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Using the Area Ratio Method for Reactivity Measuring of the Subcritical Nuclear Facility "Neutron Source" †

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Abstract

The Subcritical Nuclear Facility "Neutron Source based on the subcritical assembly driven by the linear electron accelerator" is a state-of-the-art nuclear facility designed and developed to study the properties of ADS systems, to generate neutrons for various applied and fundamental studies, and to train specialists in the field of nuclear physics and energy. The physical start-up of the facility was performed in 2020–2021. This paper describes the results obtained by using the area ratio method for measuring the reactivity of the facility during the physical start-up.

Keywords: ADS; subcritical nuclear facility; reactivity; area ratio method

1. Introduction

The Subcritical Nuclear Facility "Neutron Source based on the subcritical assembly driven by the linear electron accelerator" (SNF "Neutron Source") was designed and constructed over several years at the Kharkiv Institute of Physics and Technology (KIPT, Ukraine) in collaboration with the Argonne National Laboratory (ANL, USA) [1,2].

During 2020–2021, the physical start-up of the SNF "Neutron Source" was performed [3,4]. The pre-loaded dummies of the fuel assemblies were sequentially replaced by fresh nuclear fuel in the form of single-section fuel assemblies (FAs) of the VVR-M2 type. A tungsten neutron-generating target was used in the core during the physical start-up.

According to the IAEA [5–8], such facilities belong to accelerator-driven subcritical systems (ADS systems) for which the maximum effective neutron multiplication factor k_{eff}^{max} is limited to 0.98. However, within the framework of design development and the licensing of SNF "Neutron Source" a conservative operational safety limit of k_{eff}^{max} = 0.96 was set by the State Nuclear Regulatory Inspectorate of Ukraine for the core configuration with the tungsten target. This was done due to the possible exceedance of 0.98 in case of the target removal from the core [9].

Below is a brief description of the SNF "Neutron Source" and the main results obtained by using the area ratio method [10–12] for reactivity measurement and monitoring during the physical start-up. The appropriate numerical simulations are also presented and were performed with the MCNP 6.2 code [13] and the ENDF/B-VII.1 nuclear data library [14] to verify the accuracy of the area ratio method.

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2. Facility Description

The basis of the SNF "Neutron Source" is a subcritical assembly using low-enriched uranium (19.7% of ^{235}U) fuel driven by a linear electron accelerator. The neutron-generating target is used in the core to produce primary neutrons through photonuclear reactions using 100 MeV electrons.

The subcritical assembly (the core geometry and the fissile nuclear material mass) is designed to obtain the highest possible neutron flux intensity with k_{eff} equal to or less than 0.98 during normal operation, abnormal operation, and design accidents, which guarantees the safety of the facility.

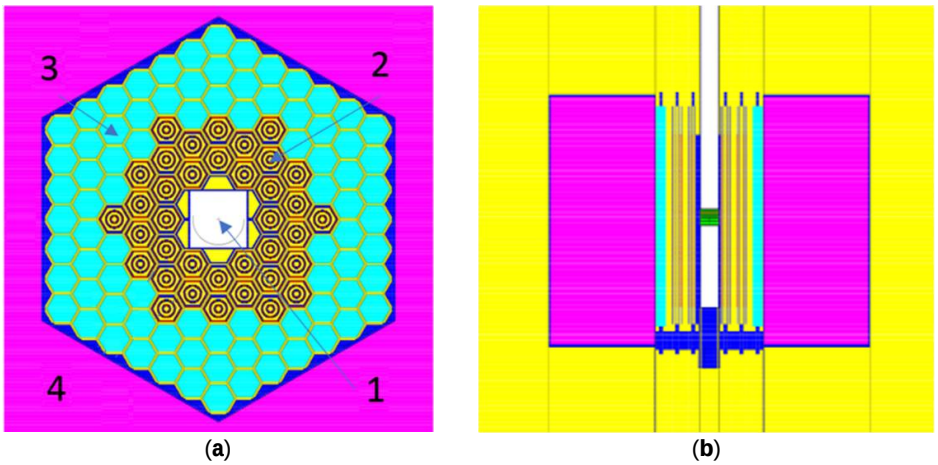
The main parameters of the SNF "Neutron Source" for the physical start-up are listed in Table 1.

Table 1. The main parameters of the SNF "Neutron Source" for the physical start-up.

Parameters	Values
Effective neutron multiplication factor k_{eff} (W-target)	0.96
Electron energy, MeV	100
Maximum beam power, kW	0.25
Beam pulse current, mA	40
Beam repetition rate, Hz	20
Pulse duration, μs	2.7
Target neutron yield, n·s^{-1}	3.86×10^{11}
Neutron flux in the core, n·cm^{-2}·s^{-1}	2.43×10^{10}

3. Simulation Model

Figure 1 shows a general view of the core simulation model. The neutron-generating target (1) surrounded by fuel assemblies (2) is located in the center of the core. The design configuration of the core with 38 FAs is shown in the figure. The neutron reflector is formed by two types of elements: beryllium elements (3) and a graphite ring reflector (4). All core elements are installed in the tank surrounded by biological shielding.



(**a**) (**b**)

Figure 1. Layout of the core simulation model: (**a**) Horizontal cross section of the model; (**b**) Vertical cross section of the model.

All parameters of the simulation model used corresponded to the real equipment of the facility core. The accelerated electron beam parameters were as follows:

- The maximum energy E_e = 100 MeV;
- The electron number N_e = 1;

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– The pulse repetition rate f_{rep} = 20 Hz;
– The time channel duration Δt = 5 μs.

4. Area Ratio Method

In the area ratio method [10–12], the time-dependent neutron flux in the core due to a pulsed external neutron source is detected, and the reactivity ρ can be expressed as the ratio of the areas corresponding to the neutron detector counts of prompt and delayed neutrons in the pulse response:

$$-\frac{\rho}{\beta_{eff}} = \frac{A_p}{A_d}, \quad (1)$$

where β_{eff} is the effective fraction of delayed neutrons, A_p is the "prompt area", and A_d is the "delayed area".

5. Results and Discussions

A typical simulated detector response to a pulse of primary neutrons from the external source in the subcritical assembly, indicating the areas corresponding to prompt neutrons A_p and delayed neutrons A_d is shown in Figure 2.

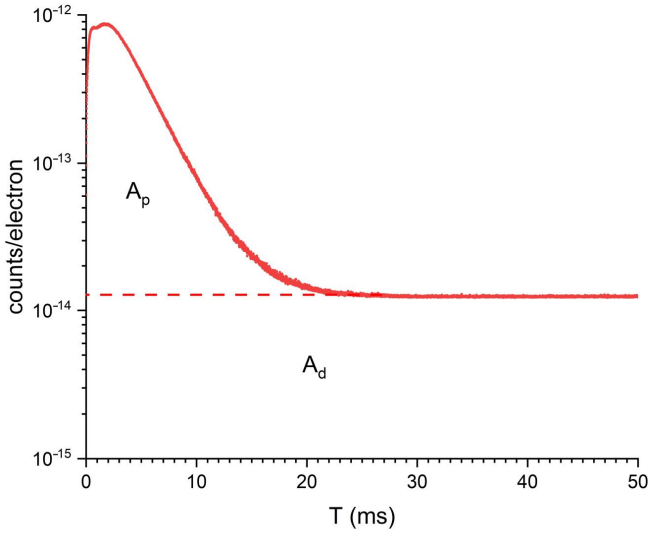


Figure 2. Simulation of a typical neutron detector response for the core with the tungsten target and 37 fuel assemblies loaded.

Table 2 presents the results of simulations of the reactivity of the subcritical assembly core with the MCNP 6.2 code [13] and the ENDF/B-VII.1 nuclear data library [14] for both the k-code and source (area ratio) modes, compared with experimental values obtained using the area ratio method in the final stages of the facility's physical start-up. Numerical simulations were performed for two values of the FA aluminum cladding thickness: 0.65 mm and 0.75 mm. The simulation results in both modes are in very close agreement. A strong dependence of the obtained results on the aluminum cladding thickness of FAs is observed. The experimental values obtained by using the area ratio method for reactivity measurement during the physical start-up fall between the simulated values for the two cladding thicknesses of 0.65 mm and 0.75 mm.

Table 2 also presents simulation estimates for the configuration with 38 fuel assemblies planned for loading into the core. The effective neutron multiplication factor k_{eff} values, corresponding to the reactivity ρ ones in Table 2, do not exceed 0.96 (Table 1), which guarantees the nuclear safety of the SNF "Neutron Source".

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Table 2. Comparison of reactivity values obtained with the area ratio method for different configurations of the core.

FAs	MCNP			Experiment
	Cladding, mm	k-Code Mode	Source (Area Ratio) Mode	
36	0.65	-0.06709 ± 0.00007	-0.06619 ± 0.00046	-0.0718 ± 0.0007
	0.75	-0.08142 ± 0.00007	-0.07944 ± 0.00055	
37	0.65	-0.05543 ± 0.00006	-0.05446 ± 0.00038	-0.0605 ± 0.0006
	0.75	-0.06953 ± 0.00006	-0.06777 ± 0.00047	
38	0.65	-0.04470 ± 0.00007	-0.04423 ± 0.00032	–
	0.75	-0.05865 ± 0.00007	-0.05723 ± 0.00041	

6. Conclusions

In this paper, a brief description of the SNF "Neutron Source" and the main results obtained by using the area ratio method for reactivity measurement during the physical start-up were presented. The agreement between the simulation results obtained and the experimental data measured is remarkable.

Since the State Nuclear Regulatory Inspectorate of Ukraine has not yet approved the loading of the 38th FA, it was decided to complete the physical start-up after the 37th FA with the possibility of justifying a separate decision and carrying out the loading of the 38th FA during the pilot operation phase of the SNF "Neutron Source".

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Abbreviations

The following abbreviations are used in this manuscript:

ADS	Accelerator-driven subcritical system
SNF	Subcritical nuclear facility
FA	Fuel assembly
MCNP	Monte Carlo N-Particle transport code
ENDF	Evaluated nuclear data file

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