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Original Article

Comparison of first criticality prediction and experiment of the Jordan research and training reactor (JRTR)

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ABSTRACT

Korea Atomic Energy Research Institute (KAERI) has carried out various neutronics experiments in the commissioning stage of the Jordan Research and Training Reactor (JRTR), and this paper introduces the results of first criticality prediction and experiment for the JRTR. The Monte Carlo Code for Advanced Reactor Design and analysis (McCARD) with the ENDF/B-VII.0 nuclear library was used for prediction calculations in the process of the first criticality approach, which was performed to provide reference for the first criticality experiment. In the experiment, fuel loading was carried out by measuring the inverse multiplication factor (1/M) to predict the number of fuel assemblies at the first criticality, and the first critical was reached on April 25, 2016. Comparing the first criticality prediction and experiment, the calculated and measured CAR (Control Absorber Rod) heights for the first criticality were 575 mm and 570.5 mm, respectively, that is, the difference between the two results was approximately 5 mm. From this result, it was confirmed that JRTR manufacturing and various experiments had successfully progressed as designed.

1. Introduction

Research reactors have played an important role in the development of neutron science, radioisotope production for medicine and industry, and quality improvement and validation of various materials through neutron irradiation. They can also be useful tools in support of present and future national nuclear power programs through development and testing of new reactor concepts and nuclear fuels, as well as in the development of human resources and skills [1]. For these reasons, many countries including the Republic of South Africa, Saudi Arabia, Kenya, etc., have established national plans to build new research reactors prior to the introduction of nuclear power plants.

The Jordan Research and Training Reactor (JRTR), owned by the Jordan Atomic Energy Commission (JAEC), is an open tank-in-pool type with 5 MW thermal power; it is located in the north of Jordan about 70 km from Amman. This reactor was built for research and development, education and training, production of medical and industrial radioisotopes, neutron activation analysis, etc. The construction permit of the JRTR was issued in 2013 by the Jordanian regulatory body, the Energy and Mineral Regulatory Commission (EMRC); first criticality (25 April) and reactor commissioning program were conducted in 2016. The major specifications of the JRTR are shown in Table 1.

For the nuclear design and analysis of the JRTR, the Monte Carlo Code for Advanced Reactor Design and analysis (McCARD) was used as the main code; this code has been developed for neutronics analysis of a neutron multiplying medium [2]. Also, a series of calculations for neutronics experiments were performed with the ENDF/B-VII.0 nuclear library generated by NJOY code [3]. Fuel was loaded according the predetermined sequence, and the inverse multiplication factor (1/M) was measured to predict the number of fuel assemblies and the critical position of control rod at the first criticality [4]. This paper presents the results of first criticality prediction and experiment for the JRTR.

2. Core configuration of the JRTR

The nuclear fuel of 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 [5]. A Fuel Assembly (FA) consists of 21 Low Enriched Uranium (LEU) fuel plates (19.75 wt% ^{235}U); the fuel meat, positioned between aluminum claddings, is made of fine U_3Si_2 particles

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Table 1
Major specifications of JRTR.

Reactor Type	Open-Tank-in-Pool
Thermal Power	5 MW
Coolant and Cooling Method	Light Water and Downward Forced Convection
Coolant Temperature	37 °C (Inlet) and 44 °C (Outlet)
Fuel	19.75 wt% enriched U_3Si_2–Al
Moderator	Light Water
Reflector	Beryllium and Heavy Water
Absorber Material	Hafnium and B_4C
Shielding Material	Water and Heavy Concrete

homogeneously dispersed in a continuous aluminum matrix. The first core of the reactor is composed using fuel assemblies of varying uranium densities (from 1.9 to 4.8 gU/cm^3), but this changes to several transition core configurations before reaching the equilibrium core to which fresh fuel assemblies with the uranium density of 4.8 gU/cm^3 are feed. In addition, the batch number and cycle length of equilibrium core are 18 and 39 days, respectively.

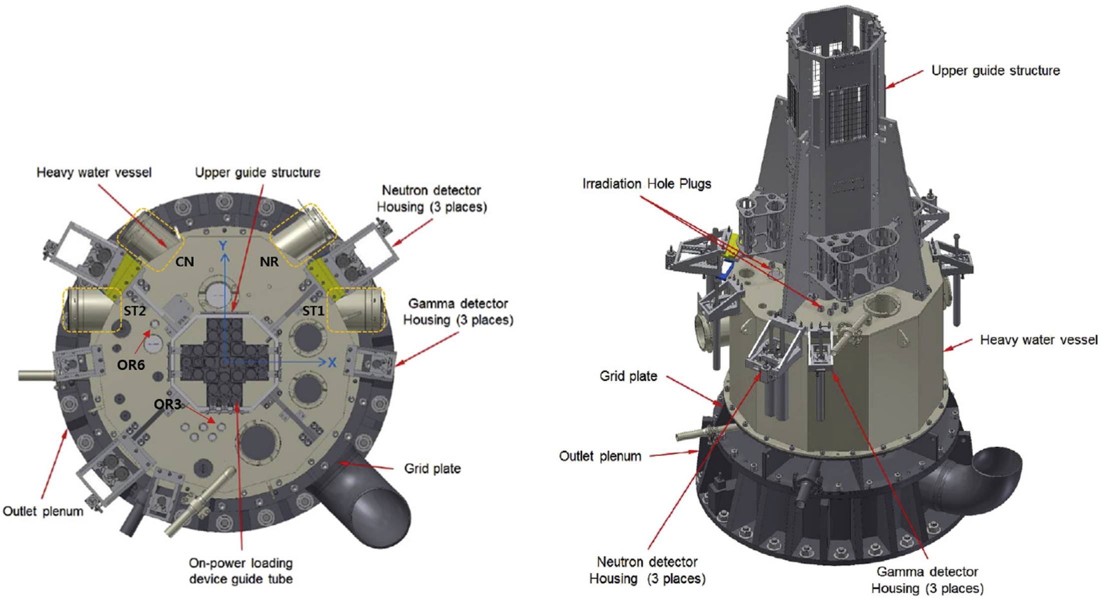
The JRTR has two kinds of reflectors (Beryllium and Heavy Water) and, especially, beryllium is used as the inner reflector, which is surrounded by an outer reflector of heavy water in a Zircaloy-4 vessel designated as the Heavy Water Vessel (HWV). Reactivity control is performed by two kinds of mechanisms: Control Rod Drive Mechanism (CRDM) and Second Shutdown Drive Mechanism (SSDM). Four CRDMs are activated to adjust core reactivity during normal operation, and they are also used as the primary means to shut down the reactor when a reactor trip is required by the Reactor Protection System (RPS), Alternate Protection System (APS), operators, etc. Two SSDMs are used as a diverse means to shut down the reactor through gravity drop-in of Second Shutdown Rods (SSRs). The neutron absorption materials of the Control Absorber Rod (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, all of which provides the flow path for primary coolant and support for FAs, reflectors, and neutron and gamma detectors (see Fig. 1). Almost all vertical irradiation facilities are located in the HWV, and the neutron beam tubes penetrate horizontally into the HWV. The JRTR has four Beam Port Assemblies (BPA) which provide a thermal neutron path between the core and the neutron experimental facilities. The standard BPAs (ST1 and ST2) can be used for research of material analyses and molecule movement when equipped with spectrometers and diffractometers. The Neutron Radiography (NR) BPA can be used for a nondestructive inspection and neutron tomography, and the Cold Neutron (CN) BPA has provisions for future installation of cold neutron research facilities. The reactor core is cooled by downward forced convection in power operation; however, it is cooled by natural convection in training mode of which the maximum power level is 50 kW and when the reactor is shut down.

A wide-range fission chamber (i.e., guarded fission chamber) is used as the neutron measurement system (NMS) that measures the thermal neutrons emitted outward from the reactor core [6]. The NMS has the capacity to measure a 10-decade range from 0% to 150% full power (FP) not saturated at a flux of 10^{11} n/s·cm^2 while tolerating gamma rays on the order of 10^6 Gy/h. It produces three types of analog outputs (direct current linear power, log power, and log rate) and digital outputs, which are produced in six identical sets, and three of which are used by the RPS and the rest are used by the Reactor Regulating System (RRS). Neutron and gamma-ray detectors are installed in the detector housing, and three Neutron Detector Housings (NDHs) and three Gamma Detector Housings (GDHs) are mounted around the outer shell of the HWV. An NDH includes two neutron detectors; their radial positions can be adjusted for a proper neutron monitoring.

3. Criticality approach method

A total of 18 fuel assemblies are loaded in the nominal core of the JRTR; the loading sequence and positions are shown in Fig. 2. As



(a) X-Y Plan View (b) Overall View

Fig. 1. Configuration of reactor structure assembly.

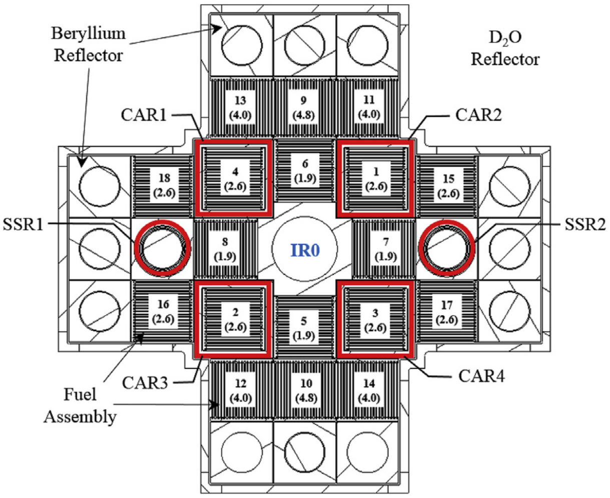


Fig. 2. Fuel Assembly Loading Sequence (Uranium Density, gU/cm^3).

can be seen in the figure, these assemblies, with uranium densities varying from 1.9 to 4.8 gU/cm^3, are loaded from the inside to the outside of the core, which is surrounded by the beryllium and heavy water reflectors. The initial critical core was made by replacing aluminum dummy fuel assemblies in the core with actual fuel assemblies one by one; the criticality approach progressed on the basis of the inverse multiplication method (1/M). When a fuel assembly is additionally inserted into a subcritical core ($k_{eff} < 1$), the neutron population converges to a certain value after exponential increase; the converged value is inversely proportional to the reactivity of the core. This phenomenon is called inverse multiplication, and the relationship of neutron density and reactivity can be described as

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

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 [7]. As the subcritical core approaches the critical state ($k_{eff} = 1$), the value of Eq. (1) converges to 0 and, therefore, before next FA loading the critical mass can be predicted by investigating the trend of 1/n versus the number of FAs. Also, as with the procedure of finding the critical mass, the critical CAR position can be predicted by investigating the trend of 1/n versus the CAR position, instead of the number of FAs. In this experiment, change analysis for 1/M started from the 8th FA, because there is no probability of reaching criticality on the basis of calculation results in spite of loading by the 7th FA.

The 1/M analysis was basically performed at every 50 mm withdrawal of all CARs, but if it was predicted that the critical CAR position is within 100 mm withdrawal, the CAR's withdrawal was reduced to 30 mm. Then, if it was predicted that the critical CAR position is within 30 mm withdrawal, the CAR's withdrawal was reduced to 10 mm, and finally if the predicted critical CAR position is within 10 mm withdrawal, the CARs were withdrawn to the predicted critical position. Since the first criticality experiment is performed under extremely low neutron flux, it is necessary to introduce an additional neutron measuring instrument other than the NMS. A BF_3 detector uses the high sensitivity $^{10}B(n,\alpha)$ reaction and has a high boron concentration and good gas multiplication performance [8], hence two BF_3 detectors were employed to measure neutron populations, which were installed at OR3 and OR6 positions close to the core (see Fig. 1). Also, the 500 mCi Am–Be neutron source was used to verify the operability of NMS and BF_3 detectors and to start up the JRTR, which was loaded at the center of the core (IR0).

4. First criticality prediction and experimental results

The measured 1/M values were obtained from two BF_3 counters installed at positions close to the core; the calculated 1/M values were derived from the average flux in these counters. Fig. 3 shows the McCARD calculation model for the JRTR, and the main equipment to be influenced for the result are reflected in this model. In order to obtain the reliability of calculation results, the calculations for the average flux in neutron counters are also performed until the calculation uncertainty is less than 5%. The expected FA number of the first criticality was 14 according to the McCARD calculation; the calculated and measured 1/M values are shown in Fig. 4(a). As can be seen in the figure, the 1/M value linearly decreased because the neutrons that multiplied in the core increased when the core was near the critical state; measured 1/M values matched well with the calculated values. For the predicted critical core loaded with 14 FAs, the change of the 1/M values according to the withdrawal of CARs is presented in Fig. 4(b) and Table 2. As shown in figure, the trend of the 1/M values was similar to the curve of the integral CAR worth, and the average difference between calculated and measured 1/M values were within 5% error. In addition, the effective multiplication factor (k_{eff}) of the JRTR core was analysed as a function of the withdrawal of CARs, and the critical CAR height was estimated to be 575 mm. These evaluations were performed with 100,000 neutrons per cycle and an initial guess for k_{eff} of 1.0. The first 25 cycles were skipped before k_{eff} data accumulation, and a total of 425 cycles were run. Fig. 5 shows the critical CAR height predicted by extrapolation of 1/M values, 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 two results is 4.5 mm, which is about 71 pcm in terms of reactivity. From these results, it is confirmed that the first criticality experiment of the JRTR was successfully performed and the McCARD predicted well the experiment results. Fig. 6 shows the Cherenkov radiation at the time of first criticality of the JRTR.

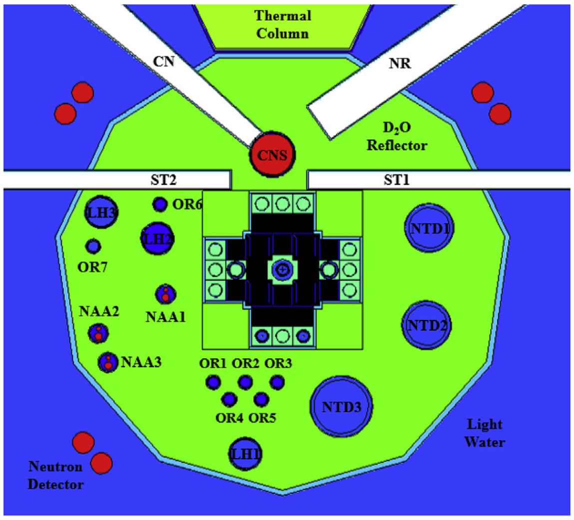
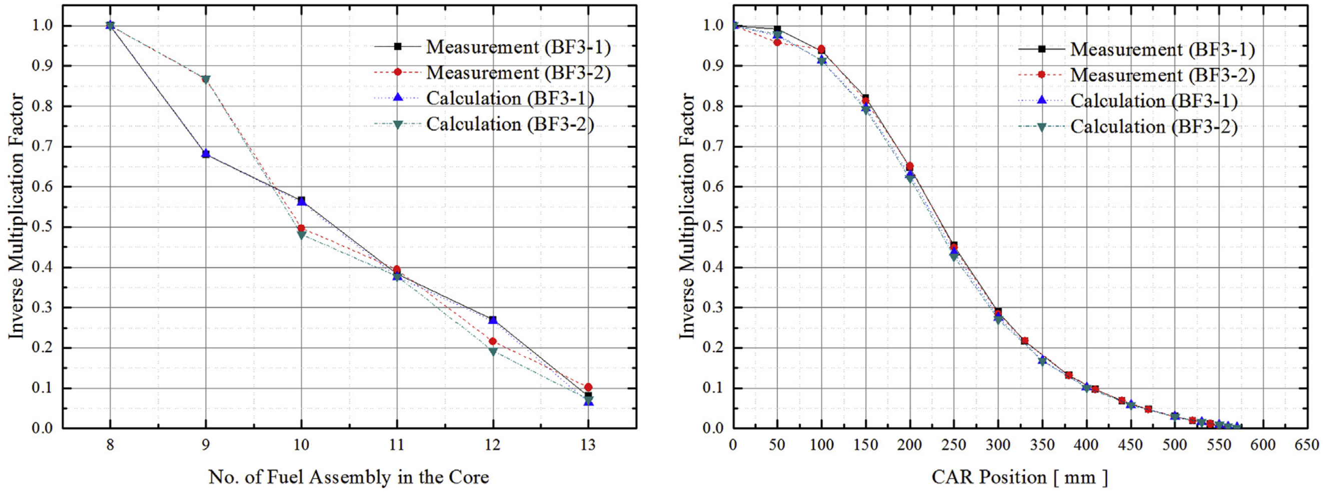


Fig. 3. McCARD calculation model for JRTR.



(a) Critical Mass

(b) Critical CAR Height

Fig. 4. Comparison of calculated and measured 1/M values.

Table 2
Calculated and measured 1/M results.

CAR Height	k_{eff}	CAR Height	Calculation		CAR Height	Measurement	
			BF3-1	BF3-2		BF3-1	BF3-2
0	0.68383 ±0.00013	0	1.000	1.000	0	1.000	1.000
50	0.69504 ±0.00013	50	0.975	0.978	50	0.991	0.958
100	0.72808 ±0.00013	100	0.914	0.913	100	0.937	0.941
150	0.77851 ±0.00012	150	0.796	0.791	150	0.821	0.812
200	0.82839 ±0.00013	200	0.629	0.621	200	0.647	0.651
250	0.87039 ±0.00012	250	0.437	0.426	250	0.454	0.449
300	0.90412 ±0.00013	300	0.275	0.271	300	0.290	0.285
350	0.93126 ±0.00013	350	0.169	0.168	330	0.216	0.217
400	0.95322 ±0.00012	400	0.103	0.101	380	0.132	0.131
450	0.97099 ±0.00012	450	0.059	0.058	410	0.097	0.096
500	0.98507 ±0.00012	500	0.029	0.029	440	0.069	0.069
530	0.99167 ±0.00012	530	0.016	0.016	470	0.047	0.046
550	0.99579 ±0.00013	550	0.009	0.009	500	0.029	0.029
560	0.99746 ±0.00012	560	0.005	0.005	520	0.019	0.019
570	0.99920 ±0.00013	570	0.002	0.002	540	0.011	0.011
574	0.99993 ±0.00012				550	0.007	0.007
575	0.99997 ±0.00012				560	0.003	0.003

5. Conclusion

The first criticality experiment of the JRTR was performed to confirm the accuracy of the reactor design and manufacturing, and the inverse multiplication method was applied to predict the first criticality by extrapolation of 1/M values. The measured results were obtained from two BF_3 counters, and a series of calculations for the experiment were performed using the Monte Carlo Code

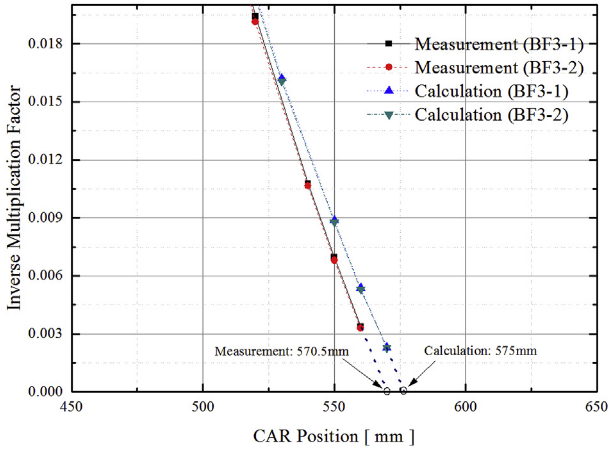


Fig. 5. Critical CAR height by extrapolation of 1/M values.

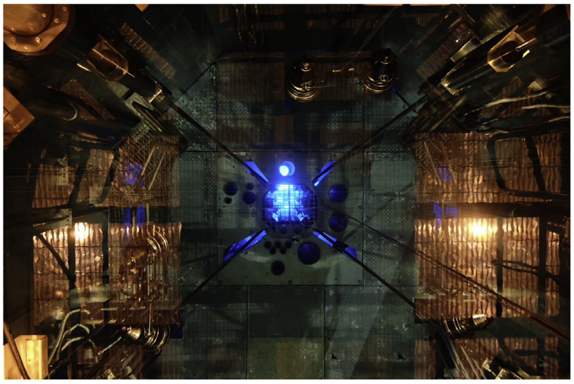


Fig. 6. Cherenkov radiation at time of first criticality of JRTR.

(McCARD) with the ENDF/B-VII.0 nuclear library. As a result, the calculated and measured CAR heights for the first criticality were 575 mm and 570.5 mm, respectively. That is, the difference between the predicted and measured results was within 5 mm (~71 pcm). From these results, it is confirmed that JRTR manufacturing and various experiments had successfully progressed as designed, and the inverse multiplication method can be a useful way to predict the critical state.

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