developed and their performance tests will be made in the in-service inspection development facility (OEC).

One of the specific in-service inspection apparatus is for the reactor vessel. The apparatus is capable of moving in the space (*ca.* 30 cm) between the reactor vessel and the guard vessel and of inspecting faults or cracks in the reactor vessel by electromagnetic acoustic transducers and fibrescopes.

3. Development of FBR key and innovative technologies

FBR key and innovative technologies should be developed to the stage when they can be introduced into the plant (Sawai *et al.* 1987; Sawai 1988). The FBR will then become commercial and the following aims realized: (1) to simplify plant systems and to enhance plant reliability; (2) to reduce the mass of plant; (3) to develop high-performance components; (4) to develop high-performance core and fuel; (5) to develop a fully automated and self-reliant plant.

It will be necessary to carry out demonstration tests of the above technologies in experimental reactors to ensure their reliability and performance before their adoption in the plant. The Joyo MK-III programme is now planned for this purpose.

This section gives some typical activities of the above R&D in Japan and an outline of the Joyo MK-III programme.

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(a) *Simplification and reliability enhancement of plant systems*

(i) *Decay heat removal by natural convection*

The decay heat removal system is very important for keeping the reactor core safe in an emergency and it must be very reliable. It is considered most suitable to remove decay heat by natural convection.

A direct reactor auxiliary cooling system (DRACS) and a primary reactor auxiliary cooling system (PRACS) have been developed which could remove decay heat by natural convection, by using the water test facility (OEC).

(ii) *Diversification of reactor shutdown system*

Diversification of reactor shutdown systems is effective in enhancing the plant's safety and reliability. One promising method is the self-actuated reactor shutdown (SASS), which exploits the temperature-dependent Curie point. The system triggers when the sodium temperature exceeds the specified temperature.

Basic performance tests were done and a demonstration test is to be made.

(iii) *High-temperature sodium-resistant ceramics*

Sodium components' cells in Monju are lined with steel plates to protect the concrete in case of sodium leaking out of the components or pipes. The development of high-temperature sodium-resistant ceramics, using alumina-based materials, has begun with the aim of replacing steel plate liners, thereby reducing labour and cost. The development aims to manufacture ceramics that could be coated onto concrete with low-temperature spray.

(iv) *Double-walled tube steam generator*

To enhance the reliability of steam generators against a water–sodium reaction caused by tube failure, a double-walled tube steam generator (figure 5) has been developed. Models of a 1 MW_t steam generator with double-walled tubes of 9Cr–1Mo steel are now being fabricated and the test of their performance begins in 1990. Also, collaboration between JAPC and the U.S. Department of Energy (DOE) is in progress on a performance test of steam generator with double-walled tube of $2\frac{1}{4}$Cr–1Mo steel.

The double-walled tube steam generator might eliminate the secondary sodium loops with support of the reactor safety design.

(b) *Reduction in mass of plant*

(i) *Shortening piping length*

Rather long piping is required to absorb thermal expansion caused by high-temperature sodium, and this makes the reactor containment large. Bellows expansion joints, floating support of components and top-entry piping to the reactor vessel are possible solutions. Figure 6 shows a bellows expansion joint and its effect on shortening piping length by $\frac{1}{2}$–$\frac{1}{3}$, which makes the reactor containment small. Various kinds of tests have been conducted on bellows expansion joints, e.g. thermal cycling, endurance, buckling, etc. Efforts will be made to establish a design standard.

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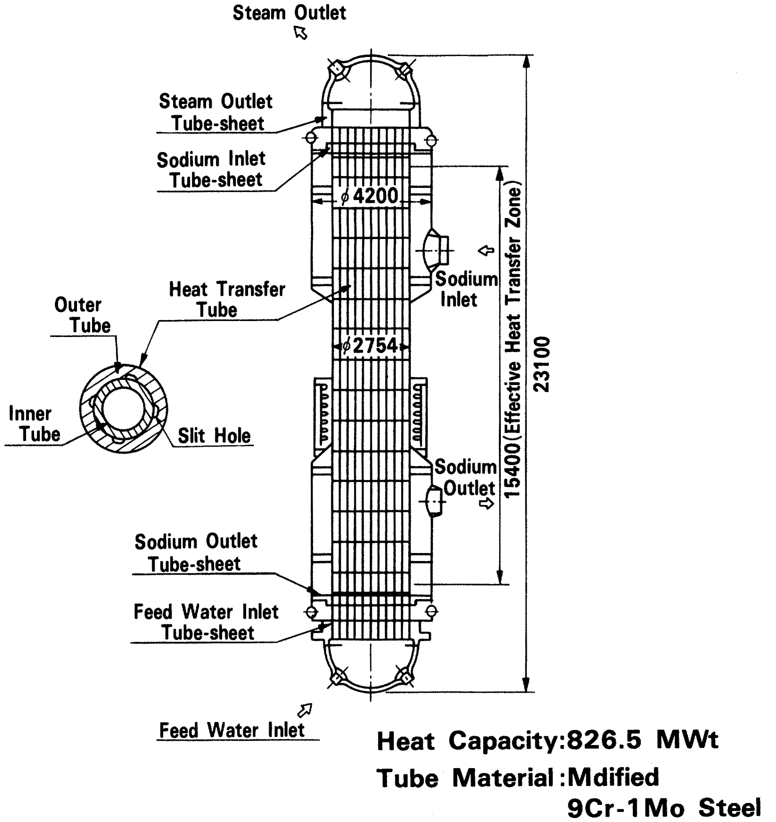

FIGURE 5. Double-walled steam generator (units are millimetres).

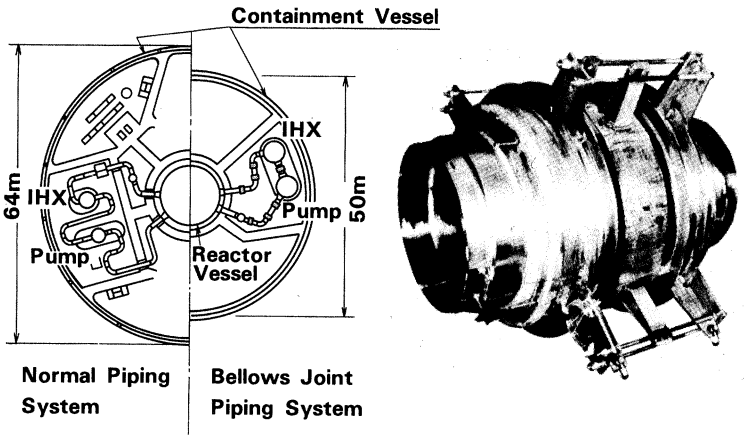

FIGURE 6. Piping layouts with and without bellows joints.

(ii) *Rationalization of reactor containment*

As the amount of heat released by an accidental sodium leak would be rather small, the design pressure of the reactor containment could be set low. This will lead to a reinforced concrete reactor containment, including rectangular-shaped structures.

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(iii) *Seismic isolation of reactor containment*

FBR components and structures are designed not only against thermal stress caused by transient sodium temperature change, but also to withstand earthquakes. The former may require a thin-shell structure.

The seismic isolation of the reactor containment could make us adopt thin-shell structure components, and be advantageous to the FBR. The development of seismic isolation systems associated with FBR has been carried out by CRIEPI and PNC.

(c) *Development of high-performance components*

The development of high-performance components is supported by R&D of improved design guides, analytical codes and high-performance materials, such as modified 9Cr–1Mo steel, modified 316 LCN stainless steel, etc.

(i) *Once-through or integrated components*

Once-through or integrated components will make the plant compact. A once-through steam generator and an integrated heat exchanger combined with sodium circulating pump are now being studied.

(ii) *High-performance pump*

R&D has begun on an inducer pump and a superconducting electromagnetic pump.

(d) *Development of high-performance reactor core and fuel*

The development of high-performance and long-lived reactor core and fuel, which aims at realizing the following advantages, has been made to increase the plant factor and to lower the fuel cycle cost: (1) high burn-up; (2) long refuelling interval; (3) high linear power of fuel pin; (4) power flattening; (5) lightweight shield.

(i) *Long-lived reactor core and fuel*

Collaboration between PNC and the U.S. DOE is now going on, using Joyo, the Fast Flux Test Facility and the Experimental Breeder Reactor II with the target of achieving 150 GW d t^{-1} in the first phase and 200 GW d t^{-1} in the second phase. Modified austenitic stainless steels (figure 4) and ferritic alloys (including the oxide-dispersion-strengthened type) are being developed to use as cladding material of long-lived fuel. Collaboration between Japan and France to develop high burn-up fuel is also underway. Metal, nitride and carbide fuels are also being studied.

Axially heterogeneous reactor cores are considered promising for power flattening and realizing a long-lived reactor core (a long refuelling interval). Experiments on heterogeneous reactor cores (JUPITER programme), both axially and radially, have been done in a U.S. zero-energy fast reactor assembly (ZPPR), Argonne National Laboratory (ANL), under the collaboration between PNC and U.S. DOE.

(ii) *Reduction of shielding*

Efforts have been made to reduce the weight and volume of the neutron shielding. Collaboration between PNC and the U.S. DOE (JASPER programme) to investigate the effect of B_4C, ZrH, etc., is in progress. Figure 7 shows that B_4C of 13 cm thickness could decrease neutron flux to $\frac{1}{10}$–$\frac{1}{100}$ of the original level, depending on neutron energy.

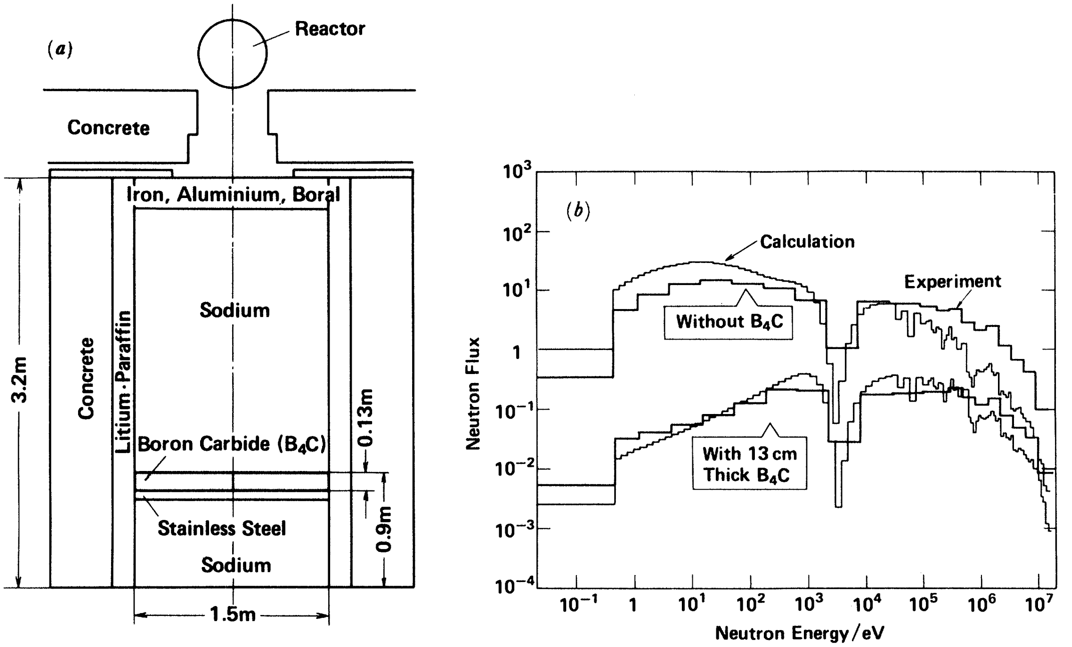

FIGURE 7. Neutron flux spectra behind FBR radial shield with and without B_4C layer. (*a*) Experimental layout of FBR radial shield. (*b*) Neutron flux spectra behind FBR radial shield.

(*e*) *Development of automated and self-reliant plant*

To operate the plant most efficiently with high reliability and safety, a study has begun on a fully automated and self-reliant plant by using artificial intelligence. The plant itself would be able to evaluate operation data and to improve the plant operation and maintenance procedures.

(*f*) *Joyo MK-III programme*

To carry out demonstration tests of improved and innovative technologies, the Joyo MK-III programme is now planned (figure 8). The programme consists of upgrading the irradiation capability, raising neutron flux by 40%, and installing innovative components and systems, such as long-lived fuel, double-walled tube steam generator, bellows expansion joints, etc.

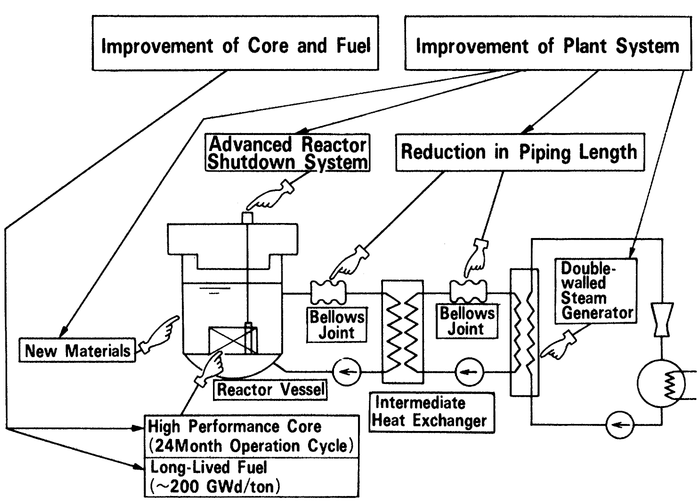

FIGURE 8. Joyo MK-III programme.

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4. Future development of fbrs

It is considered essential that improved key and innovative technologies, as well as experience of existing FBRs, should be introduced to make FBRs commercial and competitive against LWRs.

(*a*) *Demonstration* FBRs

(i) *General*

JAPC was nominated as the organization to design, construct and operate a DFBR (Itakura *et al.* 1987). A steering committee for R&D of the FBR was organized in July 1986 by JAPC, PNC, the Central Research Institute of Electric Power Industry (CRIEPI) and the Japan Atomic Energy Research Institute (JAERI), to cooperate efficiently and effectively on R&D for the DFBR. Figure 9 shows the schedule for the DFBR whose target date of completion is in the early 2000s.

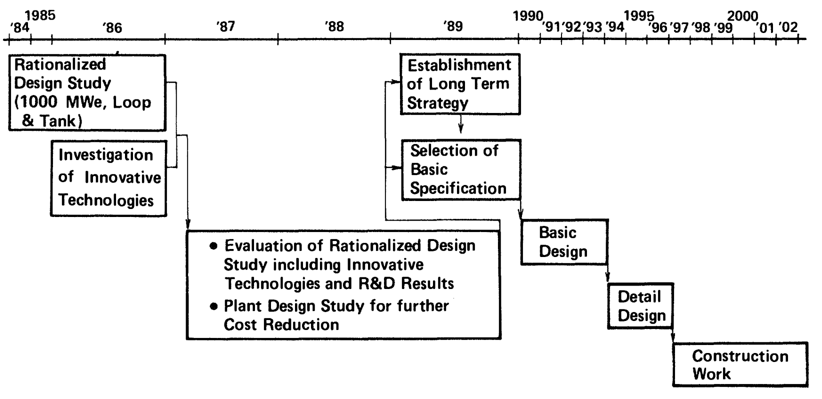

Figure 9. Schedule for DFBR development.

(ii) *Design study of the* DFBR

In 1984, the Federation of Electric Power Companies began a design study of FBRs, both loop and tank types, which JAPC took over and completed in 1987. PNC has carried out studies of large FBRs, based on the development and experience of the Joyo and Monju programmes.

Based on the above studies, a design study of a DFBR is being carried out to define its basic specifications in 1990, examining which improved technologies – such as long-lived core and fuel, improved reactor shutdown system, etc. – should be adopted in the plant.

(*b*) *The commercial* FBR

To make the concept of the commercial FBR clear, technical assessment has begun by adopting as many highly improved key and innovative technologies in the plant as possible, so that we have a common target to realize.

5. Development of the fbr fuel cycle system

Breeding more fissile material than consumed cannot be realized without the support of the fuel cycle system. Fabrication technology of FBR MOX (mixed oxide) fuel and reprocessing technology of FBR spent fuel have been developed for over 20 years in PNC (Uematsu 1987).

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(a) *Development of* FBR *fuel fabrication technology*

The FBR fuel fabrication technology has come a long way in these 20 years; 100 t of MOX fuel have been fabricated in PNC, and there have been no failures.

The Plutonium Fuel Production Facility, which consists of the FBR line and the ATR line, has the following features:

(1) the system is fully automated and operated by remote control, to reduce radiation exposure of personnel, to save labour, etc.;

(2) an advanced safeguards system is adopted.

The FBR line has a capacity of 5 t a^{-1} for Monju and Joyo fuel and this will be increased to 15 t a^{-1} in future. The FBR line was completed in 1987 and fabrication of MOX fuel began in October 1988.

(b) *Development of* FBR *spent fuel reprocessing*

Development of FBR spent fuel reprocessing started in PNC around 1970 and international cooperation on the reprocessing technology development has been undertaken with U.S.A., F.R.G and U.K.

Development facilities were constructed at the Tokai Works, PNC: the Chemical Process Facility and the Engineering Development Facilities. The former is for process tests and the latter for engineering tests of process equipment, remote handling systems, etc. To make demonstration tests on an engineering scale, a recycling equipment test facility is planned and a pilot plant for FBR fuel reprocessing will follow in the 2000s.

6. Conclusion

The development of FBRs in Japan, as well as the development of the FBR fuel cycle system in PNC, is underway to establish the nation's energy security and ensure a stable energy supply in the future.

It is considered important to cooperate internationally to promote the efficient development of FBRs and to make the FBR commercial.

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Discussion

A. Brandstetter (*Interatom, F.R.G.*). What operating conditions applied during the natural circulation cooling test on Joyo?

S. Sawai. The test simulated loss of all electrical power, with air cooling for ultimate removal of decay heat.

J. M. Cassels, F.R.S. (*Norwich, U.K.*). As a combined heat and power (CHP) theorist, I note that it is difficult to raise the thermal efficiency of electricity generating plant above 40 % unless magnetohydrodynamic (MHD) techniques can be established. Although CHP has had its failures, I would appeal for its spread.

S. Sawai. In Japan we are making a preliminary study of the use of MHD technology for the fast reactor because of its use of sodium coolant.

A. D. Evans (*BNFL, Risley, U.K.*). Could Dr Sawai confirm that a definite decision has been made to fit a steam generator to Joyo and what size it will be?

S. Sawai. We have not made a definite decision yet; however, we intend to develop a double-wall steam generator for improved reliability. Before putting this type into a new plant we consider Joyo is the most suitable test vehicle. The size to be chosen for test in Joyo is not fixed yet but we hope it will be 50 % of the plant's capacity.

R. S. Pease, F.R.S. (*Pease Partners, Newbury, U.K.*). The U.S. has plans for developing actinide incineration by fast reactors. Has Japan similar plans?

S. Sawai. We have the OMEGA programme to study the burning of actinides in fast reactors, accelerators and other facilities. Studies for carrying out tests in Joyo have begun.

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FIGURE 2. General view of Monju.

FIGURE 3. Bird's-eye view of Oarai Engineering Center.

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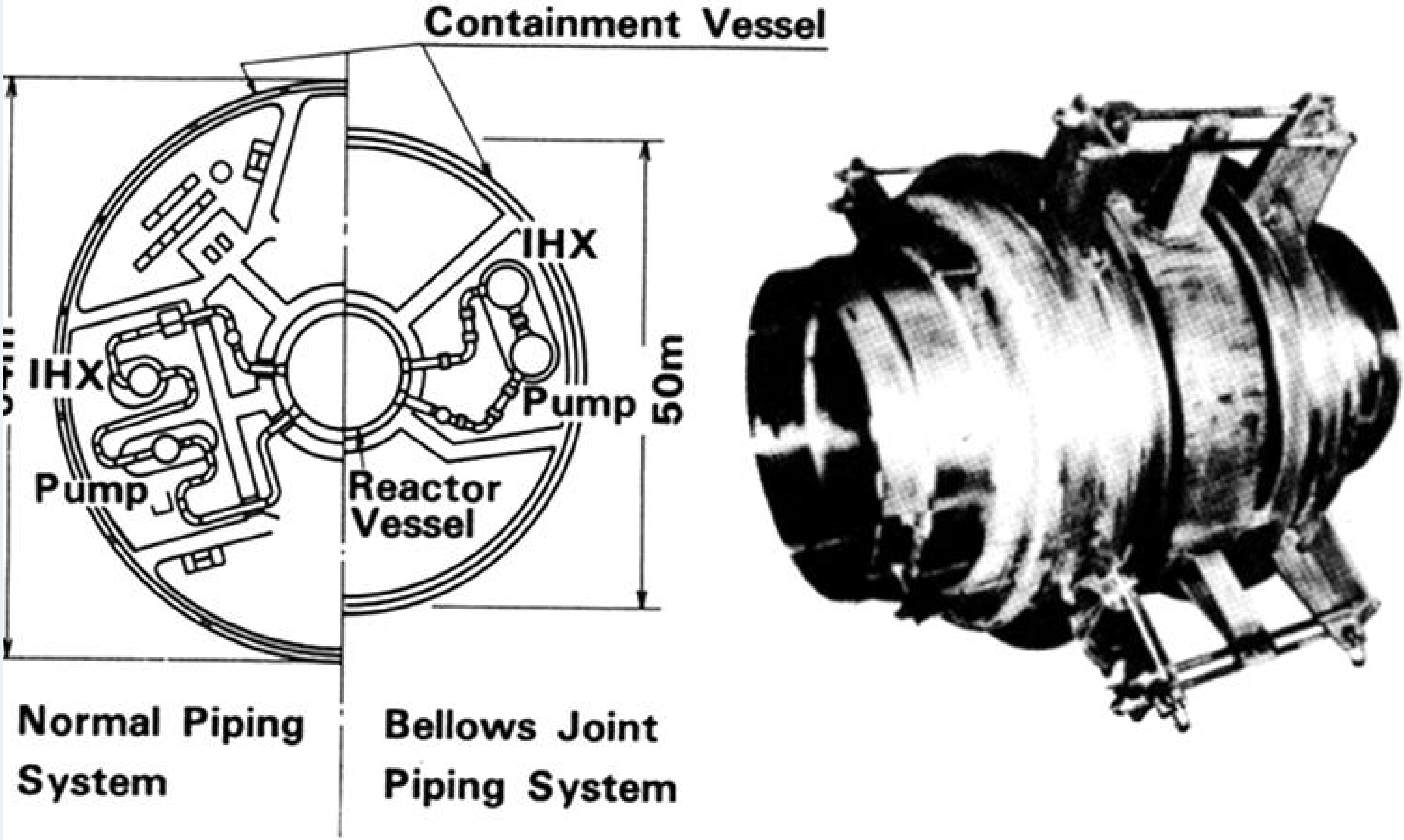

FIGURE 6. Piping layouts with and without bellows joints.