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Estimation of the Thermal Power of Nigeria Research Reactor-1 Low Enriched Uranium Core at Half Power using the Heat Balance Approach

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ABSTRACT

Reactor power estimation is crucial for the safe monitoring and evaluation of reactor operation, as the reactor power signal is normally used in the reactor automatic control system, evaluation of reactor experiments, accurate determination and calculation of fuel element burn-up as well as isotopic composition of burned fuel, normalization of calculated neutron fluxes and specifically dose rates. In this present study, the heat balance method has been applied in the estimation of the thermal power of Nigeria Research Reactor-1 (NIRR-1) specifically at the at half power. The inlet temperature, outlet temperature and temperature difference measured were of average values of 32.43 ± 1.54 ºC, 43.49 ± 2.07 ºC and 11.06 ± 0.53 ºC, respectively. On the average, the coolant flow rate through the core was 0.3966 ± 0.0188 kg/s. The power dissipated was found to be 14.97 kW, while the total heat loss was 0.23 kW. The results obtained in this current study is consistent with that of other low enriched uranium core at half power. These results have again supported the accuracy of the heat balance method; hence, it is the method is recommended for routine estimation of Miniature Neutron Source Reactors.

Keywords:
Miniature Neutron Source Reactors,
Low enriched uranium core,
Temperature measurement,
Reactor power estimation.

INTRODUCTION

In contrast to power reactors, which produce electricity, heat, or are used for naval propulsion, research reactors are nuclear reactors that are used solely as neutron sources, and are also known as non-power reactors (Alrwashdeh and Saeed, 2019). Research reactors operate at lower temperatures and are more straightforward than power reactors. They require a lot less fuel, and as the fuel is consumed, a lot less fission products accumulate. On the other hand, their fuel requires uranium that has been more highly enriched, normally up to 20% U-235, while some use 93% U-235; 20% enrichment is typically not seen to be suitable for nuclear weapons because 93% is sometimes referred to as "weapons-grade." Additionally, they have a core that has a very high-power density, necessitating unique design elements. Similar to power reactors, the core needs cooling, often through controlled or natural convection with water and a moderator is needed to reduce the neutron velocities and increase fission. Most research reactors benefit from reflectors to lessen neutron loss from the core because neutron generator is their primary purpose (Alrwashdeh and Saeed, 2019). It is apparent that the reactor thermal power calibration is essential for accurately calculating fuel burn-up. The reactor power can then be calculated using the absolute thermal neutron flux distribution over the core in both the horizontal and vertical planes (Musa *et al.*, 2012).

In reactor's thermal power calibrations, the heat balance approach is the most widely used and trustworthy method of calculating the power output of the core in high power reactors where a temperature rise across the core is produced and recorded (Mesquita *et al.*, 2007). The thermal power calibration of research reactors (RRs) evaluates the reactor's actual thermal power as a result of fission processes taking place in the reactor core. The bulk of the time, this is accomplished using neutron measurement apparatus that gauges the core's neutron flux using fission chambers. Two fission chambers that were placed close to the radiation source make up the NIRR-1's neutron measuring apparatus (CERT, 2019). The heat balancing and calorimetric approaches are two more power calibration methods that have been effective in calibrating and predicting the thermal power of RRs (Mesquita, 2007; Mesquita, 2011; Agbo *et al.*, 2015). Both methods rely on the heating effects that the reactor's thermal power produces when it is in operation. Thermocouples implanted in specifically selected areas are used to measure the entrance, outflow, and pool temperatures of the reactor's core. The NIRR-1 measures the temperature difference between the core outflow and intake using two alumel-chrome thermocouples. One is positioned outside the side beryllium annulus, close to the core inlet orifice, to detect the inlet temperature. The other one is utilized to measure exit temperature and is located near to the core output orifice at the upper part of the side beryllium annulus. These two sets of thermocouples can be used to monitor the temperature difference of the reactor coolant. A separate set of temperature meters also displays the temperature of the water entering the reactor and the water in the pool (CERT, 2019). With a nominal thermal power of 30 kW under steady-state conditions, the Nigeria Research Reactor -1 (NIRR-1) is a low power, tank-in-pool reactor, schematic diagram and sectional view are shown in figure 1 and 2, respectively (Jonah *et al.*, 2012). It was created by China Institute of Atomic Energy (Yongmao, 1985). On February 3, 2004, the reactor reached its initial criticality, and it has since been operating safely for limited radioisotope generation and neutron activation analysis (Yongmao, 1985, Jonah *et al*., 2006). The fuel element's length is 248 mm, with the active length being 230 mm and a 9 mm Al-alloy plug at each end of the fuel element. The reactor core is now a 230 x 230 mm square cylinder and is powered by U-Al4 enriched to 90% in Al alloy cladding (Jonah *et al*., 2006). Each fuel element has a ^{235}U payload of around 2.88 g, and the fuel meat has a diameter of 4.3 mm. With a 0.6 mm thickness, the cladding is made of aluminum alloy. One central control rod, active length 230 mm, operating as a shim rod, regulation rod, and safety rod, is all that the reactor (NIRR-1) has. By adjusting the control rod, which is made up of a Cd absorber, the reactor's startup, steady state operation, and shutdown functions are accomplished (Jonah *et al*., 2006). The control console, the microcomputer control system, and the two rabbit systems all of which are powered, are used to operate NIRR-1. Additionally, the temperature of the reactor water ranges between 23ºC and 46ºC when it is running normally.

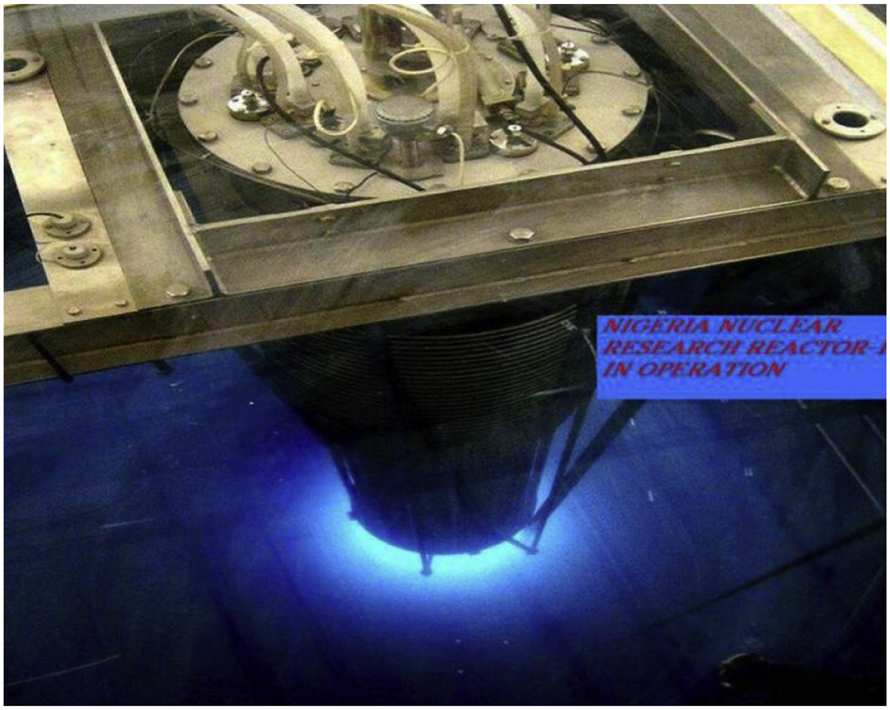

Figure 1: An operational section of Nigeria Research Reactor-1 (Sunday *et al*., 2016)

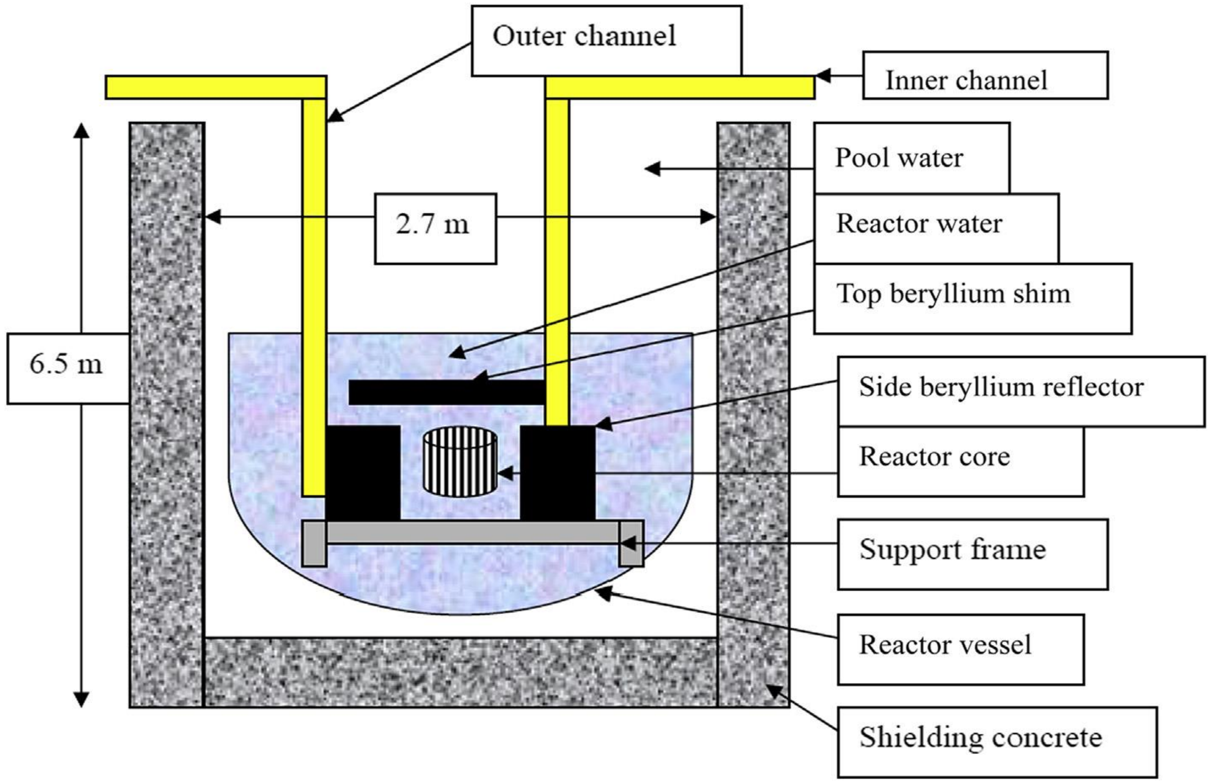

Figure 2: Diagrammatic representation of Nigeria Research Reactor-1 (Sunday *et al*., 2016).

Table 1: Parameter comparison between NIRR-1 HEU and LEU

	HEU	**LEU**
Core diameter & height	230 mm	230 mm
Grid plate	Al	Zircaloy-4
Number of fuel pins	347	335
Fuel pin diameter 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

Due to the fission process occurring inside the core, this rise in the NIRR-1 LEU core's thermal power as a result of its conversion inevitably changes the heat regime inside the core, as seen in table 1. In order to ensure the NIRR-1 LEU core operates safely, previous calibrations cannot be relied upon alone, as the comparison was made in table 1. The calibration of the NIRR-1 at half power was examined in the current work, using the heat balance techniques and the flux-to-power relationship as no such estimate has been performed after the conversion. This is crucial to understand how conversion affects thermal power calibration techniques and to improve the reactor's stability, predictability, and safe monitoring (Asuku *et al.,* 2020).

MATERIALS AND METHOD

Description of research

NIRR-1 is a miniature neutron source reactor (MNSR) designed and built by the China Institute of Atomic Energy (CIAE) (Zhou Yongmao, 1986). It is a tank-in-pool type reactor with 90% enriched uranium (U-235) as fuel as it employs Highly Enriched Uranium (HEU) (Jonah *et al.*, 2002), it has light water as moderator and coolant, and metallic beryllium as reflector (Balogun *et al.*, 2004) designed mainly to serve as a neutron source and is located at the Centre for Energy Research and Training (CERT), Ahmadu Bello University, Zaria. Also, according to Jonah *et al.* (2012), the NIRR-1 is one of the commercial MNSR facilities installed mainly for neutron activation analysis, production of short-lived radioisotopes and training (Ahmed *et al.*, 2006). This calibration is crucial for ensuring the safe and efficient operation of the reactor while using low-enriched uranium. The Nigeria Research Reactor (NIRR-1)'s stability and safety depend on accurate thermal power calibration. For the NIRR-1 to be used effectively for Neutron Activation Analysis (NAA), its maximum steady-state thermal power was increased from 31 kW to 34 kW. The Nigeria Research Reactor-1 (NIRR-1) was converted from a highly enriched uranium (HEU) core to a low-enriched uranium (LEU) core as a result of the need for a global phase-out of HEU. The current LEU core of the NIRR-1 is fueled with 13% UO_2 clad in Zircalloy-4 and it attained second criticality on November 2, 2018. Reactor physicists and operators must make sure the reactor is operating safely and steadily after it reaches criticality, taking into account changes to the reactor's power and reactivity.

Power Calibration and Data Evaluation

Along with the calculated heat losses from the reactor pool, the power lost in the core is measured. For the thermal power calibration, this is the heat balancing methodology. For short-term irradiation, the reactor was run for 1 hour with the cooling system off at a preset flux of 5 x 10^{11} n/cm^{2}s (to make the reactor run at half of its projected installed capacity). After that, the cooling system was turned on, and the reactor ran for two hours. Every 5 minutes during the 2 hours, the temperatures at the inlet and output as well as the temperature difference were recorded. During the 1 hour 45-minute period, the flow rate for each interval was measured. On a strictly thermodynamic basis, the rate of heat generation in a nuclear reactor core is directly proportional to the rate of fuel fission and the thermal neutron flux; it is also connected to the coolant temperature difference throughout the core and the rate of coolant flow through the core. According to Agbo *et al.* (2015), the equation connecting these parameters is provided, as seen in equation 1 (Agbo *et al.*, 2015).

$$Q = C_p \dot{m} \Delta T \quad (1)$$

where Q = Thermal power (heat generating rate) is the coolant flow rate$\dot{m}$ through the core, also written as (T_{out}- T_{in}) is the coolant temperature difference, T_{out} is the outlet temperature, T_{in} is the inlet temperature and is the specific heat capacity of the coolant passing through the core. The flow rate can be monitored by an orifice plate and a differential pressure transmitter, but in the case of Nigeria Research Reactor-1 (NIRR-1), which does not have installed equipment for detecting the flow rate, the flow rate can be estimated using the following fundamental formula (Agbo *et al*., 2015, Ahmed *et al*., 2008, 2011):

$$\dot{m} = \frac{\rho v}{\Delta t} \quad (2)$$

where ρ the density of the coolant is, $v$is the volume of the coolant passing through the core and Δt is change in time. It can also be calculated indirectly from the thermal balance along the core using water entry and outflow temperature readings (Agbo *et al*., 2015). The equation that relates the coolant temperature and density of NIRR-1 is given by (Mansir et al., 2012):

$$\rho = 2E - 0.5k^3 - 0.006k^2 - 0.0233k - 999.97 \quad (3)$$

where: ρ is the coolant density (kg/m^3) and k is the coolant temperature rise (◦C).

Instrumentation

High precision temperature detectors (thermocouples) were used to measure the inlet and outlet temperatures, and one of them was positioned at the outside of the side beryllium annulus close to the core inlet orifice to measure the inlet temperature. The temperature differential of the reactor coolant was monitored by two sets of thermocouples, one at the top part of the side beryllium annulus near to the core outlet orifice to detect the outlet temperature and the other at the bottom portion of the side beryllium annulus close to the core outlet orifice to detect the inlet, and the other at the core outlet orifice. To gauge the temperature of the air in the reactor chamber, a thermocouple was placed slightly above the pool's surface (Agbo *et al.*, 2015).

As a neutron flux detector, a small fission chamber with stainless steel electrodes and walls was used. The operating voltage ranged from roughly 50 to 300 V. Argon is frequently utilized as the chamber fill gas at a pressure of several atmospheres, with walls of the chambers lined with highly enriched uranium to increase the ionization current. On the same circle as the inner irradiation sites or on a circle with a radius of 165 mm and at an angle of 1440 to one another, there are two tiny vertical holes on the side annular beryllium reflector, each 10 mm in diameter and 190 mm deep. Each hole has a current-type micro fission chamber (LB 1120) to track the neutron flux at each irradiation point and send out control signals. The neutron flux detectors' placements are depicted in Figure 3. The chosen tiny fission chambers' sensitivity, linearity, follow-up capabilities, and lifetime are sufficient for NIRR-1 control.

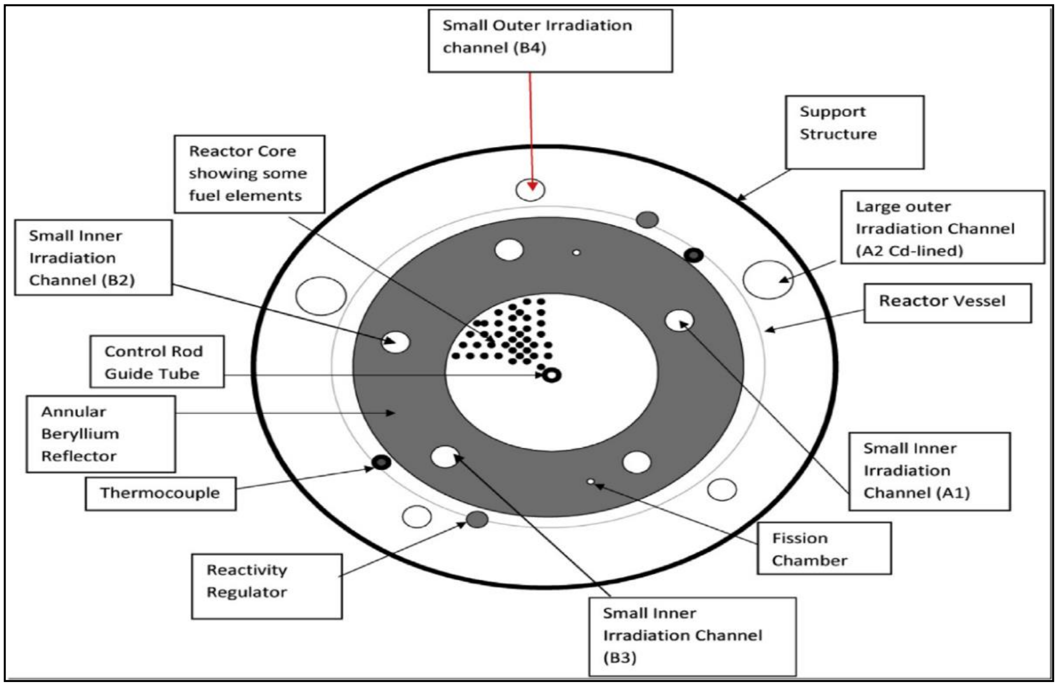

Figure 3: An illustration of the layout's essential components (Jibrin *et al*., 2016)

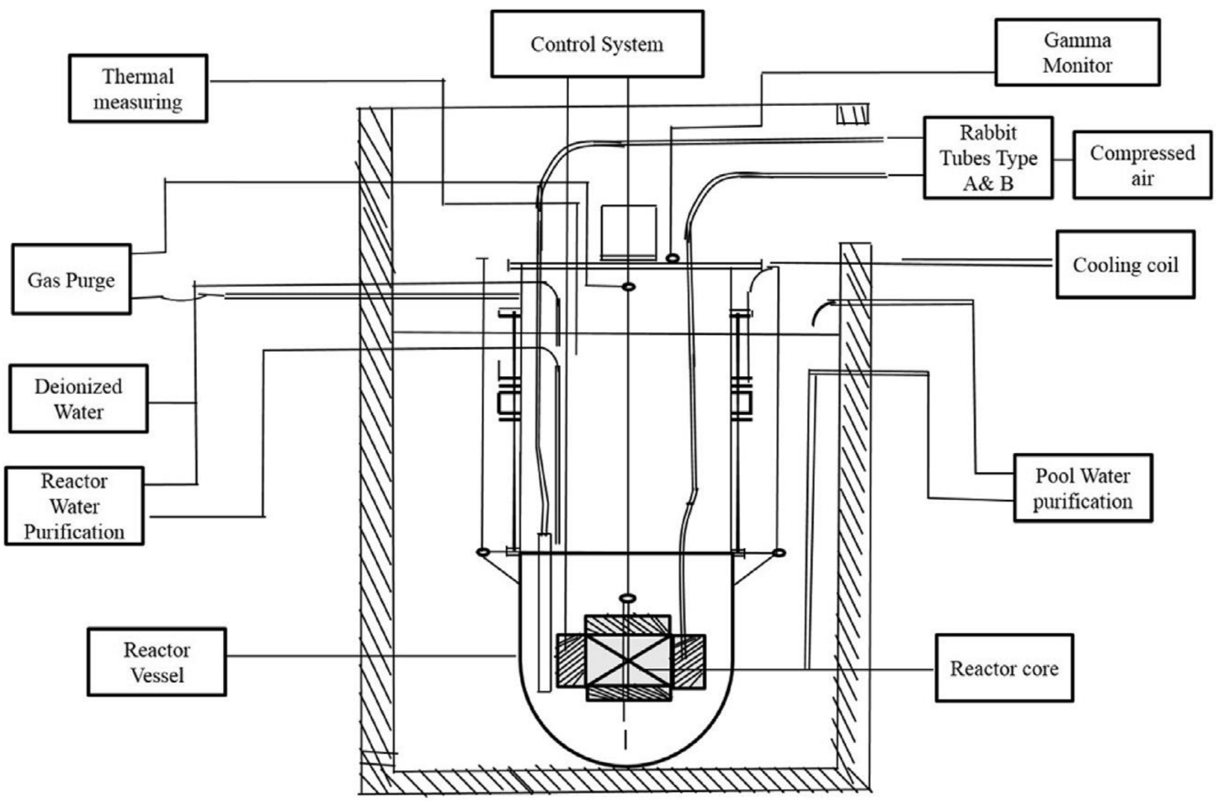

Figure 4: The System of the MNSR Reactor (Jibrin *et al*., 2016)

A separate set of temperature gauges indicates the temperature of the reactor's water inlet and the water in the pool (CERT, 2019). NIRR-1 power calibrations had previously been performed using the heat balance and calorimetry procedures (Agbo *et al.*, 2015); these calibrations were carried out when the reactor was powered by a core made of high enriched uranium (HEU), though. The HEU-fueled NIRR-1 had a maximum power of 31 kW, as shown in Table 1. In order to ensure that the NIRR-1 is effectively used for Neutron Activation Analysis (NAA), the reactor's full power has been increased to 34 kW as a result of the conversion to UO_2 Low Enriched Uranium (LEU) (CERT, 2019).

RESULTS AND DISCUSSIONS

Table 3, shows the experimental information that was tabulated during the heat balancing method of NIRR-1 thermal power calibration at half operational level. Table 4 presents and displays the variables (parameters) of the reactor that were determined using the data from Table 3.

Table 3: Parameters determined using the thermal balance method for calibration at half power (15 kW)

Time(h)	Inlet Temperature (℃)	Outlet Temperature (℃)	ΔT(℃)	$Power(kW)$	$\dot{m}(kg/s)$
9:45	30	39.5	9.5	14992.16	0.377
9:50	30	39.5	9.5	14992.16	0.377
9:55	30	39.5	9.5	14992.16	0.377
10:00	31	40.25	9.25	14984.83	0.387
10:05	31	40.25	9.25	14984.83	0.387
10:10	31	40.25	9.25	14984.83	0.387
10:15	32	40.75	8.75	14980.65	0.409
10:20	32	4075	8.75	14980.65	0.409
10:25	32	40.75	8.75	14980.65	0.409
10:30	33	42.25	9.25	14984.83	0.387
10:35	33	42.25	9.25	14984.83	0.387
10:40	33	42.25	9.25	14984.83	0.387
10:45	33	41.75	8.75	14980.65	0.409
10:50	33	41.75	8.75	14980.65	0.409
10:55	33	4175	8.75	14980.65	0.409
11:00	34	43.00	9.00	14994.25	0.398
11:05	34	43.00	9.00	14994.25	0.398
11:10	34	42.73	8.75	14980.65	0.409
11:15	34	43.00	9.00	14994.25	0.398
11:20	34	42.73	8.75	14980.65	0.409
11:25	34	42.73	8.75	14980.65	0.409

Table 4: Parameters calculated using information from Table 3.

Parameters	Value
Average coolant flow rate (kg/s)	0.3966±0.0188
Average inlet temperature (^{0}C)	32.43±1.54
Average outlet temperature (^{0}C)	43.49±2.07
Average ΔT (^{0}C)	11.06±0.53
Power dissipated (kW)	14.97
Total heat losses from the reactor pool (kW)	0.23
Total reactor power (kW)	15.23

Our results (Table 4) shows that the values of the average inlet temperature, outlet temperature and temperature difference measured are 32.43 ± 1.54 ºC, 43.49 ± 2.07 ºC and 11.06 ± 0.53 ºC, respectively. These results have been depicted in Figure 5. Also, on the average, the coolant flow rate through the core was 0.3966 ± 0.0188 kg/s, is in good agreement with the reactor's operating value (CERT, 2019).

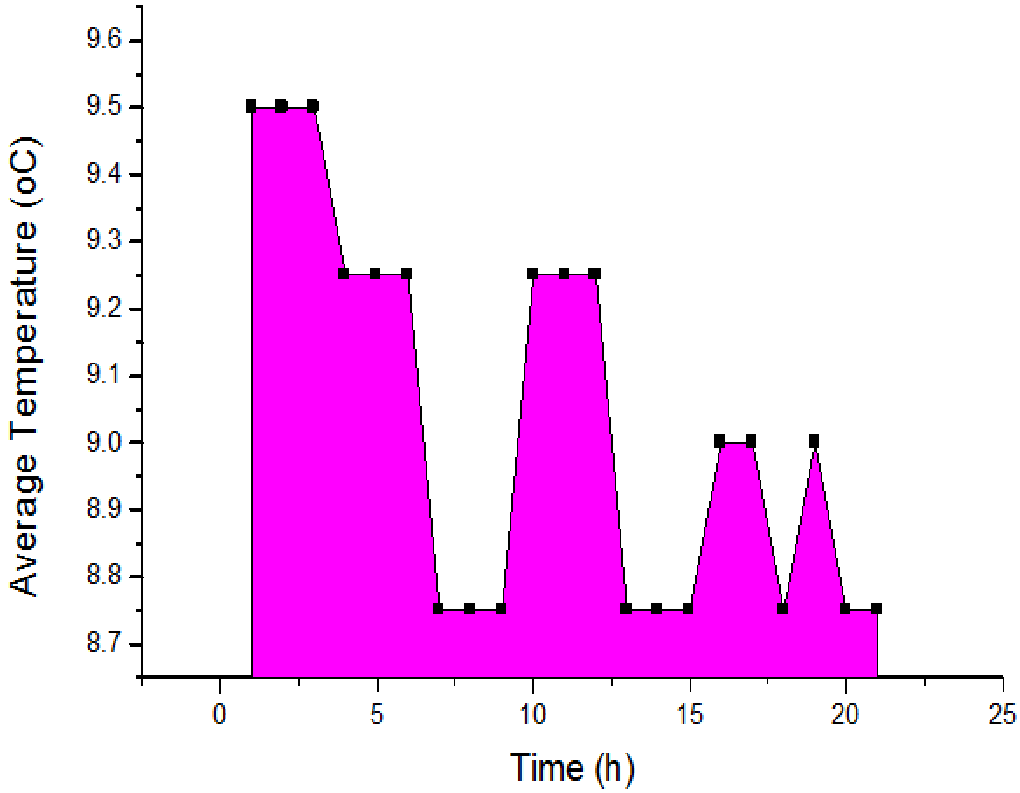

Figure 5: Average temperature rise during the calibration at half power (15 kW)

It can be observed that the average coolant temperature of 11.06 ± 0.53 ºC was quite stable as there was no significant rise in the inlet and outlet temperatures with time, despite steady increment as indicated in Table 3. This is a result of the core's small design that allows sufficient thermal circulation of coolant in the core at this power. This result agrees with that reported by Agbo *et al.* (2015) which was carried out before the conversion of the core from HEU to LEU.

The power dissipated was found to be 14.97 kW, while the total heat loss was 0.23 kW. This implies that at half power of 15.23 kW, the heat loss from the core of the reactor is not significant, hence, the stability of the reactor's core at this power, which agrees with earlier report before conversion (Agbo et al., 2015).

The close agreement between the heat balance approach and the overall power dissipation at half-power thermal calibration is reassuring for the safe and reliable operation of NIRR-1, particularly after the conversion to LEU. Based on the results, the study suggests that the heat balance approach should be used for routine thermal power calibration of NIRR-1. This recommendation is crucial for maintaining the reactor's safety and ensuring accurate fuel burn-up calculations.

CONCLUSION

The research described in this study paper focuses on the characterization of thermal power reactor of the first Nigeria Research Reactor-1 (NIRR-1), which is a low-power Miniature Neutron Source Reactor (MNSR). The need for accurate fuel burn-up calculations and other reactor characteristics prompted this calibration, particularly after converting from high-enriched uranium (HEU) to low-enriched uranium (LEU). The researchers employed the Heat Balance Method for calibration, conducting their measurements at 15 kW, which is half of the reactor's power output. The method involved assessing the rate of temperature rise and accounting for heat losses from the reactor pool to the environment. The total thermal power was determined by combining the calculated power as a function of flow rate and temperature differential with the heat loss values. The research concluded that the heat balance method and the overall power dissipation at half power thermal calibrations were in agreement, suggesting that the heat balance approach is suitable for routine thermal power calibration of NIRR-1.

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