Determination of Reproduction and Thermal Utilization Factors for The Nigeria Research Reactor-1(NIRR-1)

Ndawashi M.[1*], Hussaini S.M.[2], Aremu S.O.[1], Saidu A.[3] and Abubakar N.[1]
[1]Department of Science Laboratory Technology, Federal Polytechnic Bauchi
[2]Department of Physics, Air force Institute of Technology, Kaduna
[3]National Board for Technology Incubation, Offa.

ABSTRACT

The present study was conducted to investigate the behavior of the Nigeria Research Reactor-1 (NIRR-1) under the variation of moderator-to-fuel ratio on reproduction factor (η) and thermal utilization factor(f). The results show that the thermal utilization factor(f) was 5.55 while Reproduction factor (η) was 4.73. When plotted, the graph of both the moderator and fuel ratios against moderator-to-fuel ratio demonstrated a good behavior and stability of the reactor at a moderator- to- fuel ratio of 165. It has also been observed that reducing moderator-to-fuel ratio from its present 197 to 165 have same flux and reactor stability for an MNSR reactor like NIRR-1. This could be attributed to the fact that under moderated reactors are stable against changes in temperature (negative coefficient) while over moderated reactors are unstable against changes in the temperature (positive coefficient) in the reactivity of the core. We therefore conclude that moderator-to-fuel ratios of $197\ and\ 165$ are the best ratios to be used for efficient and safe operation of the NIRR-1.

Keywords: Miniature Neutron Source Reactor (MNSR), over moderation, under moderation.

1. INTRODUCTION

The Nigeria Research Reactor-1 (NIRR-1) installed and commissioned at the Centre for Energy Research and Training (CERT), Ahmadu Bello University, Zaria, Nigeria is a low power tank-in-pool Miniature Neutron Source Reactor (MNSR) type (schematic diagram and sectional view shown in Figs. 1 and 2, respectively) that uses highly enriched U-235 fuel in an Al cladding, has maximum nominal power of ~30 kW which is equivalent to a thermal neutron flux of $1 \times 10^{12}\ n.cm^{-2}.S^{-1}$under steady-state condition [1,2]. It was licensed specifically for neutron activation analysis (NAA), radioisotope production, nuclear engineering teaching, training and research purposes [3]. It is the 8^{th} commercial Miniature Neutron Source Reactor designed by China Institute of Atomic Energy (CIAE). The reactor's first criticality was achieved on February 3, 2004, and has been working safely since then [4-7].

Like all commercial Miniature Neutron Source Reactors (MNSR), except for the liquid metal fast breeder reactors (LMFBR) employed for nuclear fission reaction, all the remaining reactor types use moderating materials to reduce fission neutron energies to a thermal range; And light moderator (composed of light nuclei) is found to be more effective since it removes more energy per collision than other moderators and allow the neutrons to reach thermal energy more rapidly thereby reducing their lost chances through resonance absorption [8].

Accurate moderator-to-fuel ratio (N^m/N^u) of a MNSR is very important not only for safe monitoring and evaluation of reactor dynamic behavior but also for determination of fuel burn up and normalization of neutron fluxes and dose rate. Variation of moderator-to-fuel ratio in the reactor core affects the amount of neutron leakages or absorption, thermal utilization factor as well as resulting to a greater loss of neutrons by resonance absorption [5-8]. To ensure inherent safety in the reactor operation, moderator-to-fuel ratio is an important parameter to a reactor physicist since its temperature is directly dependant on the reactor flux and power [1, 9].

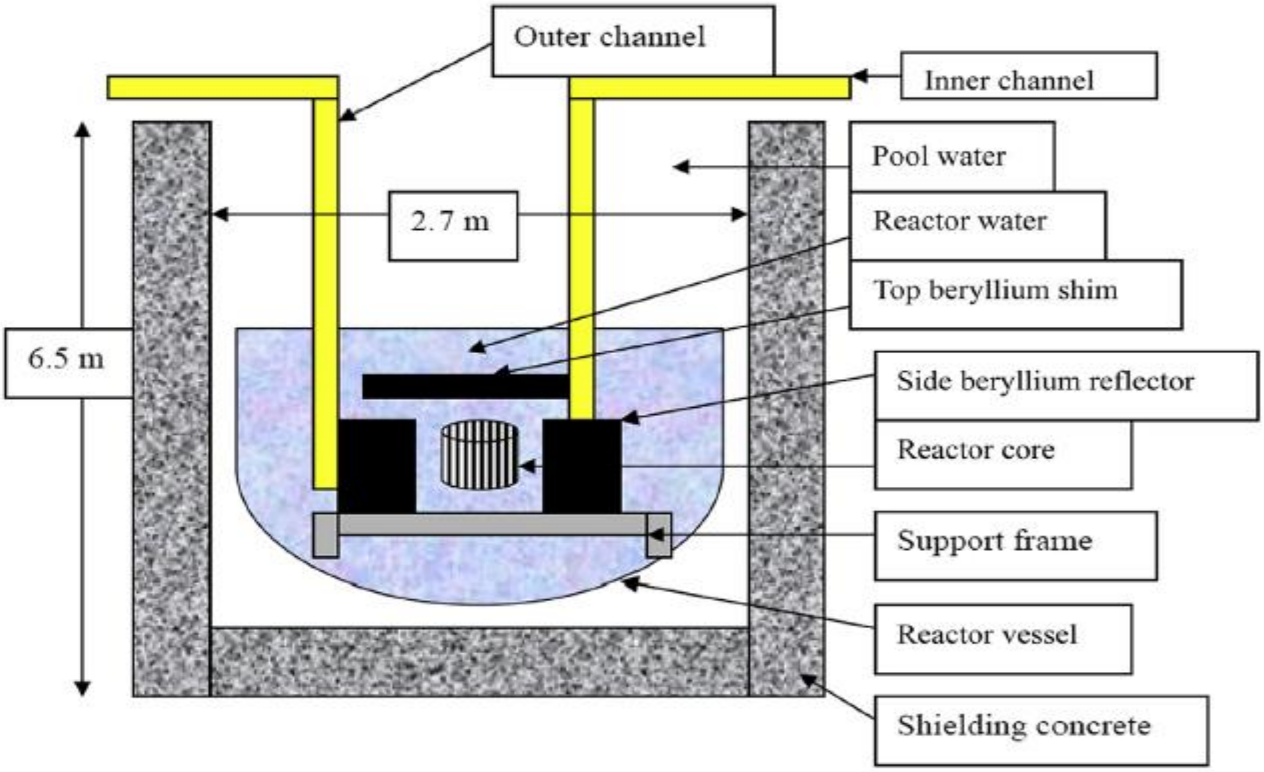

Fig. 1 - Schematic diagram of NIRR-1 [10]

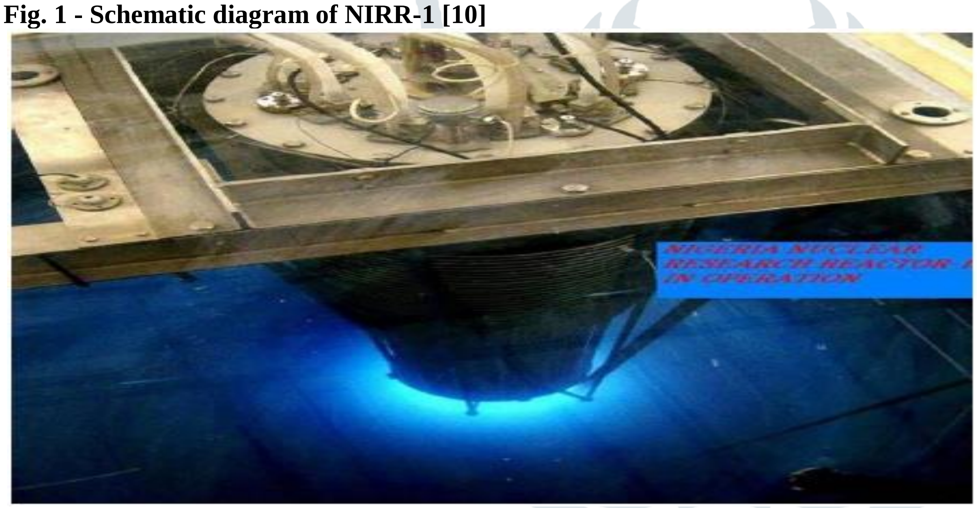

Fig. 2 - Sectional view of NIRR-1 [10].

Since the fast neutrons produce by fission can enter into several reactions thereby either allowing it size to reduce, increase or produce a second generation, there is a need to study the four factors that are completely independent of the size and shape of NIRR-1 that give the inherent multiplication ability of the moderator and fuel materials without regards to any leakage according to the infinite multiplication factor (equation 1). And to account for neutrons leakage in a real, finite reactor, the effective multiplication factor (equation 2) would be employed.

$$K_{\infty} = \mathcal{E}\rho f \eta \quad \ldots\ldots\ldots\ldots\ldots\ldots.. (1)$$

Where: $\mathcal{E}$ is fast fission factor, ρ is resonance escape probability, f is thermal utilization factor and η is reproduction factor.

$$K_{eff} = K_{\infty} L_f L_t \quad \ldots\ldots\ldots\ldots\ldots (2)$$

Where: L_f is fast non-leakage probability, L_t is thermal non-leakage probability.

For $K_{eff} = 1$, the neutron production is neither increasing nor decreasing (Critical condition).

$K_{eff} > 1$, the neutron production is greater than absorption/leakage (Subcritical condition).

$K_{eff} < 1$, the neutron production is less than the absorption/leakage (Super Critical condition).

2. METHODOLOGY

Moderation processes in MNSR

Under-moderation of NIRR-1

In practice, water-moderated reactors like NIRR-1 are design with a moderator –to- fuel ratio that make them operate in an under moderated condition since increase in temperature would decrease $N^m/_{N^u}$ due to expansion of the water as its density becomes lower. If the core overheats, then the quality of the moderator is reduced and the reaction tends to slow down (negative temperature coefficient). In the case of NIRR-1, under-moderation was achieved by choosing 90% HEU (UAl_4) as fuel material, light water as moderator and coolant, and metallic Beryllium as reflector; all under two moderator-to-fuel ratio factors:

- ❖ The ratio of the hydrogen to Uranium atoms was chosen to be 197 in order to enlarge the degree of under-moderation of the core and thereby increase its negative temperature coefficient of reactivity and to enhance the temperature feedback.
- ❖ The ratio of the core height to diameter was optimized to 1.0 in order to enlarge the worth of the top beryllium reflector and thereby extend the life time of the core. It also facilitates the flow and mixing of the inlet and outlet coolants, shortening the life of the temperature feedback.

Over-moderation of NIRR-1

Over-moderated reactors are usually unstable against changes in temperature (positive temperature coefficient in the reactivity of the core) as such they are less inherently safe than under-moderated types. With the exception of the liquid metal fast breeder reactor (LMFBR), all other reactor types that are currently employed used moderating material to reduce fission neutron energies to the thermal range. Light moderators (compose of light nuclei) are found to be more effective than heavy moderators since it removes more energy per collision than a heavy type with neutrons attending thermal energy more rapidly, and making them less likely to be lost through resonance absorption. As we make $N^m/_{N^u}$ to increase; neutron leakage decreases, neutron absorption in the moderator ($\sum m_a$) increase and cause a decrease in thermal utilization factor(f). In general, a reactor is said to be over- moderated when an increase in the moderator-to-fuel ratio decreases effective multiplication factor (K_{eff}) due to decrease in thermal utilization factor(f); but reactors are usually designed to operate in an under-moderated condition so that the moderator temperature coefficient of reactivity will always be negative.

3. RESULTS AND DISCUSSIONS

The results for the work were obtained by varying moderator-to-fuel ratio ($N^m/_{N^u}$) at constant N^m as well as at constant N^u all as shown in table 1. Similarly, equations 3 and 4 were employed to calculate the thermal utilization factor (f) as well as reproduction factor (η).

$$f = \frac{N_u}{(N_u + N^m R_\phi R_\sigma)} \quad ....\ (3) \quad \text{and} \quad \eta = (\frac{\sigma_f}{\sigma_a}) \times f \quad ....(4)$$

Table 1. Measurement of moderator-to-fuel ratio ($N^m/_{N^u}$), $N^u = constant$ & $N^m = constant$

$N^m(LT)$	$N^u(LT)$	$N^m/_{N^u}$	f	η
200	18.0	47	1.328	1.131
400	9.0	94	1.976	1.684
600	6.0	141	3.857	3.286
800	4.5	188	8.100	6.901
1000	3.6	235	-4.263	-3.632
1200	3.0	282	-2.071	-1.770
1400	2.6	329	-1.373	-1.170
1600	2.2	376	-1.025	-0.873
1800	2.0	423	-0.818	-0.697
2000	1.8	471	-0.681	-0.579

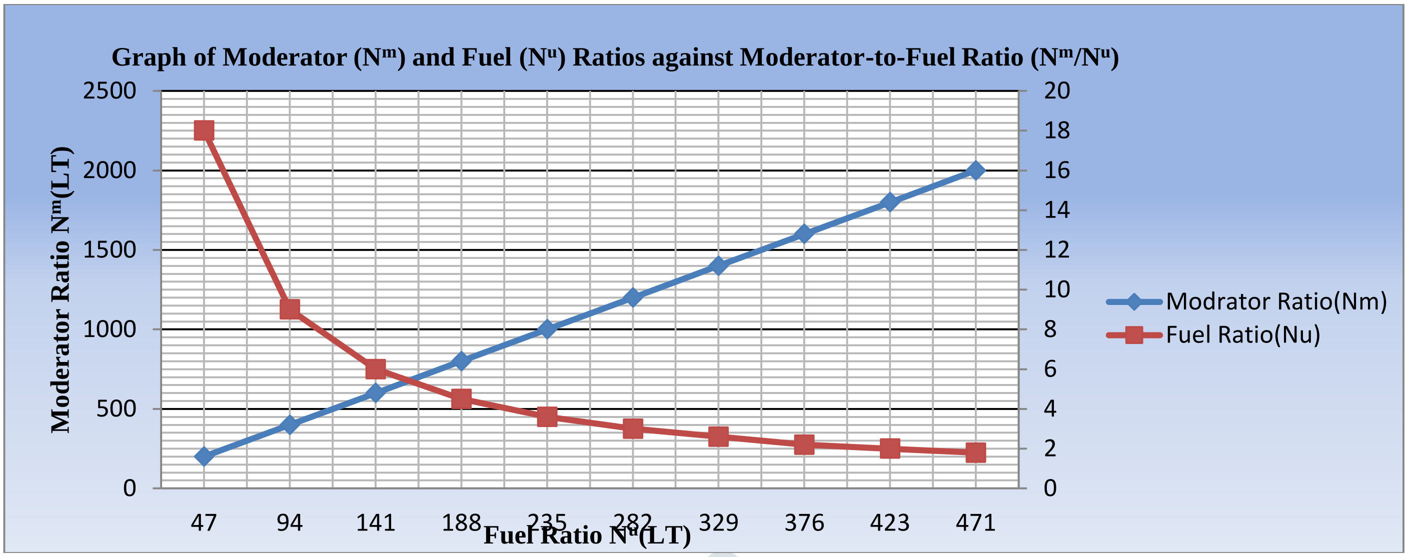

Fig.3- Graph of Moderator (N^m) and Fuel (N^u) Ratios against Moderator-to-Fuel Ratio (N^m/N^u)

Discussions

Moderation ratio

The moderator –to- fuel ratio ($^{N^m}/_{N^u}$) is an important parameter in the discussion of reactor safety and operation since its variation affect neutron leakage, neutron absorption as well as thermal utilization factor (f). As the amount of moderation (N^m) increases in the core, neutron leakage decreases, neutron absorption in the moderator ($\sum m_a$) increases and causes an increase in the thermal utilization factor (f). Having insufficient moderator (N^m) in the core causes an increase in slowing down time and results in a greater loss of neutrons by resonance absorption which also causes an increase in neutron leakage.

The Nigeria Research Reactor-1 (NIRR-1) was designed with a moderator –to- fuel ratio ($^{N^m}/_{N^u}$) of 197. However, the present work investigated possibility of using other ratios to obtain same flux and reactor stability. Our results show that the ratio 165 (fig. 3) is possible for a Miniature Neutron Source Reactor like NIRR-1 which is a light water reactor. This is in agreement with the fact that the higher the moderating ratio, the more effectively the material performs as moderator.

Furthermore, since water moderated reactors are designed with a moderator –to- fuel ratio that make them operate in an under moderated condition; our result indicated that reduction of the ratio from 197 to 165 gives a decrease in the moderator and increasing it shows an increase in the moderator (table 1). This will make the reactor maintain a negative temperature coefficient and a greater effective multiplication factor (K_{eff}) in a safe operation cycle.

Fuel ratio

As the amount of fuel (N^u) in the core decreases, neutron leakage increases, neutron absorption in the moderator ($\sum m_a$) decreases and causes an increase in the thermal utilization factor (f) as well as reproduction factor (η). Having sufficient fuel (N^u) in the core, causes a decrease in slowing down time and result in a lesser loss of neutrons by resonance absorption which also causes a decrease in neutron leakage. As illustrated in fig.3, and table 1, a decrease in the fuel ratio leads to increase in moderator –to- fuel ratio ($^{N^m}/_{N^u}$). This indicated that reduction of the ratio from 197 to 165 gives an increase in the fuel and increasing it shows a decrease in the fuel. This satisfied the argument that some reactors are designed to be under moderated in order to give a nagative temperature reactivity and greater safe regulating.

4. CONCLUSION

In the present work, we were able to determine the thermal utilization factor (f) and reproduction factor (η). We also studied different moderator –to- fuel ratio ($^{N^m}/_{N^u}$) that can be applicable for the Nigeria Research Reactor-1 (NIRR-1) which is a Miniature Neutron Source type. Our results show that $f = 5.55$ *and* $\eta = 4.73$. We have demonstrated that ($^{N^m}/_{N^u}$) of 165 is another possible ratio that could be applicable in NIRR-1 as well as MNSR. The effects of over and under moderation on infinite multiplication factor (K_∞) were also considered. The result obtained indicated that increase in thermal utilization factor leads to increase in the reproduction factor. The work has greatly contributed to the understanding of NIRR-1 behavior under different moderating ratios particularly as it affects its optimization and conversion from highly enriched fuel to low enriched.

REFERENCES

[1] Agbo SA, Ahmed YA, Ewa IOB, Jibrin and Y. Analysis of Nigeria Research Reactor-1 thermal power calibration methods. J. Nucl. Eng. and Tech. 48(2016)673-683.

[2] Ahmed YA, Balogun GI, Jonah SA, Funtua II. The behavior of reactor power and flux resulting from changes in core-coolant temperature for a miniature neutron source reactor, Ann. Nucl. Energy 35 (2008) 2417-2419.

[3] Ahmed YA, Mansir IB, Yusuf I, Balogun GI, Jonah SA. Effects of core excess reactivity and coolant average temperature on maximum operable time of NIRR-1 miniature neutron source reactor. Nucl. Eng Des. 241 (2011) 1559-1564.

[4] Balogun GI. Automating some analysis and design calculations of miniature neutron source reactors at CERT (1). Ann. Nucl. Energy 30 (2003) 81–92.

[5] Balogun GI, Jonah SA. Current status of the Nigeria MNSR (NIRR-1) and feasibility for conversion to LUE. Paper presented at 2005 international RERTR meeting: (www.rertr.anl.gov/RERTR27/Abstracts/s10-04_Jonah.html)

[6] Balogun GI, Jonah SA, IM Umar. Measures aimed at enhancing safe operation of the Nigeria Research Reactor-1 (NIRR-1), in: Book of Contributed Papers, International Conference on Operational Safety Performance in Nuclear Installations (IAEA-CN-133/19), IAEA, Vienna (Austria), November 30-December 2, 2005, pp. 93-96.

[7] Jonah SA, Balogun GI, Umar IM, Mayaki MC. Neutron spectrum parameters in irradiation channels of the Nigeria Research Reactor-1 (NIRR-1) for the k0-NAA standardization, J. Radioanal. Nucl. Chem. 266 (2005) 83-88.

[8] Jonah SA, Umar IM, Oladipo MOA, Balogun GI, Adeyemo DJ. Standardization of NIRR-1 irradiation and counting facilities for instrumental neutron activation analysis, Appl. Radiat. Isot. 64 (2006) 818-822.

[9] Yongmao Z. Technology and Use of low power research reactors, Report of IAEA Consultants Meeting (Report No. IAEA-TECDOC-384), Beijing (China), April 30-May 3, 1985, pp. 89-98.

[10] Department of Energy (DOE), DOE-HDBK-1019/2-93, Department of Energy Fundamentals Handbook: Nuclear Physics and Reactor Theory (Neutron Characteristics), vol. 2, DOE, Washington D.C. (WA), 1993, p. 1-37.