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Assessing the Effect of Fuel Burnup on Control Rod Worth for HEU and LEU Cores of Gharr-1

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Abstract: An important parameter in the design and analysis of a nuclear reactor is the reactivity worth of the control rod which is a measure of the efficiency of the control rod to absorb excess reactivity. During reactor operation, the control rod worth is affected by factors such as the fuel burnup, Xenon concentration, Samarium concentration and the position of the control rod in the core. This study investigates the effect of fuel burnup on the control rod worth by comparing results of a fresh and an irradiated core of Ghana's Miniature Neutron Source Reactor for both HEU and LEU cores. In this study, two codes have been utilized namely BURNPRO for fuel burnup calculation and MCNP5 which uses densities of actinides of the irradiated fuel obtained from BURNPRO. Results showed a decrease of the control rod worth with burnup for the LEU while rod worth increased with burnup for the HEU core. The average thermal flux in both inner and outer irradiation sites also decreased significantly with burnup for both cores.

Keywords: Control rod worth, HEU, LEU

INTRODUCTION

The reactivity worth of control rods which is their efficiency to absorb excess reactivity is an important parameter in the design and analysis of a nuclear reactor core (Duderstadt and Hamilton, 1997). The control rods worth is affected by their position in the core, their operational time, surrounding materials, fuel burnup as well as the concentrations of fission products such as Xenon and Samarium.

A reactors' control system has the following basic functions:

- Provide a means of starting the reactor by bringing the reactor power up to the desired level
- Maintaining the power at that level
- Shutting the reactor down for routine operations as well as in accidental conditions (Fadaei and Setayeshi, 2009)

An essential requirement of the control system is that it must be capable of introducing enough negative reactivity to compensate for the built-in (positive) reactivity at initial startup of the reactor (Glasstone and Sesonke, 1967). The method of reactor control employed in MNSR's like GHARR-1 is the withdrawal or insertion of the central control rod made of cadmium. Figure 1 depicts the effect of the central control rod on the radial neutron flux distribution.

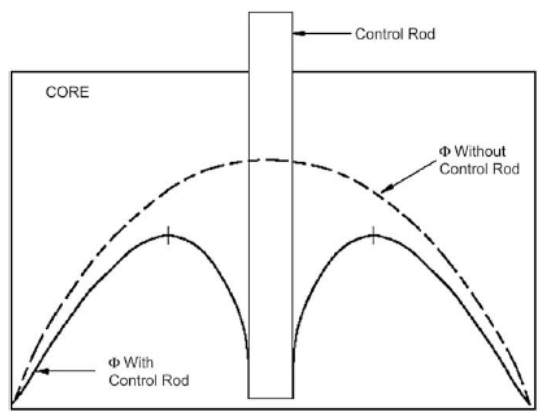

Fig. 1: Effect of central control rod on radial neutron flux distribution

Control rod insertion leads to absorption of neutrons in its vicinity and causes a distortion of the neutron flux distribution. From Fig. 1 it is seen that the neutron flux is decreased close to the control rod, but farther out nearer the core boundary, the flux is

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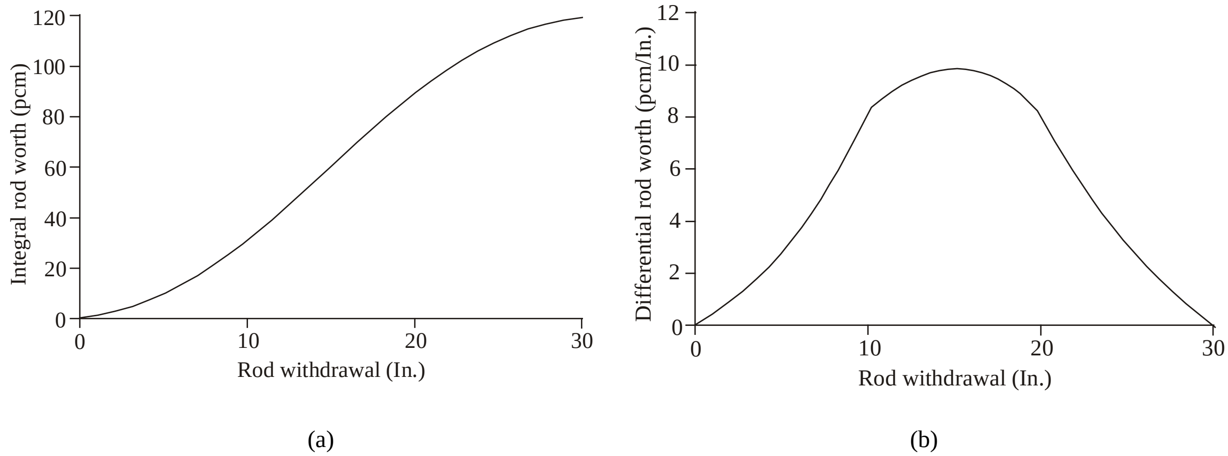

Fig. 2: Integral and differential rod worth

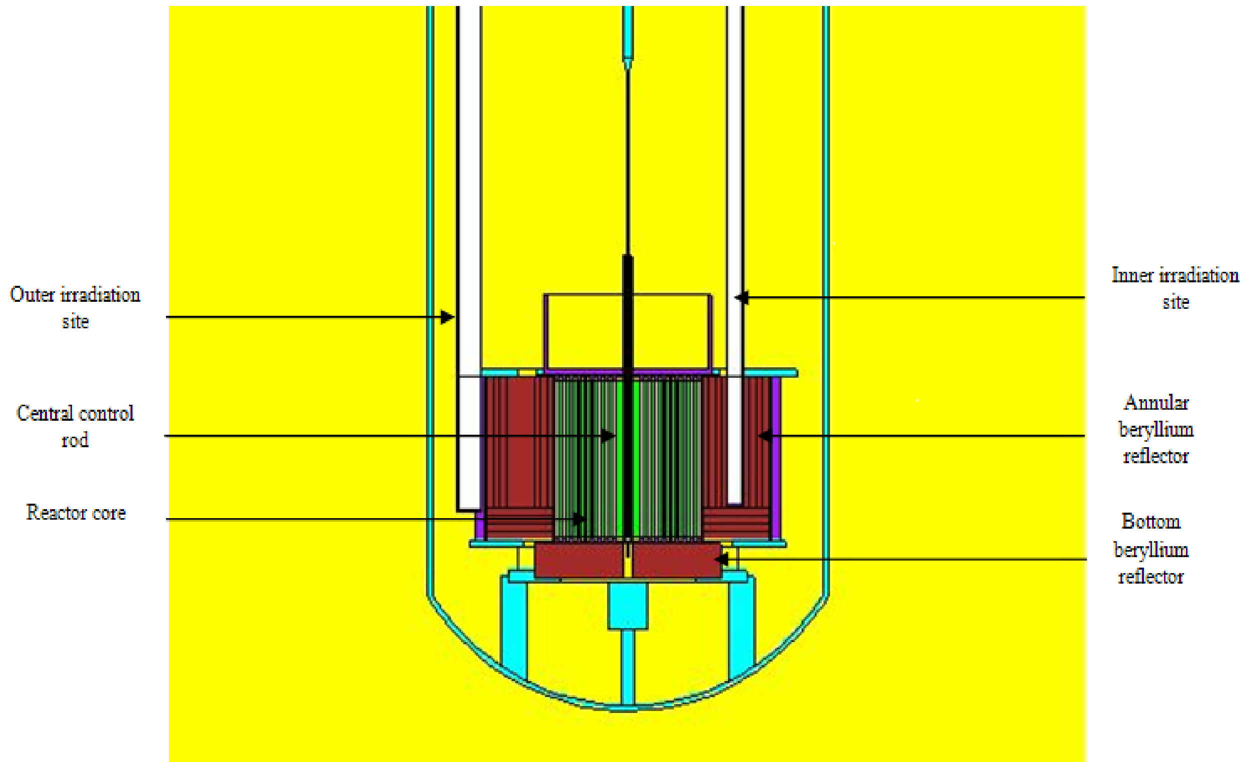

Fig. 3: MCNP plot of the vertical cross section of the GHARR-1 core

increased (Glasstone and Sesonke, 1967). There are two ways of control rod worth definition namely integral rod worth and differential rod worth as shown in Fig. 2. This study was carried out to investigate the control rod worth for both HEU and LEU cores at Beginning of core life and End of core life in view of the current core conversion program ongoing at the GHARR-1 Centre.

Control system of GHARR-1: The Ghana Research Reactor-1 (GHARR-1) is a 30 kw Miniature Neutron Source Reactor operated by the National Nuclear Research Institute. The reactor is controlled either through the main control console or through a computerized control system. The system consists of a single cadmium control rod located in the centre of the core, a neutron flux detector and a solid state comparator control device circuit. Excess reactivity of the reactor is limited to ½ β_{eff} to ensure that prompt criticality is not possible. It is possible to manually insert cadmium rabbits into the reactor to ensure reactor shutdown if a malfunction occurs in the control system. Figure 3 shows an MCNP plot of the vertical cross section of the GHARR-1 core with the central control rod. A detailed description of the reactor is presented elsewhere (Akaho *et al*., 2003).

In this study, an assessment is made of the effect of fuel burnup on control rod worth for GHARR-1 by simulating its MCNP5 model for fresh and irradiated cores. Firstly, fuel burnup was calculated for both HEU and LEU cores using the deterministic code BURNPRO, the results were then used to modify the MCNP5 model of GHARR-1. The modified deck was then simulated in order to calculate the control rod worth as well as determine the thermal neutron flux in both inner and outer irradiation sites.

MATERIALS AND METHODS

BURNPRO is a deterministic code written in Fortran which is based on the three neutron energy group approach namely fast, resonance and thermal. It calculates the fuel burnup of the 90.2% enriched core of GHARR-1 and estimates the concentrations of actinides formed as a result of burnup (Boafo *et al*., 2012). The densities of the isotopes determined by BURNPRO were supplied as input to the existing MCNP input deck for core analysis.

MCNP is a general-purpose (Monte Carlo, 2007) N-particle code that can be used for neutron, photon, electron, or coupled neutron/photon/electron transport, including the capability to calculate eigenvalues for critical systems. The code treats an arbitrary three-dimensional configuration of materials in geometric cells bounded by first-and second-degree surfaces and fourth degree elliptical tori (Breismeister, 1997). The neutron energy regime is from 10^{-11} to 20 MeV for all isotopes and up to 150 MeV for some isotopes, the photon energy regime is from 1 keV to 100 GeV and the electron energy regime is from 1 keV to 1 GeV. The simulation of radiation transport in matter involves the tracking of particles according to established probabilistic laws, commonly known as cross sections (Jonah *et al*., 2007).

Monte Carlo (2007) particle transport methods were used in the modeling, simulation and neutrinos analysis of GHARR-1 in order to ascertain the

Table 1: Composition of the fuel meat for HEU and LEU for GHARR-1

Parameter	Description HEU core	LEU core
Fuel	U-Al dispersed in Al	UO_2
Enrichment	90.20%	12.6%
Density of fuel meat	3.456 g/cm^3	10.60 g/cm^3
Density of uranium in meat	0.955 g/cm^3	9.342 g/cm^3
Weigh fraction of uranium in meat	0.273	0.881
Diameter of fuel meat	4.300 mm	4.3 mm

feasibility of potential LEU cores. It was observed that 12.6% enriched UO_2 core yielded a k_{eff} result of 1.00454 (Anim-Sampong *et al*., 2007), which compares favorably with that of the current HEU core.

In this study, the 12.6% enriched UO_2 core was used to assess the effect of fuel burnup on control rod worth. Details of both HEU and LEU fuels simulated by MCNP are presented in Table 1.

The MCNP input deck used in this study had been developed by Anim-Sampong (1993) as part of the core conversion studies initiated to convert the reactor from HEU to LEU. For the purposes of this study, the existing deck was modified: notably the fractions of the isotopes which constitute the fuel to reflect changes in the fuel composition due to burnup. Isotopes such as U-236, Pu-239, Pu-240 and Pu-241 were added to the deck to reflect the changes in the fuel composition and the concentrations of U-235 and U-238 were also changed accordingly.

The MCNP model of GHARR-1 consists of 344 HEU and 348 LEU fuel elements of cylindrical geometry which were modeled as fission sources. The weight content of U-235 per fuel element (g_U-235) for MNSR reactors can be calculated from the expression (1-2):

$$g_{U-235} = \rho_f V(1-e\%)Xf_m \tag{1}$$

where,

V : The volume of the active zone of the fuel element of porosity e%

X : The total mass fraction of uranium in the fuel

ρ_f : The fuel density in g/cm^3

The quantity f_m is defined as:

$$f_m = \frac{m_{U-235}\varepsilon}{m_{U-235}\varepsilon + m_{U-238}(1-\varepsilon)} \tag{2}$$

where,

m_{U-235} : The atomic masses of U-235

m_{U-238} : The atomic masses of U-238ε

ε : The U-235 enrichment

Table 2: Comparison of neutronic parameters for fresh and irradiated cores of GHARR-1

	HEU		LEU	
Description	Fresh core	Irradiated core	Fresh core	Irradiated core
Burnup (%)	0	1.16	0	0.72
CR worth (mk)	6.41	7.44	7.61	6.98
$\phi_{th}(n/cm^2.s)$ inner	1.22E+12	9.59E+10	1.08E+12	8.64E+10
$\phi_{th}(n/cm^2.Sec)$ outer	8.05E+11	3.35E+10	6.68E+11	3.82E+10

Table 3: Comparison of control rod worth of MNSRs with this study

	HEU		LEU	
Description	Fresh core	Irradiated core	Fresh core	Irradiated core
Jona *et al*. (2007)	7.61 mk	-	6.91 mk	-
SAR	6.80 mk	-	-	-
Khattab and Sulieman (2011)	6.54 mk	-	-	-
This study	6.40 mk	7.40 mk	7.60 mk	6.98 mk

After substitution, the gram loading of U-235 becomes:

$$g_{U-235} = \rho_f V(1-e\%)X\left(\frac{m_{U-235}\varepsilon}{m_{U-235}\varepsilon + m_{U-238}(1-\varepsilon)}\right) \quad (3)$$

The density of the fuel can then be calculated as:

$$\rho_f = \frac{g_{U-235}}{V(1-e\%)X\left(\frac{m_{U-235}\varepsilon}{m_{U-235}\varepsilon + m_{U-238}(1-\varepsilon)}\right)} \quad (4)$$

Criticality calculations were performed by utilizing the KCODE criticality source card to determine k_{eff} using the fuel elements as fission sources. Specific aspects of modeling MNSR using MCNP5 include continuous-energy cross section data and all calculations were based on the full spectrum of energy available at the MCNP5 code library at 20°C. The input file for the MCNP5 included 430 cycles made up of 30 inactive cycles and 400 active cycles with 500,000 particle histories per cycle. The GHARR-1 MCNP model was simulated for total withdrawal as well as total insertion of the control rod in order to calculate the control rod worth.

Rod worth calculation: The rod worth is calculated using the formula:

$$\rho = \frac{k_{eff\,(fullywithdrawn)} - k_{eff\,(fullyinserted)}}{k_{eff\,(fullyinserted)}} \quad (5)$$

where,

k_{eff} (fully withdrawn) : The effective multiplication factor with the control rod fully withdrawn from the core

k_{eff} (fully inserted) : The effective multiplication factor with the control rod fully inserted in the reactor core

It is known generally that considering small displacements of the control rod would yield precise results, however this method was not adopted in this study because it is time consuming particularly with the Monte-Carlo (2007) simulations.

RESULTS AND DISCUSSION

Results of control rod worth calculated by coupling MCNP with BURNPRO for fresh and irradiated cores are presented in Table 2. In Table 3, some neutronic parameters obtained after the simulation are also presented while the thermal neutron flux distributions in inner and outer irradiation channels are shown in Fig. 4 and 5.

It can be observed from Table 2 that the control rod worth increased from 6.4 to 7.44 mk for the HEU after 1.16% burnup of U-235. In the case of the LEU however, there was a reduction from 7.61 to 6.98 mk after 0.72% burnup, this reduction in the control rod worth can be attributed to the presence of U-238 responsible for the capture of neutrons in the resonance region. The resultant effect of resonance capture by U-38 is reduced thermal neutron flux which leads to reduced control rod worth.

The significant flux reduction after burnup observed from Table 2 is a major concern since high flux levels are required to ensure effective reactor utilization for neutron activation analysis at GHARR-1 centre. This problem has however been addressed by periodic addition of beryllium shims to the top tray of the reactor.

CONCLUSION

An assessment of the effect of fuel burnup on control rod worth has been carried out for both HEU and LEU cores of Ghana's MNSR by coupling BURNPRO with MCNP. The results have shown that fuel burnup has significant effect on the control rod worth of both

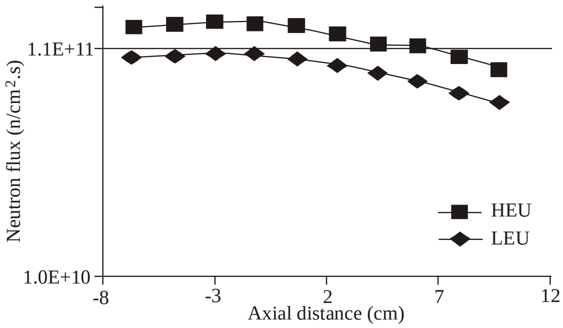

Fig. 4: Axial thermal neutron flux distribution in inner irradiation channel for HEU and LEU cores after burnup

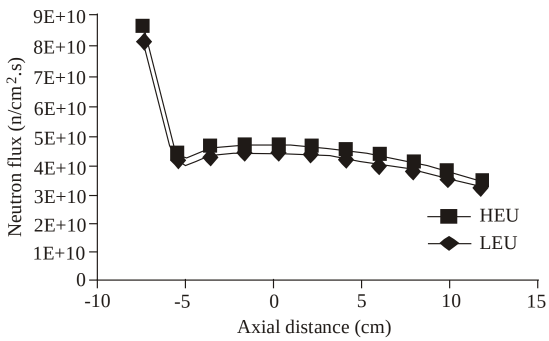

Fig. 5: Axial thermal neutron flux distribution in outer irradiation channel for HEU and LEU after burnup

cores. Average thermal flux in both inner and outer irradiation channels was also estimated as well as the flux distribution; again fuel burmup had notable effects on the flux levels which were negative. Further studies will be required to estimate the exact reactor power upgrading needed in order to ensure that reactor efficiency is not compromised as a result of core conversion from HEU to LEU.

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