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Conceptual design study of light water subcritical assembly

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ABSTRACT

Due to high level of inherent safety, subcritical assemblies are widely used for research and training purposes. This paper presents the neutronic design of a typical research subcritical assembly with domestic fuel rods. This assembly consists of fuel sub-assemblies with 4 × 4 square arrays of fuel pins. Two types of fuel pins, metal uranium with Al cladding and uranium dioxide with Zr–Nb 1% cladding, are studied. It is cooled and moderated using ordinary water and is surrounded by Beryllium as reflector. According to sub-criticality of the assembly, a 5-curie Am–Be source was located in the center of the assembly to sustain chain reactions.

The simulations were implemented by MCNPX code and neutronic parameters were calculated accordingly. Optimal fuel rod pitch and fuel rod radius were investigated and effect of different reflectors on the effective multiplication factor (k_{eff}) were studied. Then thermal, epithermal, fast and total average flux were calculated. Considering the importance of subcritical assembly feedbacks, moderator and fuel temperature coefficients of reactivity were obtained. Since the effective delayed neutron fraction and neutron generation time play an important role in the reactor kinetics, they were also calculated for this subcritical assembly.

Results of the simulation show that by arranging the fuel sub-assemblies in a 9 × 9 array, multiplication factor of about 0.8 for metal U and about 0.7 for UO_2 is achieved for subcritical assembly. The optimum thickness of Beryllium reflectors was found to be 26 cm for metal U and 31 cm for UO_2. Results also show that the subcritical assembly with metal U fuel has higher average total flux but the subcritical assembly with UO_2 fuel has larger reactivity coefficient. However, the results also prove that the subcritical assembly with both fuels is inherently safe due to negative fuel and moderator temperature coefficients of reactivity.

1. Introduction

Research reactors are useful facilities for students to gain practical experiences and become familiar with the main parameters of reactor physics. If reactor has a subcritical design, we have a system with very high safety and efficiency for learning more about neutron and reactor physics concept.

An assembly of fissionable material (called the core in reactor terminology) is subcritical if the amount of material present, coupled with its physical arrangement and complement of supplementary materials such as those that comprise the fuel lattice structure, moderators, reflectors, fuel rod cladding, etc., is insufficient to achieve a sustained fission reaction chain. In reactor language, this is signified by $k_{eff} < 1$ In fact such subcritical cores are designed so that in no conceivable scenario can k_{eff} actually approach 1 (i.e., criticality) no matter what the situation (flooding, core meltdown, structural failure, etc.). This assures that these facilities are inherently safe, at least from the perspective of criticality (Gohar and Smith, 2010).

Due to the first stage of fuel rod fabrication in Iran with the ability of fabricating specified dimensions, a 4 × 4 fuel sub-assembly has been designed that can be used in light water subcritical assembly (Roostayee et al., 2011).

MCNPX code was used to simulate the proposed research subcritical assembly. Neutronic parameters such as optimal rod pitch and fuel radius, flux in the assembly, reflector thickness, fuel and moderator temperature coefficients of reactivity, effective delayed neutron fraction and neutron generation time were obtained for subcritical assembly with two fuel types included metal uranium with Al cladding and uranium dioxide with Zr–Nb 1% cladding and the results were compared.

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Table 1
Sub-assembly and fuel rod data.

Parameter	Dimension
Outer fuel rod radius (cm)	1.36
Inner fuel rod radius (cm)	1.17
Gap thickness (cm)	0.011
Fuel diameter (cm)	1.148
Active fuel height (cm)	61.5
Fuel assembly dimension (cm × cm × cm)	6.532 × 6.532 × 89.7
Number of fuel rods in a sub-assembly	16
Fuel arrangement in a sub-assembly	Cubic – 4 × 4
Fuel rod pitch (cm)	1.633

2. Subcritical assembly description

Subcritical assembly is rectangular cubic with dimensions of 58.8 × 58.8 × 89.7 and has 81 sub-assemblies which are arranged in 9 × 9 array. The subcritical assembly is placed in a 200 cm ×200 cm ×200 cm water pool and the operating temperature is considered to be 293 K. Design parameters of the fuel sub-assemblies and its associated fuel rods are summarized in Table 1 and a view of designed fuel sub-assembly is shown in Fig. 1.

For this assembly two types of fuel with different clad types were considered. The fuel and clad material specifications are detailed in Table 2.

3. Analysis procedure

3.1. Simulation conditions

For neutronic calculation of the subcritical assembly, MCNPX.2.6 code with ENDF/VII library was used and all components of the subcritical assembly including fuel rods, neutron source and reflectors were accurately simulated. In addition, in all criticality calculations k_{eff} was determined by tracing 5000 particles in 250 cycles in which, 50 initial cycles were skipped before beginning tally accumulation.

3.2. Core arrangement design

The first step of design was achieving an arrangement of fuel sub-assemblies in which the multiplication factor is about 0.7. By considering square arrangement and increasing the number of fuel sub-assemblies, it was found that the desired multiplication factor is achieved when the subcritical assembly consists of a 9 × 9 array of fuel sub-assemblies.

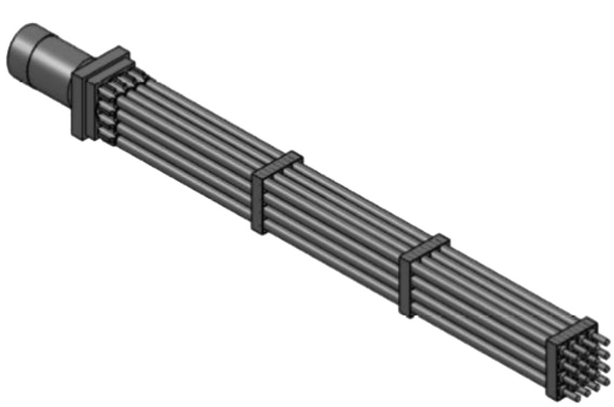

Fig. 1. View of designed fuel assembly.

Table 2
Fuel and clad material specifications.

Fuel type (enrichment: 0.711%)	Fuel density (gr/cm^3)	Fuel weight fraction				Clad type
		^{234}U	^{235}U	^{238}U	O	
Metal U	18	0.000057	0.007204	0.992739	–	Al
UO_2	10.45	0.000050	0.00627	0.87515	0.11853	Zr–Nb 1%

Calculating moderator to fuel ratio to determine fuel rod pitch is one of the major challenges facing the neutronic design of reactor cores. This is due to the fact that the moderator to fuel ratio affects the thermal utilization factor and the resonance escape probability and consequently affects k_{eff} (Department of Energy, 1993).

For calculating moderator to fuel ratio, multiplication factors corresponding to a number of hypothetical pitches with constant fuel radius (0.574 cm) were obtained. Considering the optimum pitch for each type of fuel, diagram of multiplication factor versus fuel rod radius were plotted.

Due to limitations in term of fabricating fuel in Iran, 1.633 cm and 0.574 cm was chosen for fuel rod pitch and fuel radius.

3.3. Determination of reflector material and its optimum thickness

Adding reflector around the subcritical assembly, increases multiplication factor because of neutrons return back to the core. To select the best reflector five materials including ordinary water (H_2O), heavy water (D_2O), beryllium (Be), graphite (Gr) and paraffin (C_2H_4) were investigated. Then the optimum thicknesses of reflector were determined for both fuel types.

3.4. External neutron source simulation

According to sub-criticality of assembly and the need for neutron source, four fuel rods in the center of the subcritical assembly were replaced by an Am–Be neutron source. The schematic diagram of simulated geometric configuration of ^{241}Am–Be source contained in standard Amersham X.14 capsules format is shown in Fig. 2. (Asamoahet al, 2010) and the source specification are given in Table 3 (Eleftherakis and Kocan, 2011).

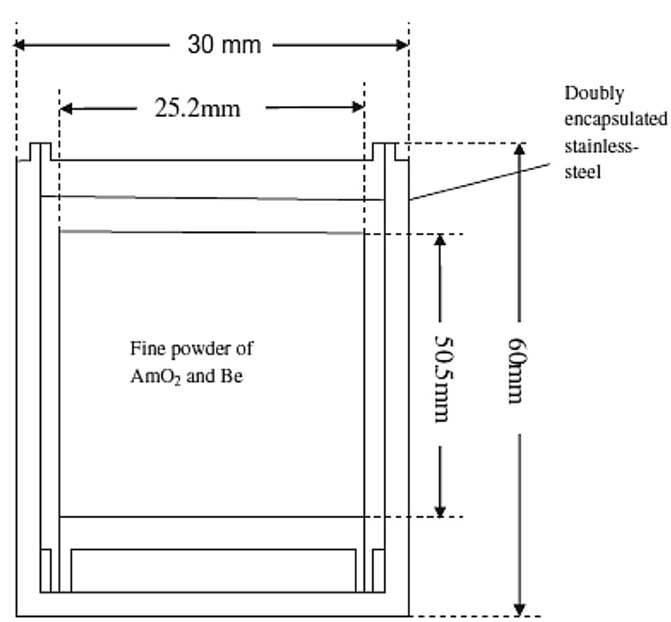

Fig. 2. Schematic cross-sectional view of the ^{241}Am–Be neutron source assembly.