Operating Experiences and Present Activities of JOYO

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Abstract

The preliminary design of experimental fast reactor JOYO was started in 1965.

After thid design, three steps of conceptual designs are carried out, and main parameters were fixed during these steps.

This paper describes the operating experiences which contain functional test before criticality, initial criticality and low power testing, power ascension tests to 50 MWt operation, power ascension tests to 75 MWt and 75 MWt operation.

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1. INTRODUCTION

The experimental fast reactor JOYO was constructed as the first step in FBR development in Japan. Its purposes are to provide the technological experience necessary for the construction of a prototype fast reactor, and also for utilization as an irradiation facility for fuels and materials.

The reactor has a core utilizing mixed oxide driver fuel of uranium and plutonium, surrounded by a blanket of depleted uranium oxide. The core has six (6) control rods; 4 safety rods and 2 regulating rods made of B_4C. The reactor has two identical sodium loops, each of which has a heat removal capacity of 50 MWt. Each heat transport loop consists of a primary sodium system, an intermediate heat exchanger, and a secondary sodium system. Air blast heat exchangers (or dump heat exchangers, DHXs) are used to dissipate the heat generated in the core into the air. JOYO has an air-tight steel containment vessel in which all the primary sodium systems, including the reactor vessel, are installed.

Although JOYO was designed with an ultimate target power level of 100 MWt, the power ascension program and licensing were planned for operation in three phases: 50 MWt (MK-I, Phase 1), 75 MWt (MK-I, Phase 2), and 100 MWt (MK-II). This program of gradual power increase was decided upon in consideration of the fact that the JOYO reactor is the first sodium-cooled fast reactor to be built in our country.

As JOYO milestone is shown on Table 1, construction of JOYO started in the beginning of 1970 at a site in the Oarai Engineering Center in Ibaraki prefecture in Japan. After the completion of construction at the end of 1974, functional test was started and initial criticality was achieved on April 24, 1977. Low power physics tests and high power tests at 50 MWt were conducted until the middle of September 1978. Normal operation at 50 MWt was begun in October 1978, and the testing was successfully completed at the end of February 1979.

A power ascension program at 75 MWt (MK-I, Phase 2) started at the beginning of July 1979, and was completed toward the end of August 1979. A four-month annual inspection and maintenance program was performed, and the reactor was licensed for 75 MWt operation in February 1980. Normal operation at the 75 MWt power level is scheduled for about two years in order to accumulate sufficient technical data on the present (MK-I) core.

The experimental results so far obtained in the 50 MWt and 75 MWt performance tests of the reactor and plant systems have been, in general, satisfactory and in good agreement with predicted values.

The MK-II program will be started in late 1982. The core will be converted to a core of 100 MWt power by replacing the MK-I fuels with MK-II fuels. The reactor will then be utilized as an irradiation facility for fuel and material in support of FBR development programs.

The main design parameters of JOYO are listed in Table 2. An outline of the reactor cooling systems, and a cross-sectional view of the reactor vessel are illustrated in Figures 1 and 2, respectively. The master schedule of JOYO is shown in Figure 3.

2. Operational Experience

2.1 Functional Tests

The preoperational function tests were performed not only to verify the functions and characteristics of components and systems, but also to get the operating characteristics and the initial data of the plant.

The functional test were divided into 3 phases; cold test, hot test and in-sodium test. (see Fig. 4)

Cold tests The tests were carried out under the room temperature-air atmosphere condition of the reactor. The main items of this phase were the tests of the fuel handling and transfer systems, the loading test of dummy fuel assemblies, the charging of sodium (about 200 tons) into the dump tanks of the primary and the secondary cooling systems, and the vibration test of sodium pipings.

Hot tests In this phase, the reactor system was pre-heated up to 200°C in argon gas atmosphere. The relative thermal displacement between core structure and rotating plugs, and the temperature distribution of main equipment were measured. The argon pressure control function, leak tightness of the system, and pre-heating of fuel handling facilities were tested.

In-sodium tests Sodium was charged into the system and maintained between 150 and 250°C. Many tests of the cooling system such as hydraulic characteristics, sodium purification, vibration characteristics of pipings, adjustment of piping supports, etc. were carried out. Functions of fuel handling, transfer, cleaning and storage were tested in sodium environment. In the final stage, control rod drive mechanism and reactor protection systems were tested. During these tests, all utility systems were operated and tested.

2.2 Initial Criticality and Low Power Testing

JOYO initial criticality tests began with the loading of core fuel subassemblies into the reactor on March 16, 1977.

Three extra neutron counting channels were provided for monitoring the counting rates during the test. In the critical approach, the dummy subassemblies (and some blanket subassemblies) were replaced by core subassemblies from the core center in fifteen steps. The number of fuel subassemblies to be loaded at each step, was limited to half the number of fuels to be loaded to the critical core estimated by inverse multiplication curves.

$$Ni = \frac{1}{2}\left(Nc - \sum_{j}^{i-1} Ni \right)$$

Ni : Numbers of feel loading at ith stage

Nc : Estimated numbers of fuel at initial criticality

The inverse multiplication curve at initial criticality are shown on Fig. 5.

The criticality was achieved on April 24 with 64 fuel subassemblies, as 63.7, fuel subassemblies at the coolant temperature of 250°C.

The minimum critical mass has been predicted as 60.7 ±5 subassemblies at 250°C in the design. The discrepancy, between the measurement and the design calculation which was corrected by the bias factor of 1.007 +0.012 as C/E value based on the mock up experiment, is about 1% in Keff.

After criticality and the arrangement of the initial core configuration for 50 MWt operation, low power phisics tests were conducted until the middle of November 1977. In these tests, core characteristics such as control rod characteristics, reaction rate distributions, temperature coefficient, fuel subassembly worths, sodium void worth, core flow distribution, and shielding characteristics were measured and compared with the design calculaitons. Table 3 shows the nuclear characteristics of the initial core.

During low power testing, the reactor was operated below 500 kWt, mostly around 10 kWt; and the coolant temperature was maintained at about 250°C utilizing the preheaters. The total reactor operation time, and cumulative power were about 400 hours and 7000 kWh, respectively, during this period.

2.3 Power Ascension Tests to 50 MWt (MK-I, Phase 1)

JOYO's power-up tests started on April 18, 1978, and the power level of 50 MWt was achieved on July 5, 1978. The power ascension tests were performed in five steps: 15%, 30, 50%, 80%, and 100% of the rated power of 50 MWt. At each power level, the core characteristics such as power coefficient and burn-up coefficient, stability and heat removal performance of the cooling systems, and the radiation level at various locations were measured. In addition, thermal transient tests such as reactor scram, primary pump trip, and loss of electric power supply system were conducted at powe levels of 50% and 100%.

The power ascension test were successfully completed on September 16, 1978. During the test period, the purity of the sodium coolant in the primary and secondary systems were maintained at a satisfactory level (Oxygen content around 3 ppm).

The DHX outlet sodium temperature regulates automatically the DHX air flow to keep DHX outlet sodium temperature at setting value. The setting value is changed at each power level to keep the reactor inlet sodium temperature constant at 370°C. (see Fig. 6)

During this test we find the DHXs characteristics that the maximum removal power at the state of blower stop is 23 MW, the minimum power is 1.6 MW and the minimum power at the state of blower operation is 5 MW.

2.4 50 MWt Operation

Normal duty cycle operation at 50 MWt started on October 26, 1978. Operation at 50 MWt was scheduled for two cycles (each cycle about 45 days of continuous operation), and was completed on February 26, 1979.

During the 50 MWt operation, the reactor behavior was very stable and the regulating rods required operator adjustment only twice a day (in the morning and in the evening) for the reactor power to be maintained at a constant 50 MWt. The measured reactivity loss was in good agreement with the predicted value of 0.31% Δ k/k for each cycle. The maximum burn-up of the core fuel was estimated to be about 11,000 MWD/T at the end of the 50 MWt operational program.

2.5 Power Ascension Tests to 75 MWt (MK-I, Phase 2)

After completion of the 50 MWt operation program, the power ascension to 75 MWt was initiated on July 3, 1979; without any modification made to the reactor. The application for authorization to operate at the higher power was submitted to the Nuclear Safety Committee in 1977, and permission had been granted in September 1978. A three-month delay in initiating the power raising program was caused by additional tests and inspections of the reactor and operating procedures due to the Three Mile Island accident in the U.S.

The power ascension and performance tests at 75 MWt were conducted in a period of about two-months from July 3, 1979 to the end of August 1979. The test items and procedures were nearly identical to those used in the 50 MWt power ascension program. The results of the 75 MWt tests and experiments were generally satisfactory, and consistent with expected values based on the 50 MWt results.

One anomaly, however, was the appearance of an unexpectedly large negative value of the power coefficient (about twice predicted values) during initial power ascension above the 50 MWt power level.

The cause of this phenomenon has been attributed mainly to the rearrangement of the core fuel subassemblies due to thermal bowing rather than the restructuring of the fuel material itself.

Following the 75 MWt performance test program, the reactor system was shut-down and another annual inspection and maintenance program was conducted. This inspection and examination program is required by Science and Technology Agency (STA) regulations to be performed on a regular basis, and included an Integrated Leak Rate Test (ILRT) of the pressure containment with the reactor system in the "hot" sodium-filled condition.

In draining the sodium collant from the primary piping during the inspection, radiation dose rates on the piping were measured. The dose rates were found to be still low, mostly less than a few mrem/h as shown in Figure 6, and the underfloor cells safe for maintenance activities. Measurement of radioactive corrosion products deposited in the piping were also attempted using a pure Ge Solid State Detector (SSD), and some nuclides (Co-58, Co-60, and Mn-54) were detected. However, these nuclides were not detectable in the coolant using normal sodium sampling techniques.

Thermal transient tests were conducted for JOYO during initial 75 MW operation to confirm that the actual thermal transient response is less severe than the design criteria values.

From the results of these tests, the following characteristics were obtained:

1) Thermal Transient Response

The measured thermal transient response was more gradual than the design criteria.

2) Natural Convection Flow in the Secondary Loop

The measured natural convection flow in the secondary loop following loss of electric power supply (Secondary Main Pump Trip), was approximately 5% of the rated flowrate with pump operation. This value was in good agreement with the calculated value.

3) Sodium Temperature Oscillation in the DHX

During the loss of power test at 50 MW operation, the sodium temperature in the Dump Heat Exchangers (DHX) oscillated so that the inlet vanes and dampers operated with a large phase lag. Accordingly, before the power ascension tests to 75 MW, a modified procedure was adopted to compensate for the phase lag caused by the sodium temperature detecting lag under natural sodium circulation conditions in the secondary loop. The operation of the inlet vanes to the DHX was limited to a small range of openings if a secondary main pump trip or loss of electric power occurred, forcing the system into a natural circulation mode. With this modification in the operating procedure, sodium temperature oscillations in the DHX were avoided.

Test result of the loss of electric power supply system are on Fig. 8.

2.6 75 MWt Operation

After the inspection and maintenance program was successfully completed in January 1980, the reactor was started-up and again operated at 75 MWt. Following the 100 hour continuous operation test, JOYO was officially licensed for 75 MWt operation on February 1, 1980.

Duty cycle operation at this power level was performed and continued six cycles. At 23rd December 1981, all the duty cycle operation at 75 MW was completed. One cycle means about 45 days operation at 75 MW power level and arround 15 days refueling.

At the end of 75 MW duty cycle operation program, maximum burn-up of the core fuel is expected to be about 40,200 MWD/T, accumulated operating times are 12,956 hr. and accumulated thermal powers are 673,300 MWH.

Total used fuel numbers are 107 (booster fuels) and 9 (fuels for test).

Fig. 9 shows the operation history of JOYO MK-I core. Total numbers of reactor trip during MK-I operation from April 24th 1977 is shown on Table 4.

3. FUTURE JOYO PROGRAMS

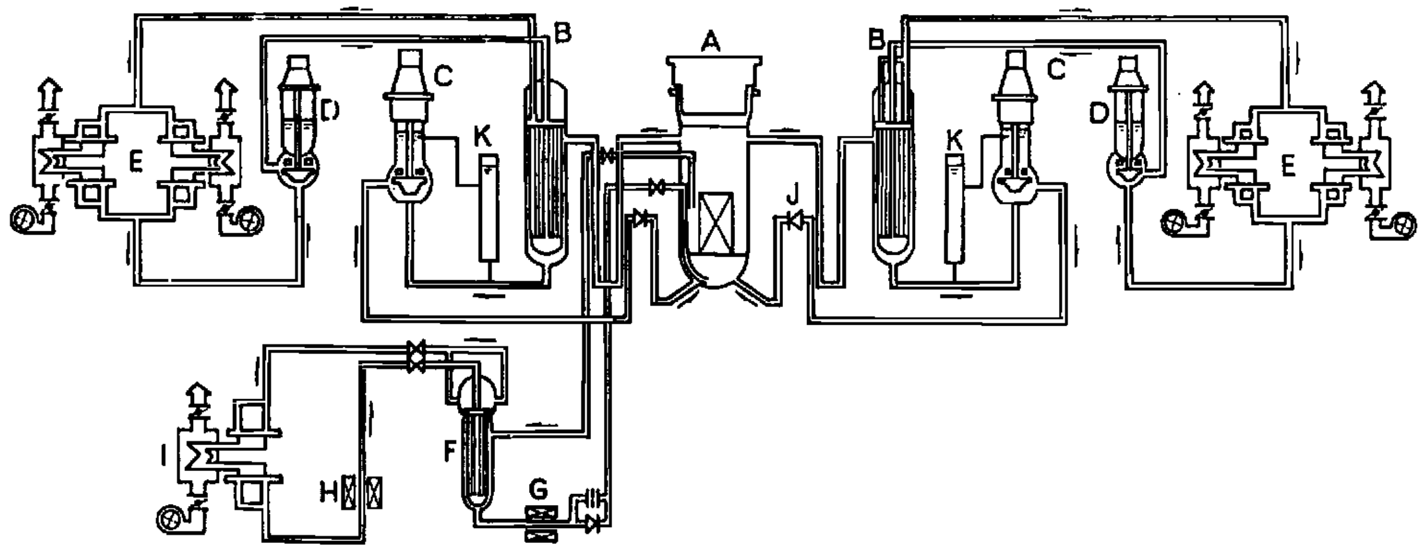
Following the 75 MWt operation program, the JOYO MK-II program was initiated in approximately 1982. In the 100 MWt MK-II program, the core will be converted to the MK-II core by replacing the MK-I driver and blanket fuel with new driver fuels containing thinner pins, and reflectors in order to increase the neutron flux in the core region. The fertile blanket region will be eliminated in the MK-II core configuration. (see Fig. 10)

Application for the safety authorization to proceed with the MK-II program was submitted together with that of the 75 MWt power ascension program to the Nuclear Safety Committee in September 1977. Permission was also granted in September 1978.

The final licensing for design and fabrication of the MK-II fuels and reflectors is underway. The design of some types of irradiation test rigs and planning for future irradiation test programs are in progress.

Construction of a new facility for assembling irradiation test rigs was founded. The facility is called the Irradiation Rig Assembling Facility (IRAF), and was located adjacent to the JOYO containment and engineering buildings.

Conversion work to the MK-II core started in January 1982, and initial criticality at MK-II core is expected in November 1982. About 10 months will be required to peform the fuel handling operations for the core conversion.



A. REACTOR
B. INTERMEDIATE HEAT EXCHANGER
C. PRIMARY SODIUM PUMP
D. SECONDARY SODIUM PUMP
E. AIR BLAST COOLER
F. AUX. INTERMEDIATE HEAT EXCHANGER
G. AUX. PRIMARY PUMP
H. AUX. SECONDARY PUMP
I. AUX. AIR BLAST COOLER
J. CHECK VALVE
K. PUMP OVERFLOW COLUMN

Fig. 1 REACTOR COOLING SYSTEM FLOW DIAGRAM

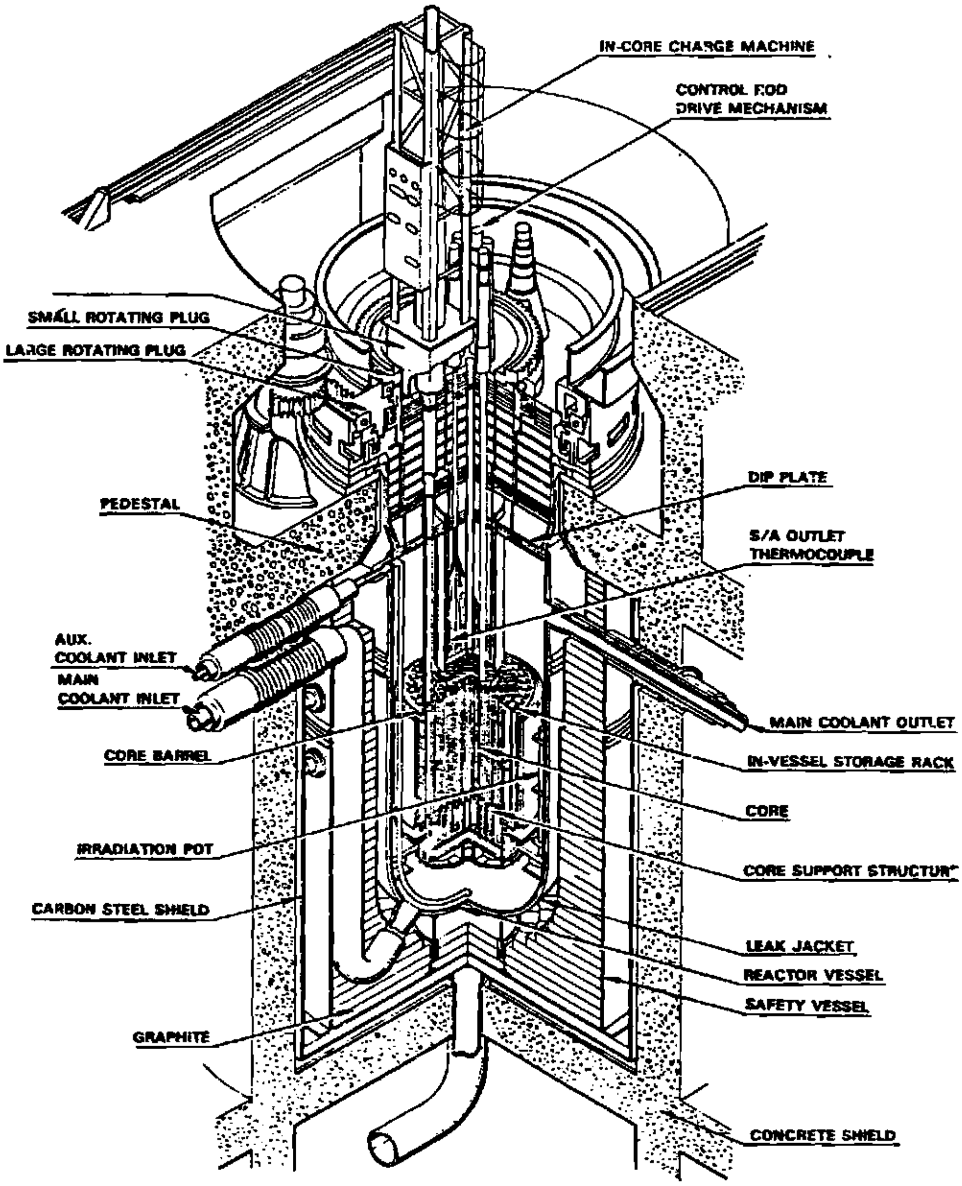


FIG. 2 JOYO REACTOR SYSTEM

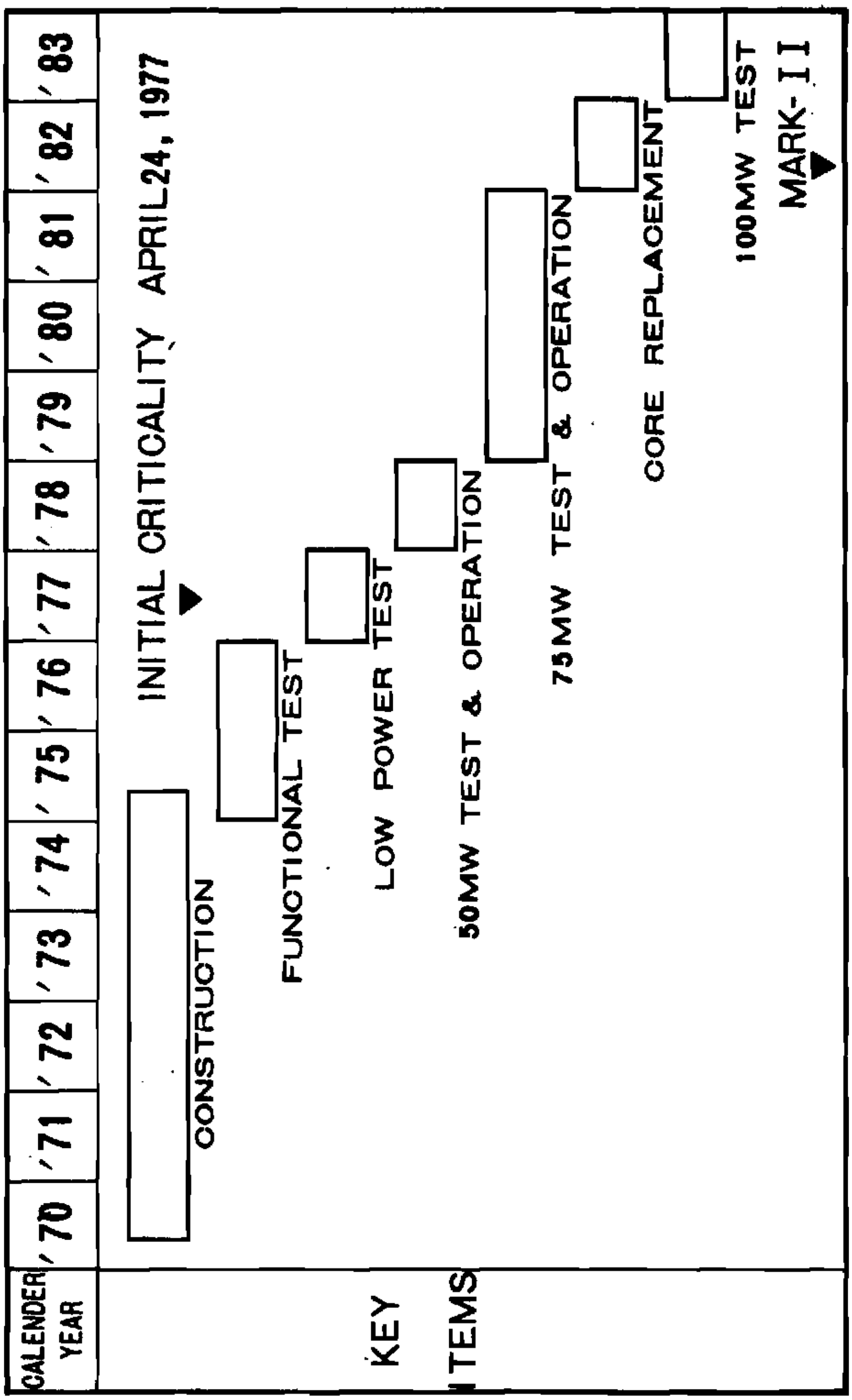


Fig.3 MASTER SCHEDULE OF JOYO

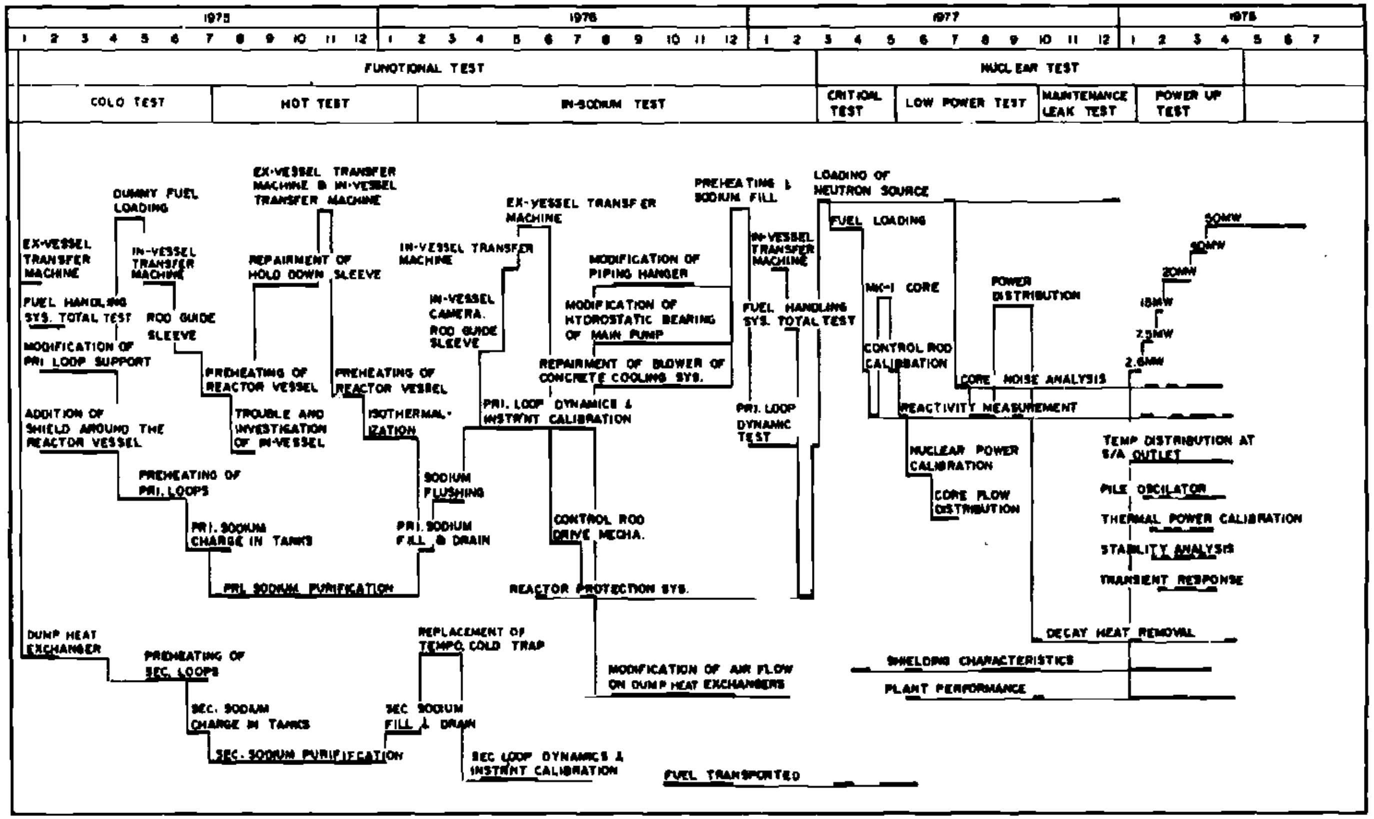


Fig.4 TIME TABLE OF JOYO FUNCTIONAL TEST

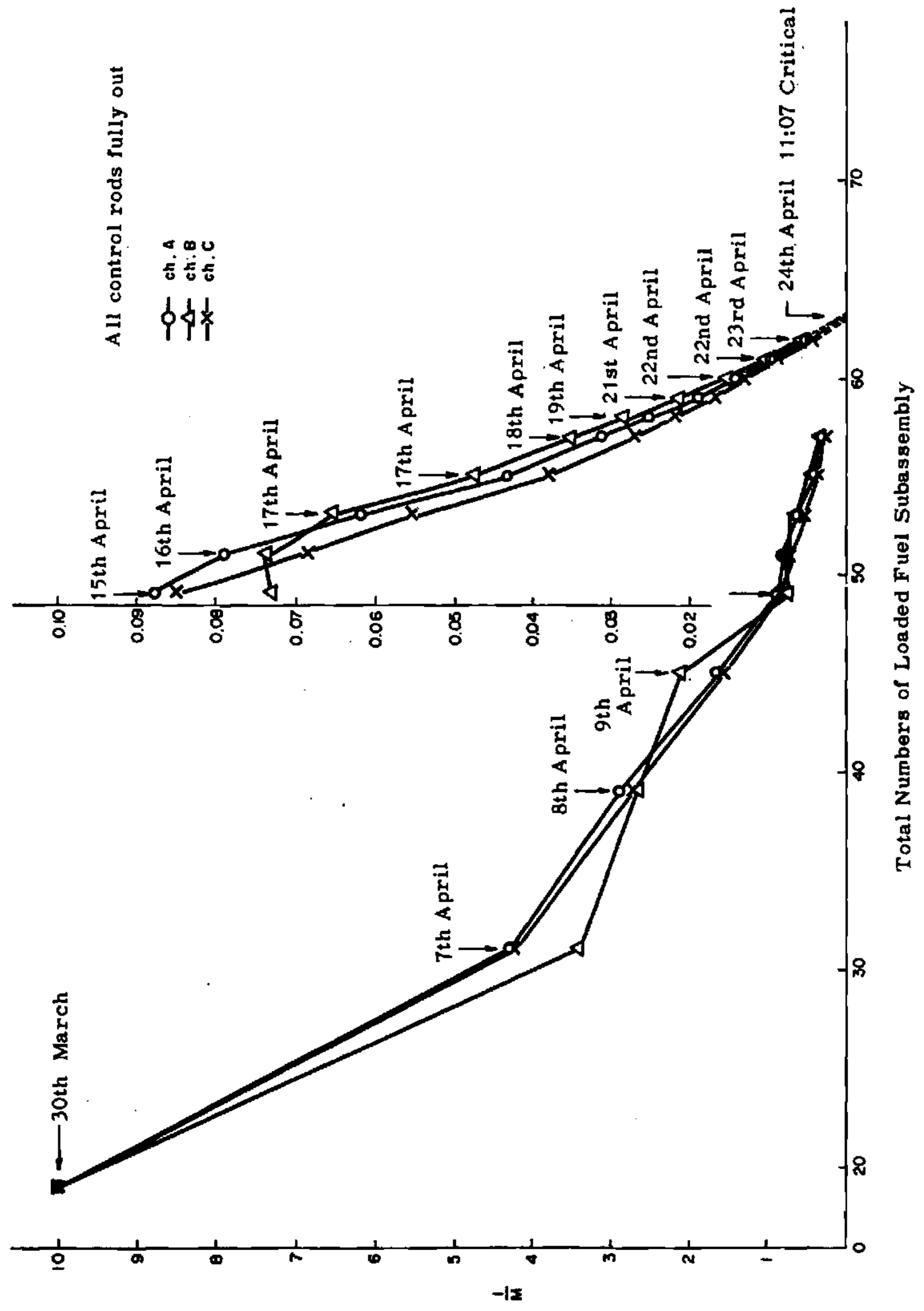


Fig.5 Inverse Multiplication Curve

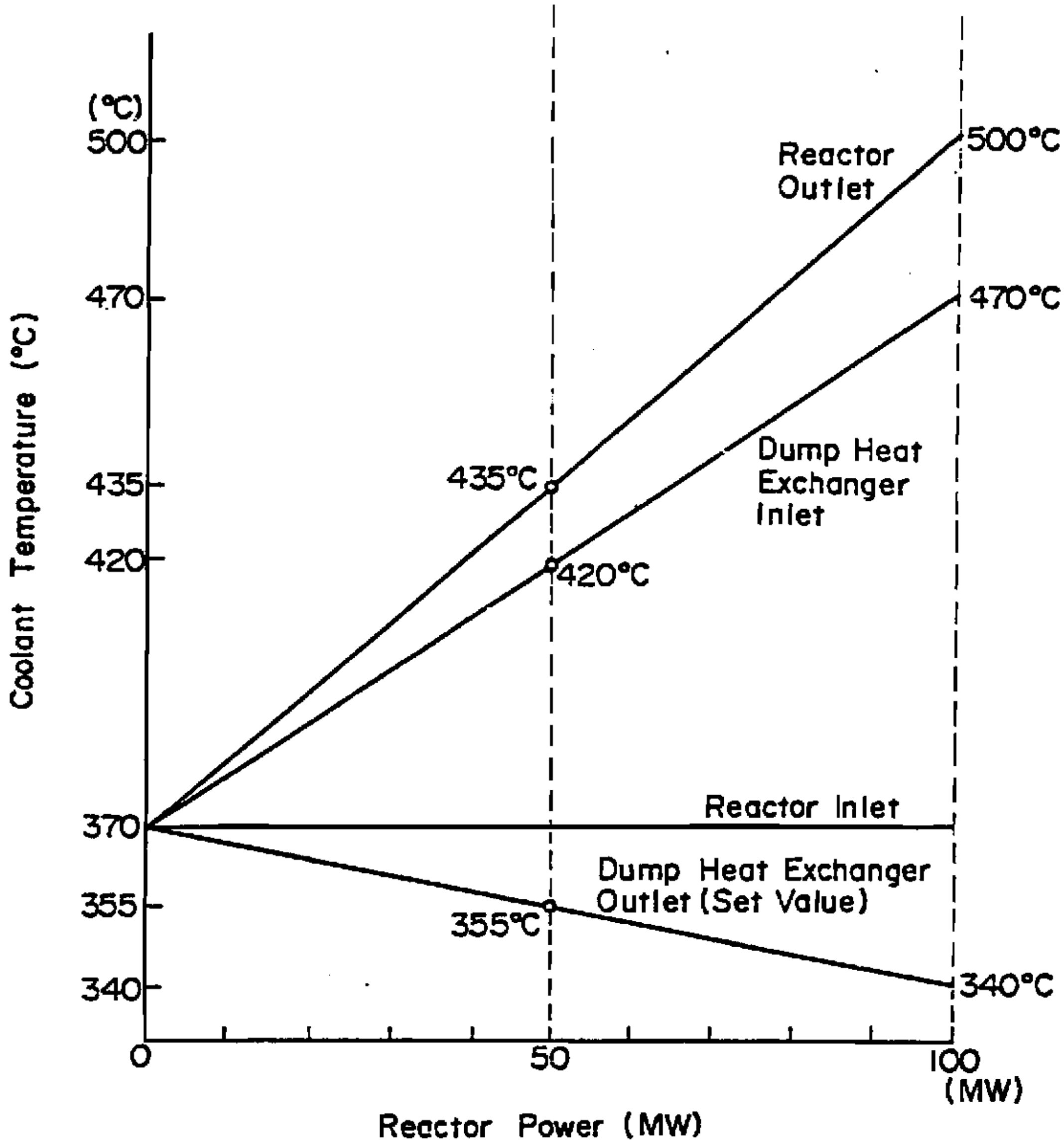


Fig. 6
REACTOR POWER V.S. COOLANT TEMPERATURE

(AFTER DRAINING PRIMRY SODIUM)

Primary Piping	Point No.	2.44×10³MWD (Sep. 78)	6.71×10³MWD (Mar. 79)	8.89×10³MWD (Nov. 79)	1.8×10³MWd (Nov. 80)
Hot	Point 1	1.3 mR/h	2.1 mR/h	3.0 mR/h	6.5mR/h
Leg	Point 2	0.4	2.5	0.75	3.2
Cold	Point 3	0.6	1.2	2.0	3.4
Leg	Point 4	0.65	1.5	2.0	5.6

Detector: G-M Tube Type Surveymeter

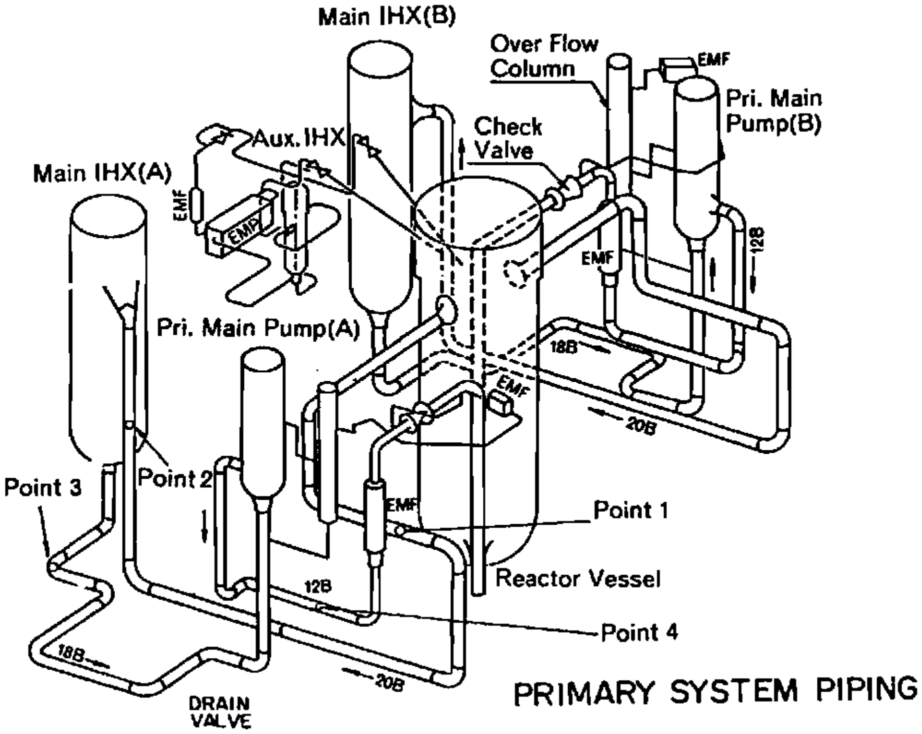


Fig.7 GAMMA DOSE RATE AT SURFACE OF PRIMARY PIPING

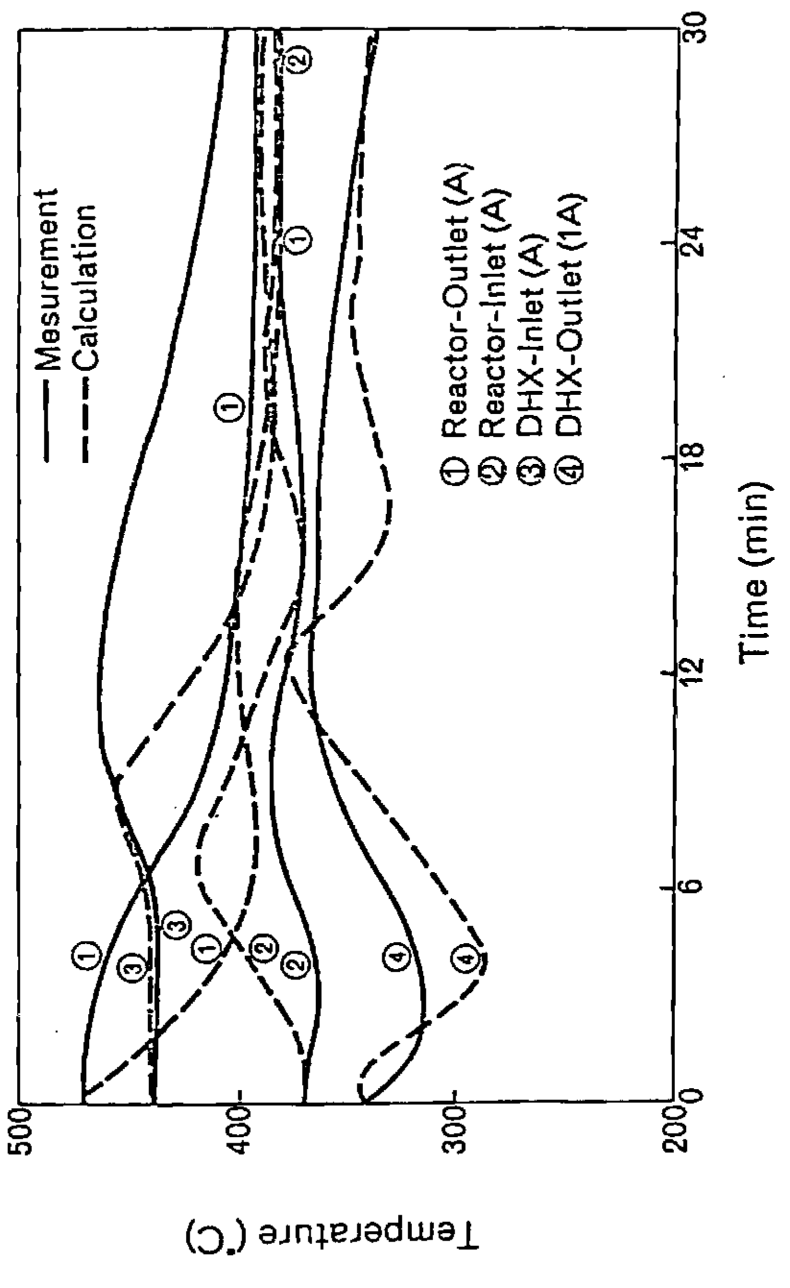


Fig.8 Loss of Electric Power (75MW)

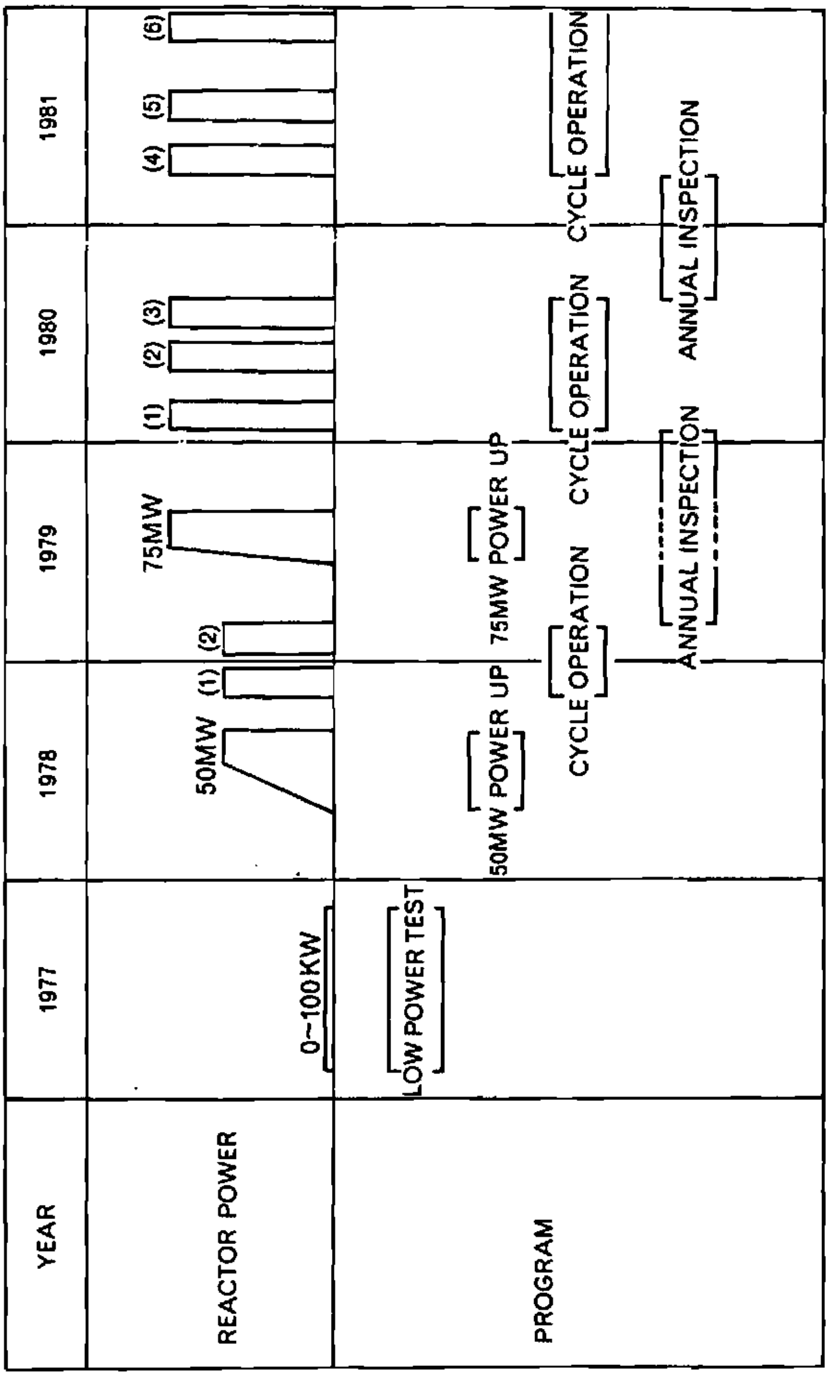


Fig.9 OPERATION HISTORY OF JOYO MARK-1 CORE

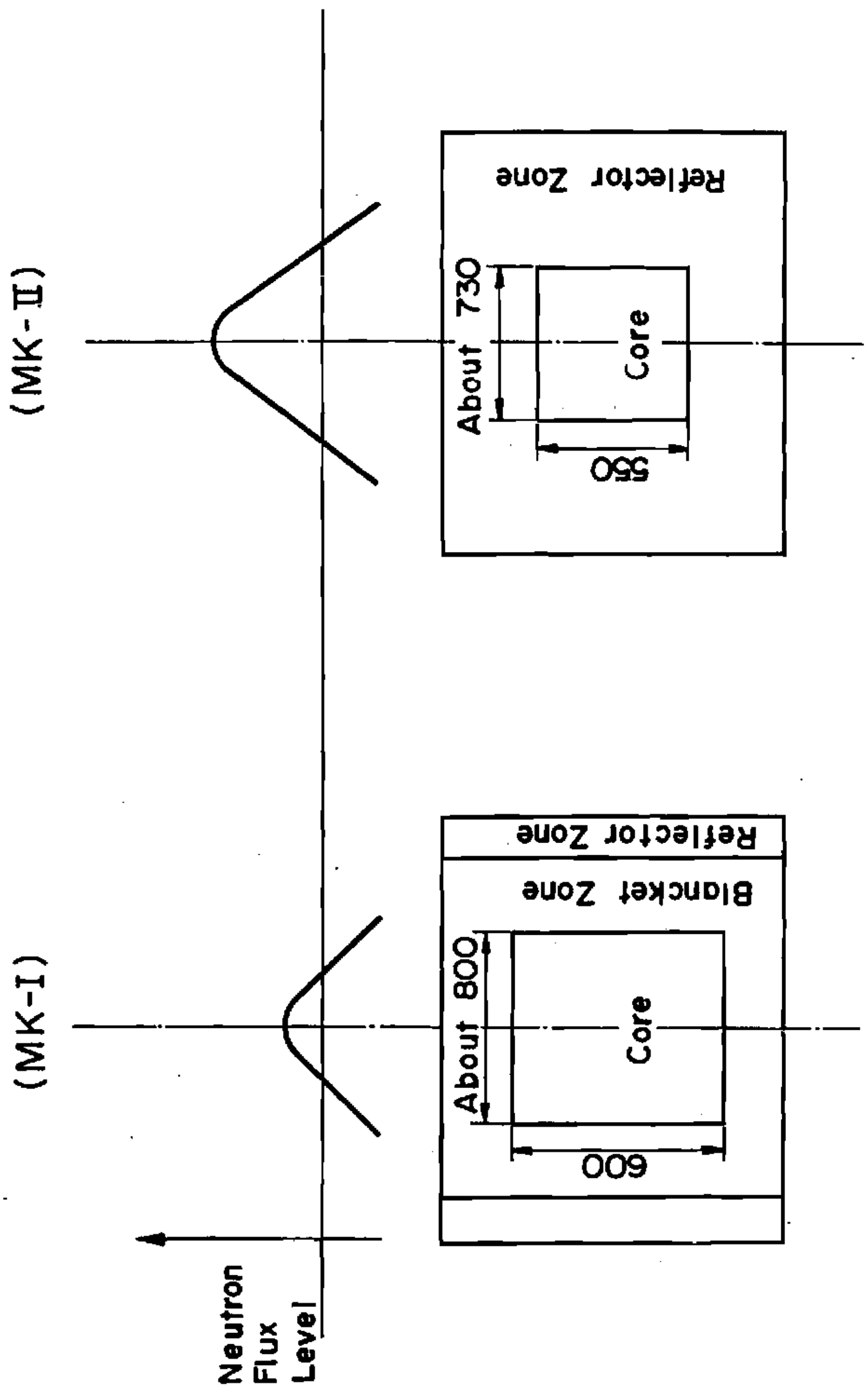


Fig.10 Core Modification

Table 1 JOYO MILESTONES

1965 - 1966	CONCEPTUAL DESIGN PHASE I
1967 - 1968	CONCEPTUAL DESIGN PHASE II
1967/10/2	FOUNDATION OF PNC
1968	CONCEPTUAL DESIGN PHASE III
1969	DETAIL DESIGN FOR CONSTRUCTION
1969/6 - 1970/2	SAFETY REVIEW BY GOVERNMENT
1970/1	INITIATION OF EXCAVATION
1970/3	INITIATION OF CONSTRUCTION (CONTRACT)
1974/12	COMPLETION OF INSTALLATION
1975/1 - 7	FUNCTIONAL TEST IN AIR
1975/7 - 1976/2	FUNCTIONAL TEST IN HIGH TEMP. Ar.GAS
1976/2 - 1977/3	FUNCTIONAL TEST IN SODIUM
1977/3 - 1977/5	APPROACH TO CRITICALITY
1977/3/8	TURNOVER TO PNC
1977/4/24	INITIAL CRITICALITY

Table 2 MAIN CORE PARAMETERS OF JOYO

		MK-I		MK-II
		First	Second	
Reactor Out Put	MWt	50	75	100
Primary Coolant Flow Rate	t/h	2,200	2,200	2,200
Reactor Inlet Temperature	℃	370	370	370
Reactor Outlet Temperature	℃	435	470	500
Core Stack Length	cm	60	60	55
Core Volume (max.)	ℓ	294	304	231
Linear Heat Rate (max.)	W/cm	210	320	400
Fuel Pin Diameter	mm	6.3	6.3	5.5
$PuO_2/(PuO_2+UO_2)$	W/O	18	18	30
U^{235} Enrichment	W/O	23	23	12
Neutron Flux (max.)	$n/cm^2 \cdot sec$	1.9×10^{15}	3.2×10^{15}	5.1×10^{15}
Neutron Flux (Core av.)	$n/cm^2 \cdot sec$	1.1×10^{15}	1.9×10^{15}	2.6×10^{15}
Max. Excess Reactivity	$\%\Delta K/K$	~4.5	~4.5	~5.5
Control Rod Worth	$\%\Delta K/K$	Safty Rod 5.6~ Regulating Rod 2.8~	Safty Rod 5.6~ Regulating Rod 2.8~	9~
Max. Burn Up (pin av.)	MWD/t	25,000	42,000	50,000
Operation Cycle		45 Days Operation 15 Days Stoppage		

Table 3 Nuclear characteristics of The Initial Core

Minimum Critical Number of Fuel Assemblies	64
Number of Fuel Assemblies of The Initial Core	70
Excess Reactivity	2.24% $\Delta k/k$ (at 250°C)
Control Rod Worth of Each Control Rod	2.1 ~ 2.2% $\Delta k/k$
Shut Down Margin	10.7% $\Delta k/k$ (at 250°C)
Iso-thermal Temperature Coefficient	-3.7% $\Delta k/k$ °C

Table 4 Numbers of "JOYO" Reactor Trip

Cause / Year	Disturbance	Instrument	Operation
1977	1	4	1
1978	1	0	2
1979	2	1	0
1980	1	2	0
1981	0	0	2
Subtotal	5	7	5
Total	17		

Disturbance means the reactor trip caused by plant protection system operation correctly.

Instrument means the reactor trip caused by malfunction or noise on instrument.

Operation means reactor trip caused by misoperation.