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Control rod calibration of the Nigeria Research Reactor-1 low-enriched uranium core

Abdulsamad Asuku[1*], Yusuf Aminu Ahmed[1], Yakubu Viva Ibrahim[1], Ahmed Rufai Abubakar[1], Ahmed Umar[1], Nana Fatima Abdulmalik[1], Sadiq Umar[2], Muhammed Hussaini Yunusa[1]

[1]*Centre for Energy Research and Training, Ahmadu Bello University, Zaria, Nigeria*

[2]*Department of Physics, Ibrahim Badamasi Babangida University, Lapai, Nigeria*

ABSTRACT

Calibration of the control rod (CR) is extremely important for startup, monitoring, compensating for the loss of reactivity and shutdown of the Nigeria Research Reactor-1 (NIRR-1) low-enriched uranium (LEU) core. The present work calibrated the entire length of the NIRR-1 LEU core CR (0–230 mm) experimentally using the period method. The maximum differential rod worth was found to be 0.043 mk when the CR was midway out of the core. The integral worth for the entire length of the CR was found to be 6.49 mk. This value is 0.51 mk (7.0%) less than the 7.0 mk obtained during the on-site zero-power experiment of the previous highly enriched uranium core. This implies that for the NIRR-1 to satisfy the minimum shutdown margin of 2.5 mk for a typical Miniature Neutron Source Reactor, the maximum excess reactivity the NIRR-1 LEU core can have to begin operation is 3.99 mk.

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1. Introduction

The global need to phase out highly enriched uranium (HEU) led to the conversion of the Nigeria Research Reactor-1 (NIRR-1) from an HEU to a low-enriched uranium (LEU) core. The current LEU core of the NIRR-1 is fueled with 13% UO_2 clad in Zircalloy-4. It attained second criticality on November 2, 2018. The major functions of the NIRR-1 include neutron activation analysis, education, and training (Ahmed et al., 2006). After a reactor attains criticality, reactor physicists and operators have to ensure a safe and stable operation of the reactor with regard to both power and reactivity adjustments. To do this, the control rod (CR) of the reactor must be calibrated. This implies that operators must have accurate knowledge of the effect of withdrawal/insertion of the CR on reactivity of the core. Without accurate knowledge of the CR's worth for specific withdrawal lengths, reactor operators would also be unable to effectively compensate for any loss in excess reactivity. Operators may also not be able to accurately insert a desired amount of reactivity into the core during routine experiments. This would make the reactor unreliable or unsafe to operate. To mitigate this, it is extremely important to calibrate the CR experimentally.

The CR of the NIRR-1 is a single rod located exactly at the center of the core. It is a multipurpose rod serving

*** Corresponding author** Abdulsamad Asuku ✉ asukuabdulsamadyisa@yahoo.com ✉ Center for Energy Research and Training, Ahmadu Bello University, Zaria, Nigeria.

as a shim rod, regulatory rod, as well as safety rod. The functions of reactor startup, steady-state operation, and shutdown are achieved through the movement of the CR. The CR is cylindrical and has a travel length of 230 mm and a total length of 290 mm. Its cladding material is stainless steel. The total length of the stainless steel is 450 mm. The thickness of its clad is 2.3 mm, while the inner diameter of the CR is 3.0 mm (see Fig. 1; note that all dimensions are in millimeters).

Available studies in the open literature on the calibration of the NIRR-1 CR (Asuku et al., 2015; Jonah et al., 2007) were carried when the NIRR-1 was fueled with HEU which had 347 active fuel pins and 3 dummy pins. In the present core, there are 335 active fuel pins and 15 dummy pins. Because the response of a core to CR insertion or removal depends on the fuel type or core configuration (assembly) (DOE, 1993), one cannot solely rely on calibrations found in previous studies to safely operate the current NIRR-1 core.

The most wildly used and relatively more accurate method of CR calibration is the positive (or asymptotic) period method (Son et al., 2017). This method is adopted in the present work to calibrate the entire length of the NIRR-1 CR (0–230 mm).

2. Theoretical Consideration

2.1. Positive period method of calibration

The positive period method of determining the worth ($\Delta\rho$) of any CR depends on the change in the reactor period (T) when a CR movement inserts a positive reactivity ($+\rho$) in the core (Singh et al., 2014; Serizawa and Natori, 1973). For the NIRR-1 Miniature Neutron Source Reactor (MNSR) (Singh et al., 2014; Yang, 1992), the reactivity, ρ, and reactor period, T, are related by Equation (1) as follows:

$$\rho = \frac{l}{KT} + \gamma\left[\sum_{i=1}^{6}\frac{\beta_i}{1+T.\lambda_i} + Q\sum_{i=1}^{15}\frac{\beta_j}{1+T.\lambda_j}\right] \quad (1)$$

β_i = delayed neutron fraction for group i;
λ_i = decay constant of delayed neutron group i (s^{-1}) = In2/$t_{1/2}i$;
l = Prompt neutron lifetime (s);
T = reactor period;
γ = effective delayed neutron coefficient;
Q = effective delayed photoneutron coefficient.

3. Methodology

3.1. Experimental procedure

To begin the experiment, it was first ensured that the reactor operated normally and had safely attained criticality under initial loading using a standard operational procedure checklist (CERT, 2011). Zero power was chosen for the experiment to ensure negligible xenon build-up and temperature effects on reactivity. It was also ensured that water levels of reactor and pool water met safety design requirements. With the reactor critical, various reactivity insertions were made through step withdrawals of the CR from 0 to 230 mm. The time it took for the reactor power to rise to double its initial value as displayed on the neutron monitoring equipment was recorded as the reactor period (Misawa et al., 2010). Four reactor periods were recorded using different stopwatches and an average period taken to minimize error. The reactivity and/or reactivity worth corresponding to the average reactor periods were determined. After every measurement, as a precaution, the reactor was shut down for about 15 minutes to allow for delayed beta decay. The critical CR position was also adjusted

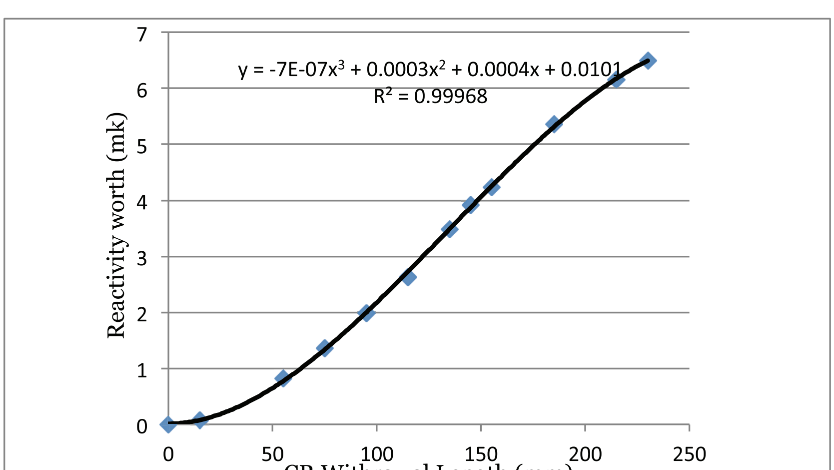

Figure 1. IRW of the NIRR-1 LEU core.

every time before another measurement was carried out. At every withdrawal length, the worth of the CR is the difference between the reactivity at the previous position (x) and that at the present position ($x + \Delta x$). The integral worth is the integral sum of the reactivity worth inserted by the CR withdrawal.

4. Results and Discussion

Table 1 shows the result of withdrawal lengths and the corresponding reactivity worth and integral rod worth (IRW) of the NIRR-1 CR from the calibration experiment. The highest worth of 1.12 mk was observed to occur when the CR moved from 155 to 185 mm withdrawal length. The integral worth, also known as the total CR worth, as can be seen in the third column of Table 1, was found to be 6.49 mk. This value is 0.51 mk (approximately 7%) less than the measured value of 7.0 mk obtained during the on-site zero-power experiment of the previous HEU core. This implies that in order for the NIRR-1 LEU core to meet the minimum shutdown requirement of 2.5 mk for a typical MNSR, the NIRR-1 LEU core cannot have an excess reactivity greater than 3.99 mk. The integral worth curve is shown in Figure 1. This curve matches the "S-shape" curve requirement from theoretical consideration and previous researches that have carried out similar work for the HEU and other reactor types (Bock and Zeilinger, 2003; DOE, 1993; Jonah et al., 2007; Son et al., 2017). The differential rod worth (DRW) is the ratio of the change in reactivity to change in CR position. It can also be defined as the slope of the IRW curve ($\Delta\rho/\Delta x$). This is shown in Figure 2. Hence, when the slope of the IRW curve in Figure 1 is taken, the result is the rate of change of reactivity as a function of unit CR position for a specific CR withdrawal length. The result of the DRW can be seen in the fourth column of Table 1. Figure 2 shows that the DRW is relatively small at the bottom (below about 75 mm) and at the top of the core (above about 200 mm) compared to the regions around the center (between 95 and 185 mm). The maximum DRW was found to be 0.043 mk. This was observed to correspond to when the CR is midway out of the core. The reason for this is that the region of maximum neutron flux is near the center of the core. This implies that the magnitude of change in neutron absorption is greatest in this region (Bock and Zeilinger, 2003; DOE, 1993; Son et al., 2017). On the other hand, the top and bottom of the core are the regions with minimum neutron flux. This explains why the DRW in the region is lowest. The equations, $y = -7E\text{-}07x^3 + 0.0003x^2 + 0.0004x + 0.0101$ and $y = -2E\text{-}09x^3 - 1E\text{-}06x^2 + 0.0005x + 0.0014$, displayed on

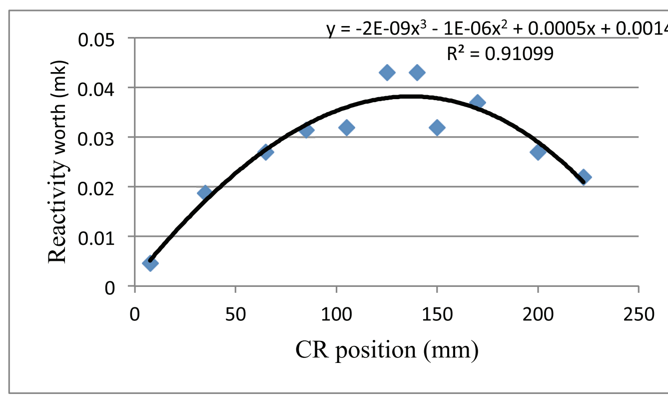

Figure 2. DRW of the NIRR-1 LEU core.

Table 1. Reactivity parameters for CR calibration.

Length (mm)	Interval	Average period (s)	Reactivity worth (mk)	IRW (mk)	DRW (mk)
0	0	0	0	0	-
15	15	28.3	0.07	0.07	0.00466
55	40	42.5	0.75	0.82	0.01875
75	20	43.7	0.54	1.36	0.02700
95	20	25.2	0.63	1.99	0.03150
115	20	45.0	0.64	2.63	0.03200
135	20	37.5	0.86	3.49	0.04300
145	10	21.5	0.43	3.92	0.04300
155	10	23.0	0.32	4.24	0.03200
185	30	36.8	1.12	5.36	0.03700
215	30	42.3	0.8	6.16	0.02700
230	15	28.4	0.33	6.49	0.02200

the IRW and DRW curves have correlation coefficients (R^2) of R^2 = 0.9997 and 0.911, respectively. This indicates a strong relationship between reactivity (y) and CR position (x). The equations can be used to estimate the integral reactivity and differential reactivity corresponding to any CR position between 0 and 230 mm of the NIRR-1.

5. Conclusion

The positive period method has been used in this work to calibrate the CR of the NIRR-1 LEU core. The IRW was found to be 6.49 mk. This is about 7.0% lesser than the measured value of 7.0 mk obtained during the on-site zero-power experiment of the previous HEU core (CERT, 2011). However, in order to meet the minimum shutdown margin of 2.5 mk recommended for a typical MNSR, the NIRR-1 LEU core cannot have an excess reactivity greater than 3.99 mk to begin operation. The maximum DRW was found to be 0.043 mk when the CR was midway out of the core. The equations, $y = -7E\text{-}07x^3 + 0.0003x^2 + 0.0004x + 0.0101$ and $y = -2E\text{-}09x^3 - 1E\text{-}06x^2 + 0.0005x + 0.0014$, can be used to estimate the integral reactivity worth and differential reactivity worth corresponding to any CR position between 0 and 230 mm of the NIRR-1 core, respectively.

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References

Ahmed YA, Ewa IOB, Umar IM, Bezboruah T, Johri M, Akaho EHK. The low power miniature neutron source reactors: design, safety and applications. UNESCO/IAEA/ICTP Publication IC/2006/020, The Abdus Salam International Centre for Theoretical Physics, Trieste, Italy, 2006.

Asuku A, Ahmed YA, Ewa IOB, Agbo SA. Application of positive period method in the calibration and determination of integral worth of MNSR control rod. Int J Nucl Energy Sci Technol 2015; 9(4):319–32.

Bock H, Zeilinger A. Eugene Wigner training course for reactor physics experiment. Atomic Institute Vienna, Vienna, Austria, 2003.

CERT. Final safety analysis report (SAR) of Nigeria Research Reactor-1. CERT Technical Report, CERT/NIRR-1/FSAR-11, Zaria, Nigeria, 2011.

DOE. Department of energy fundamentals handbook-nuclear physics and reactor theory. DOE-HDBK-1019/2-93, Washington, DC, vol. 2 of 2, pp 1–33, 1993.

Jonah SA, Liaw JR, Matos JE. Monte Carlo simulation of core physics parameters of the Nigeria Research Reactor-1(NIRR-1). Ann Nucl Energy 2007; 34:953–7.

Misawa T, Unesaki H, Pyeon C. Nuclear reactor physics experiments. Kyato University Press, Kyato, Japan, 2010.

Singh OP, Pinem S, Siswiyanto A, Suparlina L, Jujuratisbela U, Arbie B. Period-reactivity relationship measurements for reactor Serba Guna GA Siwabessy. Atom Indones 1991; 17(2):1–4.

Son NA, Hoa ND, Nguyen TT, Tuan TQ, Raul OC. Control rod calibration and worth calculation for optimized power reactor 1000 (OPR-1000) using core simulator OPR1000. World J Nucl Sci Technol 2016; 7:15–23; doi:10.4236/wjnst.2017.71002

Serizawa M, Natori H. Multivariate measurements of the reactivity equivalent of control rods. J Nucl Sci Technol 1973; 10(3):133–8.

Yang YW. MNSR reactor complex mannual. CIAE, Beijing, China, 1992.