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Prompt neutron lifetime calculations for the NIRR-1 reactor

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Abstract. Prompt neutron lifetime calculations have been performed for the NIRR-1 reactor HEU and LEU cores using the 1/*v* insertion and the Adjoint flux weighing methods. Results of calculations obtained for the HEU and LEU cores are respectively 57.3±0.8 and 47.5±0.7 for the 1/*v* insertion and 56.9±0.3 and 46.3±0.5 for the Adjoint flux. There is a good agreement seen between the two methods for both cores. The prompt neutron lifetime was observed to be shorter in the LEU than for the HEU as expected. However, the Adjoint flux weighing method seemed to be the easiest method in calculating the prompt neutron lifetime for NIRR-1.

Keywords: prompt neutron lifetime; HEU; LEU; MCNP; enrichment; MNSR; neutron activation analysis

1. Introduction

The Nigeria Research Reactor-1 (NIRR-1) is a commercial version of the Miniature Neutron Source Reactor (MNSR) designed by China Institute of Atomic Energy (CIAE). It is a pool type reactor, with a compact core having a low critical mass of about 1 kg. It is fueled with HEU consisting of 347 fuel pins in a single fuel assembly enriched to about 90.2% in UAl metal alloy clad with Al.

The fuel assembly consists of ten concentric zones or rings of 350 fuel lattices distributed about a single central control rod. The rated power is 31 kW corresponding to a peak thermal flux of 10^{12} n/cm^2.s. The core is cooled and moderated (with H/U ratio=197) by light water with beryllium as the reflector making the reactor critical with a limited (1/2 β_{eff}) built in clean cold excess reactivity of about 4 mk. It has large negative temperature coefficient of reactivity which boosts its inherent safety.

The reactor is designed specifically for Neutron Activation Analysis, Education and training

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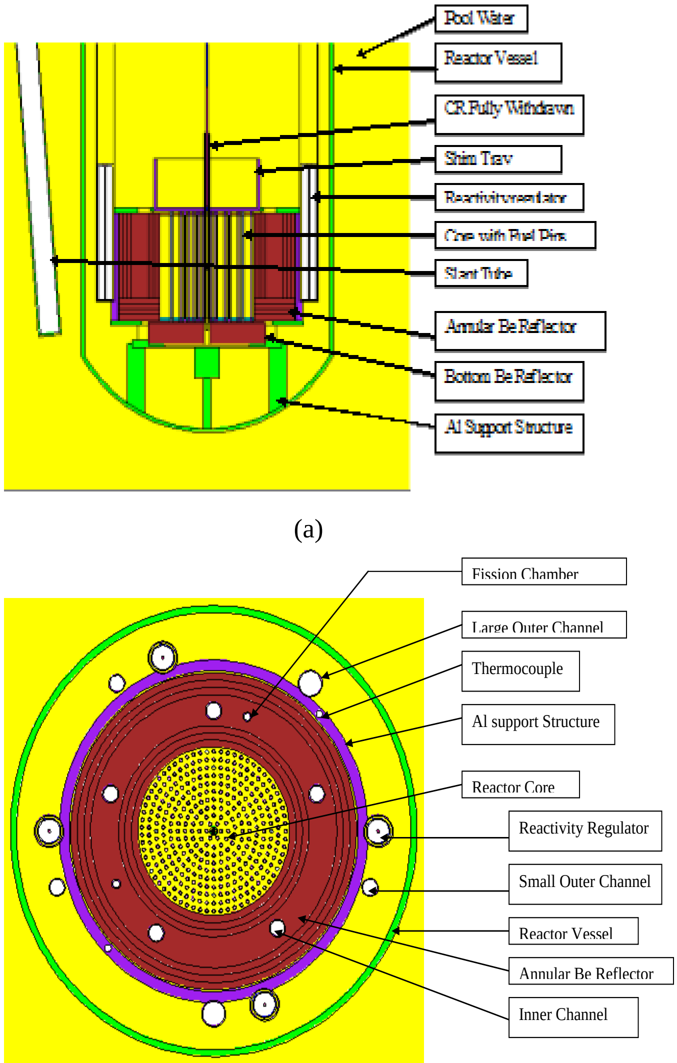

(b)

Fig. 1 MCNP Axial and Radial view of NIRR-1

and few radioisotopes production. The reactor went critical in February 4, 2004 and since then it has been operated safely (Jonah *et al*. 2007). Axial and radial view of the NIRR-1 reactor as depicted by the MCNP code reactor is shown in Fig. 1

The RERTR programme in the United States has supported the conversion of research and test reactors from the use of Highly Enriched Uranium (HEU) to Low Enriched Uranium (LEU) since 1978 (Ibrahim *et al*. 2013). Achieving the conversion of the NIRR-1 reactor from the current use of HEU is a good step in reducing and eventual elimination of HEU fuel in civil use (Trivelli 1999). A study by Jonah and Ibikunle (2009) has shown that it is possible to convert the reactor to LEU with enrichment of about 12.5% UO_2 fuel clad in Zr-4. Moreover, the core of the reactor is designed to operate for 10 years; core replacement is under consideration having operated for over

Table 1 technical specification of NIRR-1 HEU and LEU cores

Parameter	**HEU**	**LEU**
Meat density (g/cm^3)	3.456	10.6
Meat diameter (cm)	0.43	0.43
Clad thickness	0.06	0.06
Fuel meat OD	4.3	4.3
Fuel rod OD	5.5	5.5
Reactor power (kW)	31	34
Number of fuel pins in core	347	348
Enrichment (%)	90.2	12.5
Material for grid plates	LT-21	Zirc-4
Materials for grid plates	LT-21	Zirc-4
Number of fuel rods	347	348
Meat diameter mm	4.3	4.3
Cladding diameter mm	5.5	5.5

10 years. When converting from HEU to LEU materials in the fuel, density of each fuel, the fuel cladding, tie rod materials and grid plate materials have to be changed. Technical specifications of NIRR-1 HEU and LEU cores are given in Table 1.

In preparation for the conversion of NIRR-1 from HEU to LEU, point kinetics parameters such as prompt neutron lifetime must be calculated from safety point of view. In this work, we will employ two methods to calculate the prompt neutron lifetime using the MCNP code. This methods was also used by some authors (Albert and Diamond 2006, Heba 2014, Rabira and Haha 2013) for other reactors.

2. Method of analysis

2.1 The 1/v insertion method

The 1/*v* insertion method is a simple but accurate way to calculate the prompt neutron lifetime (Brestcher 1997). The method consists of inserting a small amount of 1/*v*-absorber into the core. This results in a negative reactivity insertion. The reactivity change after the absorber is calculated using

$$\rho = \frac{k_{ref} - k_p}{k_p} \tag{1}$$

where ρ is the negative excess reactivity, k_{ref} eigenvalue without 1/*v*-absorber and k_p eigenvalue with 1/*v*-absorber.

In the prompt neutron lifetime calculation, k_p was calculated for different concentrations of ^{10}B added to the reactor materials. The 1/*v* approach was performed by adding ^{10}B uniformly throughout the materials of the reactor with concentrations of 7.5×10^{-8} atoms/b-cm and 1.5×10^{-7}

atoms/b-cm. The reactivity insertion from the addition of the ^{10}B concentration was calculated using the relation (Brestcher 1997)

$$l_p' \equiv \frac{1}{N\sigma_o v_o}\frac{k_{ref}-k_p}{k_p} \tag{2}$$

Where N is the number density of the $1/v$ absorber, σ_0 is its reference absorption cross section, and v_0 is its reference speed. At v_0=2200 m/s, $\sigma_0=(^{10}B)$=3837 barns. The prompt neutron lifetime estimate, l_p, for the unperturbed core is calculated as the amount of $1/v$ absorber approaches to zero

$$l_p = \lim_{N\to 0} l_p' = \lim_{N\to 0}\left[\frac{1}{N\sigma_o v_o}\frac{k_{ref}-k_p}{k_p}\right] \tag{3}$$

The limit as $N\to 0$ was obtained by computing the eigenvalue for two different boron concentrations N_1 and N_2, evaluating l_p' for each boron concentration, and linearly extrapolating l_p' to N=0. That is

$$l_p = l_{p1}' + \frac{l_{p2}' - l_{p1}'}{N_2 - N_1}\left(0 - N_1\right) \tag{4}$$

where $l_{p1}'=l_p'(N_1)$ and $l_{p2}'=l_p'(N_2)$. The statistical uncertainty in k must be propagated through the evaluation of l_p' and the linear extrapolation to l_p.

$$\sigma_{l_p'} \equiv l_p' \sqrt{\frac{\sigma_{ref}^2 + \sigma_p^2}{\left(k_{ref}-k_p\right)^2} + \frac{\sigma_p^2}{k_p^2}} \tag{5}$$

where σ_{ref} and σ_p are statistical uncertainties in k_{ref} and k_p, respectively. The statistical uncertainty in the lifetime estimate is given by

$$\sigma_{l_p} \equiv \sqrt{\left(\frac{l_p - l_{p1}'}{l_{p2}' - l_{p1}'}\right)^2 \left(\sigma_{l_{p1}'}^2 + \sigma_{l_{p2}}^2\right) + \sigma_{l_{p1}'}^2} \tag{6}$$

where σ_{lp1}' and σ_{lp2}' are the uncertainties in l_{p1}' and l_{p2}' as calculated by Eq. (5)

The eigenvalues for k_{ref} and k_p (for the two ^{10}B concentrations) were computed using the MCNP5 version 1.50 with ENDF-VII libraries. The problem was run as a KCODE problem tracking 1.6 billion particle histories (2 million histories per cycle in 830 cycles, skipping 30 cycles for convergence). The results obtained for the $1/v$ insertion for both HEU and LEU are presented in Table 1. The MCNP code has recently been used in the calculations of reactor physics parameters of the of several reactors (Snoj *et al*. 2010, Abtin *et al*. 2013, Lylia and Houcine 2011, Abrefah *et al*. 2012, Jonah *et al*. 2012) including design of thermal and epithermal filters for radiography using reactors (Li *et al*. 2009, Ismail 2010) and detector efficiency calibration, Chan (2011) and the prediction of Isotopes (peters *et al*. 2009). The MCNP model for NIRR-1 has since been developed (Jonah *et al*. 2007) and has been optimized for various reactor physics calculations (Ibrahim *et al.* 2012, 2013).

2.2 The adjoint flux weighing method

This method of estimating the prompt neutron lifetime employs the use of (kiedrowski *et al*. 2011)

$$l_p = \frac{\langle \psi^*, v^{-1}\psi \rangle}{\langle \psi^*, F\psi \rangle} \tag{7}$$

where ψ is the neutron flux, ψ^* the adjoint flux, $\boldsymbol{v}$ is the neutron speed and F is the operator for total (prompt plus delayed) Fission. The brackets denote integration over all space, energy, and direction in the reactor. The MCNP5-1.60 has the capability of calculating the neutron lifetime based on Eq. (7); MCNP5 (2003). For the NIRR-1 reactor a new KCODE binary source distribution different from the one used in MCNP5-1.50 input was created to accommodate this new feature of calculating the prompt neutron lifetime in MCNP5-1.60. As in the case of the 1/v insertion using the MCNP5-1.50, 1.6 billion particles were tracked and the adjoint flux is calculate in 10 cycles (kiedrowski *et al*. 2011) with the *kopts* card in the criticality (KCODE) problem. The KOPTS card is specified in the data card section and takes the format

$$\text{kopts blocksize } = 10 \text{ kinetics } = \text{yes} \tag{8}$$

3. Results and discussion

The results obtained for the 1/*v* insertion method for both HEU and LEU including the eigenvalues is presented in table 1 while the result based on the adjoint flux weighing method is presented in Table 2.

The prompt neutron lifetime values obtained using the two methods are in good agreement. The two methods indicate that there is a decrease in the prompt neutron lifetime as you move from HEU to LEU as expected due to hard spectrum in the LEU fuel. This trend was also observed by some authors (Verboomen 2006, Jonah and Ibikunle 2009, Odoi *et al.* 2014).

Table 2 MCNP results with ^{10}B insertion for the HEU and LEU

^{10}B conc. Atoms/b-cm	HEU			LEU		
	k_{eff}	$l_p'(\mu s)$	$l_p(\mu s)$	k_{eff}	$l_p'(\mu s)$	$l_p(\mu s)$
0.0	1.00474±0.00002	-	57.3±0.8	1.00475±0.00002	-	47.5±0.7
7.5E-8	1.00127±0.00003	57.3±0.6		1.00176±0.00002	47.1±0.7	
1.5E-7	0.99185±0.00002	52.1±0.2		0.99883±0.00002	46.8±0.8	

Table 3 Prompt neutron lifetime estimates for HEU and LEU Core

Method	HEU l_p (μs)	LEU l_p (μs)
1/v Insertion	57.3±0.8	47.5±0.7
MCNP	56.9±0.3	46.3±0.5

The measured value of prompt neutron lifetime mentioned in the SAR is 81 μs (SAR 2005) The value of the neutron lifetime obtained using the new capability in the MCNP5 version 1.60 agrees very well with the value of 5.79±0.19 and 4.70±0.7 earlier reported for HEU and LEU core respectively (Jonah *et al*. 2007, Jonah and Ibikunle 2009) This indicates the capability in the MCNP5-1.60 to calculate neutron lifetime for NIRR-1 reactor without diluting the reactor materials with 1/*v* absorber.

4. Conclusions

The 1/*v* insertion method and the Adjoint flux weighing methods were used in the calculation of prompt neutron lifetime for the NIRR-1 reactor. The neutron lifetime was found to be shorter for the LEU core as expected due to the hard specrum. There is a good agreement between the two methods used and measured value. However, the Adjoint flux weighing method was found to be the easiest way for the calculation neutron lifetime in NIRR-1 reactor.

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