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IMPLICATION OF CONVERSION OF MNSR FROM HEU TO LEU ON NEUTRON FLUX SPECTRUM PARAMETERS IN INNER AND OUTER IRRADIATION CHANNELS

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ABSTRACT

The Nigeria Research Reactor-1 (NIRR-1) is the third Miniature Neutron Source Reactor (MNSR) to have undergone core conversion from high enriched uranium (HEU) to low enriched uranium (LEU). In order to optimize its use for NAA, the neutron spectrum parameters of NIRR-1 irradiation channels were determined using neutron foil monitors. Furthermore, the detector efficiency curves of the new gamma-ray spectrometry set up for use with the newly commissioned LEU core of the reactor have also been determined by primary gamma ray standards at two different geometries. For the neutron parameters, the epithermal flux shape factor, α for inner irradiation channel B3 and an outer irradiation channel B4 as well as the thermal-to-epithermal neutron flux ratio, *f*, for the same channels were determined by the "Cd-ratio Multi-monitor Method". Results of α-parameters were found to be -0.054±0.003 and +0.029±0.004 for channels B3 and B4 respectively. Similarly, the *f* values were determined to be 19.67±0.30 and 48.6 ±0.004 respectfully. The efficiency curves in the energy range of 59 keV to 1840 keV far and near geometries were determined for the new gamma ray spectrometry setup are presented. Data obtained for NIRR-1 LEU core are compared with reported values for other reactor facilities with similar core configuration. The results show that the conversion of NIRR-1 from HEU to LEU has little or no impact on the neutron flux parameter and by extension utilization of the reactor for NAA.

Keywords: LEU, NIRR-1, Irradiation channel, Neutron spectrum

INTRODUCTION

In 1978, the US-DOE initiated conversion of Research Reactors to LEU under the Reduced Enrichment for Research and Test Reactors (RERTR) at the Argonne National Laboratory (ANL) (Jonah *et al*., 2011). The conversion activities were expanded to support conversion of MNSR facilities under the IAEA CRP in 2006 entitled "Conversion of Miniature Neutron Source Reactors to LEU". In this regard, three of the MNSR were converted to LEU beginning with the Prototype in Beijing, China in 2016 and the Ghana Research Reactor-1 GHARR-1) in 2017. The conversion of NIRR-1 was concluded in 2018 (SAR, 2019) and thereby requiring the knowledge of the neutron spectrum characteristics of the LEU core. Irrespective of the enrichment, fuel management issue in MNSR facilities can be said to be non-existence as the reactor cores runs on a lifetime core. The fuel burnups of these facilities are less than 1% (SAR, 2019 and Kennedy *et al*., 2000). However, due to conversion from HEU (> 90% enrichment) to LEU (13% enrichment), the determination of the neutron parameter in NIRR-1 were performed using neutron flux monitors. A comparison of the core physics parameters of the HEU and LEU cores is shown in Table 1. The characterization of the neutron flux in irradiation channels of Nigeria NIRR-1 became imperative after conversion to LEU in order to optimize the reactor for Neutron Activation Analysis (NAA). Moreover, with the conversion of NIRR-1 in 2018, a new gamma ray spectrometry setup was also acquired. It consists of a GEM30-7, P- type HPGe co-axial detector, and a DSPEC-50A Advanced Digital high-performance MCA, all made by ORTEC. The spectral acquisition/analysis software installed is the ORTEC Gamma-Vision software/ MAESTRO (Jonah *et al*., 2007).

Table 1: A comparison of HEU and LEU cores of NIRR-1

	HEU	LEU
core diameter & height	230 mm	230 mm
Grid plate	Al	Zircaloy-4
number of fuel pins	347	335
fuel pin diam with cladding	5.5 mm	5.5 mm
fuel length	230 mm	230 mm
Cladding	Aluminum	Zircaloy-4
Fuel	U-Al alloy	UO_2
enrichment U-235	~90%	~13%
total mass of U-235	1.0066 kg	1.357 kg
CR diam.	3.9 mm	4.5 mm

In 2004, when NIRR-1 was critical for the first time with the HEU fuel, the neutron spectrum parameters were also determined and the NAA facilities standardized for optimal utilization (Jonah *et al*., 2005; 2006; 2007, Agbo *et al*., 2015 Anas *et al*., 2015).

Thereafter, the reactor was used for the analyses of several samples made up of biological and geological matrices using the relative and semi-absolute (i.e. k_0-INAA) NAA procedures. In this work as was done for the HEU core, we embark on the determination of the neutron parameters, which include the epithermal flux shape factor, α for an inner irradiation channel B3 and outerirradiation channel B4 as well as the thermal-to-epithermal neutron flux ratio, *f*, for the two channels using the "Cd-ratio Multi-monitor Method".

MATERIALS AND METHOD

MNSR facilities are known to exhibit stable neutron flux and as such, the neutron spectrum parameters can be determined by the Cd-ratio Multi-monitor method. Under this procedure the Cd-ratios of at least two neutron flux monitors are determined experimentally and are used to calculate the *f* and α values in the irradiation channels. Following NIRR-1 conversion to LEU, the irradiation channels designated for use are six out of total of 10, with four inner (i.e. A1, B1, B2, and B3) as well as two outer channels (i,e, A2 and B4.). Of the six channels, the inner channel A1 and outer channel A2 are lined with 1 mm Cd sheet and are connected to the Transfer System A. Therefore, both channels A1 and A2 are suitable for ENAA and FNAA procedures. Similarly, three other inner channels B1, B2, and B3 as well as an outer channel B4 are connected to the Multi-functional Transfer System B. In this work, three neutron monitoring foils recommended for reactors with stable neutron flux distributions were used as was the case for the HEU core of NIRR-1 (Jonah *et al*., 2005, De Corte et al., 1979, and Osai *et al*., 2021). The description of monitor foils deployed in this work is given in Table 2

Table 2: Description of neutron monitoring foils used in this work.

Element	Material description	Diameter	Range of mass (mg)
Au	Al-0.1%Au foil; 0.1 mm thick, IRMM-530	0.8 cm	12-14
Zn	99.95% Zn foil; 0.025mm thick, GOODFELLOW	0.8 cm	8-9
Zr	99.8% Zr foil; 0.125 mm thick, GOODFELLOW	0.8 cm	44-46

Goldman *et al*., 2005

Prior to irradiation in the respective channels, the flux monitors were cleaned with Ethanol,weighed and packed in a stack inside a cleaned polyethylene capsule for the "bare irradiation", while a second set was encapsulated inside a 1 mm thick cadmium box for the "Cd-covered" irradiation. The two sets of irradiations were carried out in the inner irradiation channel (B3) at thermal power level of 17 kW, which corresponds to a preset neutron flux value of 5.0 $e^{11}ncm^{-2}s^{-1}$. Similarly, the same procedures were repeated for the outer irradiation channel (B4) at the same preset neutron flux. Because of proximity to the reactor core and higher neutron flux values in the inner channel, B3, the bare and Cd-covered irradiations were performed for 30 minutes and 60 minutes respectively. Furthermore, for the outer channel, B4, the two irradiations were performed for 1 hour and 2 hours respectively. These irradiation protocols were carried in order to induce measurable activities of at least 10,000 counts in the flux monitors. The nuclear data properties of the four neutron monitor reactions are shown in Table 3:

Table 3: Nuclear data characteristics of the neutron monitoring reactions

Target nucleus	Product nuclide	$T_{1/2}$	E_γ (keV)	$\bar{E}_r$ (eV)	Q_o
^{197}Au	^{198}Au	2.695 d	411.8	5.65	15.7
^{68}Zn	^{69m}Zn	13.76 h	438.6	590.0	3.19
^{64}Zn	^{65}Zn	244.0 d	1115.5	2560.0	1.908
^{94}Zr	^{95}Zr	64.02 d	724.2 + 756.7	6260.0	5.36

After irradiation, the induced activity was measured using the HPGe GEM30-76) detector coupled to a digital Multi Channel Analyzer manufactured by ORTEC. The data was collected with MAESTRO emulation software. Energy and Efficiency calibrations of HPGe detector have been carried out using multi-elements primary gamma point sources in energy range of 59.5-1836.6keV (Czech Metrological Institute, 2019). The gamma ray sources were produced by Czech Metrological Institute in August, 2019. The efficiency curves were determined at two source-detector geometries that have designated for the NAA protocols with NIRR-1 irradiation and counting facilities.

Epithermal flux-shaping factor (α) is an important characteristic in the irradiation channel of a research reactor which correct for the epithermal neutron population deviation from 1/E distribution (Yucel and Karadag 2004, Jonah *et al*., 2011and Kennedy *et al*., 2000).

RESULTS AND DISCUSSION

Calibration

Results obtained for the new NIRR-1 gamma spectrometer setup at the far and near sample-detector geometries are presented in Figure 1.

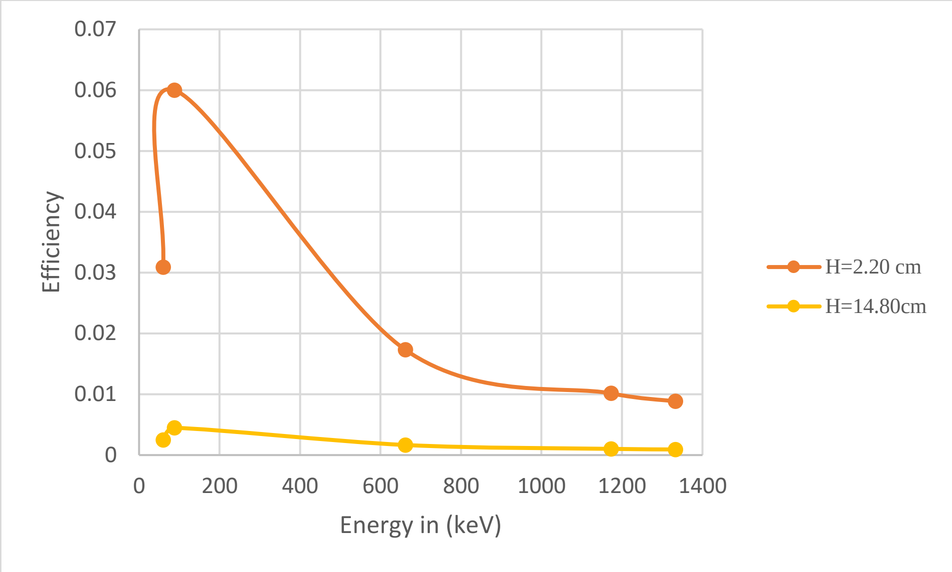

Figure 1: Variation of efficiency with gamma energy and source distance

As can be seen in the Figure, the deviation in the data is within 0.15 % of measurement
The *f* and *α* values were determined iteratively by using the "Solver" utility in EXCEL to solve equation 1 for N monitors. In our case, three monitor reactions described in Table 3 were considered.

Alternatively, the same data are determined from the plot of $\log \frac{\bar{E}_{r,i}^{-\alpha}}{(F_{Cd}.R_{Cd,i}-1)Q_{O,i}(\alpha)G_{e,i}/G_{th,i}}$ versus $\log \bar{E}_{r,i}$ as displayed in Fig. 2 for channel B3.

$$\alpha + \frac{\sum_{i=1}^{N}\left[\left(\log \bar{E}_{r,i} - \frac{\sum_{i=1}^{N}\log \bar{E}_{r,i}}{N}\right)\left(\log \frac{\bar{E}_{r,i}^{-\alpha}}{(F_{Cd,i}.R_{Cd,i}-1)Q_{O,i}(\alpha)G_{e,i}/G_{th,i}} - \frac{\sum_{i=1}^{N}\log \frac{\bar{E}_{r,i}^{-\alpha}}{(F_{Cd,i}.R_{Cd,i}-1)Q_{O,i}(\alpha)G_{e,i}/G_{th,i}}}{N}\right)\right]}{\sum_{i=1}^{N}\left(\log \bar{E}_{r,i} - \frac{\sum_{i=1}^{N}\log \bar{E}_{r,i}}{N}\right)^{2}} = 0 \quad (1)$$

where,

$$Q_{O,i}(\alpha) = \frac{Q_{O,i} - 0.429}{(\bar{E}_{r,i})^{\alpha}} + \frac{0.429}{(2\alpha+1)(0.55)^{\alpha}} \quad (2)$$

$$R_{Cd} = \frac{A_{sp,bare}}{A_{sp,Cd}} \quad (3)$$

$$A_{sp} = \left[\frac{N_p/t_m}{wSDC}\right] \quad (4)$$

where, N_p = the number of counts in the full-energy peak, w = mass of monitor, *M* = atomic mass of target nucleus, ϑ = isotopic abundance of target nucleus, γ = gamma-ray abundance of residual radionuclide, ϕ_{th} = sub-cadmium (thermal) neutron flux, $S = (1-e^{-\lambda t_{irr}})$, saturation factor, $D = e^{-\lambda t_d}$, decay factor, $C = (1-e^{-\lambda t_m})/\lambda t_m$, counting factor, t_{irr}= irradiation time, t_d= decay time, t_m = measuring time, λ = decay constant, *i* denotes the i^th^ monitor, N the number of monitors used and, $\bar{E}_{r,i}$ is the effective resonance energy of the ith monitor, F_{Cd} is the Cd-transmission factor for epithermal neutrons, $G_{e,i}$ is the epithermal neutron self-shielding factor for the ith monitor

$G_{th,i}$ is the thermal neutron self-shielding factor for the ith monitor, $R_{Cd,i}$ is the ratio of the specific activity of the ith monitor irradiated without the Cd ($A_{sp,bare}$) to that with the Cd cover ($A_{sp,\,Cd}$)

$Q_{0,i} = I_0/\sigma_0$ is the ratio of resonance integral to thermal neutron capture cross section at a neutron velocity of 2200 m/s for the ith monitor

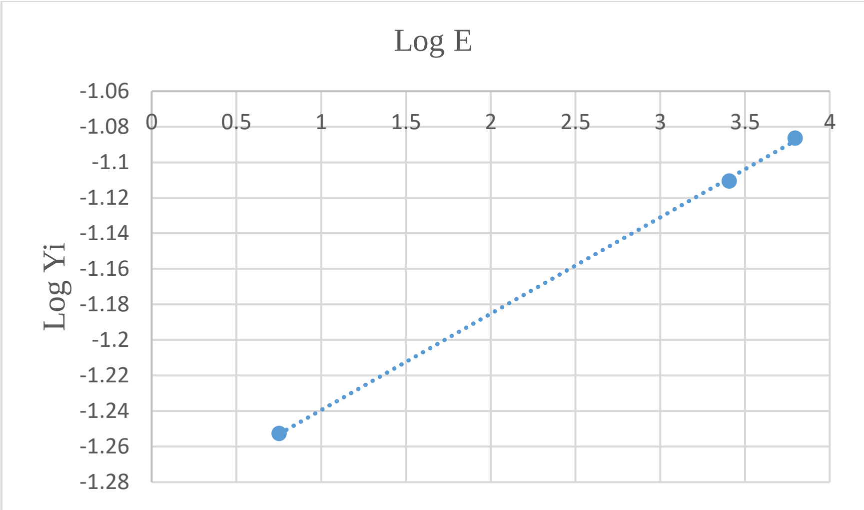

Figure 2: Cd-ratio Multi Monitor Plot (Inner Channel B3)

Results of the f and α values for the LEU in comparison with the HEU core are presented in Table 4.

Table 4: Neutron Spectrum Parameters for NIRR-1 HEU and LEU Cores

Enrichment Parameter	LEU Core		HEU Core	
	f	***α***	***F***	***α***
Inner Channel	19.67±0.30	-0.054±0.003	19.2±0.5	-0.052±0.002
Outer Channel	48.6±2.15	+0.029±0.004	48.3±3.3	+0.029±0.005

The data for the LEU core and HEU core as presented in Table 5 are comparable with each other and in an agreement with data published in the literature for these types of facilities (Jonah *et al*., 2005 and De Corte *et al*., 1981).

Table 5: Comparison of flux parameter with previous studies.

Reactor Facility (Channels)	Inner Channel		Outer Channel		Reference
	f	**α**	**F**	**A**	
GHARR-1 MNSR LEU core (1 and 6)	17.77	-0.096	45.08	-0.031	Bernard Osei (2021)
Slowpoke-2, DUSR Halifax Canada	18.8	-0.0425	57.1	-0.0098	Kennedy *et al*., (2000)
NIRR-1 MNSR (HEU) (B2 and B4)	19.2	-0.052	48.6	0.029	Jonah *et al*., (2005)
NIRR-1 MNSR (LEU) MCNP Code	__	-0.047	__	0.028	Jonah *et al*., 2011
NIRR-1 MNSR (LEU) (B3 and B4)	19.67	-0.0542	48.6	0.0289	This work

The results are an in agreement with similar work carried out in the same laboratory for NIRR-1 LEU based on MNCP simulation (Jonah *et al*., 2011), where it was affirmed that the conversion of NIRR-1 core will result in no discernible impact on the neutron parameter inthe inner irradiation channels. This attributable to retention of the core configurations of both LEU and HEU fuels except for the increase in power from 31 kW to 34 kW as result of conversion to LEU so as to compensate for the approximately 10 % loss in the nominal neutron flux. Furthermore, in order to increase the efficiency of the single Control Rod, the diameter of the Cd sheath was increased to from 3.9 mm to 4.5 mm as shown in Table 1.

It was observed from Table 4 that the larger positive value of the flux-shaping factor "*α"* which correspond to the thermalized nature of the channel which shows the softening ideal 1/E spectrum (epithermal spectrum). ((De corte, 1979; Dung *et al*., 2010 and Jovanovic *et al*., 1987;1989).)

Similarly, it was observed from Table 4 that the flux-shaping factor "*α"* is negative for the inner irradiation channel (B3) of NIRR-1, this correspond to hardened neutron spectrum of the reactor due to the under moderation and compact nature of the reactor core. These feature shows that the reactor is operated under safe condition and suitable for Neutron activation analysis experiment and also ideal for physics application (De corte, 1979 and Jovanovic *et al*., 1987;1989).Conclusion

The values of *f and α* in the inner irradiation channel B3 and outer irradiation channel B4 of the NIRR-1 LEU core have been determined in this work using the Cd-ratio Multi-monitor method. As can be seen, the data compare well for both LEU and HEU cores of the reactor as well as data of similar facilities. This work was embarked upon to stream line the reactor for utilization via INAA. Furthermore, efficiency curves of the newly installed NIRR-1gamma ray spectrometer were determined at two different geometries designated for routine INAA protocols with NIRR-1 irradiation and counting facilities.

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