Advanced Reactor Development in Japan

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ABSTRACT

Three advanced reactor development programs have been going on in Japan; heavy-water reactor, fast breeder reactor, and very high temperature reactor. In the first development program, a prototype reactor, FUGEN, reached criticality in March 1978 and a conceptual design of a demonstration plant is now under way. JOYO, an experimental fast breeder reactor, achieved criticality in April 1977, and the review of MONJU (prototype) will be done soon after the environmental impact assessment of the plant has been finished by the local government. The very high temperature reactor development was started in 1969, and design and R&D work are now being carried out, with a target date of 1985 to operate an experimental VHTR.

INTRODUCTION

There are three reactor development programs now being carried on in Japan: heavy-water reactor (HWR), fast breeder reactor (FBR), and very high temperature reactor (VHTR). Each has its own specific characteristics, and the three programs were authorized to enable Japan to solve its future energy problems which arise mainly from the scarcity of natural energy resources—in particular, uranium and oil.

The Japan Atomic Energy Commission (Japan AEC) decided to develop the heavy-water reactor and the fast breeder reactor in May 1966 as Japan's national nuclear energy projects; and accordingly, the Power Reactor & Nuclear Fuel Development Corporation (PNC) was set up in 1967 and made responsible for the work. Development of the very high temperature reactor is now carried on by the Japan Atomic Energy Research Institute (JAERI) with the cooperation of manufacturers and users.

The three reactor development programs are outlined below.

HEAVY-WATER REACTOR DEVELOPMENT

FUGEN, which is a 165-MW(e) prototype for a heavy-water-moderated boiling light-water-cooled reactor, obtained criticality in March 1978. This project was authorized by the Japan AEC in May 1966, supported by the electric utilities and many other organizations. The aim was not only to reduce the demand for natural uranium and the separative work on uranium enrichment, but also to develop a reactor that could be operated by supplying natural uranium only. Taking the present nuclear energy situation in Japan into account, the role of FUGEN-type reactors can be written as follows.

Role of FUGEN-Type Reactor

FUGEN-type reactors have the following characteristics:

1. Burnup will be increased by increasing the moderator-to-fuel volume ratio, and at the same time coolant void reactivity can become positive and increased. The use of plutonium in the core, however, reduces coolant void reactivity, with good results in increased reactor safety and stability.

2. Both uranium oxide and mixed-oxide fuel, such as (Pu + NU), (Pu + depleted U), or others, can be used effectively in the core without changing the dimensions of fuel assemblies and control rods. This offers the possibility of using many different kinds of fuel.

3. Even mixed-oxide fuel, extracted from light-water reactor (LWR) spent fuel, with the same concentration of plutonium and uranium as LWR spent fuel, may be used in FUGEN-type reactors, giving a burnup of over 16,000 MWd/MT.

In Japan, at present, plutonium for FUGEN-type reactors will be available from LWR spent fuel. The balance of plutonium may be obtained if one FUGEN-type reactor is operated along with a 1.8 LWR, as seen in Table I. In this case, about a 30% reduction of demand for natural uranium and about a 35% reduction in uranium enrichment work can be expected, compared with purely LWR (uranium recycling).

As Japan has very limited natural uranium and oil resources, the needs of natural uranium and uranium enrichment work both have to be minimized, as much as possible, especially until commercial fast breeder reactors come into practical application. LWRs constitute the main nuclear energy source for the immediate future, and plutonium can be stored in the form of spent fuel or as plutonium itself. The FUGEN-type reactor, however, can effectively utilize fuels (especially plutonium, which is derived from operation of an LWR). Taking the above into consideration, the best plan for Japan would be to introduce FUGEN-type reactors in the power generating system, so the need for natural uranium and for uranium enrichment work can both be reduced, while at the same time adjusting the plutonium storage. When commercial fast breeder reactors come into operation, the FUGEN-type reactor can be operated on slightly enriched uranium to produce plutonium.

TABLE I

Fuel Demand in a FUGEN-Type Reactor and an LWR

	Burnup (MWd/MT)	Demand of NU (kg/MW yr)	Demand of Pu (g/MW yr)	Pu Recovered (g/MW yr)	Demand of U Enrichment Work (kg SWU/MW yr)
FUGEN-type reactor					
1.44% Pu + NU	27,800	29.5	420	142	---
0.61% Pu + 0.86 ^{235}U	16,100	---	307	212	---
LWR (3.0% ^{235}U)[4]					
Once-through	30,500	169.3	---	(153)	87.5
U recycle	30,500	136.7	---	153	84.9
U-Pu recycle	30,500	107.3	224	224	63.9

Load Factor: 70%.

^{235}U Tails Assay: 0.3%.

The FUGEN Project

A conceptual design of FUGEN was done first to make clear the FUGEN concept, and at the same time to set up the R&D program. ¥ 6.85 × 10^{10} was spent on construction of FUGEN, and a further ¥ 2.9 × 10^{10} on R&D until criticality was reached.

Research and development have been carried out to support design, manufacture, construction, and operation of FUGEN, covering design codes, physics, heat transfer and hydraulics, structure and components, fuel and Zr-alloy, and reactor safety. At inception of the project, the following major works, viz., critical assembly, 14-MW heat transfer loop, full-scale components test loop, and a full-scale safety testing facility, were constructed at the O-arai Engineering Center, PNC, to confirm, by means of full-scale experiments and tests, important reactor features, such as nuclear characteristics, core heat removal and hydraulics, endurance of fuel and pressure tube assemblies, and reactor safety. Experiments and tests began in early 1970 using these facilities. Figure 1 shows the 14-MW heat transfer loop where burnout characteristics, flow stability in parallel channels, etc., are studied.

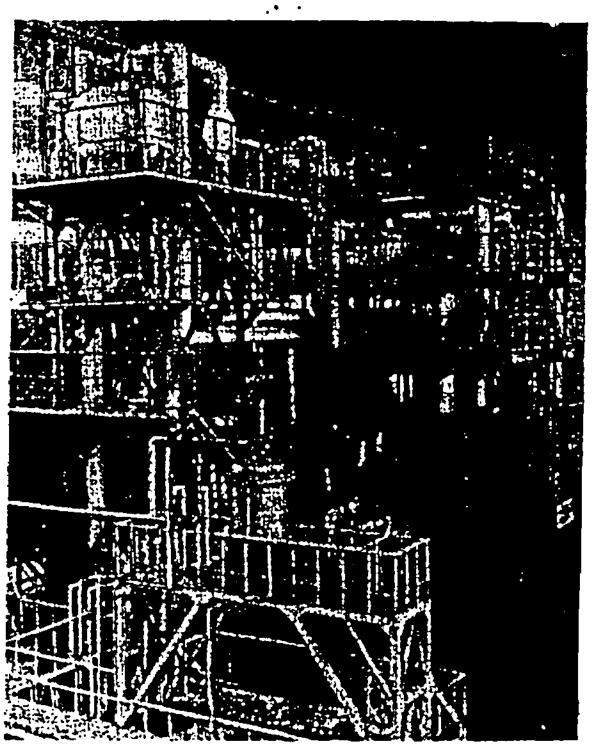

Fig. 1. 14-MW heat transfer loop.

To establish and accumulate the knowhow to manufacture important components, such as fuel assemblies, pressure tube assemblies, reactor structure, refueling machine, etc., full-scale mockups of these components were manufactured and tested. Based on the results of such R&D, these components were designed, manufactured, and installed in FUGEN.

FUGEN is designed to generate 165 MW(e), and design data and the general view below the reactor bottom face are shown in Table II and Fig. 2. Ninety-six mixed-oxide fuel assemblies are loaded in the center of the core, with 128 slightly enriched fuel assemblies in the outer region. This arrangement ensures that the reactor characteristics will change little throughout reactor life.

Construction of FUGEN started in December 1970. During the seven-year construction period many problems

TABLE II

Design Data of FUGEN and Demonstration Plant

	FUGEN	Demo Plant
Electric power (MW)	165	600
Thermal power (MW)	557	2000
No. of channels	224	448
Core height (mm)	3700	3700
Diam of calandria (mm)	4900	9200
Pressure tube		
Material	Zr-Nb	Zr-Nb
i.d. (mm)	118	130
Thickness (mm)	4.3	4.7
Pitch (mm)	240	275
Fuel		
No. of rods	28	54
Pellet diam (mm)	14.4	10.44
Pu enrichment (%)	0.67	1.44
Refueling	To demonstrate on-power	Off-power

were encountered and solved. Some were reported elsewhere.[1-3] Commissioning is under way, and the target is for FUGEN to continuously generate 165 MW(e) from the end of March 1979.

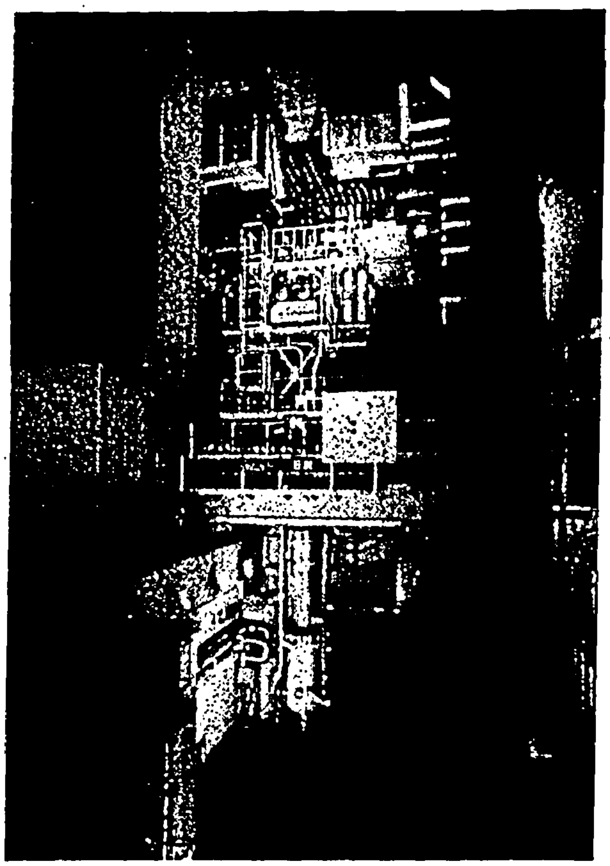

Fig. 2. General view below reactor bottom face, FUGEN.

Development of Demonstration Plant

A conceptual design of a demonstration plant (twin), next to the FUGEN project, is now being prepared, based on the accumulated experiences and R&D on FUGEN. Some modifications are being incorporated, compared with FUGEN, to reduce construction costs and to facilitate easier maintenance work in the plant.

1. Plutonium is to be combined with natural uranium in such a way that burnup may be expected to be the same as with LWR fuel.

2. More fuel rods in one fuel assembly, with rather small-diameter fuel rods, are to be adopted to lessen the number of pressure tubes and to reduce the size of the reactor core.

3. Off-power refueling is being planned.

The design data are listed in Table II. Tests and experiments on reactor characteristics, reactor core heat removal, and nuclear characteristics have already begun, using a 14-MW heat transfer loop and critical assembly. Table III shows the construction schedule for the demonstration plant.

In addition to the above design work for the demonstration plant, it is understood that the development of plants directly associated with this type of reactor, mixed-oxide fuel fabrication and the supply of heavy water, are also very important. A conceptual design for a mixed-oxide fuel fabrication plant (60 MT/yr, standard capacity) has been in preparation for two years.

FAST BREEDER REACTOR DEVELOPMENT

The development of fast breeder reactors (FBRs)[9] is one of the most important and urgent tasks for Japan, essential to maintaining the country's social life and economy. This is a result of the scarcity of natural energy resources, and the fact that the breeder reactor has the potential of producing more fuel than it consumes.

In 1968, the Japanese Prime Minister laid down the basic principles and the first phase of the program for the FBR project. It was determined that two liquid-metal-

TABLE III

Construction Schedule of HWR and FBR

		1975	1980	1985	1990	1995	2000
HWR	Prototype Reactor	FUGEN	Criticality (Mar. 1978)				
	Demonstration Reactor						
FBR	Experimental Reactor	JOYO	Criticality (Apr. 1977)				
	Prototype Reactor		MONJU				
	Demonstration Reactor						

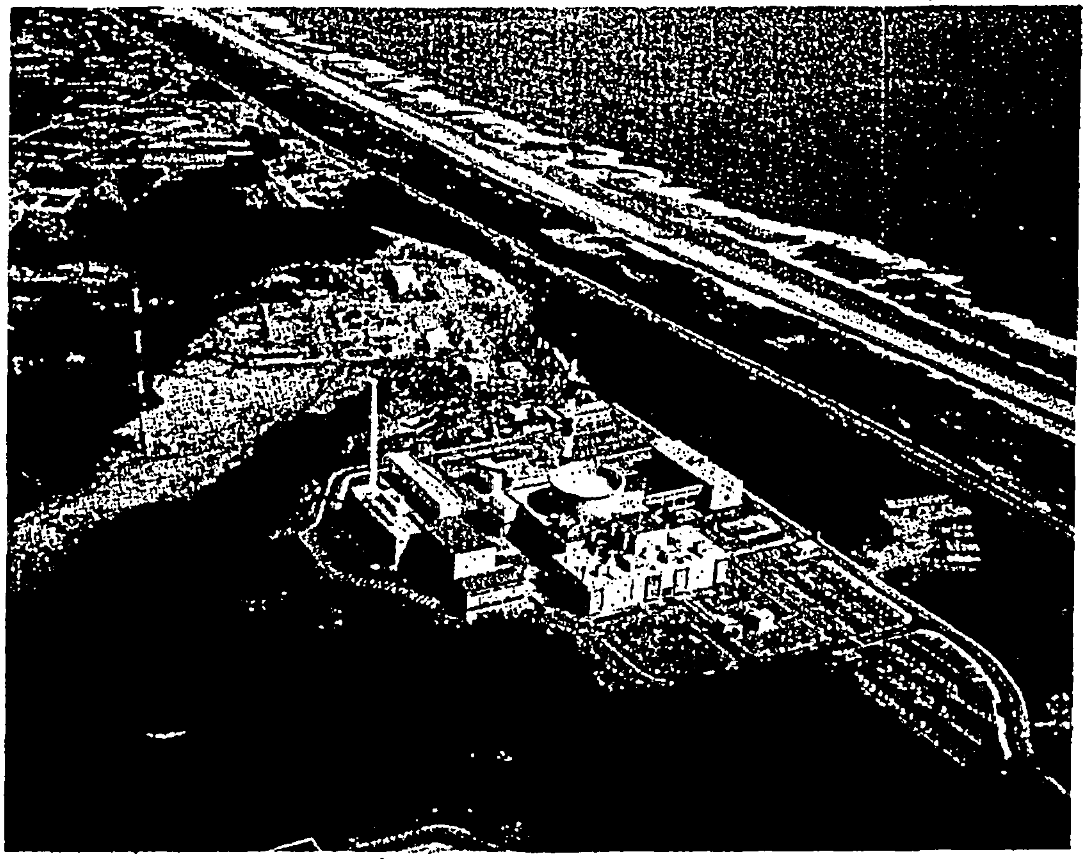

Fig. 3. General view of JOYO plant.

cooled fast breeder reactors should be constructed: one, an experimental fast reactor named JOYO (Fig. 3), about 100 MW(th), and the other, a prototype fast breeder reactor named MONJU, about 300 MW(e).

JOYO reached criticality in April 1977, and is expected to reach its initial target power of 50 MW(th) the middle of this year. A review of MONJU safety will be done by the regulatory body soon after the environmental impact assessment of the plant has been completed by the local government, which is now under way.

The major design specifications of JOYO and MONJU are summarized in Table IV, which includes the upgraded core of JOYO. Upgrading of the core is now under review by the regulatory body.

In 1976, following the oil crisis, the Japan AEC released a report from a one-year study on evaluation of the nuclear fuel cycle and the policy on development of advanced power reactors, including FBRs.

The report states that the transition from LWRs to FBRs is to be the essential route of Japan's nuclear energy development strategy; that the prototype FBR plant, MONJU, should be built as scheduled; and that construction of a demonstration fast breeder reactor should begin after MONJU comes into operation.

To reach these conclusions, the following assessments were made: the capacity of nuclear power stations in Japan would have to be more than 100 GW(e) in the year 2000, providing 30 to 40% of the total electric generating capacity, and that, by introduction of commercial FBRs in the 1990's, the cumulative demand for U_3O_8 would be, at most, 500,000 MT after the year 2020.

In 1977, a follow-on study was done by the Science and Technology Agency to evaluate issues involved in commercialization of FBR plants in Japan, including a developmental program of demonstration plants and better coordination of the industry.

The assessment was that the demonstration plants following MONJU would have a capacity of about 1000-MW(e) output, with construction to begin in 1986, and reaching criticality in 1991; that initial commercial FBR plants would follow the demonstration plant, with a successive introduction of commercial plants. The development schedule is set out in Fig. 1.[6] Reflecting the needs shown by the above study, an engineering office was established by four Japanese nuclear industrial companies to ensure that the design work of FBRs would be made most effective by establishing "common technology."

The R&D work of FBRs is being done with PNC as the core of the project, with individual R&D tasks assigned to appropriate research organizations both in Japan and overseas.

Tasks, such as the engineering tests of large components and the postirradiation examination of fuels and materials, which are crucial to the reliable operation of FBRs but cannot be assigned to other organizations, must be undertaken by PNC itself.

TABLE IV

Major Design Specification for JOYO and MONJU

	JOYO		MONJU
	Initial	Mark-II	
Power [MW(th)]	50	100	714
[MW(e)]	-	-	300
Type	sodium-cooled loop type	sodium-cooled loop type	sodium-cooled loop type
No. of core assemblies	70	54	198
No. of blanket assemblies	188	-	172
Fuel clad o.d. (mm)	6.3	5.5	6.5
Pu content $PuO_2/(PuO_2+UO_2)$	17.7	30	15.5(in)/21(out)
Max burnup (MWd/MT)	30,000	60,000	80,000
breeding ratio	1.06	-	1.20
No. of control rod	6	6	19
sodium temperature core out/in (°C)	435/370	500/375	529/397

PNC therefore established the O-arai Engineering Center in 1970, where the JOYO reactor, sodium technology and component test facilities, including the 50-MW steam generator and the postirradiation examination facilities, are located.

As steps toward the commercialization of FBRs, areas for further study include scaled-up tests of large components, improvements in the safe and reliable operation of FBR plants, improvement of fabrication and reprocessing of mixed-oxide fuels, and related safeguards technology.

Closer cooperation among the government, the electric utilities, and industrial companies, as well as with foreign organizations engaged in FBR development, are of utmost importance in the further development of FBRs in Japan.

HIGH-TEMPERATURE REACTOR DEVELOPMENT

Currently, almost all nuclear energy generated by commercial power reactors is used for production of electricity. The ratio of electricity demand to total energy demand is about 30% in Japan. The remaining two-thirds is for process heat in industry, transportation, and residential and commercial use. It is therefore necessary to utilize nuclear energy as a substitute heat source for fossil fuels as one way to ensure adequate energy supplies and efficient usage.[7]

With a view to this, JAERI has been engaged since 1969 in R&D for an experimental VHTR System, with a primary coolant helium gas outlet temperature of some 1000°C, for use by plants requiring large amounts of nonelectric energy, such as for steelmaking, chemical industries, and others. JAERI's present target of related research and development is to build and operate an experimental VHTR by 1985.

The main purposes of the experimental VHTR will be as follows:

1. to demonstrate the feasibility of multipurpose utilization of nuclear energy as a heat source by using reducing gas for direct steelmaking
2. to develop fuels that give excellent performance in a VHTR
3. to demonstrate the safety of a VHTR and prove VHTR reliability.

To achieve these purposes, related R&D work has been undertaken by JAERI. The main areas of R&D are: reactor design study, research and development on coated-particle fuel, graphite materials, structural metals for high-temperature resistance, fluid dynamics and heat transfer, reactor physics, reactor instrumentation, and structure and strength of structural components for high temperature. A high-temperature in-pile helium gas loop OGL-1 was installed in the Japan Materials Testing Reactor for fuel and graphite irradiation tests.

A vertical view of the experimental VHTR is seen in Fig. 4, and the main parameters of an experimental VHTR plant obtained from the preliminary design are as follows:

Reactor power: 50 MW(th)
Coolant temperature reactor outlet/inlet: 1000°C/395°C
Coolant pressure: 40 $kg/cm^2 \cdot g$
Primary cooling system: 2 loops with intermediate heat exchangers
Fuel: low enriched UO_2 (average enrichment is 4 wt%) prismatic block pin-type coated-particle fuel
Number of fuel elements (columns/blocks per column): 511 (73/7)
Power density (av/max): 2.2/5.9 W/cm^3
Core dimensions (diameter/height): 2.7/4.0 m
Reactor pressure vessel: steel, 5.5-m i.d.

Following check and review work by the Advisory Committee to the Japan AEC on Development of Advanced-Type Power Reactors, the JAERI work outlined above and

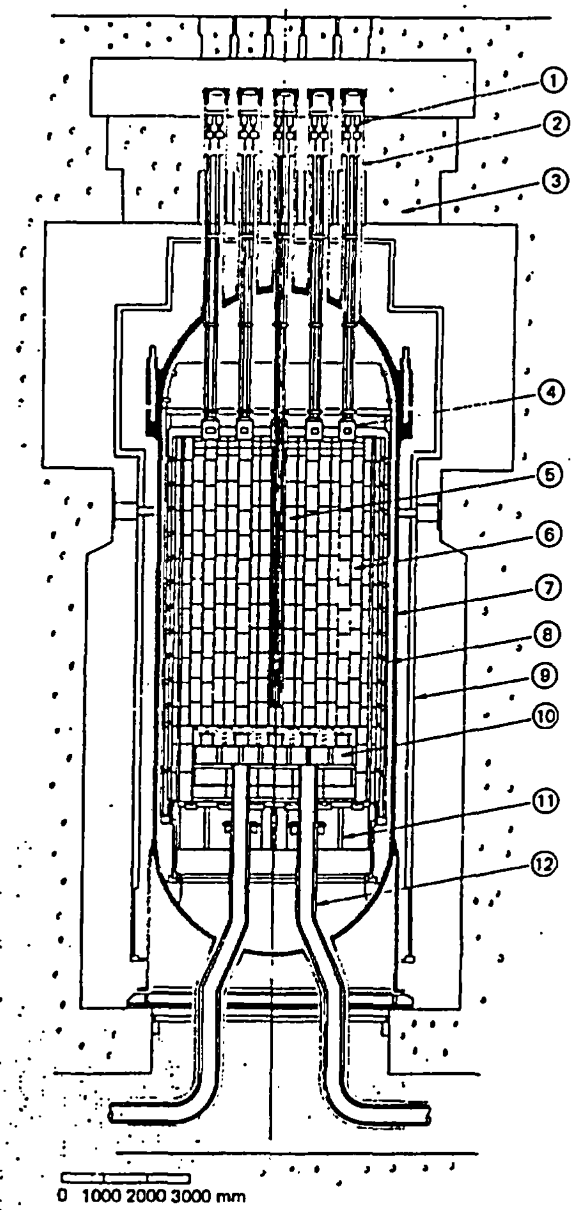

Fig. 4. Vertical view of experimental VHTR.

the necessity of using nuclear energy for process heat for Japan's future energy system were strongly confirmed on Aug. 11, 1976. The Japan AEC has approved the JAERI project, the target of which is to build an experimental VHTR to reach criticality before the end of 1985.

Aseismic tests for the reactor core have been carried out since 1976. The construction of HENDEL (helium engineering demonstration loop) with a 4 kg/s helium flow rate will begin in 1978 for helium technology development. The experimental VHTR components, such as core, core support, piping, valves, and intermediate heat exchanger, which have to operate under very severe conditions, will be tested by use of HENDEL.

Nuclear process heat application techniques are also being developed in parallel with VHTR development. In 1973, an Engineering Research Association of Nuclear Steelmaking was established as a consortium of 12 companies and an institute. The R&D on nuclear steelmaking have been going on as a national R&D program,[8] supported financially by the Agency of Industrial Science and Technology of MITI.[9] According to the program set up for nuclear steelmaking, the first six years will be spent on completion of research and development of the major components, such as high-temperature heat exchangers, refractory super-alloys, high-temperature heat insulation materials, reducing gas generating units and reduced iron manufacturing, as well as for research into systems design to link the experimental VHTR with the steelmaking system.

The VHTR will also be used in various future industrial fields, such as local gasification and hydrogen production by thermochemical water splitting.

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