NEUTRONICS EXPERIMENT RESULTS IN COMMISSIONING STAGE B OF JRTR

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ABSTRACT

Various neutronics experiments has been carried out in a stage of low power test of the Jordan Research and Training Reactor (JRTR). In particular, the approach to first criticality was performed very carefully as the Control Absorber Rod (CAR) withdrawal to get the criticality following the 1/M method. The experiments for measuring the excess reactivity and CAR worth were based on the rod-swap method. A series of calculations for these experiments were performed using the McCARD code. As a result, the difference between the calculated and measured CAR heights was less than 5 mm during the first criticality, and the calculated and measured excess reactivities were 12.1937 $ and 10.7493 $, respectively. In addition, the shape curves for the differential CAR worth were similar in the calculation and measurement, and their discrepancies for the integral CAR worth were less than 15%. Finally, the calculated and measured void coefficients were -0.2605 $/%void and -0.237 $/%void, respectively. From the above-mentioned results, it was confirmed that the JRTR was satisfied with the safety requirements established in the design specification and safety analysis report.

1. Introduction

The Jordan Research and Training Reactor (JRTR) owned by the Jordan Atomic Energy Commission (JAEC) is an open tank-in-pool type of 5 MW in thermal power, which was aimed at the research and development, education and training, and to produce medical and industrial radioisotopes. The construction permit of the JRTR was issued in 2013 by the Jordan regulatory body, the Energy and Mineral Regulatory Commission (EMRC), and its first criticality reached on 25 April, 2016 and the commissioning tests have been completed in 2016. The JRTR commissioning program can be classified briefly into three stages: Stage A, B, and C, and in particular, various neutronics experiments are included in the stage B such as the first criticality approach and measurements of excess reactivity, Control Absorber Rod (CAR) worth, void coefficient, kinetic parameters, and neuron flux.

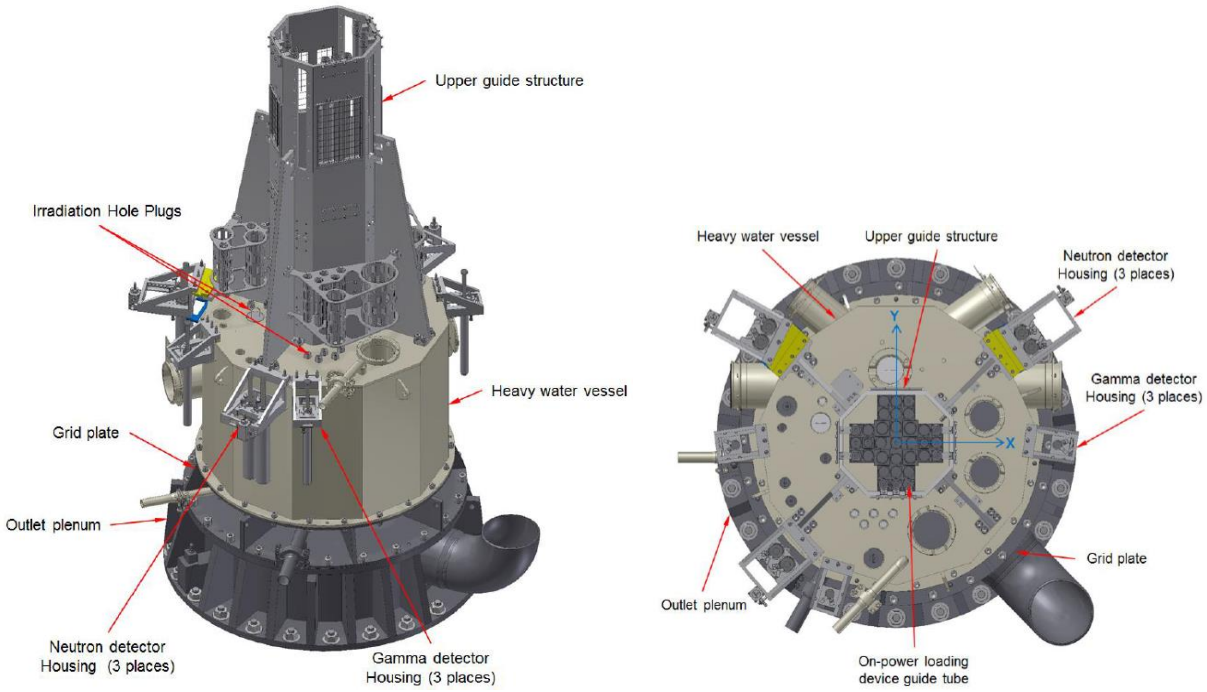
In these tests, two BF_3 counters and three wide-range fission chambers for a reactor regulating system (RRS) were simultaneously used for the reactivity measurement. A data acquisition system called NDASS was introduced for reading the neutron power signal from these detectors. It calculates the reactivity from the inverse point kinetics equations [1], and graphically displays them in real time. For the nuclear design and analysis of the JRTR, the Monte Carlo Code for Advanced Reactor Design and analysis (McCARD) code was used as the main code, which has been developed for a neutronics analysis of a neutron multiplying medium [2]. In addition, a series of calculations for neutronics experiments were performed using the ENDF/B-VII.0 nuclear library generated by the NJOY code, and this paper presents a comparison of the calculated and measured results for some neutronics tests conducted during commissioning stage B of the JRTR.

2. Core configuration of JRTR

The nuclear fuel loaded in the JRTR is a Material Test Reactor (MTR)-type fuel assembly which has been technically well proven through long irradiation experiences in many research reactors worldwide [3]. A Fuel Assembly (FA) consists of 21 Low Enriched Uranium (LEU) fuel plates (19.75 wt% ^{235}U), and the fuel meat positioned between aluminium claddings is made of fine U_3Si_2 particles homogeneously dispersed in a continuous aluminium matrix. The initial core of the reactor was composed by using fuel assemblies of varying uranium densities (from 1.9 to 4.8 gU/cc), but it will be changed to several transition core configurations before reaching the equilibrium core.

The JRTR has two kinds of reflectors (beryllium and heavy water). Beryllium, in particular, is used as an inner reflector, which is surrounded by an outer reflector of heavy water in a Zircaloy-4 vessel designated as a Heavy Water Vessel (HWV). The reactivity control is performed by two kinds of mechanism: a Control Rod Drive Mechanism (CRDM) and a Second Shutdown Drive Mechanism (SSDM). Four CRDMs are activated to adjust the core reactivity during normal operation, on the other hand, two SSDMs are used as a secondary means to shut down the reactor by dropping the Second Shutdown Rods (SSRs) by gravity when a reactor trip signal is occurred. The neutron absorption materials of CAR and SSR are hafnium and Boron Carbide (B_4C), respectively.

The Reactor Structure Assembly (RSA) consists of an outlet plenum, grid plate, HWV, upper guide structure above the HWV, and detector housings, which provides the flow path for primary coolant and supports for FAs, reflectors, and neutron and gamma detectors. Three neutron and three gamma-ray detectors are installed around the outer shell of the heavy water vessel, and the radial position of neutron detector can be adjusted at a proper position. The general and X-Y plan views of RSA are shown in Figure 1.



(a) General view (b) X-Y plan view

Fig. 1. Reactor structure assembly

3. Neutronics experiments

3.1 Fuel loading and approach to criticality

The first experiment of low power test was performed to comprise the initial critical core by replacing aluminium dummy fuel assemblies in the core by actual fuel assemblies one by one, and through this result, it was confirmed whether the initial criticality could be achieved at the initial critical core predicted by the neutronics calculation. A total of 18 fuel assemblies are loaded into the core of JRTR, and their loading sequence and position are shown in Figure 2.

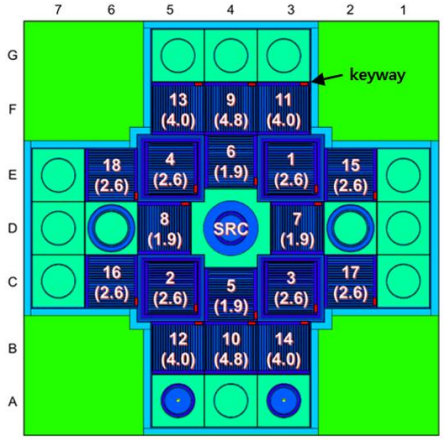


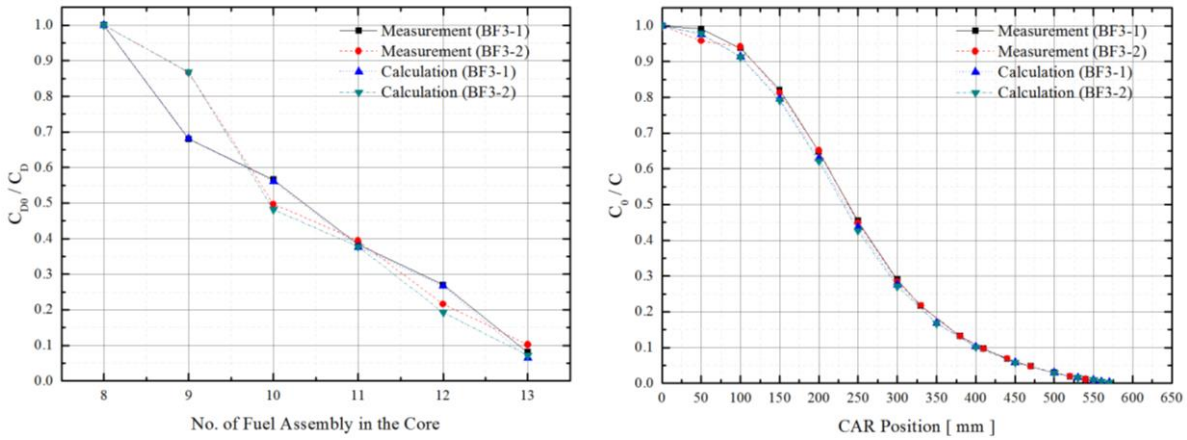
Fig. 2. Fuel assembly loading sequence (Uranium density)

The approach to the first criticality of the JRTR was progressed on the basis of the inverse multiplication method (1/M), of which the detailed contents are as follows. When a neutron source or nuclear fuel is additionally inserted in a subcritical core ($k_{eff} < 1$), the neutron population is converged to a certain value after an exponential increase, and the converged value is inversely proportional to the reactivity of the core [4]. This phenomenon is called an inverse multiplication, and the neutron density and reactivity relationship can be described as

$$\frac{1}{\mathrm{n}} = -\frac{\rho}{\Lambda s} \tag{1}$$

where n is the neutron population, Λ is the neutron reproduction time, s is the neutron source intensity, and ρ is the reactivity defined by $1 - \frac{1}{k_{eff}}$, where k_{eff} is the effective multiplication factor. As the subcritical core becomes close to the critical state ($k_{eff} = 1$), the value of Eq.(1) is converged to 0, and therefore, the critical mass can be predicted by investigating the trend of $\frac{1}{n}$ versus a number of FAs, before next FA loading. In addition, as with a procedure of finding the critical mass, the critical CAR position can be predicted by investigating the trend of $\frac{1}{n}$ versus the CAR position, instead of a number of FAs.

In this test, a series of measurements were performed with two BF_3 counters installed at a position close to the core, and the change analysis on 1/M was started from the 8th FA. Figure 3 shows a comparison of the calculated and measured results for a number of FAs and the critical CAR position. In Figure 3(a), the initial criticality was achieved at the initial critical core, loaded with 14 FAs, predicted through the neutronics calculation. In addition, the calculated and measured CAR heights for the first criticality were 575 mm and 570.5 mm, respectively, that is, the difference between the two results was only within 5 mm.



(a) Minimum critical number of FAs (b) Critical CAR position

Fig. 3. Calculated and measured results for initial criticality

3.2 Excess reactivity measurement

The second experiment was the excess reactivity measurement, which was performed to determine the excess reactivity of the first cycle operational core by loading additional fuel assemblies one by one from the minimum critical core. First, the excess reactivity of minimum critical core was measured by investing each CAR worth from the critical position to fully withdrawn position, then fuel assemblies are added to the minimum critical core one by one, until the core is fully loaded. The CAR worth is measured from the critical CAR position of the current core to that of the previous core, and the excess reactivity of the new core is determined.

The calculated and measured critical CAR positions are summarized in Table 1. The critical positions were calculated at a water temperature of 35°C because the cross section libraries were made at a 5°C interval, and the library at the nearest temperature was selected for the McCARD calculation. As shown in the table, the calculated critical CAR position was only 1.0−1.3 mm lower than the other one, which corresponds to the reactivity differnece less than 0.7 mk.

No. of FAs	Calculation	Measurement		Difference (mk)
	CAR Position (mm)	CAR Position (mm)	T (°C)	
14	565.4	566.6	34.1	0.26
15	453.6	454.8	34.0	0.39
16	398.4	399.4	34.1	0.58
17	344.8	346.1	34.0	0.62
18	310.4	311.5	34.1	0.66

Table 1. Measured and calculated critical CAR positions in excess reactivity measurement

For the minimum critical core, each CAR worth ($\Delta\rho_{CARi}$) from the critical position to the fully withdrawn position was measured using a reactivity meter without a neutron source, and Eq.(2) was used to estimate the excess reactivity of the minimum critical core, ($\Delta\rho_{14}$). Excess reactivity of the first cycle operation core with 18 FAs was estimated by adding the reactivity worth of each new fuel assembly to the excess reactivity of the minimum critical core. When

a CAR was moved up, the other three CARs were moved down step by step to compensate the positive reactivity.

$$\Delta\rho_{14} = \Delta\rho_{14CAR1} + \Delta\rho_{14CAR2} + \Delta\rho_{14CAR3} + \Delta\rho_{14CAR4} \quad (2)$$

$$\rho_{ex} = \sum\Delta\rho = \Delta\rho_{14} + \Delta\rho_{15} + \Delta\rho_{16} + \Delta\rho_{17} + \Delta\rho_{18}$$

Table 2 shows the excess reactivity of the minimum critical core, the fuel worth of each core, and the excess reactivity of the operation core estimated from the experimental data and the calculation. The estimated excess reactivity of the operation core (18 FAs) was 10.7493 $ from the measurement, whereas the calculated one was 12.1937 $. The relative difference between the measurement and the calculation was 11.85% when the calculation rigorously simulates the experiment. The rigorous simulation requires a lot of computing time because of so many cases to be calculated and the long computing time required to reduce the standard deviation of k_{eff}.

Core	Calculation ($)		Measurement ($)		Difference (%)
	$\Delta\rho_i$	$\sum\Delta\rho_i$	$\Delta\rho_i$	$\sum\Delta\rho_i$	
14th FA	1.0676	1.0676	0.8958	0.8958	16.09
15th FA	2.8940	3.9616	2.4866	3.3824	14.62
16th FA	2.4032	6.3648	2.1293	5.5117	13.40
17th FA	3.1789	9.5437	2.7823	8.2940	13.09
18th FA	2.6500	12.1937	2.4553	10.7493	11.85

Table 2. Comparison of fuel worth value in calculation and measurement

3.3 Rod worth measurement

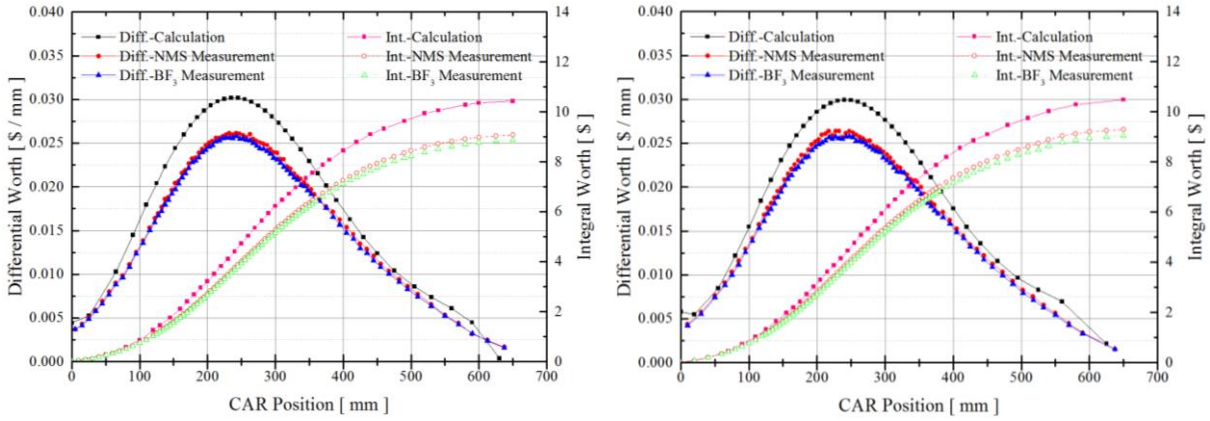
Because the CAR reactivity worth with respect to the position is an important parameter for the reactor operation, each CAR has position indicators, and its position is always monitored by reactor operators. Thus, the third test was performed to measure the integral and differential worth of each CAR, which was based on the rod swap method [5]. Because the CAR positions for the criticality were very different with those in the excess reactivity measurement, some measurements were additionally performed for specific conditions, such as a CAR was fully withdrawn or fully inserted into the core (see Table 3). As shown in the table, the measured critical CAR positions were well matched with the calculated results, and the largest deviation is only 0.54 mk.

Case		Critical CAR position (mm)				Core temp. (°C)	Difference (mk)
		CAR-1	CAR-2	CAR-3	CAR-4		
CAR-1 Up	Calculated	650.0	271.0			31.4	0.12
	Measured		270.8				
CAR-2 Up	Calculated	271.0	650.0	271.0		31.5	0.06
	Measured	270.9		270.9			
CAR-3 Up	Calculated	273.0		650.0	273.0	31.3	0.54
	Measured	272.1			272.1		
CAR-4 Up	Calculated	272.5			650.0	31.4	0.36
	Measured	271.9					

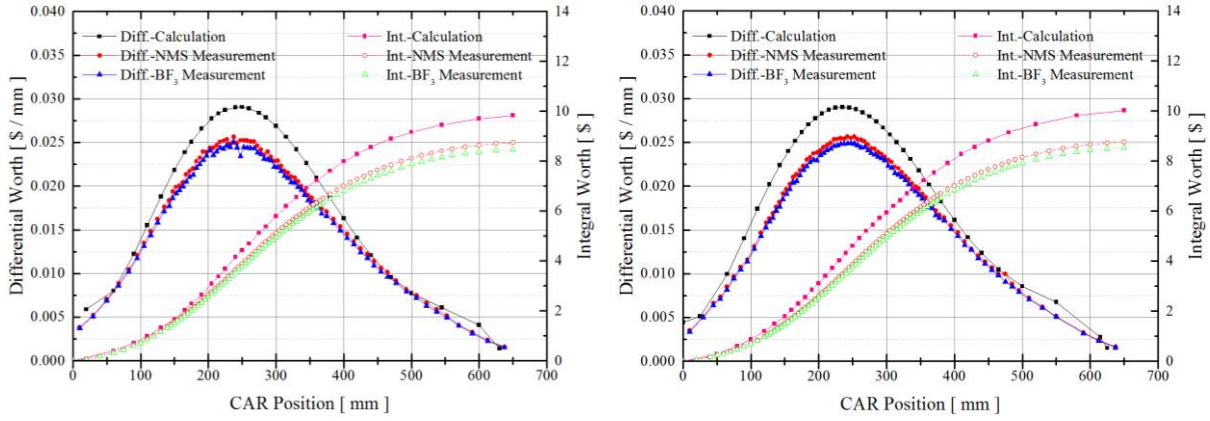
Swap for CAR-1	Calculated	0.0	376.7		650.0	31.4	0.41
	Measured		374.9				
Swap for CAR-2	Calculated	379.5	0.0	650.0	379.5	31.5	0.44
	Measured	377.5			377.5		
Swap for CAR-3	Calculated	368.9	650.0	0,0	368.9	31.4	-0.14
	Measured	369.5			369.5		
Swap for CAR-4	Calculated	650.0	371.7		0.0	31.4	0.27
	Measured		370.5				

Table 3. Measured and calculated critical CAR positions in rod worth measurement

The rod-swap started with a CAR full-down, opposite CAR full-up, and the other two CARs at a critical position. The positive reactivity by slightly moving up the full-down CAR was measured, and the increased reactor power was then adjusted to the level of the initial state by slightly moving down the full-up CAR. These works were repeated until the full-down CAR was fully up. The average count rates of the BF_3 detectors in the thermal column and the average readings of the NMSs were used for the reactivity measurement. Figure 4 shows a comparison of the measured and calculated results, and their integral worth values are presented in Table 4. The shapes of all measured and calculated worth curves are similar, but almost all calculated values are larger than the measurements. Among the measured values, those based on the NMS average signal were usually a little larger than those based on the average count rate of the BF3.



(a) CAR-1 (b) CAR-2



(a) CAR-3 (b) CAR-4

Fig 4. Differential and integral CAR worth

As shown in the table, the measured integral CAR worth values were about 11–15% smaller than the calculation. In particular, the integral CAR worth measured from the BF_3 detectors are 13.8–14.9% smaller, and those from NMSs were 11.2–12.9% smaller than the calculation.

		Integral CAR worth ($)			
		CAR-1	CAR-2	CAR-3	CAR-4
Measurement	BF_3	8.88	9.05	8.47	8.53
	NMS	9.08	9.30	8.74	8.76
Calculation		10.43	10.49	9.93	10.03
Deviation	BF_3	-14.9%	-14.6%	-13.8%	-14.9%
	NMS	-12.9%	-12.3%	-11.2%	-12.6%

Table 4. Comparison of measured and calculated integral CAR worth

3.4 Measurement of void reactivity coefficient

The coolant void reactivity is the change in reactivity due to coolant voiding, which is an important parameter for the reactor core design. For the inherent safety of the core, the coolant void reactivity coefficient shall be negative as in the case of a fuel temperature coefficient; hence, it was performed to prove that the void reactivity coefficient is negative from the experiments.

The coolant void was simulated by inserting the void simulators into gaps between adjacent fuel plates, and a void simulator was made of aluminium owing to its low neutron absorption and scattering. When the aluminium plates were inserted into all fuel assemblies, the void fraction was 4.74%. It was 2.37% for one half of the fuel assemblies. The coolant void reactivity was measured based on the difference in the critical positions of the CARs between with and without void simulators in the fuel assemblies of the core.

The void reactivity coefficient (α_{void}) of the core was the amount of reactivity change ($\Delta\rho_{void}$) caused by a unit change of the void fraction (γ_{void}), and α_{void} was calculated using $\Delta\rho_{void}/\gamma_{void}$. The value of γ_{void} was calculated based on the total volume of the inserted void simulator divided by the total coolant volume of the active core. Table 5 shows the comparison results of the experiment and calculation. The void coefficient at a 2.37% void was a little larger than that at 4.74%, but not too different. The average values of the measured void coefficients are -0.237 $/%void, whereas the calculated value is -0.2605 $/%void.

	Critical position [mm]		Reactivity Worth [$]		Void Reactivity Coefficient [$/%void]	
	Measurement	Calculation	Measurement	Calculation	Measurement	Calculation
No void	311.0	309.5	0	0	-	-
2.37% void	318.1	316.3	-0.571	-0.641	-0.241	-0.271
4.74% void	325.0	323.2	-1.106	-1.186	-0.233	-0.250

Table 5. Comparison of measured and calculated void reactivity worths

4. Conclusions

To confirm the accuracy of the JRTR design and manufacturing, various neutronics experiments were performed during commissioning stage B, and this paper describes the results measured from zero power tests. The approach to first criticality was performed very slowly and carefully following the inverse multiplication method, and the calculated and measured CAR heights for the first criticality were 575 mm and 570.5 mm, respectively. That is, the difference between the calculated and measured results was only within 5 mm. In the excess reactivity measurement, when fuel assemblies were added to the minimum critical core one by one, the calculated critical CAR position was only 1.0–1.3 mm lower than the other one. In addition, the calculated and measured reactivities were 12.1937 $ and 10.7493 $, respectively, and the relative difference between two results was 11.85%. The calculated and measured shape curves for the CAR worth were similar, but the measured integral CAR worth values were about 11-15% smaller than the calculation. Finally, the void coefficient at a 2.37 %void was a little larger than that at a 4.74 %void, and average values of measured void coefficients were -0.237 $/%void, while the calculated one was -0.2605 $/%void. From the above-mentioned results, it was confirmed that the JRTR was satisfied with the safety requirements established in the design specification and safety analysis report.

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