OPERATING EXPERIENCE OF FUGEN-HWR IN JAPAN

BY

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INTRODUCTION

Fugen is a 165 MWe prototype heavy water reactor which mainly uses plutonium-uranium mixed oxide (MOX) fuel. Power Reactor and Nuclear Fuel Development Corporation (PNC) has taken responsibility for the advanced thermal reactor (ATR) project, with its name "FUGEN" taken from the Buddhist God of Mercy. The project started in October 1967,to develop and establish the technology for this new type of reactor and to clarify MOX fuel performance in the reactor. Site construction began in december1970 at Tsuruga and the plant commenced commercial operation on March 20, 1979. Since then, Fugen has been operated successfully for more than twelve years.

The plant performance and reliability of this type of reactor has been demonstrated through the operation. All these operational experiences have contributed to the establishment of the ATR technology (ref. 1).

ROLE OF ATR IN JAPAN

ATR is a unique reactor with outstanding flexibility regarding nuclear fuel utilization, because it has superior properties concerning the utilization of plutonium, recovered uranium and depleted uranium. Furthermore MOX fuel can be loaded in full core.

Therefore the role of ATR is considered to contribute to the national energy security of Japan by reducing the demand for natural and enriched uranium. At the same time, ATR can adjust the plutonium stock by selecting fuels, plutonium or uranium, depending on the conditions as availability of nuclear fuel material and introduction of fast breeder reactors (ref. 2). Such fuel utilization is shown in Figure 1.

DESCRIPTION OF THE PLANT

Fugen is a direct cycle, heavy water moderated, boiling light water cooled, pressure tube type reactor. The main parameters are listed in Table 1 and the schematic flow diagram is shown in Figure 2. The reactor has two independent coolant circuits, each consisting of a steam drum, two recirculation pumps, an inlet header and associated pipes. Each of 224 cluster type fuel assemblies is loaded in a vertical Zr-2.5%Nb alloy pressure tube. Figure 3 shows the configuration of the reactor and the reactor coolant system.

Four kinds of standard fuel are used in the core ; MOX fuel type A and type B of different fissile material content, UO_2 fuel type A and type B of different enrichment. Besides these standard fuels, four special fuel assemblies (UO_2) are also used, which contain specimens of the pressure tube material for irradiation tests. These fuel assemblies are shown in Figure 4. Since Fugen is also used as an irradiation bed for the development of ATR fuel assembly, nine experimental fuel assemblies, the same with the ATR demonstration plant called demonstration fuel assembly, are now loaded in the core.

The fuel handling systems, of which the major component is a computer-controlled refuelling machine situated at the bottom of the reactor, is designed so that either on- or off-loaded refuelling can be performed. Figure 5 shows fuel handling and storage facilities. At present, however, only off-load refuelling scheme is adopted in order to avoid the problem of pellet-clad interaction which would occur during the on-power loading of fuel.

Plant control system are shown in Figure 6. During routine operation, the reactor thermal power is controlled to maintain the rated electric power. The electro-hydraulic control system governs the turbine control valves to maintain constant steam pressure and turbine speed. The water level in the steam drum of each loop is controlled by three-element signals of the main steam flow, the feed water flow and the steam drum water level.

Core reactivity is controlled by 49 motor-driven control rods and by adjustment of liquid poison (^{10}B) concentration in the moderator. Four of the control rods are automatic regulating rods, each of which is installed in the central position of each quadrant of the core. The liquid poison concentration is increased by injecting ^{10}B into the dump tank of heavy water circuit, and reduced by passing the heavy water through strong basic ion exchange beds.

The clean-up of the moderator during the operation is achieved by treating the heavy water with the mixed resin beds consisting of strong and weak basic ion exchange resin to remove impurities except boron dissolved in the moderator.

OVERALL PERFORMANCE

As shown in Figure 7, Fugen commenced commercial operation on March 20, 1979 and has continued stable full power operation for more than twelve years, except during scheduled shutdowns for maintenance, inspection and refuelling. The overall electrical load factor for the past twelve years (March 1979 - March 1991) is more than 63%, and the cumulative electric power output is 11.0 million MWh at the end of March 1991.

The causes of the unscheduled shutdown in the past twelve years have not been peculiar to the Heavy Water Reactor, and the repair works have been smoothly carried out.

Fugen is the first thermal reactor to use MOX fuel. A total of 479 MOX, 424 UO_2 and 11 demonstration fuel assemblies was loaded into the core through initial loading and sixteen refuellings. The maximum burnup of discharged fuel reaches 24.4 GWd/t for MOX fuel and 19.8 GWd/t for UO_2 fuel assembly. No fuel has failed for more than 2,860 effective full power days of operating up to the end of March 1991.

CORE MANAGEMENT

A scatter loading scheme of symmetrical quadrant is adopted in every cycle to make core management and power control simple. The refuelling scheme and the control rod pattern are decided so as to achieve the power generating plan, to satisfy the fuel design and plant safety criteria and to maximize the average burnup of discharged fuels. The power flattening is achieved by means of control rods and fuel shuffling. Fuel shuffling has been actively adopted from the 8th cycle and the power flattening has been successfully achieved. The fuel loading history is listed in Table 2. Figure 8 shows cumulative MOX fuel utilization in Fugen. While in the initial core, 96 MOX fuel assemblies were loaded, in the 16th cycle core, the number of MOX fuel assemblies is 161, 72% of total fuel assemblies in the core. Since the 4th cycle, type B fuels, which have higher fissile content, have been used, instead of type A fuels initially used in order to reduce the fuel cycle cost by obtaining higher burnup.

While the withdrawal of control rods raises the power from cold condition up to 40% of rated thermal power, the control of ^{10}B concentration in the moderator is mainly used from 40% to 100% power. A slow power raising procedure is adopted above certain power level to reduce the pellet-clad interaction (PCI).

During power operation, short-term reactivity changes are controlled by control rods, mainly by the automatic regulating rods. The moving range of the regulating rod is restricted to ±5% of the full stroke to maintain within the power distribution envelop in each cycle. The long-term reactivity loss caused by fuel burnup is compensated by removal of ^{10}B from the moderator.

CORE CHARACTERISTICS

By adopting the scatter loading scheme and fuel shuffling, it is almost unnecessary to insert the control rods in order to suppress the radial power peaking

While boiling water cooled HWRs tend to have a large positive void reactivity, the reactivity can be reduced to nearly zero by using MOX fuels. The coolant void coefficient of Fugen is very small. This has been demonstrated at the time of stepwise speed change of recirculation pumps that causes the rapid void fraction change in the core.

FUEL INSPECTION

Every spent fuel assembly is inspected visually and dimensionally using an inspection instrument installed in the spent fuel storage pool. As the result of inspection, no abnormal appearances in fuel rods have been found except crud adhesion.

Post irradiation examinations (PIE) for the MOX fuels burned to 18,200 MWd/t have been carried out to get detail experimental data. Most of the crud is easily removed prior to PIE by ultrasonic washing. Non-destructive tests such as visual and dimensional inspection, gamma-scanning, and destructive tests such as puncture and metallographic test are carried out (ref. 3).

MAINTENANCE AND INSPECTION

Annual inspection and maintenance in Fugen are carried out to confirm the safety and integrity of the systems and to satisfy the regulations, safety guides, JEAC (Japan Electric Association Codes) and the technical specification of Fugen. The contents of the inspections and maintenance are as follows;

- Function test and overhaul of the components
- Tests of the instrumentation and control system
- Visual inspection and sipping test of the fuel assemblies
- In-service inspection of the major components

The time schedule of the 1st and 4th annual inspection are shown in Figure 9 and Figure 10, respectively.

All failure and maintenance data of Fugen plant are documented and recorded in the computerized maintenance management system (MMS) through on-line terminals. The MMS supplies statistical performance data of every equipment and supports maintenance personnel to review maintenance period or procedure and to make a plan of a modification work.

PLANT EXPERIENCE

Neutron detector

The local power monitors (LPM) system consists of 64 miniature fission chamber detectors located in the moderator through the core. Each of 16 LPM strings contains four detectors spaced vertically at equal intervals to provide uniform coverage in the axial direction of the core. In Fugen, a long-life regenerative neutron detector has been developed, which is composed of a combination of ^{235}U and ^{234}U. Two assemblies containing the new type detectors have been loaded in the core since the first cycle to test those irradiation characteristics. The total neutron irradiation dose reached 1.3 $\times 10^{22}$ nvt. No abnormal characteristics have been found. The test results confirm that the new type detector has four times longer life compared with the ordinary one.

In-service inspection of pressure tubes

The reactor has 224 pressure tubes made of heat-treated Zr-2.5%Nb alloy. A remote-controlled in-service inspection (ISI) equipment has been developed. The equipment is capable of performing three kinds of inspection; ultrasonic flaw detection, measurement of inner diameter and visual inspection of the internal surface. ISI of pressure tubes was carried out in the forth annual inspection in 1984 and eighth annual inspection in 1989 using this pressure tube monitoring equipment (ref. 4).

Stress corrosion cracking

Cracks were found in the type 304 stainless steel piping of the residual heat removal system, high pressure core injection system and low pressure core injection system during the scheduled shutdown in November 1980. The metallographic and fractographic investigation showed that the crack resulted from inter-granular stress corrosion cracking (SCC) in high temperature pure water, the same as experienced in BWRs. Based on the experience and R&D on the SCC performed in BWRs in Japan, all the defect pipes were replaced with 316 (low carbon) stainless steel pipes. In addition, pipes which had the possibility of the SCC have been also replaced with the new pipes or applied with the method of induction heating stress improvement (IHSI) in each annual inspection and maintenance. To supplement these countermeasures, hydrogen gas has been injected into primary coolant to reduce the content of the dissolved oxygen since December 1985.

Chemical decontamination

Chemical decontamination method is considerably beneficial for reduction of occupational radiation dose. In August 1989 and January 1991, the chemical decontamination for each primary cooling circuit was performed successfully in Fugen as the first experience in the operating nuclear power station in Japan. The R&D for decontamination started in 1977 and had confirmed material integrity during and after decontamination and characterized the decontamination reagent. By the chemical decontamination in Fugen, the decontamination factor was obtained 3.4 and 5.1, respectively.

WATER CHEMISTRY

The primary coolant in Fugen is kept neutral with no chemical additives as in BWRs'. Specification of the primary coolant is shown in Table 3, and the measured values indicate good chemistry. One of objectives of the primary coolant chemistry control is to suppress iron transport to the core as low as possible, since the reduction of iron input is effective to reduce surface dose of the primary circuits. From this point of view, oxygen injection into the feed water has been carried out (ref. 5).

Heavy water of Fugen contains no chemical additives except boron. Purification of heavy water is carried out using resin beds in order to prevent corrosion of the system and to minimize accumulation of deuterium in the helium gas used as blanket gas of the moderator. The typical chemistry parameters are listed in Table 4.

In early days of the start-up test in 1978, unexpected deterioration was found in weak basic ion exchange resin beds used in the heavy water purification system. This was caused by deuterium peroxide, and resulted increase of the conductivity and the radiation dose in the heavy water system. Countermeasures to improve the quality of the heavy water, such as nitrogen gas reduction from helium covering gas, cooling of the resin beds and improvement of the resin have been carried out. By this, the conductivity reduced by half and increase of radiation dose stopped. Decomposition of deuterium peroxide with a catalyzer and employment of a strong basic resin are being studied for optional countermeasures.

HEALTH PHYSICS

Typical example of radiation dose level change in the reactor building is shown in Figure 11. The occupational dose rate is mainly dominated by the annual inspection and maintenance works. Average annual occupational dose rate from 1978 to 1990 is 6.1 man-Sv/y. Forty percent of that was resulted from works for countermeasures of stress corrosion cracking. It should be mentioned that total tritium intake since 1978 is negligible in the total man-Sv. The computerized occupational dose rate monitoring system using thermo-luminescence dosimeter badge is working to make the radiation protection management more effective.

Average annual release of noble gases, liquid waste excluding tritium, gaseous tritium and liquid tritium to environs are 7×10^{10} Bq, 7×10^{7} Bq, 1.2×10^{12} Bq and 6.5×10^{12} Bq, respectively. These values are well below the control targets in spite of build up of radioactivity.

R&D FOR THE DEVELOPMENT OF ATR

Several R&D items for the development of ATR are now underway on Fugen site. These works prepare useful data for design and commissioning works of the ATR demonstration plant.

Fuel assembly

Three MOX fuel assemblies of new type, which are the same type of the ATR demonstration plant consisting of 36 fuel rods, have been loaded since 9th cycle. One of these are to be irradiated for about 4 years and others for about 6 years to reach the design discharge burnup of the ATR demonstration plant. After irradiation, two of these are inspected through the post irradiation examination. In addition, two 36 rods MOX fuel assemblies which are so called "segmented fuel" and use Zr-lined cladding and/or hollow pellet have been irradiated since March 1987 for the development of the high performance fuel. Six Gd topped MOX fuel assemblies in order to confirm the burnup characteristics of Gd in the MOX fuel have been irradiated since June 1990 and will be confirmed the integrity of fuel assemblies after the high irradiation, nearly 40,000 MWd/t.

Pressure tube material

The pressure tube material (H.T. Zr-2.5%Nb) to be used in the ATR demonstration plant, is now under irradiation in the special fuel assembly in order to confirm the integrity under high fluence exposure.

Instrumentation

On-line ^{10}B concentration measurement equipment and the failed fuel detector are equipped on Fugen system and to be confirmed the equipment performance.

CONCLUSION

Fugen is the first to use mainly plutonium mixed oxide fuel in thermal neutron power reactors in Japan. A total of 479 MOX, 424 UO_2 and 11 demonstration fuel assembles have been loaded the core through initial loading and 15 refuelling times. The maximum burnup of discharged fuel has reached 24.4 GWd/t for MOX fuel and no fuel has failed.

In this type of reactor, the use of plutonium makes the coolant void coefficient nearly zero, thereby providing good reactor stability. Exchange of control rod pattern is seldom necessary due to the flat power distribution.

Plant experience has demonstrated the reliability of the main components and systems. Some problems experienced during the plant operation are not peculiar to the atr, and the repair works have been smoothly carried out.

The operational experiences are expected to contribute effectively to the design works, construction and operation of the 606 MWe ATR demonstration plant to be constructed at Ohma-cho, Aomori prefecture.

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Reactor type	Heavy water moderated, boiling light water cooled, pressure tube type	
Output	Gross thermal output	557 MWt
	Gross electrical output	165 MWe
Core	Core height	3,700mm
	Core diameter	4,050mm
	Lattice	240mm Square lattice
	Number of fuel channels	224
	Fuel inventory	34 t as metal
Fuel	Fuel material	MOX type A (% Pu fiss.) 0.8/0.8/0.6 MOX type B (% Pu fiss.) 1.6/1.6/1.1 UO_2 type A (% ^{235}U) 1.5/1.5/1.5 UO_2 type B (% ^{235}U) 1.9/1.9/1.9
	Pellet diameter	14.4mm
	Fuel assembly	28 fuel rods, 12 spacers
	Total length of fuel assembly	4,388mm
	Cladding material	Zircaloy - 2
	Cladding thickness (min.)	0.8mm
Pressure tube	Material	Zr - 2.5Wt% Nb alloy
	Inner Inside diameter	117.8mm
	Thickness	4.3mm
	Length	5m
Steam drum	Diameter	2m
	Length	16m
	Material	Low carbon steel clad with stainless steel
Calandria tube	Material	Zircaloy - 2
	Inner Inside diameter	156.4mm
	Thickness	1.9mm
Moderator	Heavy water inventory	160 t
	Heavy water temperature(max.)	70°C
Control rods	Number of control rods	49
	Material	B_4C in stainless steel
	Mechanism	Motor driven wire drum
Primary coolant system	Coolant	H_2O
	Coolant pressure in steam drum	68kg/cm^2
	Coolant temperature in steam drum	284°C
	Coolant flow rate	7,600 t/h
	Steam exit quality (mean)	14%
	Number of cooling loops	2
Primary containment	Configuration	Cylindrical steel
	Diameter	36m
	Height	64m
Turbine System	Steam pressure	63.5kg/cm^2
	Steam temperature	279°C
	Steam flow rate to turbine	910 t/h
	Rotational speed	3,600rev/min.
	Generator rating	200MVA

Table 2 Fuel Loading from 1st to 16th Cycle

	Number of Fuel Assemblies Loaded in Core															
Fuel Cycle Fuel Type	1st	2nd	3rd	4th	5th	6th	7th	8th	9th	10th	11th	12th	13th	14th	15th	16th
MOX	96	92	80	76	88	92	108	128	129	117	113	121	133	137	155	151
UO_2	124	128	140	144	132	128	112	92	88	100	102	94	82	78	60	59
Special Fuel	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4
Demo.Fuel(Ⅰ)	0	0	0	0	0	0	0	0	3	3	3	3	3	3	3	2
Demo.Fuel(Ⅱ)	0	0	0	0	0	0	0	0	0	0	2	2	2	2	2	2
Demo.Fuel(Ⅲ)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	6
Average burnup of discharged fuels (MWd/t)	6,440	7,710	9,220	9,560	9,080	9,870	12,300	15,570	16,210	16,070	15,870	16,640	16,780	17,210	17,700	——

Table 3 Chemistry parameters of primary coolant

	Unit	Specification
PH	—	5.5 - 8.5
Conductivity	μS/cm	<1.0
Cl^-	ppm	<0.2
SiO_2	ppm	<2.0
BO_3	ppm	<2.0
Dissolved oxygen	ppm	<0.4

Table 4 Chemistry parameters of heavy water

	Unit	Specification
PH	—	4.5 - 8.5
Conductivity	μS/cm	<5.0
Cl^-	ppm	<1.0
SiO_2	ppm	<1.0
Suspended solid	ppm	<0.5

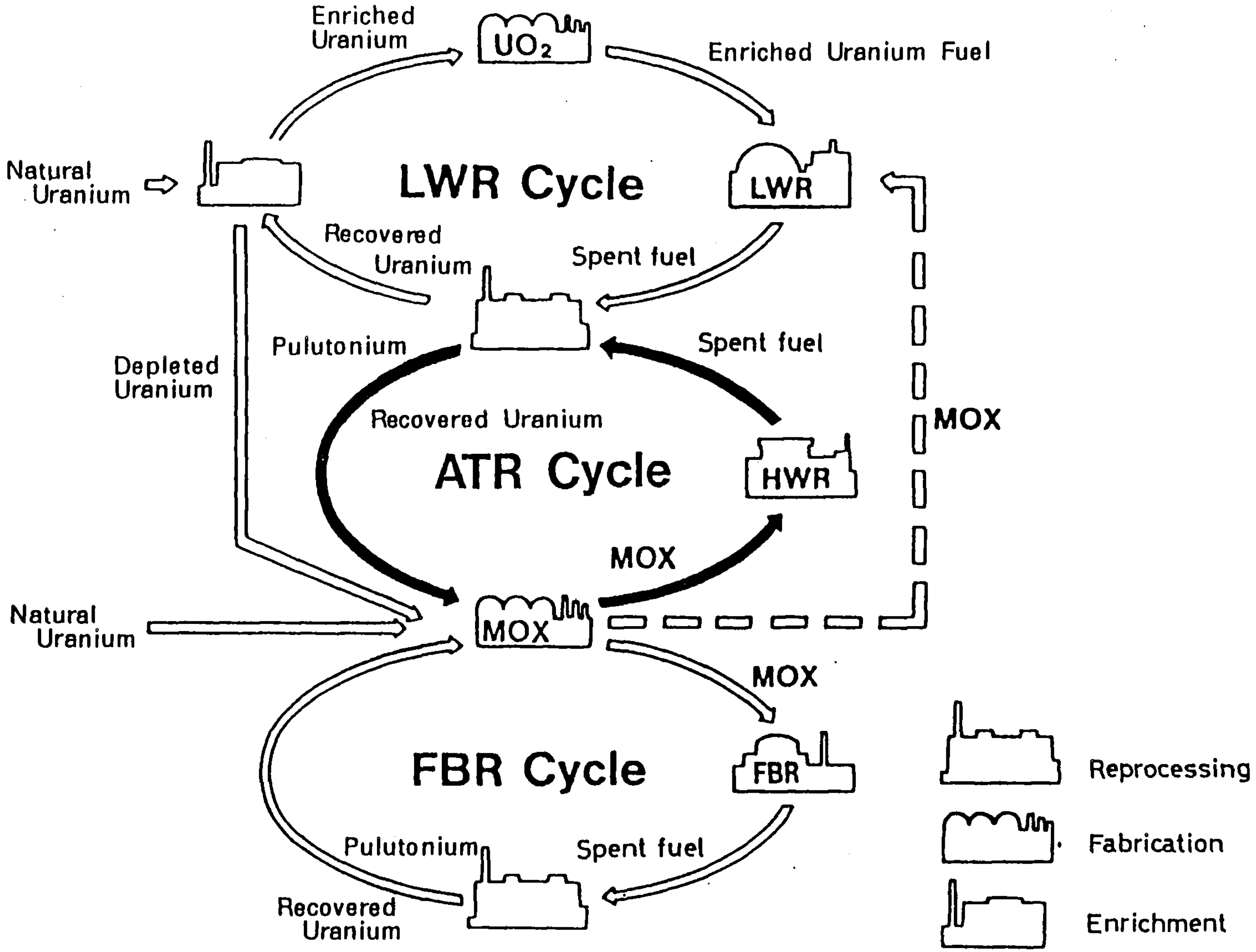
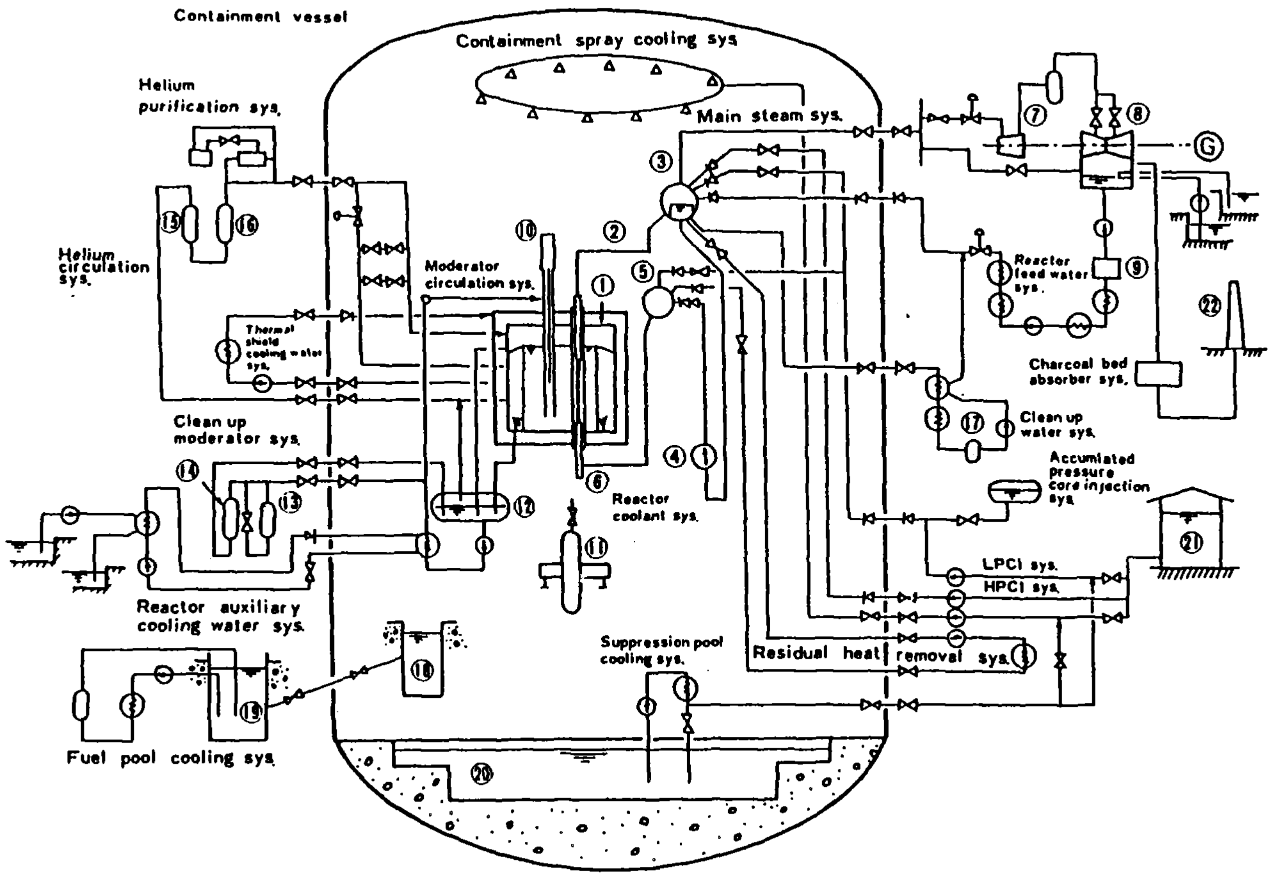


Fig.1 Nuclear Fuel Cycle in Japan



Key to components

① Calandria tank
② Outlet riser tubes (224)
③ Steam drum (2)
④ Recirculation pump (4)
⑤ Lower header (2)
⑥ Inlet feeder tubes (224)
⑦ High pressure steam turbine
⑧ Low pressure steam turbine
⑨ Condensate demineralizer
⑩ Control rod drive mechanism
⑪ Refuelling machine
⑫ Heavy water dump tank
⑬ Liquid poison removal resin bed
⑭ Heavy water purification resin bed
⑮ Pre - heater
⑯ Recombiner
⑰ Clean up demineralizer
⑱ Fuel exc' ange pool
⑲ Spent fuel storage pool
⑳ Suppression pool
㉑ Condensated water storage tank
㉒ Main stack

Fig. 2 Schematic Flow Diagram of Fugen

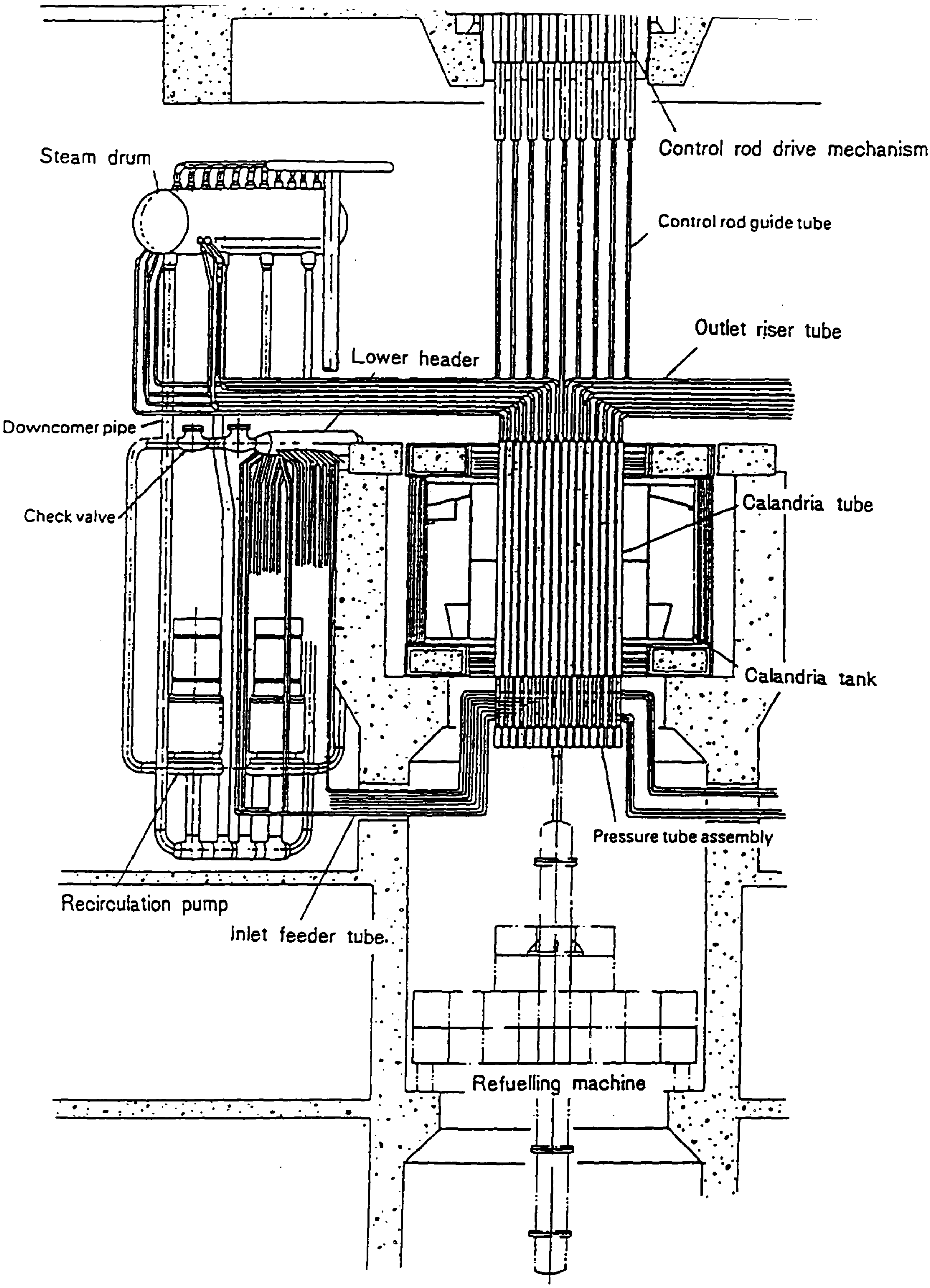
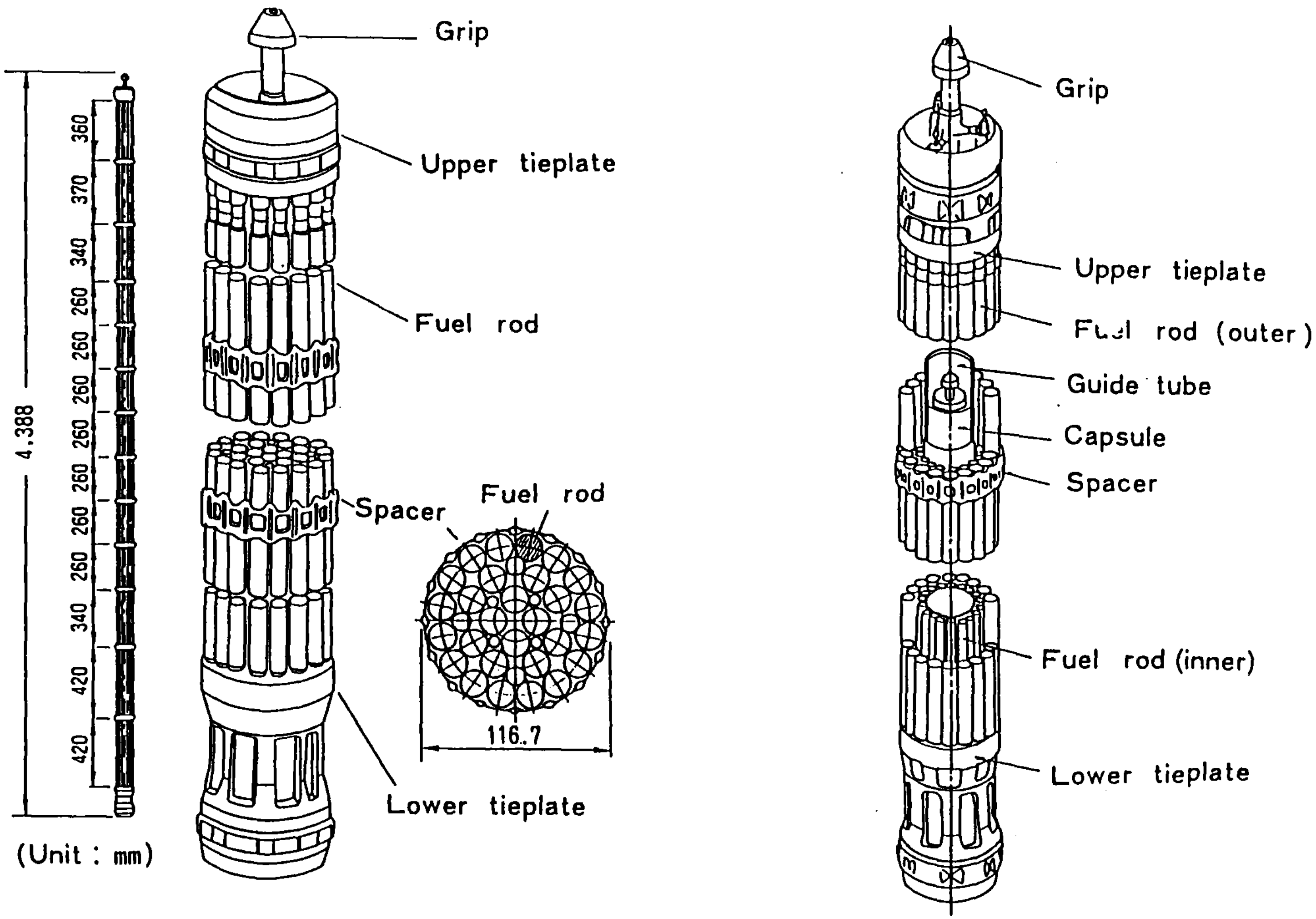


Fig. 3 Reactor Core and Reactor Coolant System (Vertical)



Fuel assembly

Special fuel assembly
for irradiating samples

Fig.4 Schematic View of Fugen Fuel Assembly

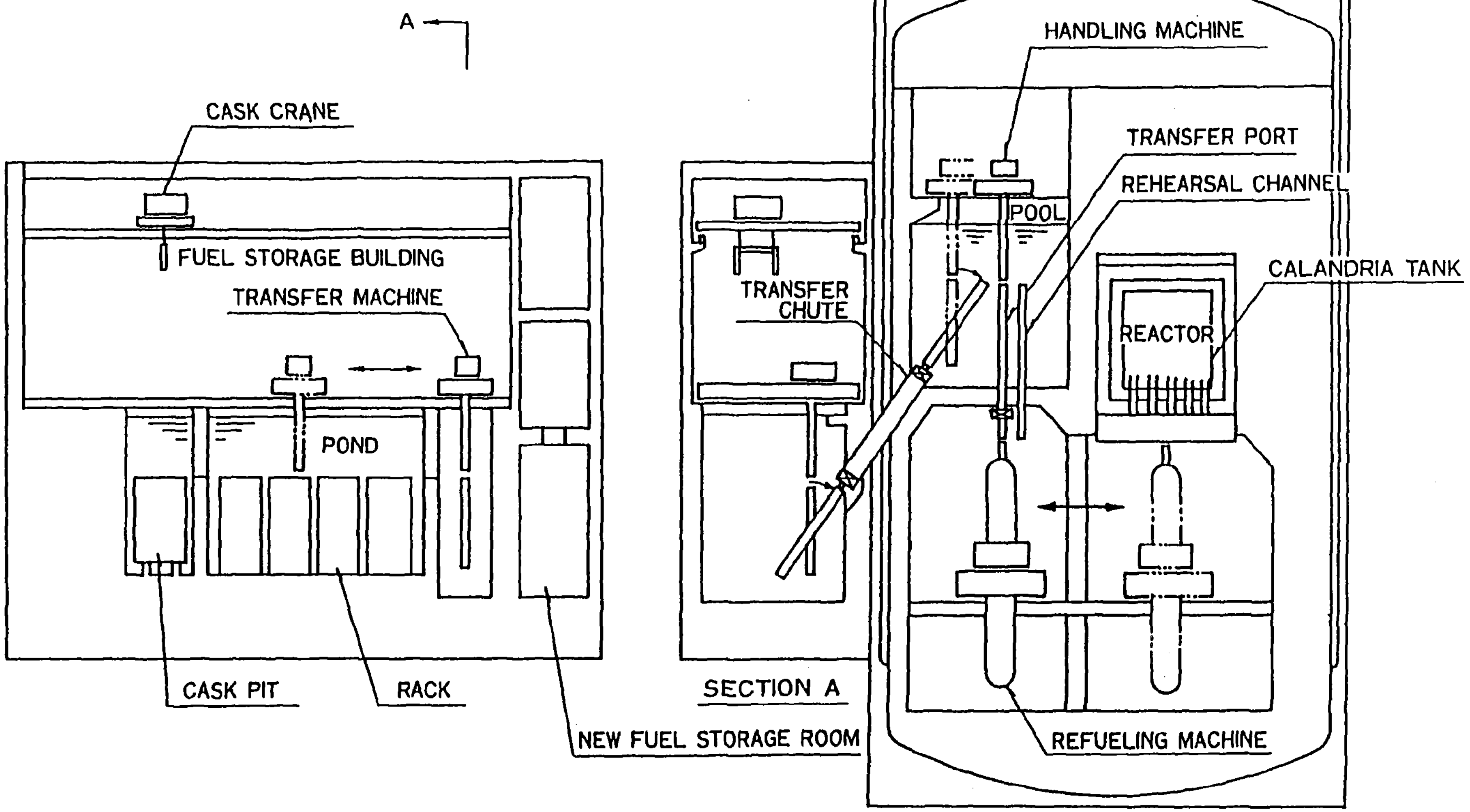


Fig.5 Fuel Handling and Storage Facilities (Vertical)

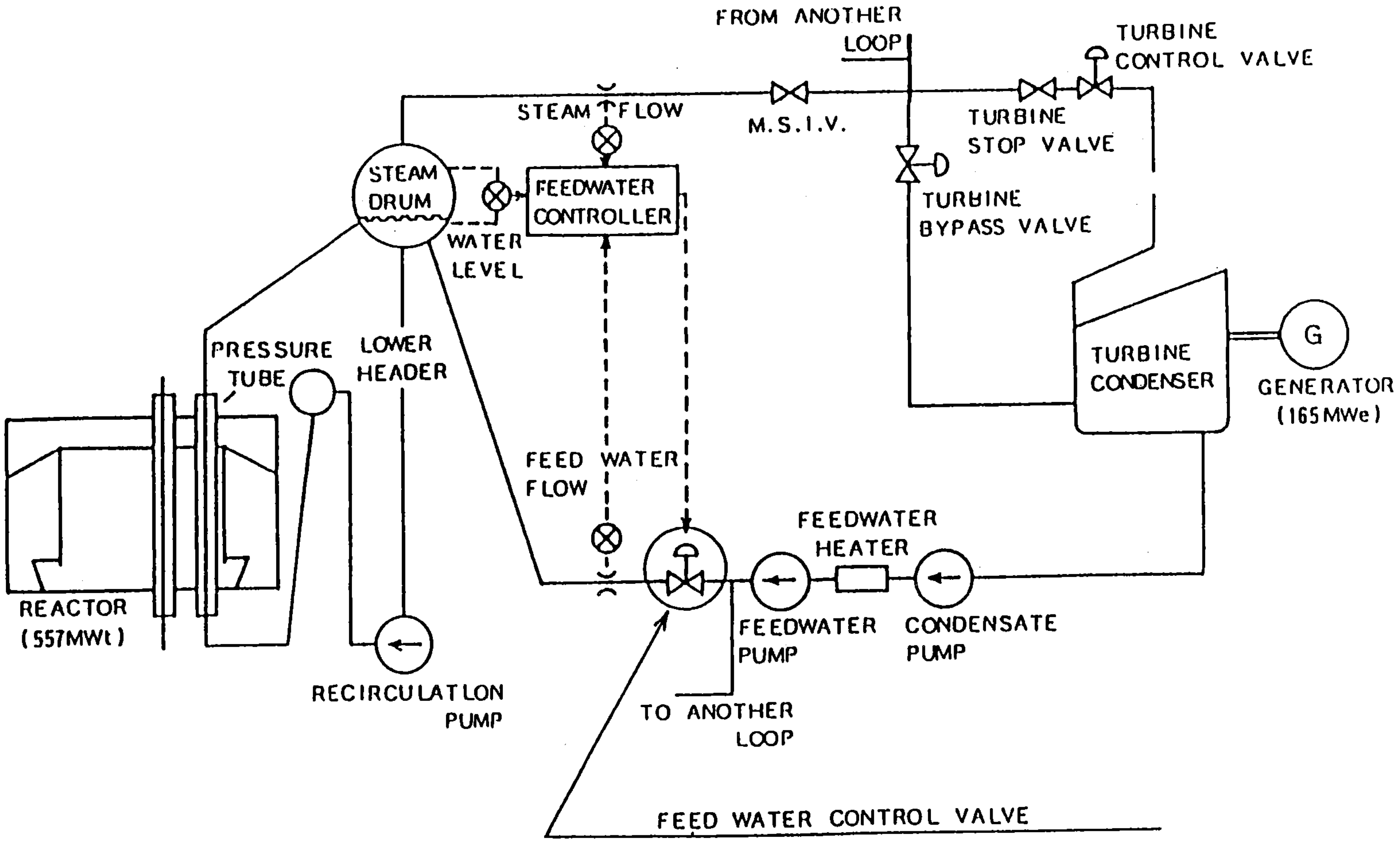


Fig.6 Schematic Flow Diagram of Feed Water Control System

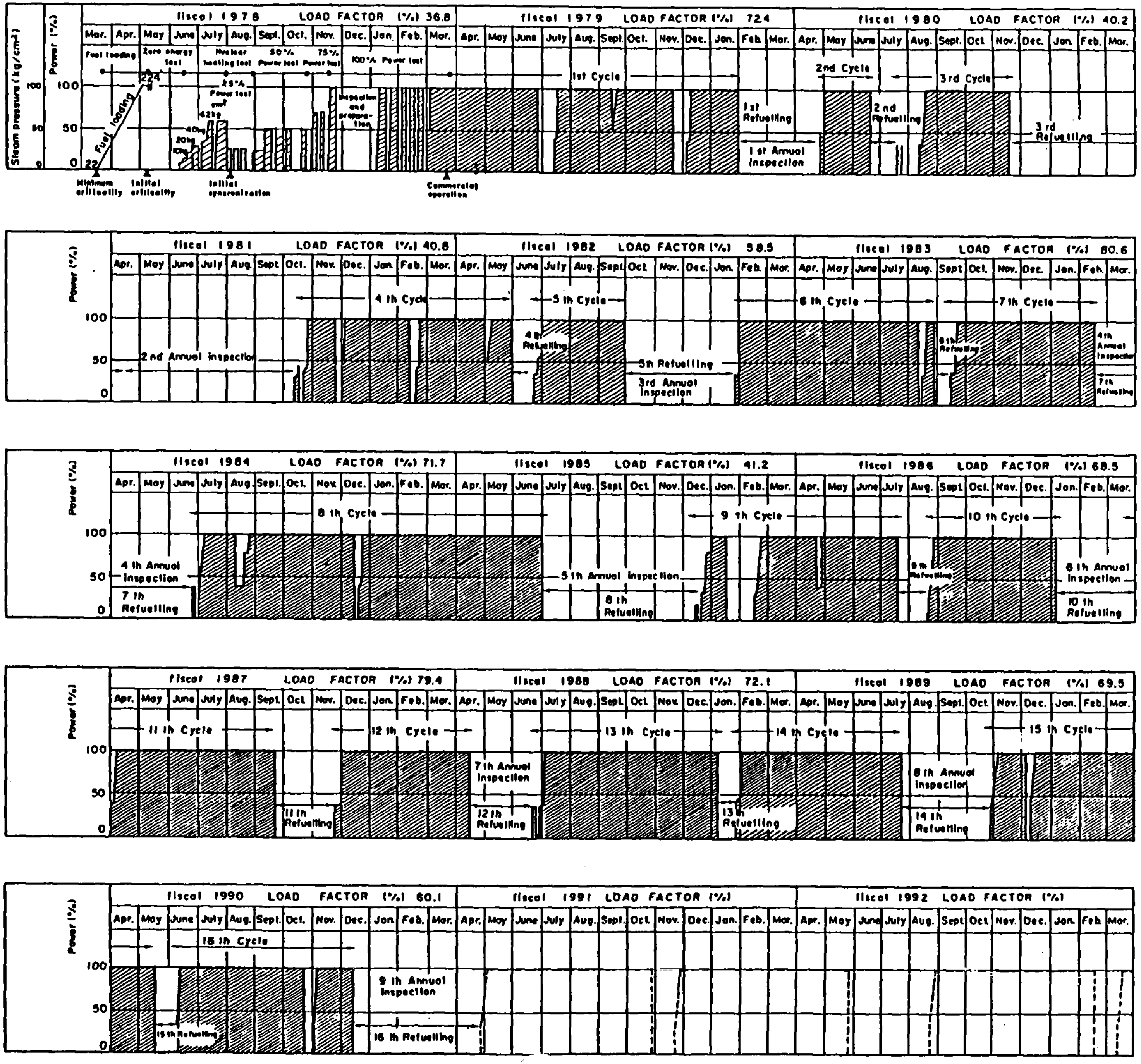
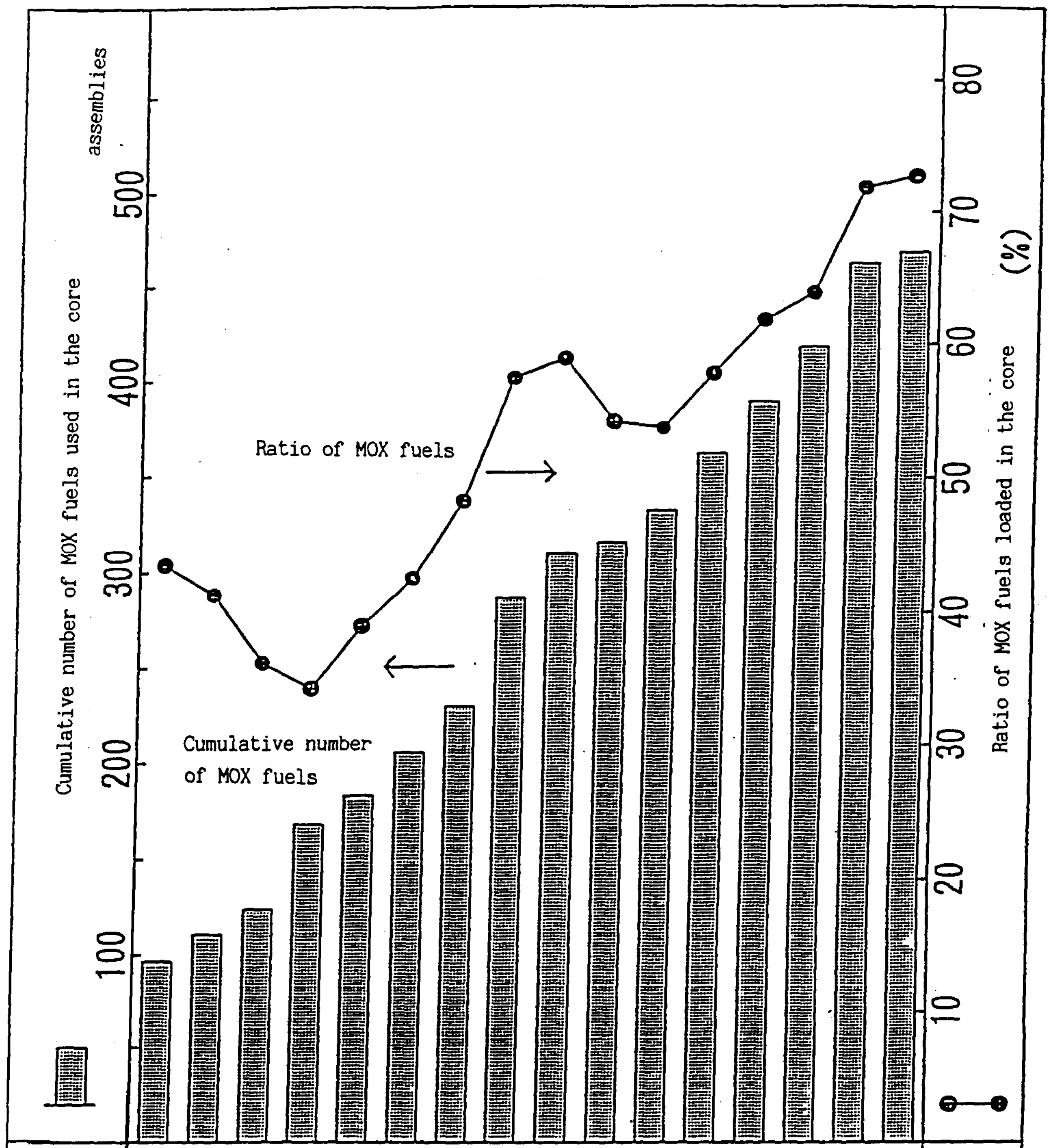


Fig. 7
Operating History
in Fugen



Cycle No.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Operation period	78.3 ⇩ 80.2	80.4 ⇩ 80.6	80.7 ⇩ 80.11	81.10 ⇩ 82.5	82.6 ⇩ 82.9	83.1 ⇩ 83.8	83.9 ⇩ 84.2	84.6 ⇩ 85.7	85.12 ⇩ 86.7	86.8 ⇩ 87.1	87.3 ⇩ 87.9	87.11 ⇩ 88.4	88.6 ⇩ 89.1	89.1 ⇩ 89.7	89.10 ⇩ 90.5	90.6 ⇩ 90.12

including demonstration fuel assemblies

Fig. 8 MOX Fuel Utilization in the Fugen

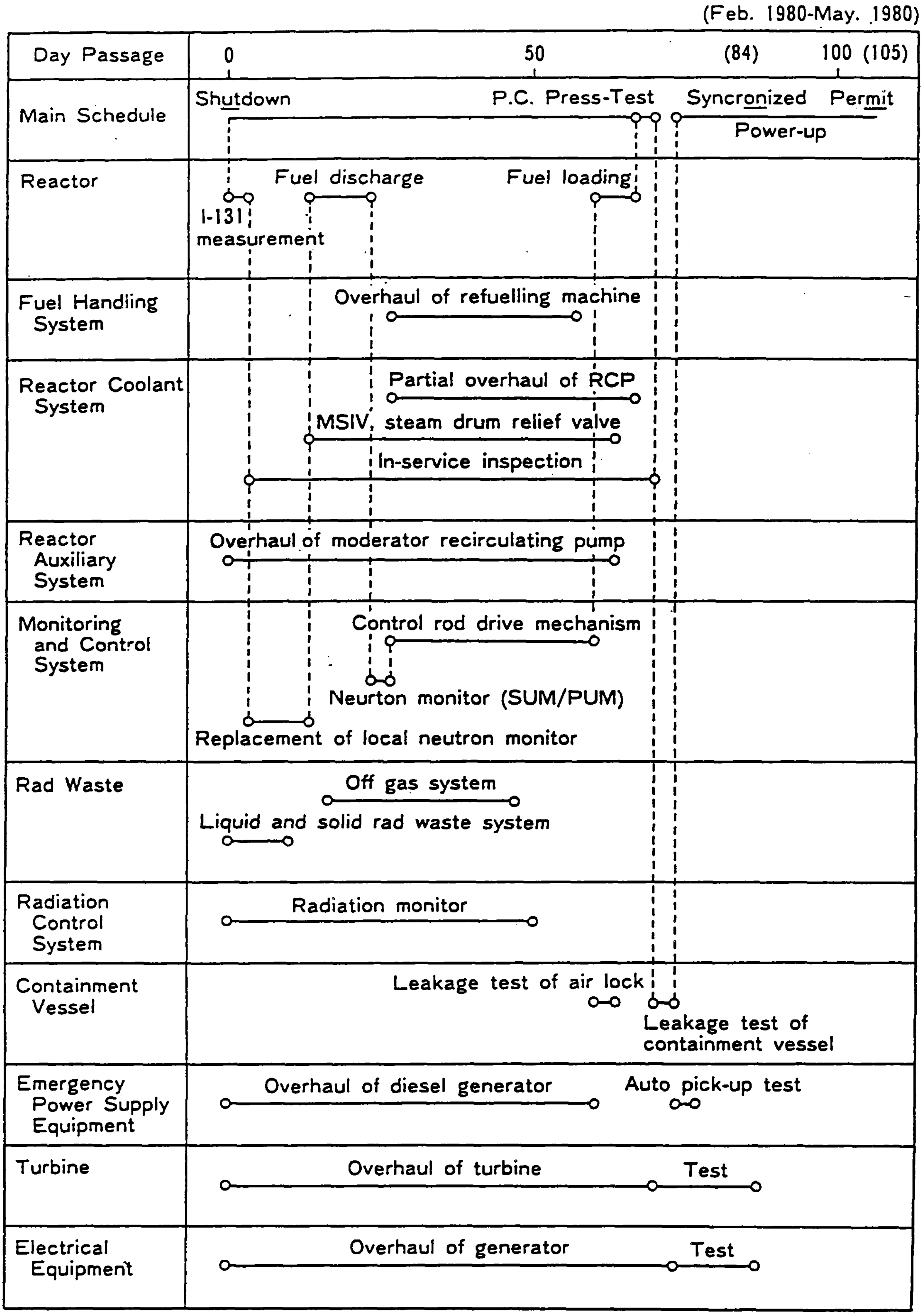


Fig.9 Time Schedule of the First Annual Inspection

(Feb. 1984-July. 1984)

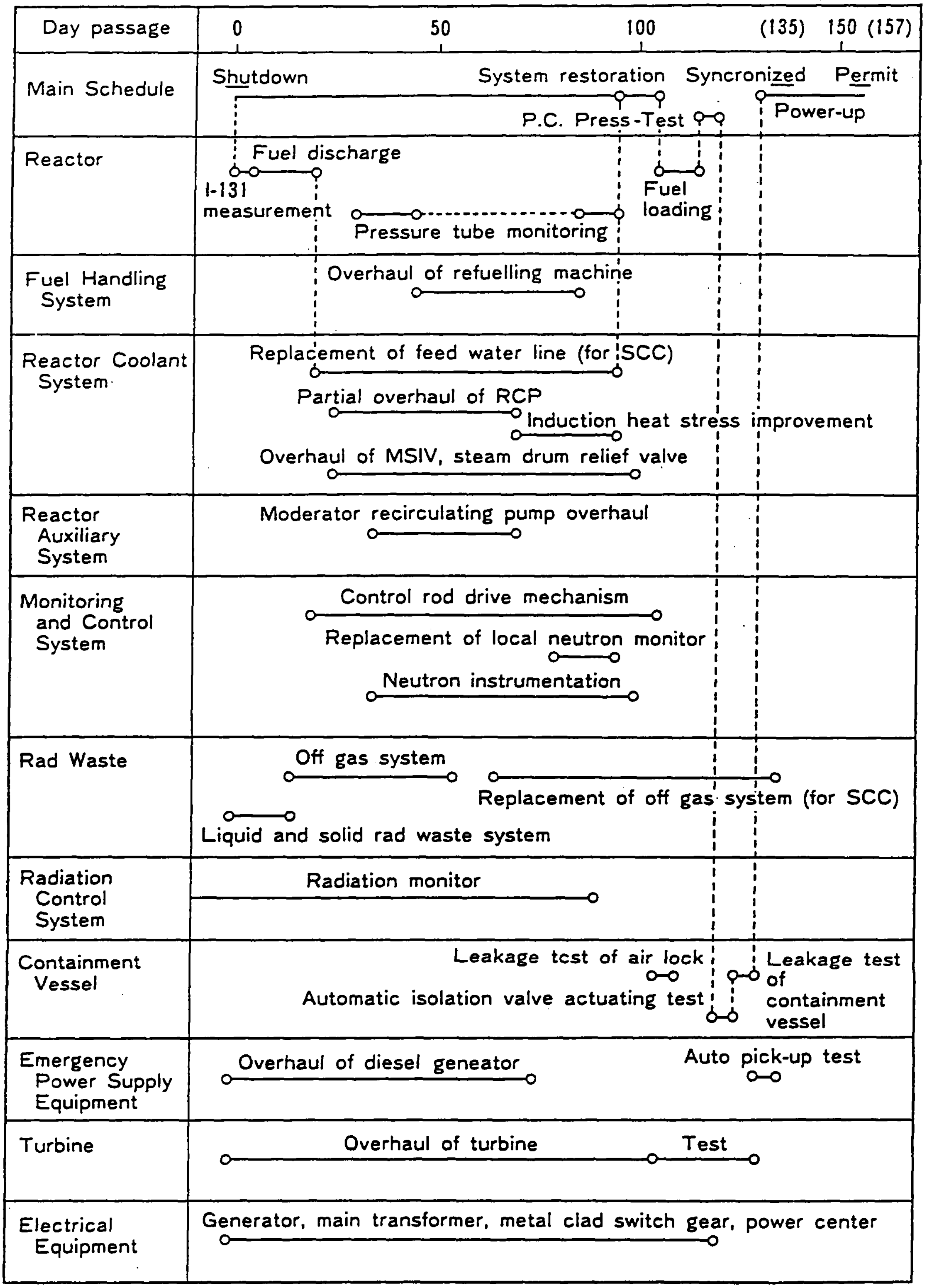


Fig. 10 Time Schedule of the Fourth Annual Inspection

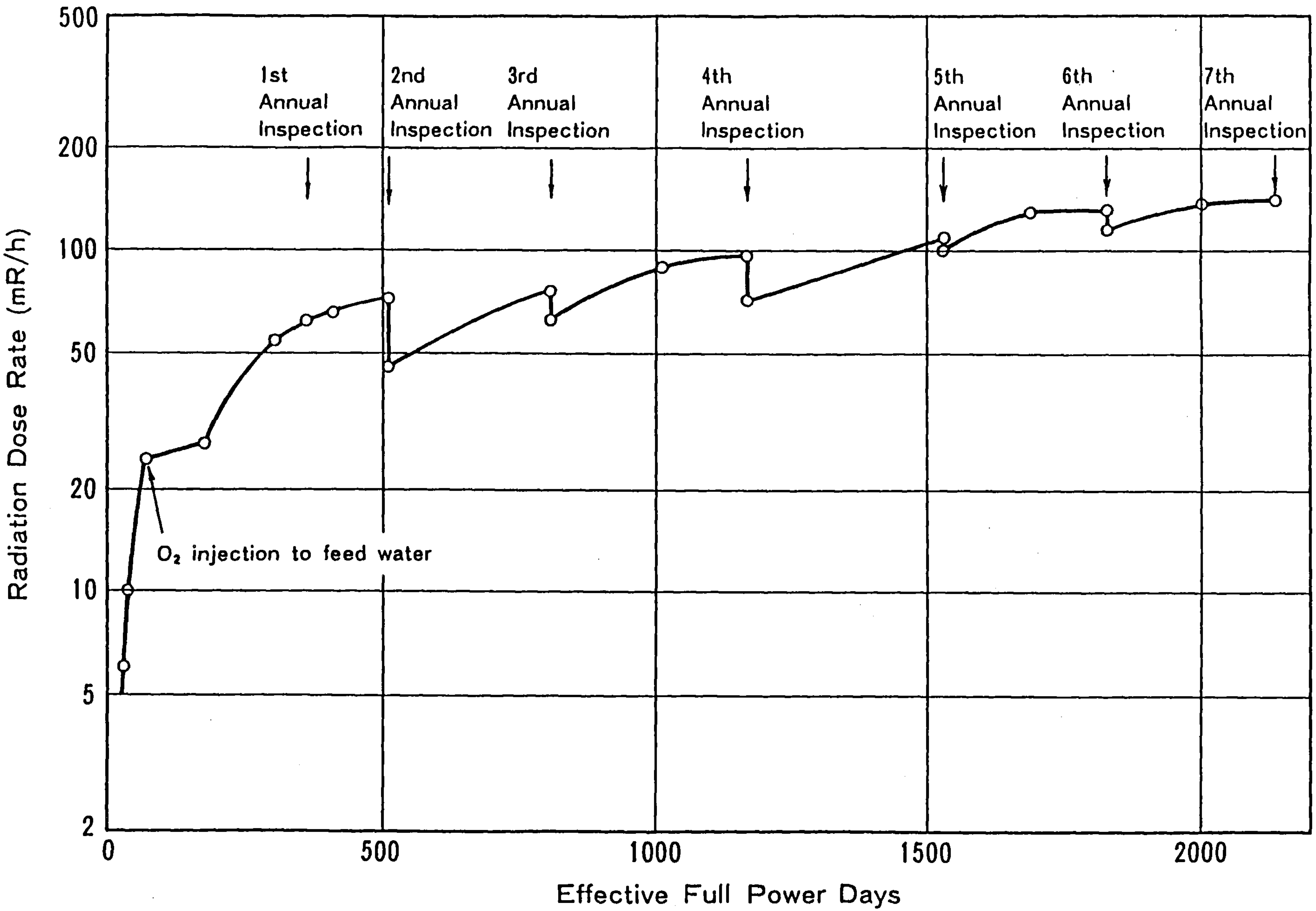


Fig.11 Radiation Dose Levels of Outlet of Recirculation Pump