Investigation of JRR-3 Control Rod Worth

Changed with Burn-up of Follower Fuel Elements

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Abstract.

In JRR-3, control rod worth (CR worth) has been measured in an annual periodical inspection by inverse kinetics method (IK method). The CR worth is used for prediction of excess reactivity and estimation of control rod position at reactor start-up. Because the CR worth tends to be affected by burn-up of fuel, the CR worth would change noticeably when the fuel burn up or the burn-up distribution in the core changes with the fuel exchange. The paper is investigating the influence of the fuel burn-up on the CR worth. These results show that the CR worth is affected by relation between follower fuel burn-up and the local burn-up around the control rod.

1. Introduction

The JRR-3(Japan Research Reactor No.3) has 6 control rods (Sa-1, Sa-2, S-1, S-2, R-1, and R-2), and the control rod worth (CR worth) has been measured in an annual periodical inspection by inverse kinetics method (IK method). The CR worth is one of the important data for management of reactor operation, and used for the prediction of control rod position at start-up and the estimation of the excess reactivity during the reactor operation. Because the CR worth would be affected by fuel burn up, the difference between the measured CR worth and the actual one would be enlarged as the fuel burns up. In particular, the CR worth would change after the fuel exchange. For these reasons, it must be necessary to grasp the CR worth precisely to operate the reactor more safely.

Table 1 shows the CR worth measured in 7 years. It is shown that the maximum difference in the total worth is about 3.1%Δk/k and would be caused by the difference in burn-up. In the paper, the CR worth in different burn-up is calculated by simulating the measurement with IK method, and the influence that the burn-up of fuel gives to CR worth is investigated by the result.

Table 1. Control Rod Worth of JRR-3 Measured by IK method

Fiscal Year	R-1	R-2	S-1	S-2	Sa-1	Sa-2	Total
2000	3.949	3.942	4.140	4.237	4.818	5.017	26.103
2001	3.344	3.263	3.393	3.553	4.665	4.768	22.986
2002	3.562	3.552	3.752	3.764	4.219	4.319	23.168
2003	3.490	3.500	3.858	3.806	4.327	4.196	23.177
2004	3.755	3.947	3.752	3.663	4.029	4.127	23.273
2005	3.728	3.671	3.768	3.941	4.371	4.490	23.969
2006	3.890	3.792	3.820	3.950	4.242	4.319	24.013

(unit: %Δk/k)

2. Outline of JRR-3

JRR-3 is a light water moderated and cooled, beryllium and heavy water reflected pool type research reactor with maximum thermal power of 20MW using low enriched uranium (LEU) plate-type fuels. The reactor core of the JRR-3 is composed of 26 standard fuel elements, 6 follower fuel elements with neutron absorber, and 12 pieces of beryllium reflector, and installed on the bottom of the reactor pool. A heavy water tank is installed around the core. An operation cycle is continuous operation for 26 days, seven operation cycles are conducted for a year. Figures 1 and 2 show the overview of JRR-3 and the schematic view of control rod. Tables 1 and 2 show specification of JRR-3 and the control rod.

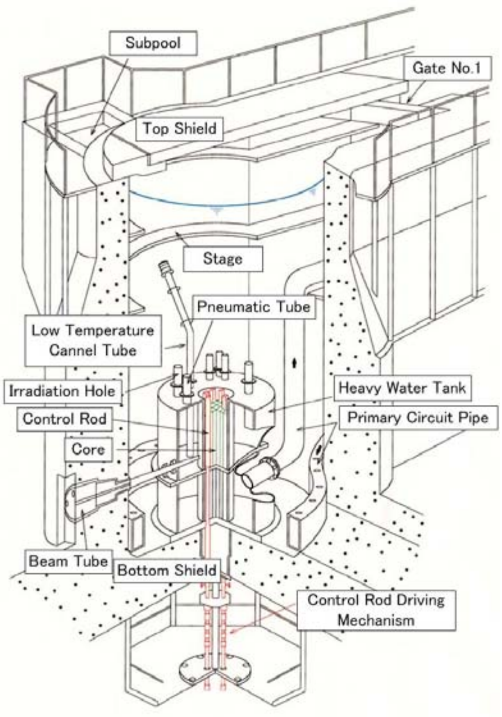

FIG. 1. Overview of JRR-3

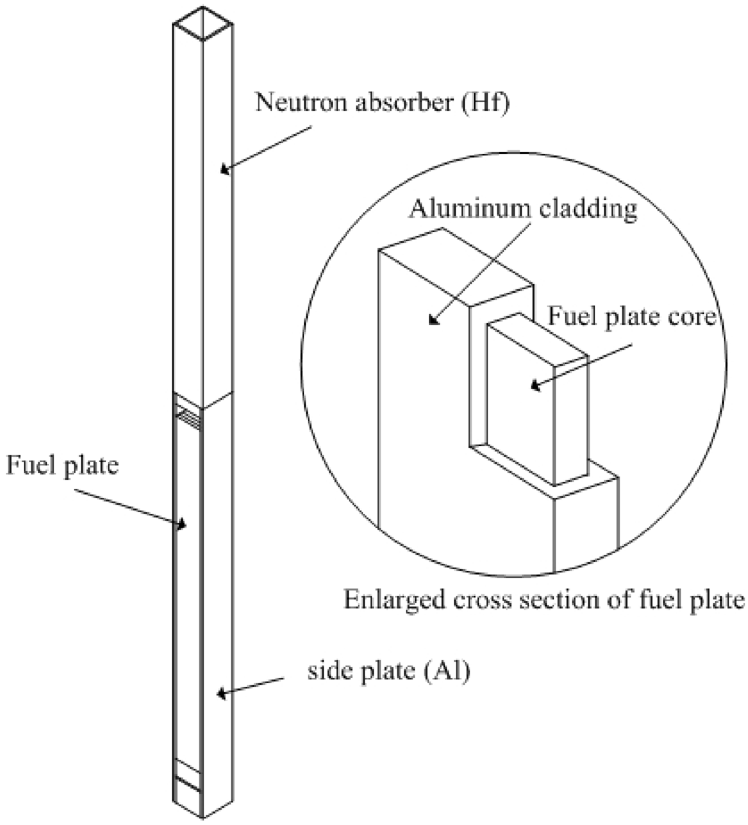

FIG. 2. Control Rod of JRR-3

Table 2. Specification of JRR-3

Name	JRR-3 (Japan Research Reactor No.3)
Purpose	Beam Experiments, Irradiation tests of fuels and materials, RI production, Activation analysis
Type	Light water moderated and cooled, pool type reactor with low-enriched uranium
First Criticality	Mar.22 1990 with alminide fuel core Sep.17 1999 with silicide fuel core
Maximum Thermal Output	20,000kW
Shape and Size of Reactor Core	Cylindrical, ϕ0.6m.0.75mH
Coolant	Light water
Fuel	26 standard type, 6 follower type
Control Rod	Hafnium ; 6
Operation Mode	Cycle operation ; 26 days/cycle

Table 3. Specification of Control Rod of JRR-3

(1) Neutron Absorber	
Material of absorber	Hafnium
Size of Neutron Absorber	64 x 64 x 800 [mm]
Atom Density of Hf	4.4873 x 10^{-2} [atom/cm^3]
(2) Follower Fuel	
Size of Fuel	64 x 64 x 880 [mm]
U-235 Enrichment	19.75 %
U-235 Contents	302 [g]
Size of Fuel Plate	1.27 x 60 x 770 [mm]
Fuel Plate Number	17/Element
Fuel Plate Material	Dispersed U_3Si_2-Al
Cladding Material	Aluminium Alloy

3. The method of the Investigation

3.1. Factor to change CR worth

The following factors would affect the CR worth.

- Burn-up of neutron absorber.
- Burn-up of follower fuel
- Burn-up distribution in the reactor core.

3.2. Calculation model

The CR worth was calculated with simulating the IK method using MCNP code (A General Monte Carlo N-Particle Transport Code), Version 5. Continuous-energy nuclear and atomic data libraries, ENDF/B-VI cross-section libraries, were used. Figure 3 shows the calculation model of JRR-3 reactor core. Table 3 shows the comparison between the calculation results and the measurement ones. This shows that the calculation result agrees to the measurement result in the error range, and it is confirmed that the calculation results are reliable.

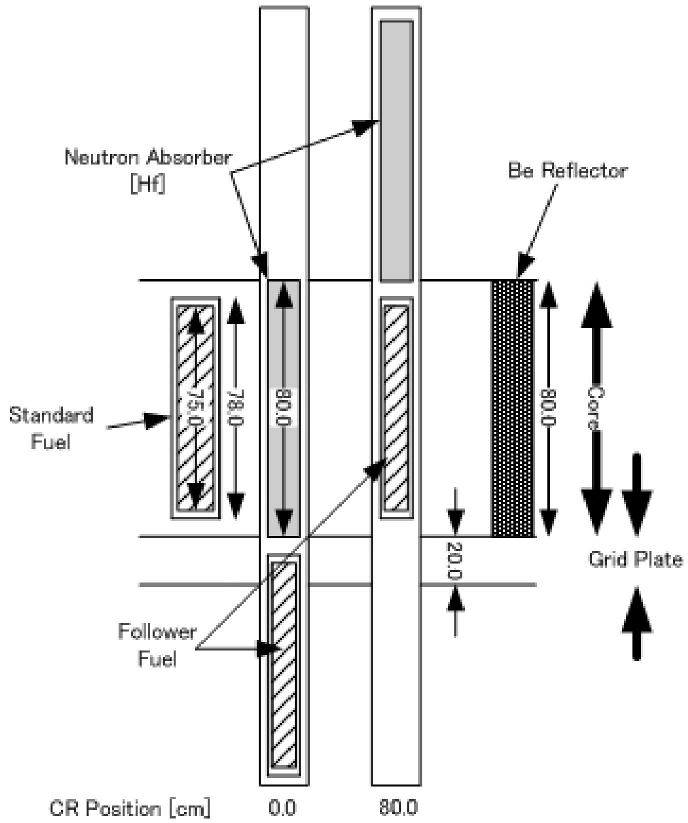

FIG. 3. Calculation Model

Table 4. Measurement Result and Calculation Result of the R-1,2 CR worth

Control Rod	Mesurement Result (%Δk/k)	Calcuration Result (%Δk/k)
R-1	3.210	3.190±0.08
R-2	3.463	3.379±0.09

4. Investigation of the factors

4.1. Burn-up of Neutron Absorber

Hafnium (Hf) is used as neutron absorber in JRR-3. Neutron absorption cross section of Hf is large, and the isotopes produced by neutron absorption have similar cross sections. Table 5 shows the abundance ratio and the thermal neutron absorption cross section of the Hf isotope. The ^{181}Hf becomes the ^{181}Ta by β decay in half-life of 45 days, and $^{181}Ta(n,\gamma)^{182}Ta$ has about 21barns as the thermal neutron absorption cross section. That is why ability as the neutron absorber does not change by burn-up greatly.

Table 5. The abundance ratio and the thermal neutron absorption cross section of the Hf isotope

Isotope	Abundance ratio (%)	Thermal Neutron Cross Section (barns)
^{174}Hf	0.16	400
^{176}Hf	5.21	<30
^{177}Hf	18.56	370 to ^{178}Hf
		1.4 to ^{178m}Hf
^{178}Hf	27.1	30 to ^{179}Hf
		50 to ^{179m}Hf
^{179}Hf	13.75	65 to ^{180}Hf
		0.2 to ^{180m}Hf
^{180}Hf	35.22	10
$_{72}$Hf	100	105

4.2. Burn-up of follower fuel

Table 6 and figure 4 show the change of CR worth of R-1 when follower fuel is burned up from 0% to 40% in the core with different average burn-up. In the equilibrium core, the average burn-up of reactor core is from 20% to 40%. In the initial core (average burn-up is 0%), the range of change of CR worth with follower fuel burn up is less than 0.1%Δk/k. In the equilibrium core, when follower fuel burn-up is lower than the average burn-up, the worth become smaller as follower fuel burn-up increaces. And when follower fuel burn-up becomes higher than average burn-up, the worth does not change so much. The reason is as follows: When follower fuel burn-up is lower than average burn-up of core, it is easy to fission than other fuel. Therefore the reactivity change by the burn-up of follower fuel is large, and the influence is large. But when follower fuel burn-up is higher than average burn-up, it is hard to fission than other fuels. Therefore the reactivity change by the burn-up of follower fuel is small, and the influence to give CR worth is very small.

Table 6. Calculation result of the R-1 CR worth in the different burn-up of follower fuel

Average Burn-up of Reactor Core	Burn-up of Follower Fuel				
	0%	10%	20%	30%	40%
0%	3.08±0.08	3.00±0.08	3.01±0.07	3.03±0.08	2.99±0.08
20%	2.87±0.08	2.73±0.07	2.65±0.08	2.60±0.08	2.62±0.08
30%	2.79±0.08	2.71±0.08	2.64±0.08	2.49±0.07	2.50±0.08
40%	2.77±0.07	2.67±0.08	2.59±0.08	2.49±0.07	2.43±0.08

(unit: %Δk/k)

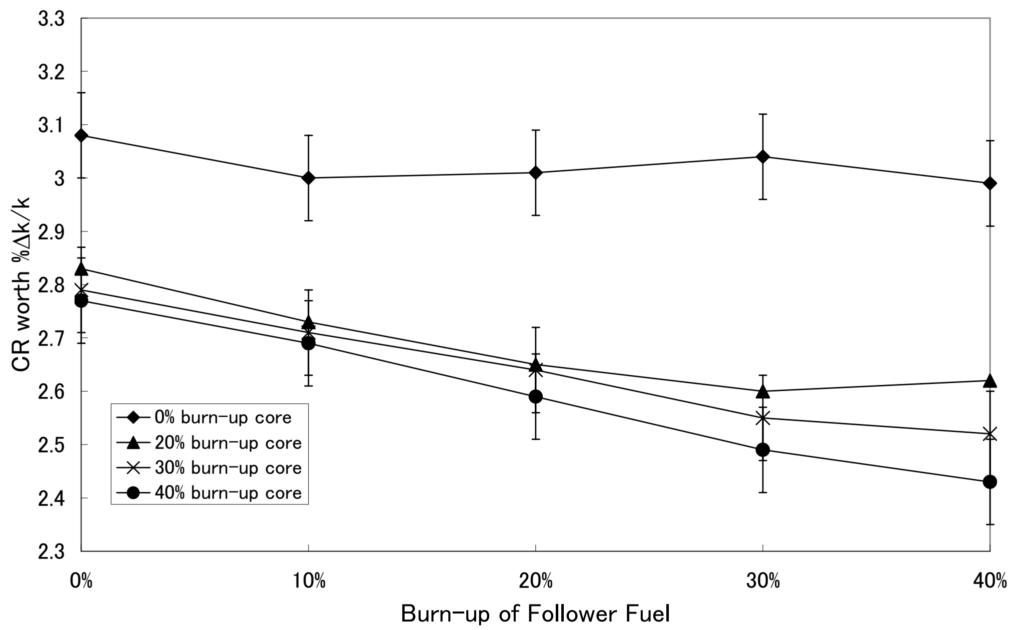

FIG. 4. The R-1 CR worth and the burn-up of follower fuel

4.3. Burn-up distribution of reactor core

Figure 5 shows the burn-up distribution in the core at the end of R3-19-05 cycle (the fifth cycle in JFY 2007) and the beginning of the R3-19-06. Between R3-19-05 cycle and R3-19-06 cycle, 12 fuel elements were exchanged (4 standaerd fuels and 4 follower fuels are new, 4 standard fuels are shuffled). Therefore the burn-up distribution in the core was changed appreciably. Average burn-up of R3-19-05 cycle reactor core is 38.4% ,and that of the R3-19-06 cycle is 25%. Table 7 shows the calculation result of the CR worth at the end of R3-19-05 cycle and the beginning of the R3-19-06. The calculation results of one control rod and the all rods show a difference of 0.27 %Δk/k and 1.09 %Δk/k at a maximum, respectively. This shows that the local burn-up around the control rod affected the change of CR worth.

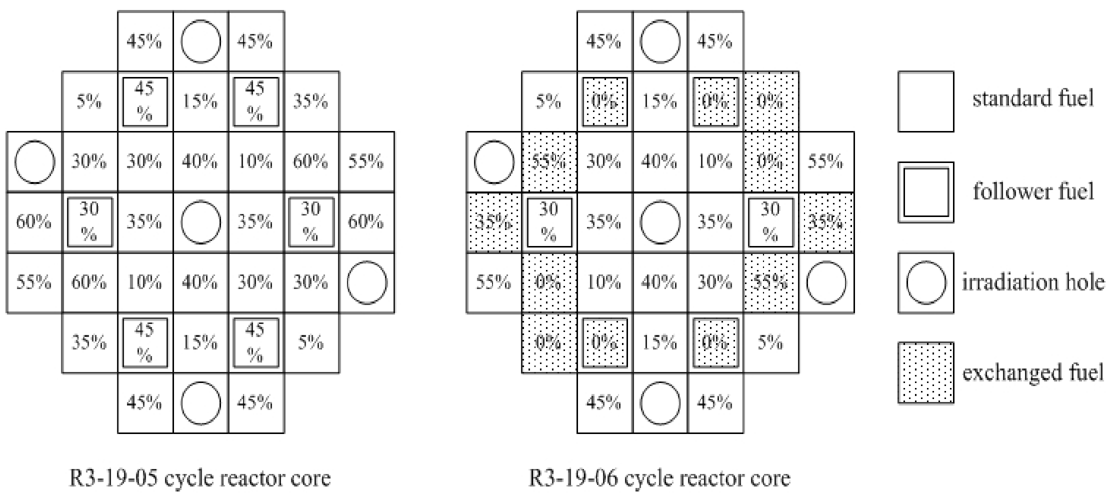

FIG. 5. Burn-up distribution of the reactor core

Table 7. The calculation result of CR worth in the different burn-up distribution of reactor core

	CR worth (%Δk/k)	
Control rod	R3-19-05 cycle (before fuel exchange)	R3-19-06 cycle (after fuel exchange)
R-1	3.14±0.08	3.36±0.08
R-2	3.54±0.08	3.72±0.08
S-1	3.19±0.08	3.34±0.08
S-2	3.23±0.08	3.50±0.08
Sa-1	4.12±0.08	4.27±0.08
Sa-2	4.24±0.08	4.36±0.08
Total	21.46±0.21	22.55±0.19

5. Conclusion

The factors to affect the CR worth in JRR-3 are investigated. The results are as followed.

- The influence of the burn-up of neutron absorber is very small, because the neutron absorption cross section of the daughter nuclide of the hafnium is large.
- When follower fuel burn-up is lower than the average burn-up of reactor core, the influence of the burn-up of follower fuel is large.
- The influence of the local burn-up around the control rod is large.

These results show that the change of CR worth is affected by relation between follower fuel burn-up and the local burn-up around the control rod. For the precise estimation of the CR worth, it is important to grasp not only a core average burn-up and follower fuel burn-up but also the burn-up of each fuel element precisely.Using these results, the convinient method to estimate the CR worth would be established.

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