REACTOR PHYSICS TESTS FOR THE JOYO MK-III START-UP CORE

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The performance test of the JOYO MK-III core was conducted to fully characterize the upgraded core. The measured data of reactor physics tests were accumulated and compared with the calculation results. These data will be used as the benchmark data for validating nuclear data library and testing reactor calculations.

1. INTRODUCTION

JOYO had been operated from 1983 to 2000 as the MK-II fast neutron irradiation facility. In order to meet various requirements for irradiation tests, JOYO was recently upgraded to the MK-III design. The four main components of the MK-III upgrade[1] are 1) increase in fast neutron flux and enlargement of irradiation space, 2) improved irradiation test subassemblies, 3) modified heat transfer system for the 40% power increase, and 4) improved plant availability. MK-III performance tests began in July 2003 to fully characterize the upgraded core and heat transfer system. Results of the tests, which focus on the neutronics characteristics, are presented here.

2. CHANGES IN THE SUBASSEMBLY LOADING FOR THE MK-III UPGRADE

Figure 1 and **Table 1** show the core configurations and main parameters of the MK-II and MK-III cores. The fuel region is divided into two radial enrichment zones in the MK-III core to flatten the neutron flux distribution. The maximum number of driver fuel subassemblies was increased from 67 to 85. The equivalent diameter of the initial MK-III core is approximately 80 cm. This increases the fraction of the core volume where test irradiations can be done in a high neutron flux. The core height was decreased from 55 cm to 50 cm to obtain a higher neutron flux with smaller power peaking. With these core modifications, the maximum fast neutron flux ($E \geq 0.1$ MeV) increased from 3.2×10^{15} n/cm^2·s to 4.0×10^{15} n/cm^2·s and the reactor power increased from 100 MWt to 140 MWt.

Two of six control rods were shifted from the third row to the fifth row to provide high-fast-neutron-flux loading positions for instrumented-type irradiation subassemblies. The outer two rows of radial stainless steel reflectors were replaced by the shielding subassemblies, which contain 45 % enriched boron carbide. This reduces the total neutron flux at the in-vessel spent fuel storage rack to about 30 % of the MK-II core value.

3. APPROACH TO CRITICALITY AND EXCESS REACTIVITY

3.1 Measurements

Because of the many reactor loading changes, the approach to criticality was carried out cautiously. Biases based on calculations of the last MK-II operational cycle were used along with the calculated predictions of excess reactivity and control rod worths to predict the critical rod bank position of the initial MK-III core. At each rod withdrawal step, counts of source-range monitors were measured and compared to check for reasonable agreement. Inverse count rate was plotted versus the calculated reactivity insertion, as shown in **Fig. 2**.

The isothermal core temperature during the excess reactivity measurement was about 250 ^{o}C. Based on the measured critical rod bank position and the measured rod worths as described below, the zero power excess reactivity was estimated to be 2.99 ± 0.09 %Δk/kk'. The measured excess reactivity was within a safety requirement limit.

3.2 Calculation

Excess reactivity was predicted by five methods in preparation for the initial MK-III approach to criticality.

- The "MAGI" method was the standard method used for MK-II analyses.[2] The base MAGI calculation uses finite-difference diffusion theory with one mesh per subassembly and 5 cm mesh intervals axially. It uses 7-group homogeneous neutron cross sections based on JENDL-3.2. A difference between the measured and calculated excess reactivity for the last MK-II operational cycle is +0.69 %Δk/kk' which is applied to the base-calculation prediction for the MK-III core as the bias correction factor.

• The "HESTIA" method was adopted as the standard method for MK-III core management analyses. Consequently, it was used for the approach to criticality. It features finer detail in space (24 triangles/subassembly and 2.5 cm axial mesh in the fuel) and energy (18 groups for neutron and 7 groups for gamma-ray) to improve calculation accuracy. The bias correction factor for the excess reactivity is +1.89 %Δk/kk'. In other respects, the approach is the same as MAGI.

• The "JUPITER" method applies mesh, transport, heterogeneity and three other corrections to a 6 triangle per subassembly diffusion theory calculation. The bias correction factor is +0.67 %Δk/kk'.

• The MCNP code was used to model the reactor components pin by pin, with continuous energy JENDL-3.2 cross sections. The bias correction factor is +0.25 %Δk/kk'.

• The "JUPITER Adjusted" method is the same as the "JUPITER" method except the ADJ2000R adjusted cross section set [3] is used instead of the bias correction for the base calculation.

A comparison of the excess reactivity results, measured and predicted by each of the calculation methods, is shown in **Fig. 3**. The range of calculated values brackets the measured value. The approach described in Ref. [4] was used to derive the uncertainties in the calculated values using the covariance and sensitivity coefficient. All of the calculated values are within two standard deviations from the measured value.

4. CONTROL ROD CALIBRATIONS

All the six control rods have the same poison-type design. The poison section contains B_4C enriched to 90 % in ^{10}B. The poison section is 650 mm long, which is also the axial distance the rod can move. As noted above, two of the rods, No. 2 and 5, are in the fifth row in the MK-III design. Each of these rods is worth about 40 % as much as any of the four rods in the third row.

4.1 Period Method

4.1.1 Measurement

Reference calibrations use a period-like method with uniform rod bank positions. The measured rod is moved from 0 mm to 650 mm in steps about 9 ¢ each. An example of a differential rod worth profile from the reference calibrations is shown in **Fig. 4**. It can be seen that the random error at each calibration step can be significant. However, the effect on the full-travel rod worth is very small.

4.1.2 Calculation

The base calculation uses transport theory, 7 group cross sections and an XYZ geometry representation of the core in the TRITAC code [5] considering the actual rod bank positions at the measurement. The bias factors are based on the period measurements in the last MK-II operational cycle.

Experimental and calculated control rod worths of the reference calibrations are compared in **Table 2**. The rod worth uncertainty has an estimated random component of 0.3 % and an estimated systematic component of 1.0 %, which add in quadrature to 1.0 %. Converting reactivity unit from cent to Δk/kk', adds the 3 % uncertainty in k_{eff}, for a total uncertainty of 3.2 %. The biased calculated worths are smaller than the measured ones by 3 % to 4 % for rods in the third row but are 1 % for rods in the fifth row.

4.2 Juggling Method

Juggling calibrations are more dynamic measurements, in which exactly critical condition is not required once the calibration begins. This is the routine calibration approach at JOYO for calibrating control rods in the third row. At the beginning, two rods are at 295 mm (poison inserted to 30 mm below the fuel center) and other two rods are at 650 mm (fully withdrawn). These four rods are calibrated over the 295 mm to 650 mm range by alternately moving one rod up and another rod down in steps. The reactivity and power traces during several steps of such a calibration are shown in **Fig. 5**.

The reference and juggling calibration measurement results are compared in **Table 3**. In order to make this comparison, the effect of the different rod shadowing in the two approaches was removed by calculation verified with measurement data described in 4.3. Both measurement results agree within 0.9 %. As the juggling method is performed in a short time, it is practical as a routine control rod calibration procedure and can be used as the alternative for the period method.

4.3 Shadowing Measurement

Shadowing measurements were performed to test the ability of calculations to account for shadowing effects. Accordingly, one of the shadowing experiments consisted of calibrating Rod No. 1 two times, once with Rod No. 4 half inserted (325 mm) and once with Rod No. 4 fully withdrawn (650 mm) as illustrated in **Fig. 6.** The results from all four shadowing experiments are shown in **Table 4**. For example, in the first case of the table, Rod No. 1 was calibrated first with Rod No. 4 half down and then with Rod No. 4 up. According to the measurement, the worth of Rod No. 1 increases by 6 % when Rod No. 4 is down, while the calculation estimates 4 % increase. Thus, it is confirmed that calculated adjustments that account for shadowing are accurate.

5. ISOTHERMAL TEMPERATURE COEFFICIENT

5.1 Measurement

To begin the isothermal temperature coefficient measurement, a uniform temperature of approximately 250 ^{o}C was established throughout the primary system (isothermal), and the excess reactivity was determined. Next the reactor power was increased in 20 ^{o}C steps, measuring excess reactivity at each step, until the primary system reached approximately 350 ^{o}C. The next day, the reactor temperature was brought back to 250 ^{o}C by cooling the coolant sodium by the natural air circulation in the dump heat exchangers with the temperature decreasing in 20 ^{o}C steps. The ascending and descending measurements were repeated, providing four measurements of the temperature coefficient.

The measurements results are shown in **Table 5**. There is a clear difference between coefficients measured with the temperature increasing and decreasing. This difference is considered to be related with a time lag of control rod drive shaft expansion during the measurements.

5.2 Calculation

The calculated isothermal temperature coefficient has two main components, Doppler broadening of neutron cross section resonances, and thermal expansion of the fuel and core. The values of these components are -0.00053 and -0.00315 %Δk/kk'/^{o}C, respectively. A ultra fine group correction [6] was used in the computation of Doppler broadened cross sections. The items contributing to the thermal expansion include the coolant density reduction, the core radial expansion and the fuel axial expansion. The ratios of the calculated coefficient to the experimental ones are shown in **Table 5**. The average C/E is 0.994 for the ascending temperature measurements, 0.954 for the descending temperature measurements.

6. POWER COEFFICIENT

During the MK-III performance test, the reactor power was repeatedly increased and decreased, and the burn-up and power dependence of the power coefficient was measured with the same reactor inlet temperature condition. The measurement results are shown in **Fig. 7**. The measured power coefficients were negative in all the power range. The absolute value of the power coefficients were decreased, when reactor power reached 120 MWt for the first time. This is considered to be caused by the restructuring of the fuel pellet. Further investigation will be performed to understand the change of the power coefficient.

After that, power coefficient was measured 7 times. The measured results of November 4th and 8th are shown in Fig. 7. These values became about a half of the ones measured at the low burn-up of the MK-III performance core mostly considering fresh fuels, and were same in the MK-II equilibrium core.

7. CONCLUSIONS

The core performance of the upgraded JOYO MK-III was successfully evaluated by a series of reactor physics tests. The MK-III design predictions are consistent with the performance test results obtained to date. Most of the C/Es are within 5% of unity. The measurements provided benchmark data for nuclear data library and testing reactor calculations. The JOYO MK-III will be ready to serve as a powerful irradiation test facility for the fast reactor development needs of JAPAN and the world.

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Table 1. Main Core Parameters of JOYO MK-II and MK-III

Specification			MK-III Core	MK-II Core
Reactor Thermal Power		(MWt)	140	100
Max. Number of Driver Fuel*			85	67
Equivalent Core Diameter		(cm)	80	73
Core Height		(cm)	50	55
^{235}UEnrichment		(wt%)	18	18
Pu Content: Pu/(Pu+U)		(wt%)	23/30**	30
Fissile Pu Content: (^{239}Pu+^{241}Pu)/(Pu+U)		(wt%)	16/21**	21
Max. Linear Heat Rate of Fuel Pin		(W/cm)	420	400
Max. Burn-up of Fuel(Pin Average)		(GWd/t)	90	75
Total Neutron Flux		(n/cm^2・s)	5.7x10^{15}	4.5x10^{15}
Fast Neutron Flux		(n/cm^2・s)	4.0x10^{15}	3.2x10^{15}
Number of Control Rod	In the 3rd Row		4	6
	In the 5th Row		2	0
Reflector/Shielding			SUS/B_4C	SUS/SUS
Flow Rate of Primary Sodium		(t/h)	2,700	2,200
Primary Coolant Temperture (Inlet/Outlet)		(℃)	350/500	370/500
Operation Period per Cycle		(day)	60	70

*Includeing "Number of Irradiation Test Fuel"
**Inner Core / Outer Core

Table 2. Period Method Results of the Total Worth

Rod	Exp. Worth (%Δk/kk')	Base Calc. (%Δk/kk')	Bias Factor	Biased Calc. (%Δk/kk')	C/E
1	2.09 ±0.07	2.01	1.00	2.01	0.96
2	0.80 ±0.03	0.80	0.98	0.79	0.98
3	2.03 ±0.07	1.97	1.00	1.99	0.97
4	2.08 ±0.07	2.01	1.00	2.01	0.97
5	0.78 ±0.03	0.80	0.98	0.79	1.00
6	2.06 ±0.07	1.97	1.00	1.97	0.96

Table 3. Rod Worths (295-650mm) Measurements from Two Approaches

Rod	Period Method (%Δk/kk')	Juggling (%Δk/kk')
1	1.13	1.14
3	1.11	1.12
4	1.13	1.14
6	1.14	1.15

Table 4. Shadowing Experiment Results

Measured Rod No.	Shadow Rod No.	Change in Rod Worth	
		Exp.	Cal.
1	4	+6%	+4%
1	6	-7%	-7%
5	3	+6%	+6%
5	6	-14%	-14%

Table 5. Isothermal Temperature Coefficient

	Temperature Direction	Isothermal Temp. Coef. (%Δk/kk'/ °C)		C/E
		Exp.	Cal.	
1	ascending	-0.00370	-0.00368	0.995
2	ascending	-0.00375		0.981
3	descending	-0.00386		0.952
4	descending	-0.00385		0.955

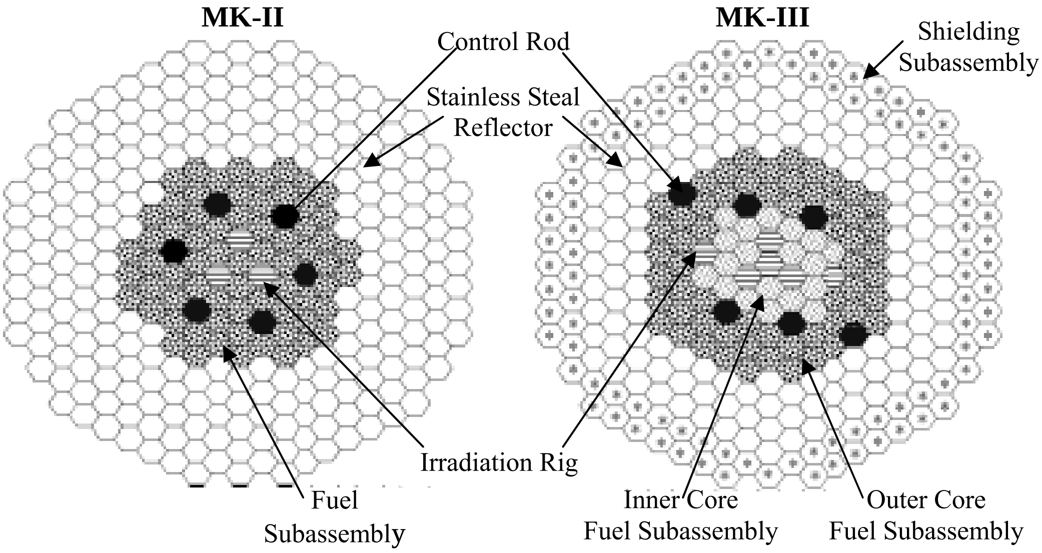

Fig. 1. Comparison of JOYO MK-II and MK-III cores

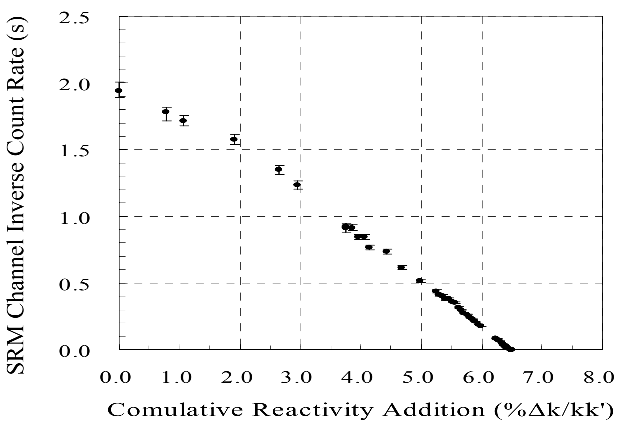

Fig. 2. MK-III Initial Approach to Criticality

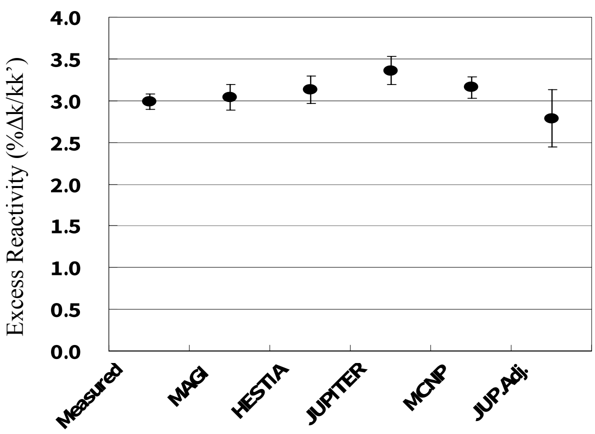

Fig. 3. Measured and Calculated Excess Reactivity

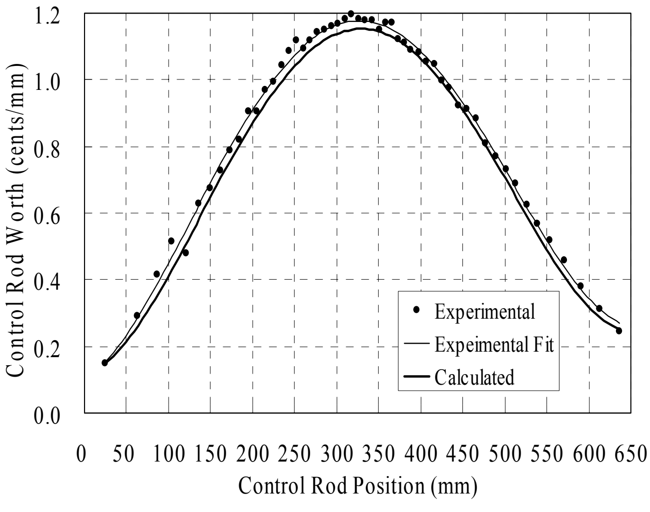

Fig. 4. Comparison of Calculated and Measured Axial Rod Worth Profile

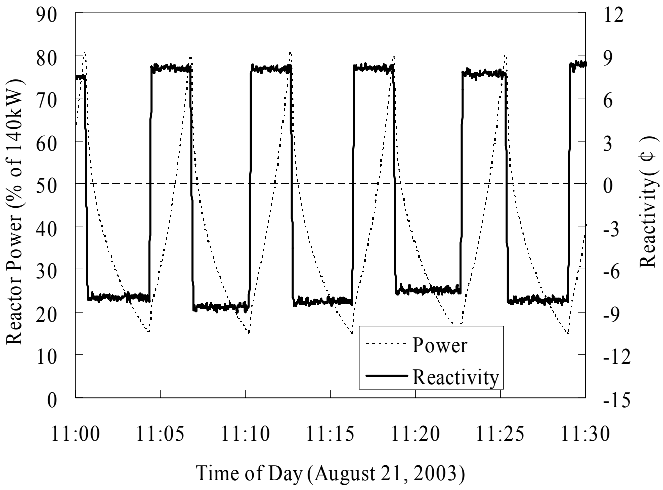

Fig. 5. Reactivity and Power Traces from a Juggling-Type Rod Calibration

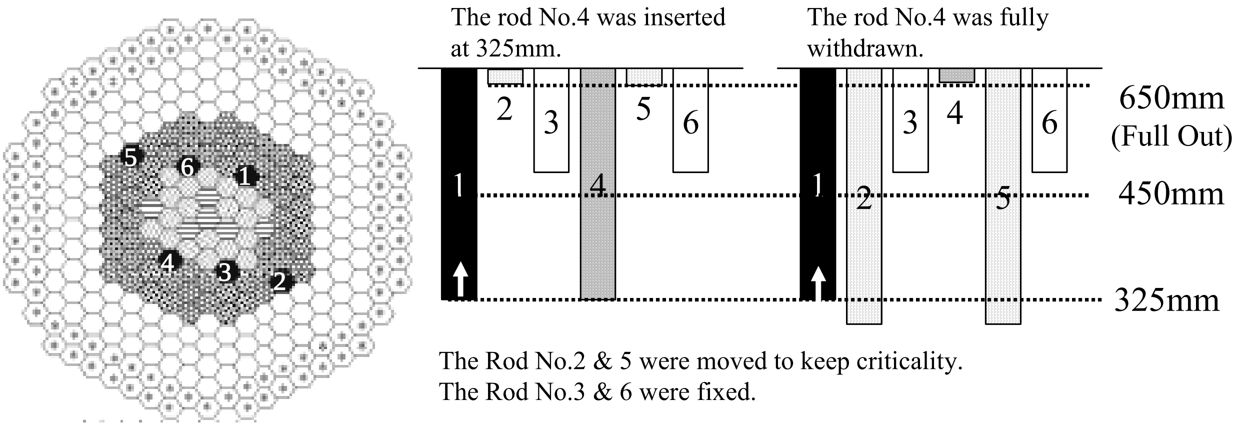

Fig. 6. Control Rod Pattern of Shadowing Effect Measurements

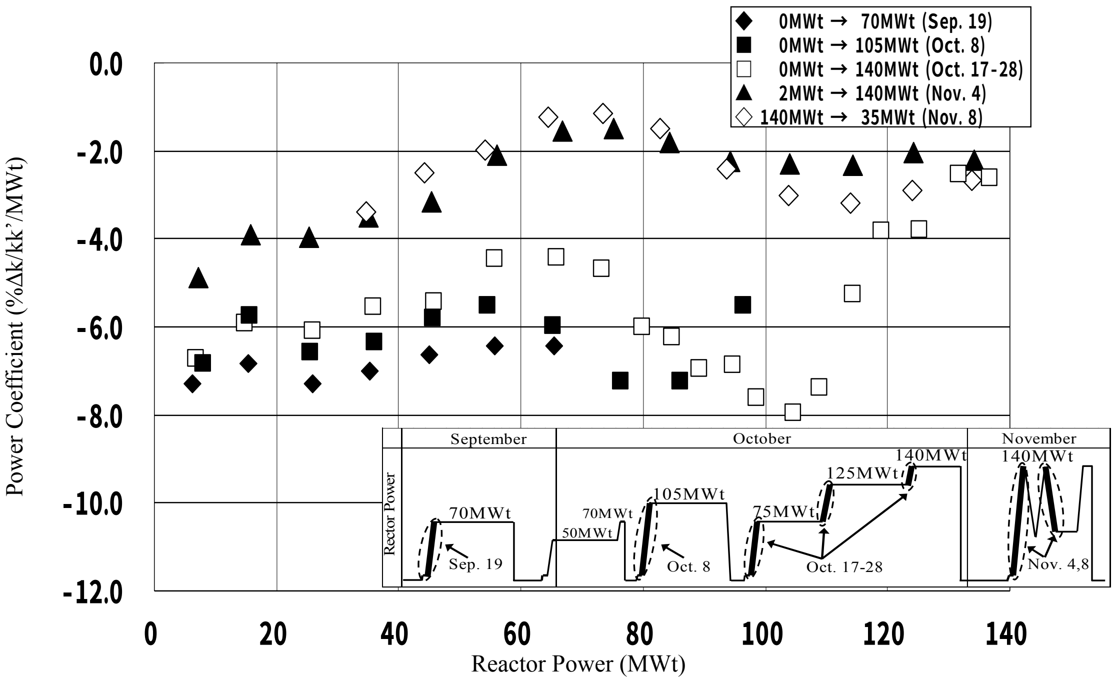

Fig. 7. Power Coefficient Measurements Results