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Neutronic design study of accelerator driven system (ADS) for Jordan subcritical reactor as a neutron source for nuclear research

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HIGHLIGHTS

- A proton is accelerator is coupled to a subcritical assembly with Pb target.
- The spallation neutron source is investigated.
- 3-D Monte Carlo simulating of radiation transport is performed for the system.
- The neutron flux showed an increase of seven orders of magnitude compared to the current JSA Pu-Be source driven core.

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ABSTRACT

In this paper, a preliminary neutronic design study of an accelerator driven subcritical system for Jordan Subcritical Assembly (JSA) is presented. The conceptual design of coupling the JSA core with proton accelerator and spallation target is investigated, and its feasibility as a neutron source for nuclear research, and possibly for target irradiation and isotope production evaluated. 3D MCNPX model of the JSA reactor, the accelerator beam, and the Pb target was developed, based on actual reactor parameters. MCNPX calculations were carried out to estimate the absolute radial and axial neutron flux in the reactor, and to calculate the multiplication factor K_{eff} and heat generated in the reactor. Numerical results showed an enormous increase in the neutron flux, by seven orders of magnitude, compared to the current JSA core design using Pu-Be source. In this research the results obtained are discussed and compared with those of the JSA, and do confirm the feasibility of utilizing the JSA as a viable nuclear research facility with adequate neutron flux.

1. Introduction

Subcritical systems are nuclear reactors that require external source of neutrons to sustain a chain reaction (Xoubi, 2016a). One of the strongest neutron sources is provided by spallation reactions, where protons are accelerated to directly interact with a heavy metal target (Chen et al., 2015), yielding numerous number of neutrons to drive the reactor. The coupling of an accelerator with such a reactor constitute an Accelerator Driven Subcritical (ADS) reactor.

Accelerator Driven Subcritical Systems (ADS) have been proposed as feasible burners for the transmutation of actinides and fission products (SNF) (Wang et al., 2015; Velasquez et al., 2015; Bowman et al., 1992), energy-producing reactors (Clausse et al., 2015; Yoshiie et al., 2014), tritium production, and as a future neutron source (De Bruyn et al., 2015).

Demonstrator's experiments have been carried out worldwide to prove the feasibility of such concepts, and to gain practical understanding of the nuclear behavior of ADS. The MYRRHA project at SCK-CEN, which can be operated at subcritical mode coupled with proton accelerator of 600 MeV. The project will serve as a demonstrator for the transmutation of nuclear waste system. Talamo et al. (2013). The YALINA subcritical assembly, which is a zero power reactor that can be operated in pulsed mode using small deuteron accelerators, and attaining an enormous gain in neutron production (Bécares et al., 2013; Soule et al., 2004). The MUSE program at MASURCA, which may be operated in pulsed mode using small deuteron accelerators, and attaining an enormous gain in neutron production (Yamamoto and Shiroya, 2003).

The feasibility of coupling Kyoto University Research Reactor in Japan with ADS to be used as a future neutron source, called “Neutron Factory” was confirmed by Yamamotoa and Shiroyab study (Kim et al., 2016; Herrera-Martínez and Kadi, 2006).

Spallation target design and analysis have been investigated by several studies (Felcini et al., 2006; Junsheng et al., 2004; Chen et al., 2016; Sheng et al., 2001; Shilun et al., 2002; Seltborg et al., 2003), while other studies have investigated ADS neutron production and

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source efficiency (Sheng et al., 2001; Shahbunder et al., 2010; Heidet et al., 2015).

Jordan Subcritical Assembly (JSA) is a zero-power light water reactor, driven by a conventional plutonium-beryllium (Pu-Be) source. The reactor maximum neutron flux is 3.72×10^4 n/cm^2 s (Xoubi, 2016a), posing a challenge to nuclear research and sample irradiation, where a much higher flux is required. Thus limiting the facility use to teaching and training of undergraduate nuclear engineering students (Xoubi, 2016a, b).

The aim of this study is to investigate a conceptual neutronic design of coupling the JSA subcritical reactor core with ADS and a spallation target, and to evaluate its feasibility as a neutron source for nuclear research, and possibly for target irradiation and isotope production. In Section 2, a description of the ADS design concept, the subcritical reactor core, and spallation target are presented. In Section 3, the ADS reactor modeling, and simulations of spallation neutrons, criticality and reactor physics calculations will be presented with a brief description of the analysis code. In Section 4, numerical results obtained through this study will be presented, compared with original core parameters, and discussed. Summary of the main results and conclusions is presented in Section 5.

2. Design concept

The conceptual design of the ADS is carried out on the basis of the current JSA parameters, without any major changes in the reactor structure, fuel, moderator, or other systems. The Design concept is based on coupling an accelerator to the present core, thus replacing the fixed PuBe neutron source that currently drive the assembly with a spallation neutron source, as shown in Fig. 1.

It is envisioned that this will amplify the neutron flux by several orders of magnitude, expanding its application to nuclear research and sample irradiation. The current average total neutron flux in the JSA level is 10^3, limiting its capabilities to nuclear teaching and training applications, the amplification of the flux to 10^{10} level, would render many research and irradiation applications of the facility.

The core fuel configuration was changed in order to make room for the spallation target and the beam tube. 21fuel rods were moved from the center, however only 20 rods were placed in the periphery to preserve core symmetry, thus making the total fuel loading 312 fuel rods.

2.1. Core description

The JSA at the Jordan University of Science and Technology (JUST) is a light water reactor, that is composed of 313 fuel rods of low enriched (3.4 wt% U^{235}) uranium oxide. The fuel rods are configured in a

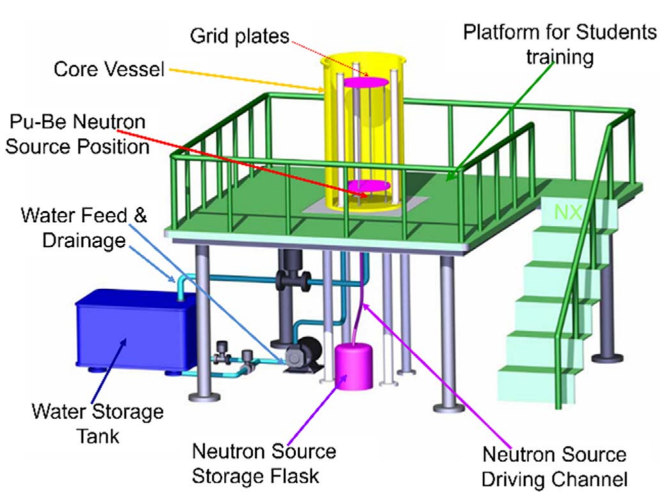

Fig. 1. Layout of the JSA subcritical reactor, showing major systems without the ADS.

square lattice of 19.1 mm pitch, and loaded into an open top cylindrical vessel to make up the core (Xoubi, 2013).

The fuel rod height is 55 cm, and is comprised of 43 pellets cladded with zirconium alloy (Zr-4), each pellet contains 5.03 g of uranium and is 10 mm in height. The core radius is 20 cm, and is positioned in the center of the water filled reactor vessel, whose diameter and height are 120 cm and 132 cm, respectively. The core is reflected by water on all sides, the side reflector is 40 cm thick and the top-and-bottom reflectors are 38.5 cm thick. The JSA is driven by a plutonium-beryllium (Pu-Be) neutron source, located under the core at the centerline (Xoubi, 2013). The subcritical reactor is primarily used as a hands-on tool for teaching and training nuclear engineering students. A layout of the subcritical assembly (Xoubi, 2013) is shown in Fig. 1.

2.2. ADS target

Previous studies (Abánades et al., 2008; Vivanco et al., 2014; Mongelli et al., 2005) investigating protons impairing on heavy metal targets have shown that lead, tungsten, tantalum, lead-bismuth, and uranium materials produce the highest neutron yield per incident proton. For the JSA applications and operation at low power and low temperature, a lead (Pb) target is selected. In addition to producing one of the highest number of spallation neutrons per proton, lead has a very low neutron absorption cross section of 0.171 barns (NIST, 1992).

Preliminary calculations of the neutron yield per proton energy are performed for four cylindrical target sizes and two proton beams. Based on the results shown in Table 1 the target size was selected to be 5 cm in radius and 20 cm in height, with a 5 cm beam, and a proton energy of 250 MeV. We consider that such a target with the associated beam is sufficient for the JSA, where it is desirable to select a small target and beam that will not occupy a large volume of the core, and will limit the target heating. The proton energy of 250 MeV is also considered sufficient for the zero power JSA operation, where it is desirable to maintain the operation at ultra-low power. Another consideration is that such mid-energy (250 MeV) proton beam maybe delivered by available commercial accelerators.

3. Methodology

In this study, Monte Carlo calculations were performed using MCNPX code version 2.6.0 (Pelowitz, 2008), which is capable of simulating radiation transport in complex three-dimensional nuclear systems of all type of radiation such as neutrons, protons, photons, and electrons as well as their interactions (Soule et al., 2004). MCNPX began as a merger of a continuous energy MCNP (Briesmeister, 1997) and a high-energy particle transport code LAHET (Prael and Lichtenstein, 1989). The code current version includes physics modules such as the Bertini and ISABEL models taken from the LAHET Code System (LCS), CEM 03, and INCL4 (Pelowitz, 2008; Kirk, 2010).

Calculations throughout this study used ENDF/B-VII cross-section libraries, protons are transported using LAHET physics, and nucleon and pion interactions use the Bertini intra-nuclear cascade model. All tallies in MCNPX fixed source (nps) and criticality (K_{code}) calculations, are normalized per source particle (Pelowitz, 2008), thus the accelerator beam protons will be used as the normalization constant, to calculate the neutron flux and other outputs absolute value.

3.1. ADS reactor modeling

A three-dimensional, full detail model is developed for the accelerator driven subcritical reactor, the model consist of two parts, the subcritical reactor is modeled based on the actual JSA design parameters, and the accelerator part is modeled based on the conceptual design parameters. The simulation model is used with the continuous energy neutron ENDF/B-VII cross-section data libraries and S(α,β) thermal data was used as a nuclear analysis computational tool to