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THE RESULTS OF THE NSC KIPT SUBCRITICAL ASSEMBLY NEUTRON SOURCE FACILITY PHYSICAL START UP *

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Abstract

Subcritical Assembly (SCA) Neutron Source facility (NSF) of the National Science Center "Kharkiv Institute of Physics & Technology" (NSC KIPT), Kharkov, Ukraine is Accelerator Driven System with tungsten or uranium neutron generating target and 100MeV/100kW electron linear accelerator as a driver.

The facility physical start-up (PS) was started in the middle of 2020 and completed in August 2021. The program of the facility PS supposes to operate with tungsten neutron generating target and to carry out stepwise fuel element loadings with neutron multiplication factor and reactivity measurements at the end of each loading step. During the PS it was supposed to load 38 fuel elements in several loading steps. 200 W electron beam was used for neutron multiplication factor and reactivity measurements.

After loading of 37 fuel assemblies the measured value of neutron multiplication factor was 0.943. Because of nuclear safety reasons it was decided to complete the facility PS and make some clarifying simulations for 38 loaded in the core fuel assemblies taking into account tolerances for fuel mass, geometry and nuclei data uncertainty to be sure that the value of multiplication factor will be not higher than 0.96.

During the facility PS the results of the reactivity and neutron multiplication factor measurements were in a good agreement with results of Monte-Carlo simulations for NSC KIPT SCA Neutron Source facility.

All facility systems showed good operation performance.

INTRODUCTION

NSC KIPT, Kharkiv, Ukraine, together with the Argon National Laboratory (ANL, USA), developed SCA "Neutron Source" driven by the linear electron accelerator with energy 100 MeV and maximum beam power on the neutron-generating target (NGT) 100 kW [1]. Primary source neutrons required to operate the facility are generated in reaction (γ, n) by electron beam slows down on the tungsten neutron-generating target (NGT). Neutron flux is enhanced in the core of the facility loaded with fuel assemblies (FAs) with 19.7% enriched ^{235}U.

PS program stipulated step-by-step loading of 37 fresh FAs into the NSF core with simultaneous measurement of the neutron multiplication factor k_{eff} and SCA reactivity ρ using 1 over N (neutron multiplication) and area ratio methods. The on-line monitoring of the facility reactivity value should be done with neutron flux to electron beam current ratio method.

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All physical experiments provided by the PS program to determine and verify the neutron and physical characteristics of the facility were performed at a power of the order of about 10^{-3} of the maximum facility power. So, all multiplication factor and reactivity measurements were performed at repetition rate of electron beam 20 Hz; pulse current ≤ 40 mA that corresponds to the average electron beam power of about 200 W.

In accordance with the PS program loading of FAs into the core of NSF consists of the following steps:

- 3 loads of 4 FAs;
- 9 loads of 2 FAs until 30 FAs are in the core;
- Loading one FA at a time until 35 FAs are in the core;
- After report to the State Nuclear Regulation officials obtaining a separate permission to load the three remaining FAs;
- Loading of 2 FAs, one at a time, with subsequent measurement of k_{eff}.

After 37 FAs are loaded and the required measurements are taken, a report is prepared and sent to State officials.

The following neutron and physical characteristics of NSF were measured with the required accuracy after each step of FAs loading into the core:

*measurement of neutron multiplication factor k_{eff} using 1 over N (multiplication) method:

$$k_{eff} = 1 - N_0/N_i,$$

where N_0 is the number of neutrons registered without fuel loading into the core,

N_i is the number of neutrons registered after i step of the fuel loading into the core;

*measurement of reactivity (ρ) using "area ratio" method:

$$\rho/\beta_{eff} = N_p/N_d,$$

where β_{eff} = 0.00748 efficiency of the delayed neutrons (MCNP simulations),

N_p is the number of registered prompt neutrons,

N_d is the number of registered delayed neutrons;

*on-line monitoring of system reactivity by the ratio of neutron flux to electron beam current:

$$\rho = \rho_{ref}(\Phi_{ref}/I_{ref})/(\Phi_i/I_i),$$

where ρ_{ref} is the value of reactivity measured by area ratio method at some reference state of SCA,[2]

Φ_{ref} is the measured reference neutron flux,

I_{ref} is the measured reference value of the accelerator-driver current,

Φ_i is the current value of neutron flux at i-th SCA state,

I_i is the accelerator current at i-th SCA state.

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CORE CONFIGURATION

Core configuration of NSF calculated using MCNPX code is given in Fig. 1.

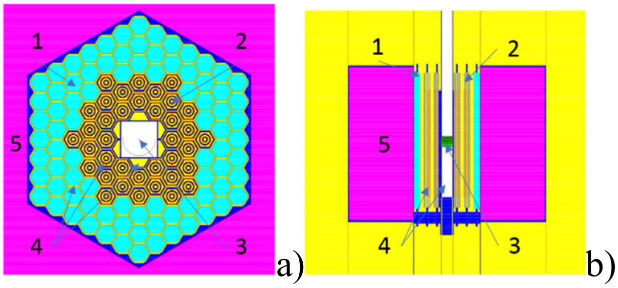

Figure 1: Core configuration of SCA NSF with 37 loaded FAs: a) – horizontal (cross-section), b) – vertical cross-section. 1 – elements of beryllium reflector, 2 – FAs, 3 – tungsten neutron-generating target, 4 – water of cooling loops of the target and SCA, 5 – graphite reflector.

Neutron-generating target is in the center of NSF core. At PS stage, the tungsten neutron-generating target was loaded into the core. The fuel used in FAs is 19.7% enriched uranium dioxide of ^{235}U in the cladding of aluminum alloy SAV-1, which is also used to fabricate all structural elements of NSF contained in 6 m^3 tank filled with cooling demineralized water. In order to prevent the core from drying out, the cooling water is drawn the SCA tank by siphon method with the system of disruption when water level drops by 10 cm in the tank. All elements of SCA core are placed on distancing grid. An autonomous water cooling system is used to cool the neutron-generating target. Maximum coolant temperature in primary cooling loops is 35°C. SCA is surrounded with the heavy concrete biological shielding.

Electron beam with energy 100 MeV and power of 100 kW is generated by the linear accelerator located horizontally [2,3]. Electron beam is directed to the neutron-generating target by the transportation channel consisting of two 45-degree dipole magnets, focusing quadrupole magnet and two scanning magnets which allow scanning the electron beam on the surface of the neutron-generating target.

MEASUREMENT RESULTS FOR THE 37TH LOADED FAs

In the course of the PS the measurements of neutron multiplication factor and SCA reactivity were performed at all consecutive stages of FAs loading using 1 over N (multiplication) method and the area ratio method. In addition to measurements of the above values, the critical number of FAs was determined at each loading stage using 1 over N curve.

Fig. 2 shows pulse responses of SCA to external neutron pulse for each stage of FAs loading. After the load of 37 FAs the number of neutrons registered in the pulse response of SCA in each measurement channel increased by a factor of 20 compared to the neutron yield from SCA without FAs.

When measuring the neutron multiplication factor k_{eff} using 1 over N (multiplication) method, a series of 6 measurements were performed. A single measurement consisted of 3600 accelerator pulses with repetition rate f_{rep}=20 Hz and pulse current 35-40 mA.

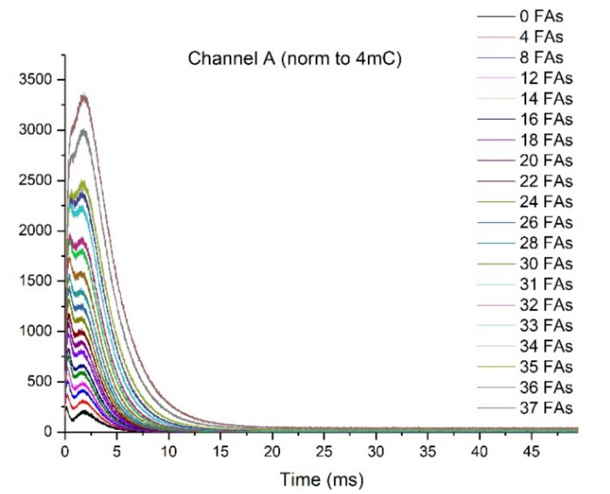

Figure 2: Pulse responses of SCA to external neutron pulse. All curves are plotted for beam charge of 4 mC absorbed in NGT.

Fig. 3. shows the 1 over N curve for measurement channel A for each step of FAs load into the core of SCA. Similar results were obtained for channels B and C. Fig. 4 shows the measured neutron multiplication factor k_{eff} for all measurement channels compared to MCNPX simulation with KCODE.

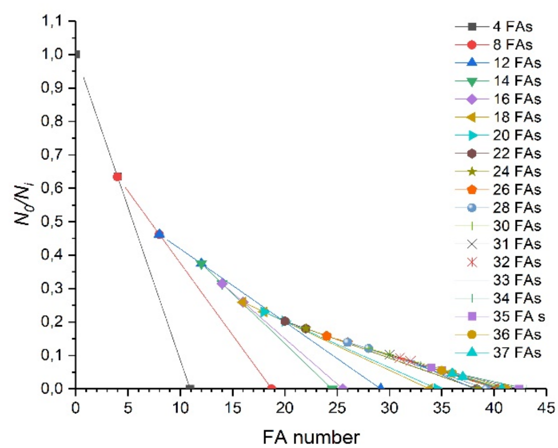

Figure 3: 1 over N curve for measurement channel A up to 37 FAs loaded into the NSF core.

The results of measurements for loads of 4 and 37 of FAs for all measuring channels are given in Table 1. Under 37 FAs the average value of k_{eff} for three channels was 0.958 with the range of measurements from 0.952 to 0.961 with

Table 1: Results of k_{eff} Measurements with Neutron Multiplication Method

FA N	k_{eff} ANL-simul.	Channel	k_{eff}	$\langle k_{eff} \rangle$	$(\langle k_{eff} \rangle - k_{sim})/k_{sim}$, %
4	0.275	A	0.312	0.311	+ 13.1
		B	0.295		
		C	0.327		
37	0.946	A	0.961	0.958	+ 1.3
		B	0.952		
		C	0.960		

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deviation - 0.55%...+ 0.28% from the average value. Statistical error of each measurement in the series does not exceed $\sigma \approx 1$ %. Critical number of FAs loaded into the core is 41 FAs.

Reactivity of NSF with 37 FAs loaded into the core was measured by area ratio method in series of 5 measurements of 36000 accelerator pulses each, respectively. Number of pulses per measurement was selected in such a way as to gain 4 mC absorbed charge in NGT under chosen beam power. Scope of statistics in each measurement was selected based on the need to obtain statistical accuracy of one measurement at level $\sigma = 1…1.2$ % which gives accuracy of determining the reactivity in the series $\sigma_{tot} \cong 0.5$ %.

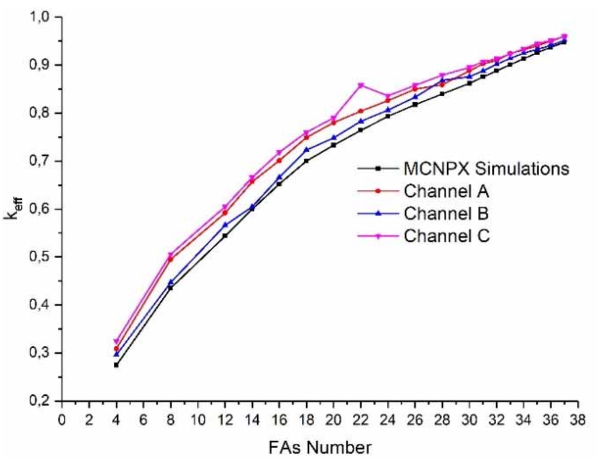

Figure 4: k_{eff} measurement values with neutron multiplication method for each fuel loading step (from 4 till 37 FAs).

Results of reactivity ρ measurements with area ratio method for each step of fuel loading are shown in Fig. 5.

From the measurement results it follows that under 37 loading FAs average reactivity in dollars is -8.11 with the measurement range from -8.12 to -8.09 (-0.17%;+0.22% of the average value) that corresponds average k_{eff} value of 0.943.

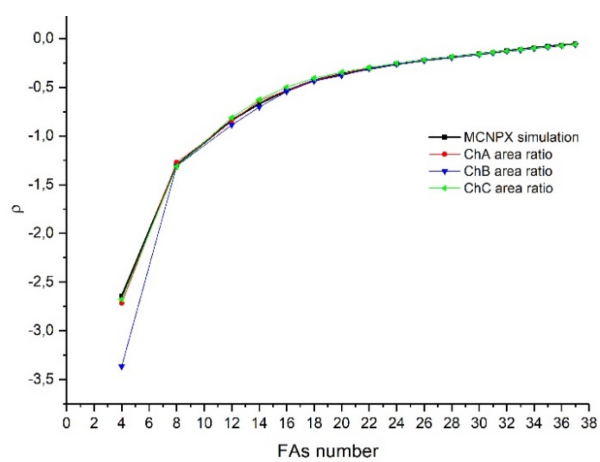

Figure 5: Reactivity (ρ) measurement values with area ratio method for each fuel loading step (from 4 to 37 FAs).

ERRORS IN k_{eff} DETERMINATION

PS program of NSF "Neutron Source" regulates that k_{eff} value cannot exceed 0.96 when 38 FAs are loaded into the core. Since the measured k_{eff} was 0.943 when 37 FAs were loaded into the core, loading of 38 FAs could result in the value approaching or exceeding the k_{eff} value 0.96. Calculation using MCNPX program with conservative approach, i.e. accounting for maximum tolerance values for geometry and fuel mass composition and uncertainties in nuclear data provided the value slighhtly exceeding 0.96.

Based on this, it was decided to complete PS with 37 loaded FAs and, in accordance to current IAEA recommendations, to perfrom the calculation of k_{eff} taking into account the random variation of FAs parameters within the passport data.

Having performed the corresponding calculations, the nominal value of neutron multiplication factor as well as RMS values of all errors due to geometry tolerances, mass composition of FA and uncertainties of nuclear data wre detrmined. The simulations were performed with use of WHISPER code. Final maximum value of neutron multiplication factor in NSF NSC KIPT taking into account all errors for 38 loaded FAs is

$$k_0 = k_{eff} + \Delta k_{eff} + \overline{\Delta k_{eff}} =$$

$$0.94407 + 0.00020 + 0.00879 = 0.95306,$$

where $\Delta k_{eff}, \overline{\Delta k_{eff}}$ are the errors because of nuclear data uncertainties and geometry and mass mismatching, respectively.

As can be seen from the result, the obtained value of the neutron multiplication factor does not exceed the nominal value $k_{eff} = 0.96$ set by the regulatory documents, therefore, loading of 38 FAs in the subcritical assembly of NSC KIPT is permissible and nuclear safe. k_{eff} value is below the established limit by 0.007, total margin of subcriticality is 0.047.

CONCLUSION

Measurement results of reactivity and neutron multiplication factor during PS of NSF "Neutron Source" NSC KIPT demonstrated that the parameters measured by two different methods at each step of the fuel loading have a good match with the design parameters of NSF "Neutron Source" and parameters given in PS program of the facility.

This allows us to conclude that the design values of neutron characteristics of NSF "Neutron Source" NSC KIPT are obtained, nuclear and radiation safety are ensured during PS of the facility and it is possible to move the facility to the pilot and industrious stage.

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