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FUGEN is a 165MWe prototype of a heavy water, moderated boiling, light water-cooled reactor using mixed oxide (MOX) fuel. In parallel with the FUGEN project, design and development are being carried out on a 600MWe demonstration plant. The FUGEN type HWR is considered in Japan to contribute to Japanese energy security by using plutonium and depleted uranium extracted from LWRs' spent fuel, thereby reducing the demand for natural uranium and enriched uranium. The development of plutonium utilization is stressed. A check and review are being carried out of the Demonstration Plant programme.

LECTURE*

Development of FUGEN type HWR in Japan

S. Sawai†

FUGEN is a 165MWe prototype of a heavy water, moderated boiling, light water-cooled reactor, and the project was begun in October 1967 with the support of the government, utilities, manufacturers, institutes and so on. The Power Reactor and Nuclear Fuel Development Corporation (PNC) is responsible for completing the FUGEN project, as well as for establishing the technology of the FUGEN type HWR. Much research and development work was carried out and FUGEN came into commercial operation on 20 March 1979. FUGEN had generated a total of about 2 million MWh by 17 November 1980, when the reactor was shut down according to the schedule. During the scheduled shutdown, small cracks were found in the stainless steel pipes of the residual heat-removal system and emergency core-cooling system. It was discovered that these were caused by stress corrosion cracking in SUS 304 stainless steel pipes, and repair work is now going on.

In parallel with the FUGEN project, design and development work has been carried out on a 600MWe FUGEN type HWR demonstration plant. The check and review of the Demonstration Plant programme have been made since March 1980 by an ad hoc committee organized by the Japan Atomic Energy Commission (Japan AEC).

The present status of FUGEN and development of the 600MWe Demonstration Plant are summarized in this Paper.

Role of the FUGEN type HWR

In Japan, 21 LWRs 15GWe in total are in operation, and reactors built in the near future will be mainly LWRs. Plutonium will then be stored in the form of LWRs' spent fuel or plutonium itself extracted by reprocessing.

In the FUGEN type HWR,[1] plutonium could make the coolant void reactivity more negative, which would give good results in increasing reactor stability and safety. The FUGEN type HWR could also effectively use both plutonium and uranium, and has good fuel utilization. However, there are few natural energy resources in Japan, and the demands for natural uranium and enriched uranium have to be minimized, especially until FBRs are commercialized.

Therefore the FUGEN type HWR is considered in Japan to contribute to national energy security, coupled with LWRs, by using plutonium and depleted uranium extracted from LWRs' spent fuel, thereby reducing the demands for natural uranium and enriched uranium. At the same time, the FUGEN type HWR could adjust the plutonium stock by selecting the fuel to be used – plutonium or uranium – depending on the conditions. Such fuel utilization of FUGEN type HWR is shown in Fig. 1; the FUGEN type

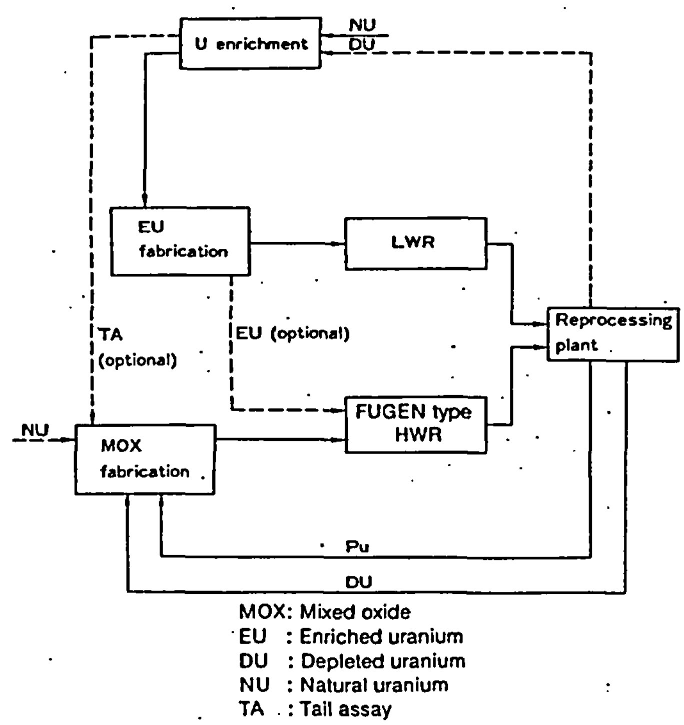


Fig. 1. Fuel utilization in FUGEN type HWR

* To be held on 8 October 1981 at the ICE, London.
† Power Reactor and Nuclear Fuel Development Corporation of Japan.

Table 1. Plutonium content in MOX fuel for DCA experiments

	Isotope content, wt%				
	Pu-238	Pu-239	Pu-240	Pu-241	Pu-242
Fuel					
5s, 0.54wt% $PuO_2 + UO_2$	0.021	90.360	8.640	0.915	0.064
8s, 0.87wt% $PuO_2 + UO_2$	0.019	90.314	8.682	0.918	0.067
8r, 0.87wt% $PuO_2 + UO_2$	0.84	64.92	21.77	9.46	3.01

HWR will aid the establishment of the technology of plutonium utilization. When commercial FBRs are available, enriched uranium will be used in the FUGEN type HWR.

If the FUGEN type HWR were introduced into the power generating system in Japan, assuming a maximum of 25% newly built reactors and introducing the FBR in the year 2010, the demands for accumulated natural uranium and enriched uranium in 2025 would be expected to be reduced by 8% and 13%, respectively, compared with the case of LWR-FBR.

As the spent fuel of FUGEN type HWR may contain less than 0.2% of U-235, uranium recycling will not be considered in FUGEN type HWR. This could lessen the problem caused by the accumulation of U-236, which may be encountered in uranium recycling.

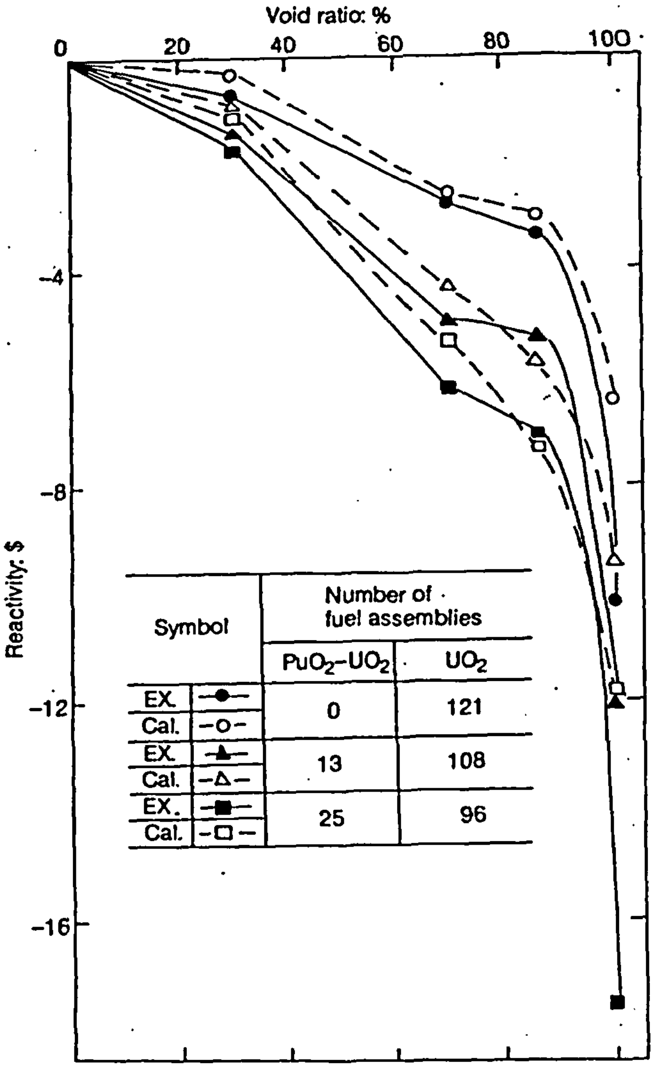


Fig. 2. Effect of plutonium on coolant void reactivity

Development of plutonium utilization

Reactor physics characteristics of plutonium fuelled core

The development of clarification of the effects of plutonium (including plutonium isotope composition) on reactor physics characteristics, especially coolant void reactivity, power distribution in a fuel assembly, etc., has been stressed using the Deuterium Critical Assembly (DCA), Oarai Engineering Centre, PNC.

Three kinds of MOX fuel assemblies, changing plutonium enrichment and plutonium isotope composition were prepared for DCA experiments, as shown in Table 1.

Material bucklings of MOX fuels were determined by replacing progressively uranium oxide fuel assemblies to MOX fuel ones.[2] Coolant void reactivity has been measured and analysed under the following conditions

(a) in the clean lattice
(b) in the lattice with heavy water containing boron
(c) in the lattice with control rods inserted.

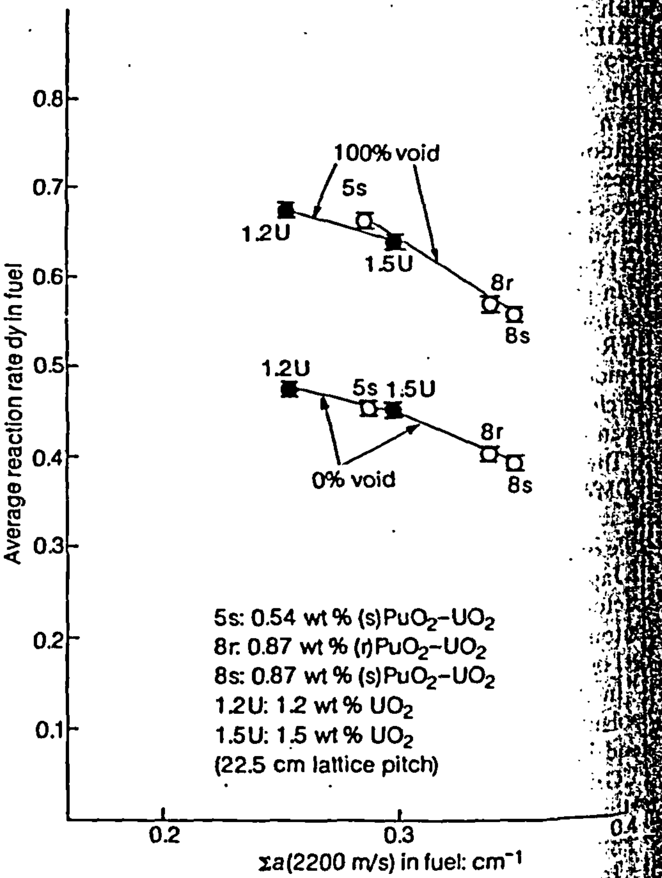


Fig. 3. Relationship between average reaction rate in fuel and Σa

Table 2. Reactor physics data on criticality of FUGEN

	Minimum criticality core		100 fuels core		Full core	
	Measured	Calculated	Measured	Calculated	Measured	Calculated
Fuel						
MOX fuels	22	21	96	96	96	96
Special fuels	0	0	4	4	4	4
U oxide fuels	0	0	0	0	124	124
Content of ^{10}B, ppm	<0.005	0	10.3	11.32	12.9	13.89
Temp. of D_2O, °C	11.9	11.9	14.2	14.2	16.0	16
Temp. of H_2O, °C	16.0	16.0	16.0	16.0	24.0	24.0
Position of central control rod, %	56.3	100	67.0	100	67.5	100

Figure 2 shows the effect of plutonium on coolant void reactivity in the clean lattice.

Figure 3 shows the relationship between average reaction rate in fuel and its macroscopic cross-section (2200m/s). The data of MOX fuels 5s, 8s and 8r (Table 1) are on a line, which would mean that Pu-239 and Pu-241 have almost the same characteristics of thermal neutron reaction rate against their resonances and Pu-240 may have little effect on reaction rate within low enriched plutonium fuels. More details are reported in other papers.[3,4] Experiments are now going on to clarify the effect of a stainless steel control rod on the power distribution of the adjacent assembly, for load following operation in the FUGEN type HWR.

Reactor characteristics of FUGEN were measured and analysed by the computer codes which have been developed based on DCA experiments and their analyses (Table 2). Plant dynamics and refuelling programmes have been settled by such analyses backed up with the real data obtained in FUGEN itself. Typical plant dynamics compared with their analyses are shown in Fig. 4. A good prediction could be expected in the analyses of the reactor performances of FUGEN.

Development of MOX fuel

MOX fuel fabrication. Mixed oxide fuel fabrication was begun in 1965, and fuel assemblies were irradiated in JRR-2, GETR, Halden, Saxton and SGHWR, as seen in Table 3. Besides these, MOX fuel assemblies were manufactured for critical assembly experiments, as follows:

800 elements: for TCA (LWR critical assembly)
252 elements (9 assemblies): for two-region critical assembly
2600 elements (92 assemblies): for DCA.

Based on the fabrication experiences and development, the ATR Line (10t/year) was set up in the Plutonium Fuel Fabrication Facility (PFFF), PNC, and 168 MOX fuel assemblies had been fabricated for FUGEN by May 1981.

Development has been carried out on MOX fuel fabrication with emphasis on the remote handling and automation of machines and apparatus installed in glove boxes, such as pellet fabrication (Fig. 5) and inspection apparatus, out-gas and welding chamber. Figure 6 shows an MOX fuel assembling machine for FUGEN having the function of automatic recording of pin gap measurements.

Table 3. Irradiation tests of MOX fuel

	No. of rods	Composition	Rod o.d., mm	Clad thickness, mm	Active length, mm	Maximum LHR, kW/ft	Burn-up, MWD/TM Average	Burn-up, MWD/TM Maximum	Irradiation period
Capsule									
GETR	2	2.0% PuO_2–NUO_2	13.6	0.5	92	14.9	1180	1260	Feb. 68–Mar. 68
GETR	2	2.0% PuO_2–NUO_2	13.6	0.5	95	10.5	910	980	Feb. 68–Mar. 68
GETR	1	2.5% PuO_2–NUO_2	11.7	0.75	70	15.5	5250	5350	Sep. 68–Dec. 68
GETR	3	3.1% PuO_2–NUO_2	12.23	0.7	100	16.8	2600	3540	Nov. 68–Mar. 69
JRR–2	3	6.0% PuO_2–NUO_2	10.72	0.625	90	9.1	4000	4800	Oct. 78–Mar. 79
JRR–2	1	1.1% PuO_2–NUO_2	10.72	0.625	240	13.7	4300	4800	Nov. 78–Apr. 79
Elements									
HBWR	9	2.5% PuO_2–NUO_2	11.7	0.75	1400	10.6	9660	12500	Jun. 68–Mar. 70
HBWR	9	3.1% PuO_2–NUO_2	12.23	0.7	1400	9.9	4730	6070	Mar. 69–Mar. 70
Saxton–GETR	2	1.5% PuO_2–NUO_2	9.93	0.59	992	14.4	25370	38050	Nov. 71–Nov. 75
HBWR	7	1.2% PuO_2–7%EUO_2	16.46	0.86	1400	15.1	5000	6670	Jun. 75–Oct. 76
HBWR	6	5.8% PuO_2–NUO_2	12.52	0.86	1380	13.1	6830*	8196	Jul. 79–Mar. 82
HBWR	12	8.1% PuO_2–NUO_2	12.52	0.86	550	14.0	2100*	2520	Jun. 80–Mar. 83
Assembly									
Saxton	4	4% PuO_2–NUO_2	9.93	0.59	992	15.6	5340	8750	Nov. 71–May 72
Saxton	68	5% PuO_2–NUO_2	9.93	0.59	992	11.6	2830	6680	Nov. 71–May 72
SGHWR	28	2.1% PuO_2–NUO_2	16.46	0.88	3510	14.9	6420	9860	Oct. 75–Apr. 77

* Up to Feb. 1981.

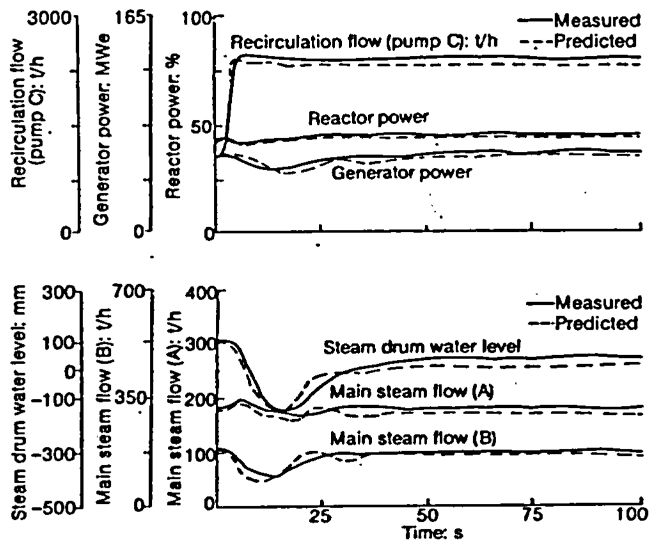


Fig. 4. Typical plant dynamics compared with analyses

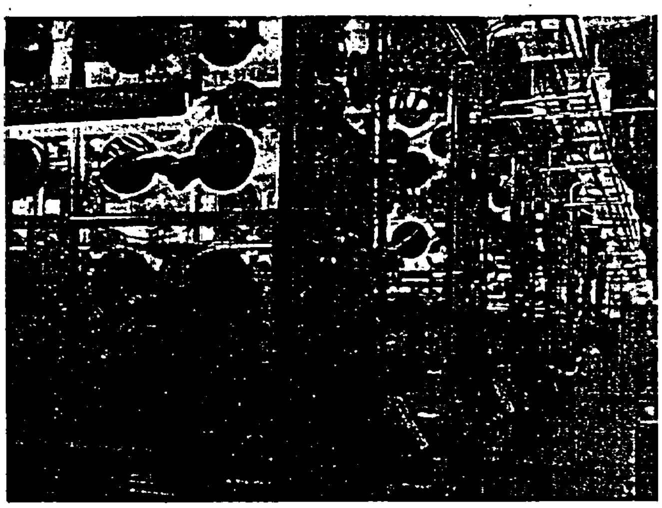


Fig. 5. MOX pellet fabrication glove boxes

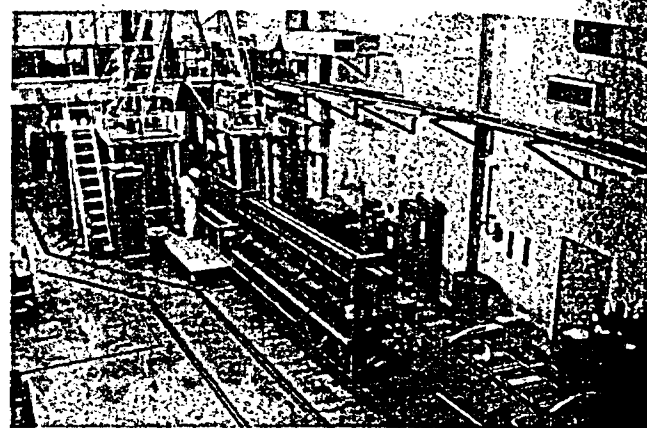
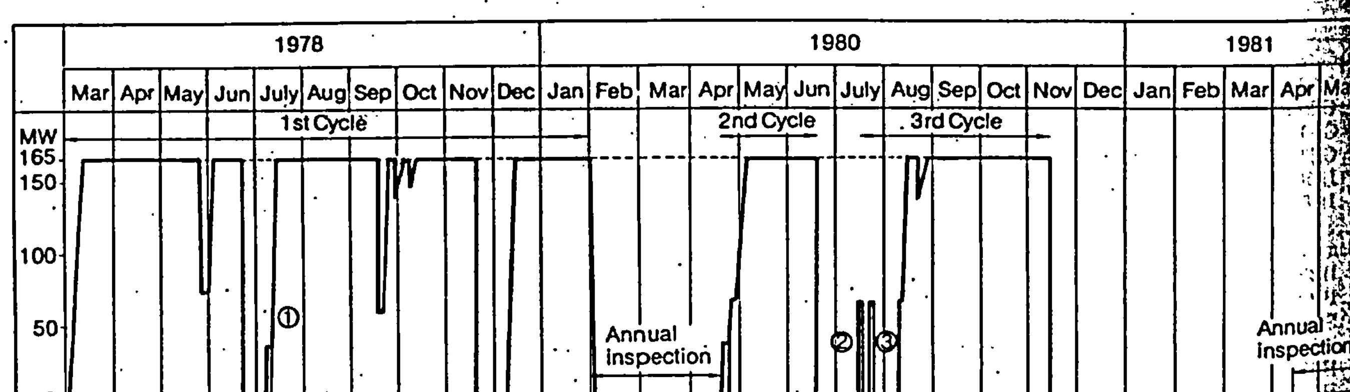


Fig. 6. MOX fuel assembling machine

Efforts also have been made in establishing inspection technology, as well as quality control. In order to measure easily plutonium spots in an MOX fuel pellet, alpha autoradiography was developed, using scintillation of ZnS(Ag) by alpha radiation. This alpha autoradiography could clearly photograph plutonium spots, over 20μm, without darkening the room.

Irradiation of MOX fuel. Irradiation tests of MOX fuel, including those in SGHWRs, are listed in Table 3. The maximum peak fuel burn-up reached was 38 050MWD/t and no fuel was ruptured in any test. As seen in Fig. 7, a total of 124 MOX fuel assemblies has been loaded in FUGEN, and no fuel assemblies have been ruptured.

Evaluation of irradiated MOX fuels has been made mainly by comparing the irradiation results with their analyses calculated by design codes and also with the performance of uranium oxide fuels. Figure 8 shows evaluation results of a 28 rod cluster MOX fuel assembly for FUGEN tested in the SGHWR.[5] Good agreement was obtained between the test results and their analyses. Considering the irradiation tests of both MOX and uranium oxide fuels, there may be little difference in dimension between them. This evalu-



① Scram, due to low water level in steam drum
② Scram, due to turbine trip
③ Scram, due to turbine trip

Cycle	1st loaded	2nd loaded	2nd withdrawn	3rd loaded	3rd withdrawn
MOX fuel	96	16	20	12	24
UO_2 fuel	128	20	16	24	12
Special fuel	4	0	0	0	0

Fig. 7. FUGEN operational history

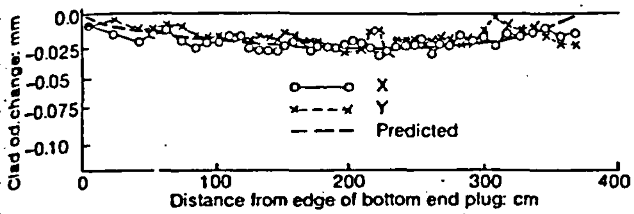


Fig. 8. Comparison of predicted and measured outer diameter changes for inner ring pin

tion is backed up by pin gap measurements of spent fuel assemblies withdrawn from FUGEN.

FUGEN

FUGEN (Fig. 9)[1,6,7] is designed to generate 165MWe and is to be refuelled with as many MOX fuel assemblies as possible, considering the role of FUGEN type HWR in Japan. FUGEN reached criticality on 20 March 1978 and power up tests were then followed. A year after criticality, FUGEN came into commercial operation and the operational history is shown in Fig. 7. A plant factor of 72.4% was achieved in the fiscal year 1979 and 40.2% in the fiscal year 1980. Scrams have occurred three times, as shown in Fig. 7; however, they were not serious.

In the initial core, 96 MOX fuel assemblies were loaded in the centre region of the core and 124 uranium oxide fuel assemblies around them. Besides these fuel assemblies, four special fuel assemblies, which contain specimens of a pressure tube assembly for irradiation tests, were also loaded. Concerning MOX fuel assemblies, 124 assemblies have been loaded in FUGEN since start-up, details of which are given in Fig. 7. The maximum burn-up reached 9700MWD/t and no MOX fuel assemblies have ruptured yet. More enriched MOX fuel assemblies, whose total fissile contents are each 2.0% ($Pu_{fissile}$ + U-235), will soon be used in FUGEN and an average burn-up of 17 000MWD/t is expected.

The annual inspection was carried out from February to April 1980. In-service inspections of the primary cooling system, dismantling and inspecting components, such as the control rod drive mechanism, were made. In the inspection, the total radiation dose was 230man rem.

First, oil snubbers were installed in FUGEN to support pipes and components in case of an earthquake. However, oil may be affected by radiation, which would mean some

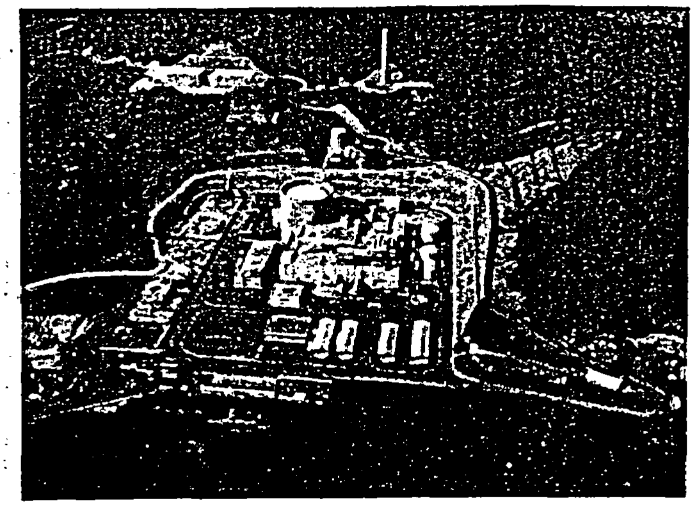


Fig. 9. FUGEN power generating station

Table 4 Design data of FUGEN and Demonstration Plant

	FUGEN	Demonstration Plant
Electric power, MWe	165	600
Thermal power, MWe	557	1930
Reactor		
Core dia., mm	4053	6951
Core height, mm	3700	3700
No. of channels	224	648
Calandria dia., mm	7950	9750
Pressure tube		
Material	Zr–Nb	Zr–Nb
Inside dia., mm	117.8	117.8
Fuel		
No. of rods/ass	28	36
Pellet dia., mm	14.4	12.4
Enrichment (Pu_f + U-235)	2.0	2.7
Burn-up (average), MWD/t	17000	27000
Clad thickness, mm	0.88	0.90
Clad material	Zry-2	Zry-2
Max. linear heat rating, W/cm	574	492
Control rods		
B_4C	49	76
Stainless steel	0	17
Primary cooling system		
No. of loops	2	2
Recirculation flow, t/h	7600	22600
Steam flow, t/h	910	3300
Steam drum pressure, kg/cm² per g	68	69

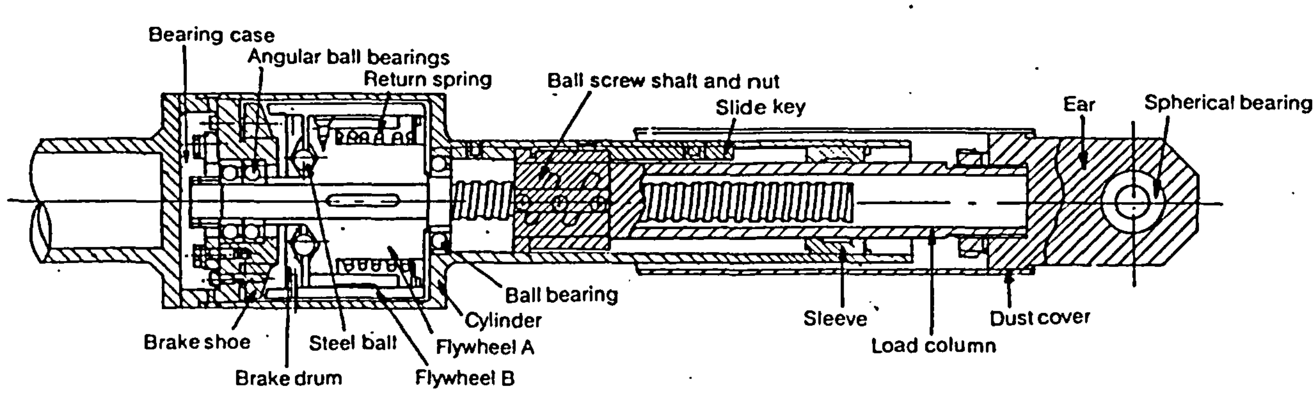


Fig. 10. Mechanical snubber

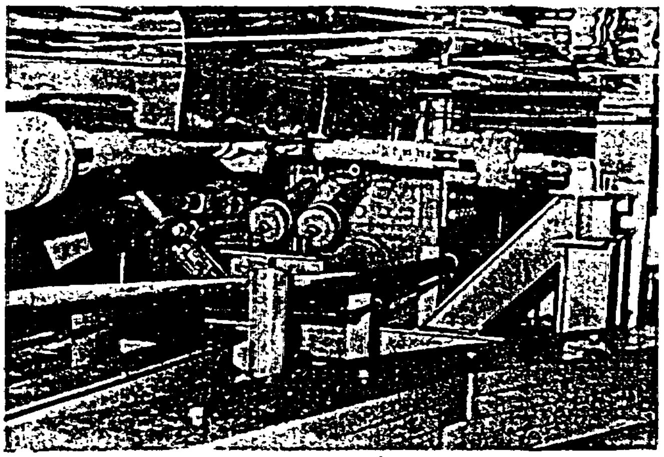


Fig. 11. Mechanical snubber installed and connected to reactor inlet piping of FUGEN

maintenance work would have to be carried out under rather high radiation conditions. A mechanical snubber (Figs 10 and 11) was developed by PNC with the support of Sanwa Tekki Corporation. Mechanical snubbers can follow thermal expansion with little resistance; however, when an earthquake occurs, it can restrain the pipe movement by the force generated by the inertia of the rotating mass. In FUGEN, oil snubbers were replaced by mechanical snubbers which require little maintenance work and reduce radiation exposure for workers.

Some stress corrosion cracking was found in the stainless steel pipes of the residual heat-removal system and emergency core-cooling system during the scheduled shutdown in November 1980. Repair work is now going on to replace SUS 304 stainless steel pipes by SUS 316L stainless steel pipes.

600MWe Demonstration Plant[7,8]

The 600MWe FUGEN type Demonstration Plant (Fig. 12) is designed mainly to use MOX fuel, and its design data are listed in Table 4 with those of FUGEN. The design and the principle of FUGEN are to be followed for the Demonstration Plant, especially for important systems and components such as the emergency core-cooling system, pressure tube assembly and control rod drive mechanism. Some improvements and modifications, however, are made due to scaling up, economy and experiences obtained in FUGEN and LWRs.

Improvements for scaling up and economy

Higher burn-up. The plutonium content of MOX fuel assemblies is arranged in order to give almost the same fuel burn-up as LWRs, and the total fissile content of MOX fuel

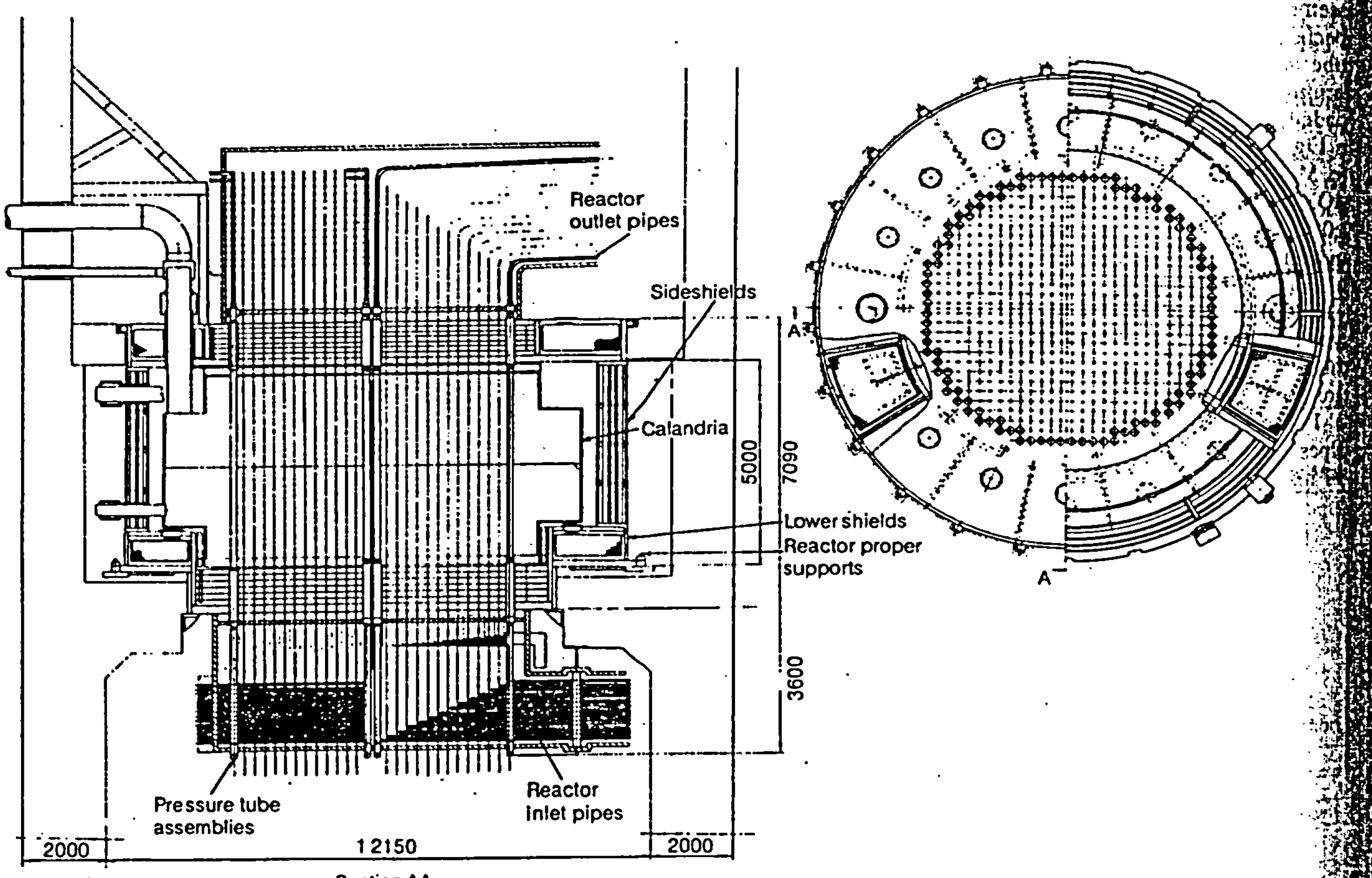


Fig. 12. 600MWe Demonstration Plant

would be 2.7% in an equilibrium cycle, giving 27 000MWD/t of burn-up.

Increase in average channel power. In order to reduce the number of pressure tube assemblies, average channel power is raised to 120% of FUGEN's, by adopting a 36 rod cluster fuel assembly with reduced fuel diameter. The maximum design linear heat rating is set to 492W/cm, considering the full scale MOX fuel irradiation test in SGHWRs (for FUGEN).

Elimination of dump space. With FUGEN, a dump space is set around the core tank, which makes a calandria large. In the Demonstration Plant, therefore, the dump space is eliminated and a rapid poison injection system is to be installed, thereby reducing the diameter of the calandria.

Modifications based on experiences with FUGEN and LWRs

Design for stress corrosion cracking. SUS 316L or SUS 304L are to be used in pipes of the primary cooling system and emergency core-cooling system. Special attention and consideration will be given to piping design in order to prevent water stagnating in pipes as much as possible and to reduce welded parts in piping.

Design for crud. Powdered resin will be used in the purification system for the primary coolant to reduce the amount of crud in the primary cooling system. Stainless steel pipes with low cobalt will be used in the primary cooling system.

Design for load following operation. The reactor is controlled by control rods and boron concentration in heavy water. With the latter, daily load following and burn-up will be done or compensated for. Seventeen stainless steel control rods, which mitigate the power change of fuel, are installed to meet load following operations such as automatic frequency control, and governor free operation, with 76 B_4C control rods for safety.

Acknowledgement

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