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Experimental validation of the neutronic parameters in the Jordan subcritical assembly

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ABSTRACT

Following the construction of the Jordan Subcritical Assembly (JSA) on the campus of the Jordan University of Science and Technology (JUST); a detailed experimental study of the facility was performed to measure different reactor parameters. In this paper, the reactivity and activation reaction rate in JSA were determined experimentally and then validated with the calculated results from Monte Carlo Simulation Radaideh et al. (2018a). The reactivity and criticality analysis were implemented using the source jerk method, while the foil activation technique was used for activation reaction rate and flux characterization. The experimental subcritical reactivity in dollars was -5.498 ± 0.045 while k_{eff} for the facility was 0.96476 ± 0.00771. The multiplication factor calculated using Monte Carlo codes of JSA was 0.96553 ± 0.00002. In addition, it was found that the source jerk results had large uncertainties due to the counting error. ^{115}In foils were used to measure the activation reaction rate. The absolute axial and radial reaction rates were measured by averaging the measured counts for three photo-peaks of ^{116m}In. The experimental results were validated by the calculated reaction rates from MCNP5. The error in the activation reaction rate measurements were dominated by the peak area measurement error. The calculated and measured activation reaction rate results demonstrated very good agreement with a maximum deviation of approximately 11% in both directions. In this work, the neutron source strength was experimentally determined using the foil activation technique. The value estimated for the source was $1.02 \times 10^6 \pm 0.9\%$ (n/s) which is very close to the reported value.

1. Introduction

Nuclear research facilities usually operate in three modes, subcritical ($k_{eff} < 0.95$), near-critical ($0.95 < k_{eff} < 1$), and critical ($k_{eff} = 1$). The reactor is said to be subcritical, if the amount of fissionable materials coupled with its physical arrangement and other supplementary materials are insufficient to maintain the fission chain reaction. Subcritical reactors are mainly used for training and research purposes due to their inherently safe features Kamalpour et al. (2014). They can be also used as neutron sources, for energy production, and for spent fuel transmutation Shahbunder et al. (2010). Many subcritical assemblies have been built around the world including Subcritical Assembly in Dubna (SAD) Polanski et al. (2006); Shvetsov et al. (2006), Yalina-Booster subcritical assembly Bécares et al. (2013); Talamo et al. (2011); Persson et al. (2005), Delphi subcritical assembly Szieberth et al. (2015), Nuclear Chicago model 9000 Papastefanou (2004); Vega-Carrillo et al. (2015), and others Maldonado et al. (2008); Sinha et al. (2015).

Jordan Subcritical Assembly (JSA) is located at the campus of the Jordan University of Science and Technology (JUST). JSA is the first nuclear facility in Jordan that was built to help students and researchers to perform experiments in a highly safe environment. JSA is a zero-power light water reactor operating in near-critical mode and it is driven by a conventional external neutron source: plutonium-beryllium ^{239}Pu-Be source. JSA is fueled with low enriched uranium and light water is used as moderator and reflector. To run the subcritical assembly, the external neutron source is inserted at the bottom of the core using a pneumatic system. Previous studies performed on JSA were computationally-based studies. In our previous paper Radaideh et al. (2018a), a comprehensive modeling and simulation of the JSA facility was performed, where criticality and neutronic parameters were calculated using MCNP5 X-5 Monte Carlo Team (2003), Serpent Leppänen et al. (2015), and KENO-V.a (SCALE) Bowman (2011). The flux and neutron spectrum of the facility were also computationally

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characterized using MCNP5 by this study. Additional computational studies on the JSA were performed by Xoubi (2018, 2016, 2013). The design of the JSA was firstly introduced by Xoubi Xoubi (2013). In this study, the neutron multiplication factor k_{eff} was calculated using MCNP5 based on core configuration of 313 fuel rods. Xoubi (2018) performed a neutronic analysis of the JSA to enhance the neutron flux within the facility by replacing the ^{239}Pu-Be source with a proton accelerator and a spallation target. The analysis was performed using MCNPX and the results showed that the proton accelerator source could increase the flux within the facility by seven orders of magnitude; making it more suitable for research activities. Also, Xoubi (2016) calculated the absolute neutron flux in both radial and axial directions of the facility by employing the KCODE and NPS features of MCNP5.

Plenty of experimental studies on source-driven systems and research reactors have been performed. Malkawi and Ahmad (2000) performed a foil irradiation experiment based on different types of foils (e.g. Au, Cu, Fe) to determine the neutron spectrum experimentally. The measured neutron spectrum was validated later using different codes Malkawi and Ahmad (2001); Malkawi et al. (2013). Tesinsky et al. (2011) performed a foil activation analysis to calculate the reaction rate within the YALINA-Booster subcritical facility. In this study, the experimental reaction rates were validated with those calculated by MCNP5. A discrepancy between the experimental and calculated results was found, especially in the fast energy range. These discrepancies were attributed to experimental uncertainties such as detector efficiency and more importantly to nuclear data libraries. Additional experimental studies to characterize the neutron flux using activation foil techniques can be found in these references Kulage et al. (2013); Alloni et al. (2013); Abrefah et al. (2010); Ben-David and Huebschmann (1962); Radulović et al. (2014). A study on the subcritical experiment Yalina about comparing different reactivity determination methods was performed by Persson et al. (2005). Three different experimental methods were explored: (1) the slope fit method, (2) area-ratio (Sjöstrand) method, and (3) source jerk method. The experimental results were validated with MCNP5 simulations with different nuclear data libraries. The comparison showed good agreement between the slope fit method and the calculated results while the source jerk results showed significant differences due to the statistical uncertainties associated with the source jerk method. Lee et al. (2010) employed the Feynman-α method to determine the subcriticality level of subcritical PWRs in Korea. The results showed that Feynman-α can treat the pulse signals more efficiently because it can extract subcriticality information from the random neutron pulse signals and hence revealing the core status. However, the effect of the electrical and gamma noises on the Feynman curves was not quantified, and was left for further study. Other experimental studies on Yalina-Booster were performed, including applying experimental methods such as the prompt decay constant and the area-ratio (Sjöstrand) methods, to determine the reactivity of the facility Bécares et al. (2013). The study focused on developing corrections to the experimental results to take into account spectral and spatial effects; such that experimental and computational results agree. Additional experimental studies performed at the Kyoto accelerator-driven assembly can be found in these references Pyeon et al. (2017a, b).

Due to the lack of experimental studies on the JSA to validate the computational models, this paper presents experimental measurements of the criticality and kinetic parameters using source jerk method as well as the axial and radial activation reaction rates using foil activation techniques. The results of this study are used to validate the computational models of the JSA created using MCNP5, Serpent, and SCALE in the previous study Radaideh et al. (2018a). The low neutron flux and the higher uncertainty associated with it make the experimental work very challenging in any facility. In the source jerk experiment, the subcritical reactivity was calculated and compared with the calculated value obtained from the three prescribed codes. To reduce the experimental uncertainty in the measure k_{eff}, the source jerk experiment was repeated several times and the average value was calculated. For the activation reaction rate calculations, several foils were irradiated to measure the radial and axial reaction rate distributions within the JSA core. The activation rate of the foils was used to validate the activation rate calculated using MCNP5. The gamma counts emitted by the activated nuclides were measured using High Pure Germanium (HPGe) detectors. To reduce the uncertainty during the measurements, The foil material was chosen so that it captures the highest number of neutrons and produces radioactive nuclides with high photo-peak yields. The neutron source strength of the JSA is also measured using the foil activation techniques to provide accurate and experimental measurements of the source. The uncertainty of the source measurement was reduced by using many foils at different locations. Although this study forms a direct application of the experimental methodologies available in literature, this work is among the first experimental efforts on any nuclear facility in the country of Jordan. Jordan is in the process of adding nuclear energy as part of its energy mix. Therefore, this work could form a basis for validation of any future experimental or computational studies.

The remaining sections of the paper are organized as follows: section 2 describes the experimental methodology implemented in this paper. Section 3 presents the results of the source jerk as well as the foil activation analysis, along with the discussion of these results. The conclusions of this work and future studies are presented in section 4.

2. Experimental modeling

2.1. Facility description

JSA is fueled with low enriched uranium and contains light water as a moderator and reflector. The JSA core consist of 313 low enriched Uranium (3.4% wt ^{235}U) fuel rods; each fuel rod consists of fuel pellets, insulator pellets, pressure springs, an upper end plug, and a lower end plug. The fuel rod is 550 mm in height and 10 mm in diameter, each fuel rod contains 43 ceramic fuel pellets of Uranium dioxide (UO_2) with a ^{235}U enrichment of 3.4%. The fuel pellets are surrounded with a cladding tube made of Zirconium alloy (Zr-4) with thickness of 0.007 mm and a helium gas filled the gap between the fuel pellets and cladding tube with thickness of 0.00085 mm 313 fuel rods are loaded into a water-filled vessel in a square lattice form as shown in Fig. 1. The neutron source used in JSA is a ^{239}PuBe neutron source located just below the core bottom. To start and shutdown the reactor, the neutron source is raised to and lowered from the core using a pneumatic system. Additional details regarding the configuration and structure of JSA are described in this reference Radaideh et al. (2018a).

JSA core vessel contains positions for seven axial experimental channels of diameter of 10 mm. The radial position of these channels is shown in Fig. 1. The first experimental channel (i.e. EC1) is close to the center while the last experimental channel (i.e. EC7) is close to the periphery. These experimental channels have been used in the foil activation experiment to contain the foils during irradiation. Three BF_3 neutron detectors are used to measure the neutron counts during operation. The relative position of the detectors is shown in Fig. 1. The counts measured by the three BF_3 detectors were used in this study during the source jerk analysis to calculate the subcritical reactivity.

2.2. Reactivity and kinetic parameters determination

The reactivity of a nuclear facility measures the deviation of the reactor from the critical state. The reactivity is important to measure other parameters such as the neutron multiplication factor and the effective delayed neutron fraction. There are different methods to calculate the system reactivity such as slope fitting method, area-ratio (Sjöstrand) method, Rossi-α and pulsed Rossi-α, Feynman-α, and others.

A category of the reactivity determination methods called kinetic methods involves different techniques such as the source-jerk, the rod-