Progress in Nuclear Energy 85 (2015) 344–351

Contents lists available at ScienceDirect

Progress in Nuclear Energy

journal homepage: www.elsevier.com/locate/pnucene

The use of heat balance method in the thermal power calibration of Nigeria Research Reactor-1 (NIRR-1)

S.A. Agbo [a, *], Y.A. Ahmed [b], B. Yahaya [a], U. Iliyasu [c]

[a] Physics Department, Ahmadu Bello University, Zaria, Nigeria
[b] Centre for Energy Research and Training, Ahmadu Bello University, Zaria, Nigeria
[c] Physics Department, Sokoto State University, Sokoto, Nigeria

ARTICLE INFO

Article history:
Received 10 April 2015
Received in revised form
13 July 2015
Accepted 21 July 2015
Available online xxx

Keywords:
Thermal power
Heat balance
Burn-up
Temperature
Reactor
MNSR

ABSTRACT

The knowledge of the reactor thermal power calibration is important for neutron flux and burn-up determination. Burn-up is linearly dependent on the thermal power of the reactor and its accuracy is crucial for the determination of the mass of burned ^{235}U, fission products and decay heat power generation. Power monitoring of reactors is done by means of nuclear instrumentation, but its calibration is always done by thermal procedures. The aim of this paper is to present the result of the thermal power calibration of Nigeria Research Reactor-1 (NIRR-1), a low power Miniature Neutron Source Reactor (MNSR). In order to cover the whole range of the reactor, the calibration was performed at three different power levels: low power (3.6 kW), half power (15 kW) and full power (30 kW). The method used in the calibration involved the steady state energy balance of the cooling loop of the reactor. For this method, the measurement of the inlet temperature, outlet temperature and temperature difference were carried out and also flow-rate of the coolant passing through the core was determined. The heat losses by (conduction, convection and evaporation) were evaluated and the values added to the power calculated as a function of flow rate and temperature difference gives the total thermal power. In a quest to fully understand the behavior of the reactor and ascertain its maximum operable time, a special cadmium string of 1.16 mk inserted during commissioning into one of the inner irradiation channels, was removed and the reactor operated at full power in this condition. The thermal power dissipated in the core during this test period was also computed. The values of the thermal power obtained at low, half, full power and when the cadmium string was removed were: (3.7 ± 0.3) kW, (15.2 ± 1.2) kW, (30.7 ± 2.5) kW and (31.3 ± 8.2) kW respectively. Comparing the results obtained with NIRR-1 flux parameters and preset power on the console, it was observed that calibration at lower power yielded more accurate result with a deviation of only 6.8%.

1. Introduction

Thermal power calibration of low power research reactors (up to 1 MW) are performed during the initial startup and their results are used for many years (Mesquita et al., 2007; Ahmed et al., 2008, 2011). However, heat capacity usually change when experimental installations are made, changes in the collimator or mechanical modifications like the case of NIRR-1 installation of cadmium-lined irradiation channel (Ahmed et al., 2013). Consequently, the need to calibrate the reactor with the present installations in and around the core is very crucial.

From the time Nigeria Research Reactor-1 (NIRR-1) was commissioned in 2004 till date, attempts were made to determine the effects of core excess reactivity on maximum operable time (Ahmed et al., 2011), measure its flux stability (Ahmed et al., 2008; Musa et al., 2012) and ascertain its flux variation in the irradiation channels (Musa et al., 2012). No comprehensive effort was made to calibrate NIRR-1 power despite its usefulness in utilization and experimental work. Available literature (Mesquita et al., 2007, 2011) showed that heat balance method is less cumbersome and straight forward with good results. This work explored this method in the thermal power calibration of NIRR-1.

The knowledge of online reactor power level has been a problem to Miniature Neutron Source Reactor (MNSR) operators. The Integrated Safety Assessment for Research Reactor (INSARR) mission 2009 has recommended for power display in NIRR-1 control

* Corresponding author.
E-mail address: sundayagbo131@yahoo.com (S.A. Agbo).

http://dx.doi.org/10.1016/j.pnucene.2015.07.013

console to have redundant systems or components that perform the same safety function by incorporating into the systems or components different attributes, such as principles of operation and operating conditions and for reactor safety and international standard. The need for accurate power level determination is a safety criteria and operational limiting condition. In the operational limits and conditions (OLCs), we have the power limit which said that the power should not be more than 20% of the full power. However, no power display in NIRR-1 control system. Research reactors are often involved with experiments which require an accurate determination of the reactor power. Normalization of experimental measurements cannot be possible unless the statistical variation of the reactor power is known.

NIRR-1 is a Low-Power, tank-in-pool reactor with nominal thermal power of 30 kW under steady state condition (Jonah et al., 2012). It is designed by China Institute of Atomic Energy (CIAE). The reactor first criticality was accomplished on 3rd February, 2004 and has been working safely for Neutron Activation Analysis (NAA) and limited radioisotope production (Balogun et al., 2005 Jonah et al., 2005; 2006). The current core of the reactor is a 230 × 230 mm square cylinder and fueled by $U\text{-}Al_4$ enriched to 90% in Al-alloy cladding. The reactor (NIRR-1) has only one central control rod with an active length of 230 mm serving as shim rod, regulation rod and safety rod. The functions of reactor startup, steady-state operation, and shutdown are achieved by moving the control rod which is made up of a Cadmium absorber (Jonah et al., 2006). A Schematic diagram of NIRR-1 is shown in Fig. 1.

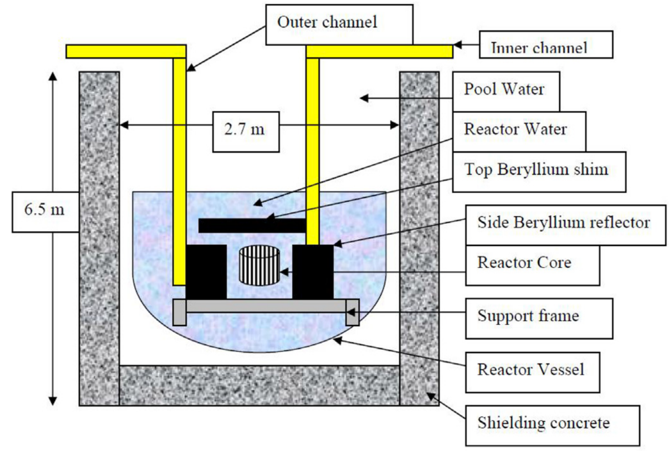

Fig. 1. Schematic diagram of NIRR-1.

It has been pointed out in the NIRR-1 Safety Analysis Report (SAR, 2005) that the decay heat in NIRR-1 is removed by natural circulation of the reactor vessel water in a manner similar to that during operation. It has also been established in (SAR, 2005) that a number of thermal hydraulic tests and calculations, especially from the dynamic experiments, have shown that the natural circulation of the prototype MNSR (which is comparable to NIRR-1) has the following characteristics:

i) Negative feedback effect:

This occurs when the temperature difference between the inlet and outlet coolant of MNSR increases; the floating force and circulating head will increase to make the flow velocity high, which in turn will limit the rise in temperature.

ii) Insufficient circulation:

Because of the small size of the core, the distance from the inlet orifice to the outlet orifice is small. The water, after being heated in the core goes out through the upper part of the core. Part of the water does not get sufficiently cooled before it sinks down, resulting in part of outlet water being carried back into the core due to siphoning effect. This direct re-circulation of the part of hot water causes a rise of the inlet water temperature. This phenomenon is called insufficient circulation, which speeds up the rise of the coolant temperature in the core and shorten the function time of the temperature effect. It is thus not possible to cause the inlet water temperature to rise in such a short time by heating the core only, but by the coupling action between the inlet and the outlet coolant. Consequently this offers some benefit to the reactor safety.

As the reactor is operated, energy is released through the fission process. The majority of this energy appears as energy carried by fission fragments, gamma rays, neutrons and beta particles emitted (Jevremovic, 2008). When these particles interact with the surrounding materials, heat is produced. This process heats up the fuel meat and starts the chain of heat transfer The heat released from nuclear fuel is transferred to the coolant through the heat conduction of fuel and cladding, and the heat convection between cladding outer surface coolant. Then, the heat is carried out of the reactor core by the coolant.

Recently, our group (Musa et al., 2012) determined the radial and axial neutron flux distribution in irradiation channel of the NIRR-1 using foil activation technique. This attempt is to characterize the newly installed cadmium-lined irradiation channel in the reactor. Our results showed that the installed cadmium line did not affect NIRR-1 flux stability. As an extension of the work, we ventured here into thermal power calibration of NIRR-1 by heat balance method. This work analyzed the accuracy of heat balance method in the thermal power calibration of NIRR-1.

2. Heat balance method of reactor power calibration

The power released by fission (heat generation rate) in a nuclear reactor core is related to the fission rate of the fuel, the thermal neutron flux present, macroscopic cross section for fission and volume of the core according to the equation given by (DOE, 1993):

$$P = \frac{\phi_{th}\Sigma_f V}{3.12 \times 10^{10}\frac{fission}{Watt-sec}} \tag{1}$$

where P = power

ϕ_{th} = thermal neutron flux (neutrons/cm^2-sec)
Σ_f = macroscopic cross section for fission (cm^{-1})
V = volume of core (cm^3)

On a straight thermodynamic basis, this same heat generation rate is also related to the coolant temperature difference across the core and the flow-rate of the coolant passing through the core. The equation relating these parameters is given by (Mesquita et al., 2007, 2011):

$$Q = C_p\dot{m}\Delta T \tag{2}$$

where Q = Thermal power (heat generation rate), $\dot{m}$ is the flow-rate of the coolant passing through the core, ΔT also expressed as ($T_{out}-T_{in}$) is the coolant temperature difference, T_{out} is the outlet temperature, T_{in} is the inlet temperature and C_p is the specific heat capacity of the coolant passing through the core.

The flow-rate can be measured by an orifice plate and a differential pressure transmitter. But in the case of NIRR-1 which does not have an installed device for measuring the flow rate, the flow