THE IMPACT OF HEU TO LEU CONVERSION ON UTILIZATION OF NIRR-1

S.A. JONAH, Y.V. IBRAHIM, A.S. AJUJI, G.I. BALOGUN,
Centre for Energy Research and Training,
Ahmadu Bello University,
Zaria,
Nigeria

M.Y. ONIMISI
Department of Physics,
Nigerian Defence Academy,
Kaduna,
Nigeria

Abstract

The Nigeria Research Reactor-1 (NIRR-1) is a Miniature Neutron Source Reactor (MNSR), which is currently fueled by Highly Enriched Uranium (HEU). The reactor is equipped with ten irradiation channels mainly for Neutron Activation Analysis (NAA) and limited radioisotope production. A neutronics feasibility study has shown that it will be feasible to convert NIRR-1 from HEU (90.2%) to LEU (~12.5%) fuel. In this work, the impact of the proposed LEU fuel on neutron spectrum parameters in the experimental channels of NIRR-1 has been studied. The knowledge of the neutron spectrum parameters in irradiation channels of research reactors is required in several applications, especially for analytical works via the NAA technique. These include the thermal-to-fast neutron flux ratio, f, and the non-ideality of epithermal neutron flux parameter, α, especially for the implementation of the k0-NAA method. Although, experimental methods have been recommended for the determination of the f and α values, a parametric method was developed and used to calculate the neutron parameters in inner and outer irradiation channels of the current HEU core and the proposed LEU core of the reactor. In this regard, the MCNP code was used to calculate the neutron flux distribution in 640 neutron energy group structure and the cross section data of monitor reactions also in 640 neutron energy group structure were extracted from ENDF libraries. On the basis of the data, the Cd ratios of Au, Mn, Co, Th, and U were computed and used to calculate f and α values. A comparison of measured data for the current HEU core with the calculated was used to verify the parametric method. The α-value in the inner channel of the HEU core was calculated to be -0.056±0.004 in comparison with a measured value of -0.052±0.002. However, the α-value in the inner channel of the LEU core was calculated to be -0.047±0.006. Similarly, the α-value in the outer channel of the HEU core was calculated to be 0.021±0.005 in comparison with a measured value of 0.029±0.003. The α-value in the outer channel of the LEU core was calculated to be 0.028±0.004. As expected, these results indicate slightly "hardened" neutron spectra distributions in the respective irradiation channels of the LEU core in comparison with the current HEU core

1. INTRODUCTION

Miniature Neutron Source Reactors (MNSRs) are compact low-power nuclear research reactors designed and manufactured by the China Institute of Atomic Energy (CIAE), Beijing, China. The Nigeria Research Reactor-1 (NIRR-1) is one of the commercial MNSRs sited outside China. It is used mainly for neutron activation analysis, production of short-lived radioisotopes and training of nuclear engineers as well as technicians. The training programme is in connection with the deployment of nuclear power plants in Nigeria. Both the commercial MNSR, and the prototype at the CIAE in China have cores with highly enriched uranium (HEU). However, the core configuration of the prototype MNSR differs from those of commercial MNSRs with regards to the material composition of the fuel meat, the number of fuel pins and their dimensions. Recently, the CIAE has successfully installed a variant of the MNSR, called the In-Hospital Neutron Irradiator (IHNI), which has been designed exclusively for the treatment of cancer via the boron neutron capture therapy (BNCT) technique (Ke Guoto et al., 2009). The IHNI has similar design characteristics as the commercial MNSR and these include tank-in-pool structural configuration, under moderated core, light water moderator, metallic beryllium reflector, and heat transfer by natural convention. In the frame work of the IAEA Coordinated Research Project entitled “Conversion of MNSR to LEU”, it has been established that it would be feasible to convert NIRR-1 to LEU by UO_2 fuel with enrichment of 12.5% (Jonah et al., 2009a). Since NIRR-1 is specifically designed for NAA, conversion to LEU should not compromise its utilization capacity, especially with respect to the neutron spectrum parameters. Because of its stable neutron flux characteristics, MNSR facilities are excellent neutron sources for the k_0-INAA method (Jonah et al., 2009b). The accurate knowledge of neutron parameters in irradiation channels of a nuclear research reactor is very important towards the development of irradiation and counting protocols for the utilization of any research reactor via the implementation of the k0-standardized NAA method. The neutron spectrum parameters, f (flux ratio of thermal to epithermal neutrons) and α (measure of the deviation of epithermal neutrons from the ideal *1/E* distribution) are needed for implementation of k0-NAA method. These parameters can be determined experimentally through the so-called “Cd-ratio for multi-monitor” method (De Corte, 1987). For the current NIRR-1 HEU core, experimental procedures have been developed for the determination of the neutron spectrum parameters (Jonah et al., 2005). Therefore, in order to further assess the performance of the proposed LEU fuel with respect to NAA, a computational method has been developed for the calculation of neutron spectrum parameters in the irradiation channels. In this work, the Monte Carlo code MCNP5 version 1.40 (Breismester, 2000). was used to calculate the neutron spectral distributions in a 640-group energy structure from 10^{-10} to 20 MeV. The calculated data in combination with the neutron capture cross section data of some dosimetry reactions extracted from the data library (ENDF-VII, 2006) were used to determine the Cd-ratios, which were then used to deduce the f and α parameters in the inner and outer channels of the current HEU core as well as the proposed LEU core.

2. MATERIALS AND METHOD

In a previous work (Jonah et al., 2007), an MCNP model of the reactor was developed from geometry of HEU core of NIRR-1 from SAR, 2005. An MCNP geometric diagram of NIRR-1 axial plane showing the irradiation channels is depicted in Fig. 1. As a follow up to developed MCNP model of the HEU core, feasibility search for qualified LEU fuels was performed for conversion from HEU to LEU. Results obtained indicate that a core fueled by UO_2 fuel with 12.5% enrichment would reproduce this same neutronics data as the current HEU core (Jonah et al., 2009a). Consequently, in this work, the validated MCNP models of NIRR-1 HEU core and the proposed LEU were used to determine neutron energy spectral distributions in 640 energy–group structure in the irradiation inner and outer channels respectively. The standard MCNP volume–averaged track length estimator via tally card f4:N was used to calculate the neutron flux distributions in the irradiation channels on the basis of the 640 group energy structure. Reaction rate of a given flux monitor irradiated by energy–dependent neutron flux density, $\varphi(E)$ having an energy dependent cross section $\sigma(E)$ is given below as:

$$R = \int_0^\infty \varphi(E)\sigma(E)dE \quad (1)$$

Considering that the energy bin is relatively small for the 640 energy group structure, the equation above, which describes a continuous representation can be modified to a discrete interval description given below:

$$R = \sum_{0}^{\infty} \varphi(E)\sigma(E) \tag{2}$$

where,

$\varphi(E)$ = neutron flux density per unit energy interval;
$\sigma(E)$ = energy-dependent activation cross section.

The $\varphi(E)$ values were obtained from the standard MCNP output for the respective irradiation channel and processed by a computer programme developed in-house into point-wise data format for the calculation of the reaction rate.

Furthermore, capture cross section data of monitor reactions as a function of energy, $\sigma(E)$ were retrieved from the data library (ENDF-VII, 2006) at the Nuclear Data Services website of the IAEA, Vienna, Austria. Specifically, cross section data of the following monitor reactions, $^{197}Au(n,\gamma)^{198}Au$, $^{598}Co(n, \gamma)^{60}Co$, $^{238}U(n, \gamma)^{239}U$, $^{232}Th(n, \gamma)^{233}Th$, were considered in this work. On the basis of a Cd-cut off energy of 0.55 eV and using the expression below, Cd-ratios (R_{Cd}) of monitor reactions were calculated.

$$R_{Cd} = \frac{\sum_{0}^{20MeV} \varphi(E)\sigma(E)}{\sum_{0.55eV}^{20MeV} \varphi(E)\sigma(E)} \tag{3}$$

The “Cd-ratio for multi-monitor” method using flux monitors had been employed for apriori determination of these parameters in the irradiation channels of current HEU core of NIRR-1. Detailed description of the methodology has been described by Jonah et al., 2005. Therefore, the same methodology was used in this work. However the Cd ratios of the monitor reactions were calculated by the expression given in eq. 3 and used to determine f and α parameters for the HEU and LEU cores.

3. RESULTS AND DISCUSSION

Results of a typical simulated energy-dependent neutron flux distributions obtained by MNCP in the irradiation channels of NIRR-1 HEU core are displayed in Fig. 2. The neutron spectral distributions obtained for the LEU core are identical with the HEU core. This is because for the proposed LEU core, the dimensions of the current HEU core are retained except for changes in the materials of the fuel and dimensions of control rod and its guide tube. Furthermore, as expected, the neutron spectrum parameters in the inner channels exhibit pronounced epithermal and fast neutron components compared with the outer channels. This is due to compact nature of the cores and the proximity of the inner channels to cores. The Cd-ratios of monitor reactions for the two cores are shown in Table 1. Similarly, the calculated f and α parameters for the proposed LEU core as well as a comparison of measured and calculated f and α values for the HEU core are given in Table 2. The experimental data were performed immediately after commissioning and were taken from Jonah et al., 2005. As shown, the measured data for the HEU core agree well with calculated data, which indicate the suitability of the computational method used in the present work. The calculated data of the LEU core in inner and outer channels are slightly lower than for the HEU core indicating hardening of the neutron spectra for LEU core due to higher composition of ^{238}U in the LEU fuel. This indicates that the impact of LEU conversion of NIRR-1.on neutron spectrum parameters for NAA is minimal. This is because the configuration of the current HEU core is identical with the proposed LEU core except for the changes in fuel composition and the dimensions of CR and guide tube.

Table 1 Comparison of calculated Cd ratios of monitor reactions in NIRR-1 HEU core and LEU cores

Reaction	Inner		Outer	
	LEU	HEU	LEU	HEU
$^{197}Au(n,\gamma)^{198}Au$	1.88±0.06	2.01±0.07	3.95±0.10	4.12±0.11
$^{238}U(n,\gamma)^{239}U$	1.10±0.03	1.15±0.03	1.38±0.06	1.49±0.07
$^{59}Co(n,\gamma)^{60}Co$	7.28±0.82	8.05±0.85	26.50±2.10	29.98±2.11
$^{232}Th(n,\gamma)^{233}Th$	2.22±0.07	2.02±0.06	4.90±0.18	4.68±0.16

Table 2 Comparison of neutron spectrum parameters of NIRR-1 HEU and LEU cores

	α		*f*	
Core	Inner	Outer	Inner	Outer
HEU (Experiment) [4]	-0.052±0.002	0.029±0.005	19.2±0.5	48.3±3.3
HEU (calculated)	-0.056±0.004	0.021±0.005	17.2±1.1	46.7±2.9
LEU (calculated)	-0.047±0.006	0.028±0.006	14.7±0.7	43.7±2.8

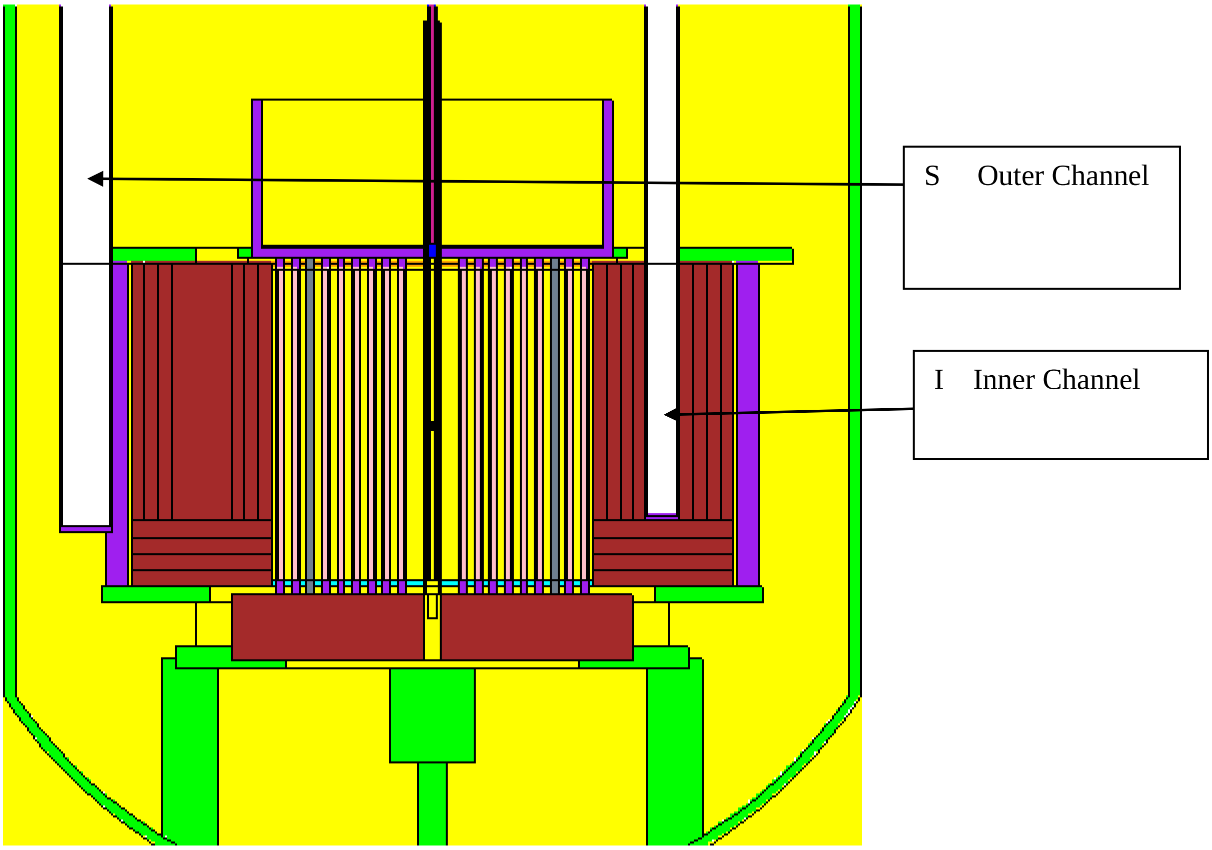

Fig. 1 An MCNP geometric diagram of NIRR-1 axial plane showing one each of the inner and outer irradiation channels.

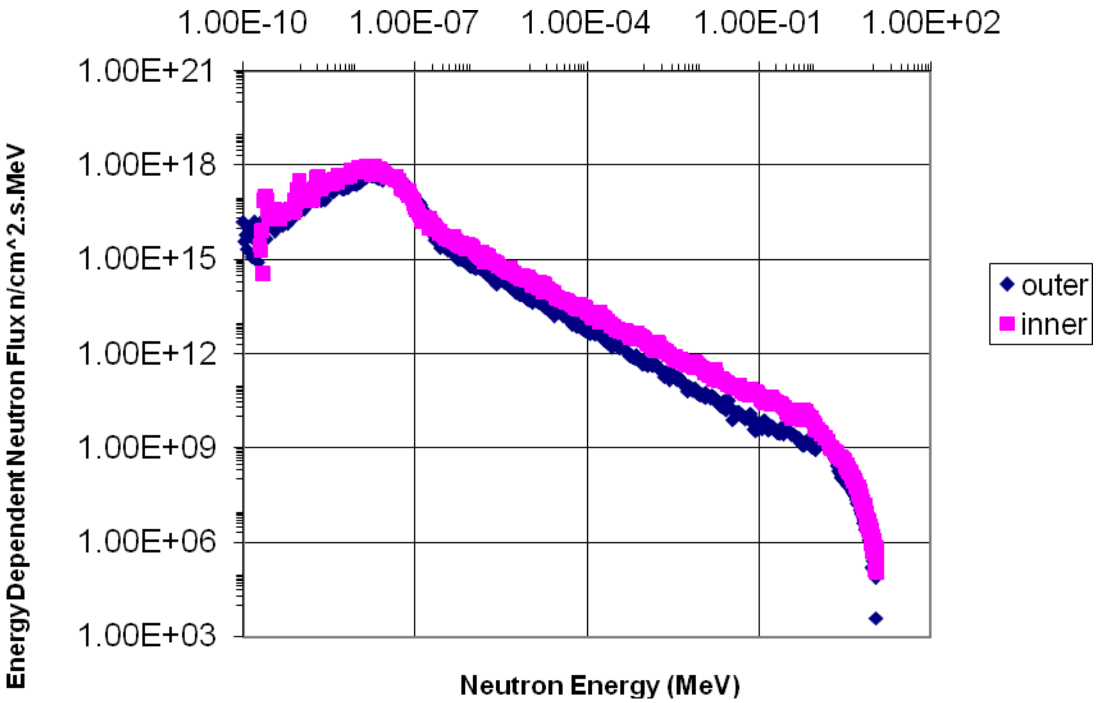

Fig. 2. Comparison of MCNP simulated energy dependent neutron flux distributions in an inner and an outer irradiation channels of NIRR-1.

4. CONCLUSIONS

The impact of HEU to LEU conversion on the neutron spectrum parameters of a commercial MNSR facility, NIRR-1 has been investigated via a computational method. In the methodology used, Cd-ratios of monitor reactions in the inner and outer irradiation channels of the current HEU core and a proposed LEU core were calculated using a combination of neutron spectral distributions in 640 group energy structure and cross section data also in 640 group energy structure. Results obtained indicate good agreement between experimental data and calculated data for the current HEU core, which underscores the suitability of the computational method developed. Furthermore, the calculated data for the proposed LEU core exhibits similar trends with the HEU core except for further hardening of the neutron spectra. However, the investigation revealed that the impact on utilization vis-à-vis neutron spectrum parameters in irradiation channels as a result of conversion of commercial MNSR is minimal.

ACKNOWLEDGEMENTS

This work is supported in by the Coordinated Research Project (CRP), Research Contract of the International Atomic Energy Agency (IAEA), Vienna, Austria entitled “Conversion of Miniature Neutron Source Reactor to LEU” No.. NIR/13934

REFERENCES

[1] BRIESMEISTER, J.F., 2000. MCNP-A General Monte Carlo N-Particle Transport Code Version 4C. LA-13709-M, Los Alamos National Laboratory, USA.

[2] DECORTE F., The k0-Standardization Method: A Move to the Optimization of Reactor Neutron Activation Analysis, Habil. Thesis, University of Gent (1987).

[3] ENDF-Evaluated Nuclear Data File ENDF/B-VII.0 2006 http://www-nds.iaea.org/exfor/endf.htm.

[4] JONAH, S.A., BALOGUN, G.I., UMAR, I.M., MAYAKI, M.C., « Neutron spectrum parameters in irradiation channels of the Nigeria Research Reactor-1 (NIRR-1) for the k_0-NAA standardization,” J. Radiaonal. Nucl. Chem. **266** (2005) 83-88.

[5] JONAH, S.A. LIAW, J.R., MATOS, J.E., "Monte Carlo simulation of core physics parameters of the Nigeria Research Reactor-1(NIRR-1)" Annals Nucl. Energy **34** (2007)953-957.

[6] JONAH, S.A., IBIKUNLE, K., LI Y., "A feasibility study of LEU enrichment uranium fuels for MNSR conversion using MCNP" Annals of Nuclear Energy **36** (2009) 1285–1286.

[7] KE, G., SUN, Z., SHEN, F., LIU, T., LI, Y., ZHOU, Y. "The study of physics and thermal characteristics for in-hospital neutron irradiator (INHI)," Appl. Radiat. Isotopes **67** (2009) 5234–5237.

[8] CENTER FOR ENERGY RESEARCH AND TRAINING, Final Safety Analysis Report of Nigeria Research Reactor-1. CERT Technical Report-CERT/NIRR-1/FSAR-01, CERT, Abu, Zaria, Nigeria.