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Research of neutron-physical characteristics of the Subcritical Nuclear Facility “Neutron Source” of NSC KIPT during the physical start-up

Presented by Corresponding Member of the NAS of Ukraine I.M. Onishchenko

National Science Center “Kharkov Institute of Physics and Technology” jointly with the Argonne National Laboratory developed, designed and constructed the Subcritical Nuclear Facility “Neutron source based on the subcritical assembly driven by electron linear accelerator”. The article presents the main results obtained during the physical start-up of the plant, the program of which involved the staged loading of fuel assemblies into the core with subsequent measurements of its neutron-physical characteristics. In total, 37 fuel assemblies of WWR-M2 type were loaded into the facility core. The values of the effective neutron multiplication factor k_{eff} and reactivity ρ of the subcritical assembly were measured after each loading step using the multiplication and area ratio methods. In addition, the neutron flux to electron current ratio method was tested for on-line reactivity monitoring. The investigations were performed when the accelerator was operated with 100 MeV electron beam energy, 2.7 μs electron pulse duration, 20 Hz pulse repetition rate and ≤ 40 mA beam pulse current. The obtained results were analyzed in terms of ensuring the facility nuclear safety at the next stage of its commissioning which is the pilot operation.

Keywords: *subcritical nuclear facility, neutron source, physical start-up, effective neutron multiplication factor, reactivity.*

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Introduction. National Science Center "Kharkov Institute of Physics and Technology" (NSC KIPT) jointly with the Argonne National Laboratory (ANL) developed, designed and constructed the Subcritical Nuclear Facility "Neutron source based on the subcritical assembly driven by electron linear accelerator" (SNF "Neutron Source") [1—3].

The technological process of intensive neutron flux generation at such facilities is based on the multiplication of primary neutrons in the fissile material. The configuration, geometry and mass of the fissile material is chosen to provide the value of neutron multiplication factor k_{eff} lower 0.98 in normal, abnormal, and accident conditions. Such solution guarantees the nuclear safety of the plant, and this is its fundamental difference from research and power reactors operating in the mode of self-sustained nuclear chain reaction of actinide fission.

After completion of construction, installation and commissioning works, as well as individual and comprehensive tests of all systems, the physical launch of the SNF "Neutron Source" was initiated. The corresponding program included the step-by-step loading of fuel assemblies (FAs) into the core and measurements of the effective neutron multiplication factor k_{eff} and reactivity ρ of the subcritical assembly after each step of the loading by using the multiplication and area ratio methods. In addition, the neutron flux to electron current ratio method for on-line reactivity monitoring was tested with the aim of using it in the next stage of commissioning the SNF "Neutron Source" — pilot operation.

Experimentally determined core characteristics were compared with the results of numerical Monte Carlo simulations performed using MCNP 6.2 code and ENDF/B-VII.0 nuclear data library.

The first fresh fuel loading into the core of SNF "Neutron Source" was started in 2020.

1. Facility description. The base of SNF "Neutron Source" is the subcritical assembly (SCA), where low-enriched uranium (with 19,7% enrichment by ^{235}U isotope) is used as fissile material for primary neutron multiplication.

A high current electron linear accelerator (LINAC) of 100 MeV electron energy [4, 5] and the neutron generating target [6] is used to generate the external primary neutrons via photo-nuclear (γ,*n*) reactions in plates of heavy materials (tungsten) of the target due to the hard gamma radiation produced by the deceleration of electrons in the target material (bremsstrahlung).

Simulated data on the neutron yield per 100 MeV electron for the tungsten target are given in [3]. The neutron spectrum has a maximum at about 1 MeV, which is similar to the fission spectrum. The high-energy component of the spectrum is not sensitive to the electron energy, and its magnitude is very small.

Generated primary neutrons cause the fission of ^{235}U isotope of FAs. The resulting neutron generation rate and the value of neutron flux in the SCA core, respectively, is determined by intensity of the primary neutron flux and by the value of the effective multiplication factor k_{eff}. The process of fission and neutron generation stops when the acceleration electron beam is switched off.

Fig. 1 shows a general view of the SCA core. A neutron-generating tungsten target is installed in the center of the core, around which FAs of WWR-M2 type are located. The neutron reflector is formed by two types of elements. The first one is beryllium elements (82 items). The second one is the ring of graphite consisting of blocks enclosed in a sealed housing made of the aluminum alloy SAV-1. All core elements are installed in a fuel mark attached to this casing. The core and neutron-generating target SCA are equipped with independent cooling circles with demineralized water as coolant. The shape and geometry of the moving elements of the core are identical to FAs of WWR-M2 type.

All SCA core elements are located inside the 6 m^3 tank made of the aluminum alloy SAV-1 and surrounded by biological shielding made of heavy concrete with the density of 4.85 g·cm^{-3}.

All loading/unloading/reloading operations of the main elements inside the tank are performed by the fuel-handling machine.

Fig. 2 shows a vertical cross section of SNF "Neutron Source" layout and technological equipment allocation.

After passing the accelerating sections, the electron beam is directed to the target through a transport channel consisting of two 45-degree dipole magnets, a quadrupole lens and two scanning magnets, which allow scanning the electron beam and distributing it uniformly over the surface of the target plates. Behind the first dipole magnet of the transportation channel there is a magnet-induction electron beam current detector (MID) made by "Bergoz Ltd." (France) which allows to measure beam current with accuracy of about 1%. An electron beam loss sensor is installed after the second dipole magnet of the transport channel. The electron current is detected on the target by measuring the electron current using the MID with minimum beam loss in the transport channel after the second dipole magnet.

Prior to the physical start-up, LINAC was configured for stable, reproducible operation with the following electron beam parameters:

beam energy — 100 MeV;
repetition rate — 625 Hz;
pulse duration — 2.7 μs;
pulse current — 0.6 A;
average beam power — 100 kW.

Table 1. **Results of MCNP simulations of FAs loading during the physical startup**

FAs	k_{eff}	std, $n \cdot 10^{-5}$	ρ	β_{eff}	std, $n \cdot 10^{-5}$
4	0.26854	3	−2.72384	0.00799	13
8	0.42698	4	−1.34203	0.00794	10
12	0.5352	5	−0.86846	0.0079	9
14	0.59216	5	−0.68873	0.00803	9
16	0.64486	4	−0.55072	0.00789	8
18	0.6932	5	−0.44259	0.0076	8
20	0.72727	5	−0.37501	0.00789	8
22	0.75933	5	−0.31695	0.00768	7
24	0.78961	5	−0.26645	0.00761	7
26	0.81427	5	−0.22809	0.00777	7
28	0.83751	6	−0.19402	0.00747	7
30	0.86007	6	−0.1627	0.00776	7
31	0.87376	5	−0.14448	0.00778	7
32	0.88674	5	−0.12773	0.00765	7
33	0.90005	5	−0.11105	0.00758	7
34	0.91257	5	−0.09581	0.00752	7
35	0.92525	5	−0.08079	0.00765	7
36	0.93713	6	−0.06709	0.00758	7
37	0.94748	5	−0.05543	0.00759	7
38	0.95721	6	−0.0447	0.00744	7

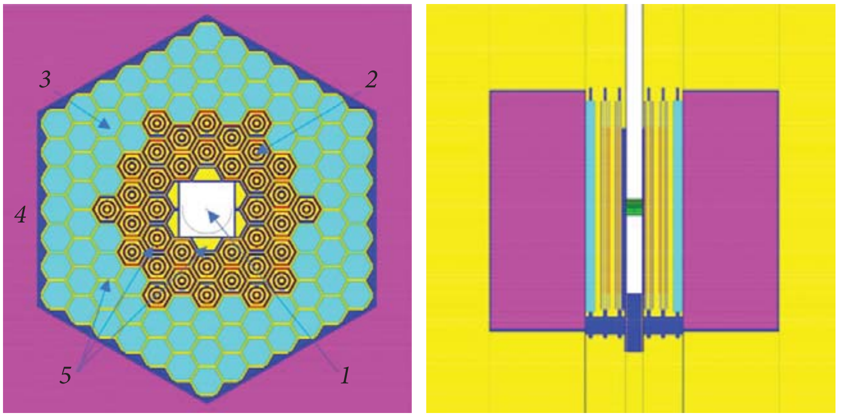

Fig. 1. Layout of the core: *a* — horizontal cross-section (*1* — neutron generating target, *2* — FAs, *3* — beryllium reflector elements, *4* — graphite reflector, *5* — cooling channels); *b* — vertical cross-section

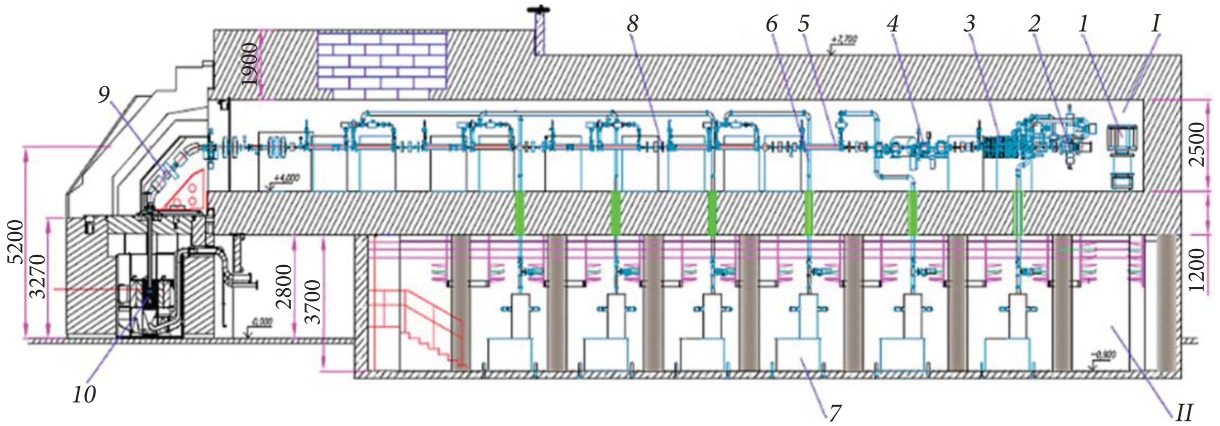

Fig. 2. Vertical cross section of SNF “Neutron Source” layout and technological equipment allocation: *I* — LINAC tunnel; *II* — klystron gallery. *1* — electron gun power supply; *2* — electron gun; *3* — first accelerating section; *4* —energy filter; *5* — accelerating section; *6* — waveguide circuit; *7* — klystron modulator; *8* — quadrupole triplet; *9* — transportation channel; *10* — SCA tank

2. Fuel loading steps. Step-by-step loading of fresh FAs into the SCA core was carried out in the following sequence: from the 1st to the 3rd loadings four FAs each, from the 4th to the 12th — two FAs each, and from the 13th to the 20th — one FA each.

Loading of fresh FAs into SCA core was performed according to cartogram (see Fig. 1) obtained by simulations using the MCNP 6.2 code [7].

Table 1 shows the obtained simulated values of the effective neutron multiplication factor k_{eff} and reactivity ρ of the SCA core for each step of FAs loading.

3. Neutron flax monitoring system. The neutron flux monitoring system with three measuring channels is equipped with a set of neutron detectors of CFUF34, CFUF54 and CFUF28 types with different sensitivities in each channel [8].

The characteristics of the detectors are presented in Table 2. Fission chambers manufactured by “Photonis” (France) are used as neutron detectors. The CFUF34 type and CFUF54 detectors are located above the graphite reflector alternately at a vertical distance of 849 mm from the median plane of the SCA and 540 mm from the center of the neutron generating target in the radial direction. Three CFUF28 type detectors are located 90 mm above the median plane behind the graphite reflector at distance of 625 mm from the center of the SCA. The CFUF34 and CFUF54 type detectors are arranged at 60° angle to each other.

The CFUF34 and CFUF54 detectors can be operated in individual neutron counting and fluctuation modes. In addition, CFUF28 detectors can operate in current mode. The detectors located above the graphite reflector were used for measurements during the physical start-up of SNF "Neutron Source". Detectors in median plane are designed to monitor the neutron flux in output neutron channels.

Accelerator timing system generates synchro-pulses that control the operation of accelerator systems, including synchro-pulse whose front edge corresponds to the start of the accelerated electron pulse. This synchro-pulse controls the system for recording the neutron response of the SCA to an external neutron pulse.

Reception and primary generation of signals from neutron detectors are performed by the RNL-04.06 wide range analogue modules manufactured by "Regtron" (Hungary).

The signal from the division chamber is fed to the input of the preamplifier. It amplifies the measurement signal and divides it into pulse and variable components. The pulse signal is processed in the amplifier with amplitude discriminator. The amplitude discriminator converts the incoming detector pulses into standard pulses if the discriminator threshold voltage is exceeded.

The measured pulse signals are given from the RNL-04.06 wide range analogue modules to inputs of the neutron flux counter unit (NFCU) and the pulse response counter unit (PRCU) controlled by strobe-pulse of the accelerated electrons. NFCU and PRCU are based on PSI-8101RT controllers with NI6602 module that contains eight 32-bit counters. PRCU contains of the strobing generator with duration of control pulses from 1 up to 100 μs which provides measurement of the SCA response to an external neutron pulse.

The strobing pulses with 5 μs duration were used in the performed measurements. In addition to the normative functions, NFCU also provides measurement of neutron registration time after the synchro-pulse.

Before the physical start-up of the facility, the discrimination curves of CFUF34 detectors were measured under real experimental conditions based on manufacturer's recommendations. The discrimination curves measured at high voltage U = 400 V for all three detectors CFUF34 are shown in Fig. 3.

The value of discrimination threshold was chosen to be 0.6 V for all three detectors. This was done for two reasons: 1) the manufacturer's data sheets for neutron detectors specify the range 0.6—

Table 2. **Characteristics of detectors of the neutron flux monitoring system**

Characteristics	Dimension	CFUF28	CFUF34	CFUF54
Sensitivity to thermal neutrons in pulse mode	$s^{-1}/(cm^{-2} \cdot s^{-1})$	10^{-2}	10^{-3}	10^{-5}
Sensitivity to thermal neutrons in fluctuation mode	$A^2 \cdot Hz^{-1}/(cm^{-2} \cdot s^{-1})$	10^{-28}	$4 \cdot 10^{-29}$	$4 \cdot 10^{-31}$
Sensitivity to thermal neutrons in current mode	$A/(cm^{-2} \cdot s^{-1})$	10^{-15}	—	—
Neutron flux density range in pulse mode	$cm^{-2} \cdot s^{-1}$	10^2—10^8	10^3—10^9	10^5—10^{11}
Neutron flux density range in fluctuation mode	$cm^{-2} \cdot s^{-1}$	10^6—$3 \cdot 10^{11}$	10^7—$3 \cdot 10^{12}$	10^9—$3 \cdot 10^{14}$
Neutron flux density range in current mode	$cm^{-2} \cdot s^{-1}$	10^8—10^{12}	—	—

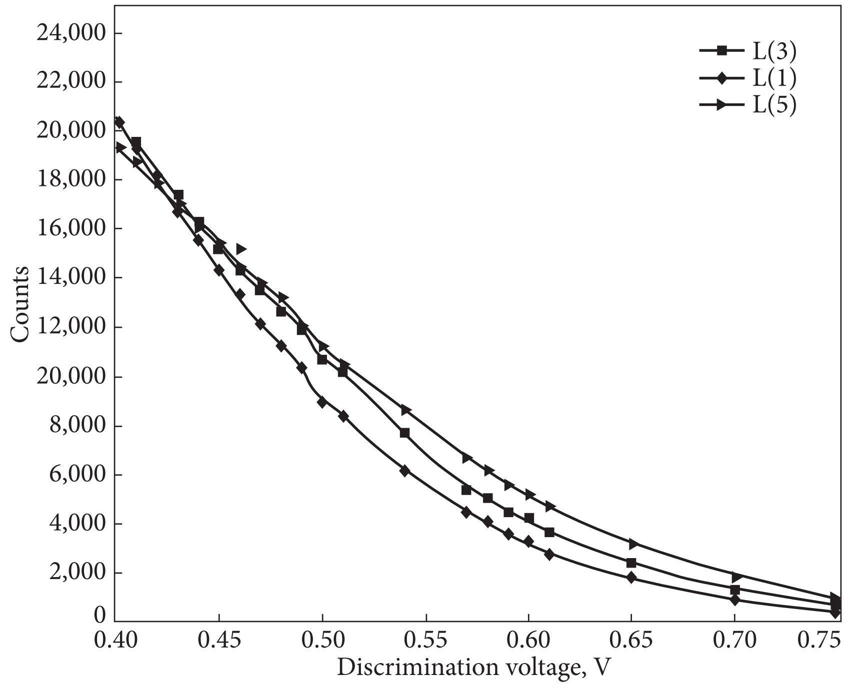

Fig. 3. Discrimination curves of CFUF34 neutron detectors

0.9 V as the recommended value of the discrimination threshold; 2) the regions of the discrimination curves between 0.56 V and 0.61 V have a minimum slope angle. Further measurements at several loads compared the measured reactivity at several close values of the discrimination voltage.

4. Pulsed external neutron source. It was determined by computer analysis of the SCA model by using the MCNP 6.2 code that after the loading of 37 FAs the prompt neutrons from the SCA under external neutron pulse of 3 μs duration decay within 23 ms, and therefore, for reliable experimental registration of the delayed neutron flux from the SCA, the acceptable duration of registration of the neutron response to the external neutron pulse is 50 ms, which corresponds to the pulse repetition rate of accelerated electrons of 20 Hz.

The accelerator pulse current during the physical start-up was selected to be ~ 40 mA in order, on the one hand, to have the acceptable neutron count rate and to ensure the use of CFUF34 detectors until the complete loading of FAs (37 items) into the core. On the other hand, such value of the electron pulse current provides the possibility to perform measurements using CFUF54 detectors at the late stages of FAs loading (after the loading of 28 FAs), which ensures the cross-linking of results of SCA reactivity measurements by two different types of neutron detectors. Thus, the parameters of the accelerator beam for the facility start-up should be:

beam energy — 100 MeV;
repetition rate — 20 Hz;
pulse duration — 2.7 μs;
pulse current — ≤ 40 mA;
average beam power — ~ 200 W.

Time of establishment of quasi-static equilibrium at selected parameters of electron beam and standard characteristics of delayed neutrons was estimated to be 270 seconds and was verified experimentally [9].

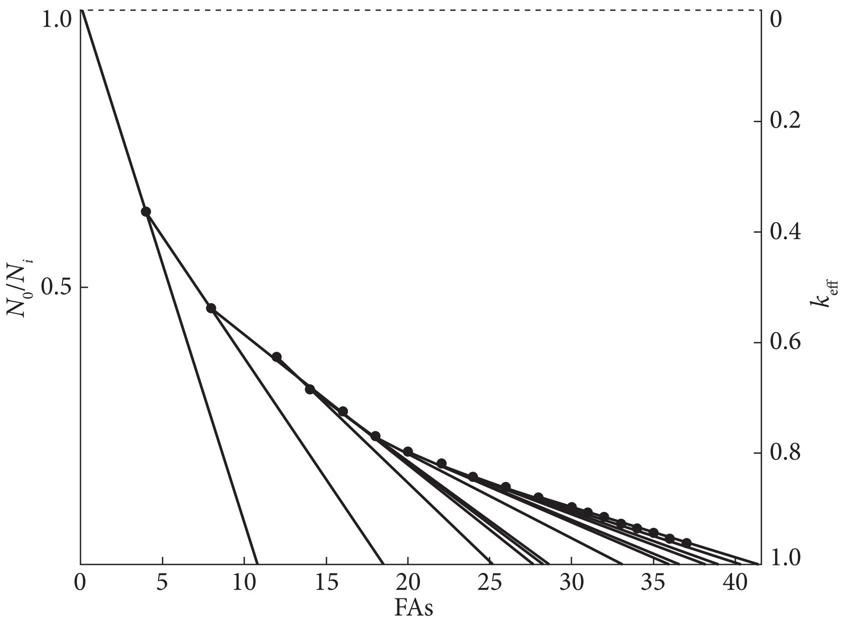

Fig. 4. Inverse count curve for each loading up to 37 FAs loaded into the core

5. Physical start-up results. ***Using the multiplication method.*** Measurements of the effective neutron multiplication factor k_{eff} of the SCA core using the multiplication method were performed based on the ratio [10]:

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

where N_0 is the number of neutrons registered without the loading of fuel elements into the core, N_i is the number of neutrons registered after i-th stage of loading of fuel elements into the core.

During the measurements of the effective neutron multiplication factor k_{eff} using the multiplication method, a series of 5—6 measurements, consisting of 3600 accelerator pulses with 20 Hz accelerator repetition rate and 35—40 mA pulse current were performed at each stage of FAs loading.

Fig. 4 shows the results of inverse curve plotting for each step of FAs loading into the SCA core.

Critical value of the number of FAs in the SCA core was determined by intersection of linear approximation of inverse count curve with abscissa axis. After loading of 37 FAs at the core the value of k_{eff}, measured with the multiplication method, was equal to 0.95939 and critical value of the number of FAs in the SCA core was $m_{crit} = 41$.

Fig. 5 shows the effective neutron multiplication factor k_{eff} of the core at each step of FAs loading measured with the multiplication method averaged for three measuring channels in compere with MCNP 6.2 code results.

Using the area ratio method. Measurements of the reactivity ρ of the system by the area ratio method (or the area method) is based on the ratio [10]:

$$-\frac{\rho}{\beta_{eff}} = \frac{N_d}{N_p}, \tag{2}$$

where β_{eff} is the effective fraction of delayed neutrons, based on simulations by the MCNP 6.2 code for each step of the fuel loading (see Table 1), N_p is the number of registered prompt neu-

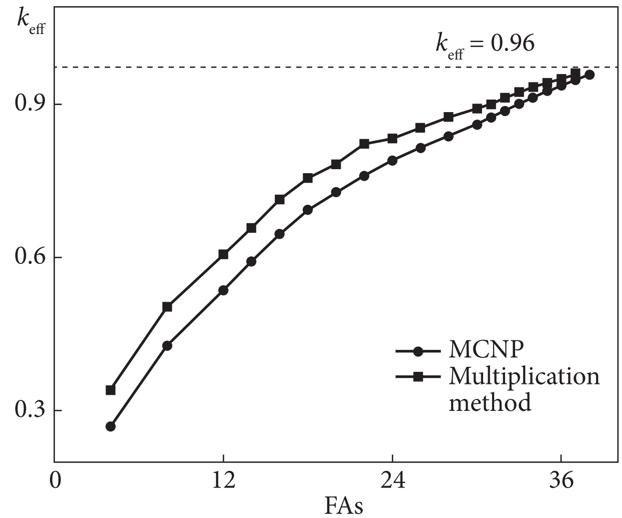

Fig. 5. Effective neutron multiplication factor k_{eff} of the core at each step of FAs loading measured with the multiplication method in compare with simulation results

trons, N_d is the number of the registered delayed neutrons. This ratio is obtained in the point reactor model when a quasi-stationary neutron flux equilibrium is established in the SCA core under the existing parameters of the external neutron source. During the facility start-up the core reactivity value ρ was measured sequentially from five measurements of 36000 electron pulses at a pulsed beam current of about 40 mA.

To measure reactivity based on the ratio (2), it is necessary to measure the neutron response of the SCA to an external neutron pulse with sufficient statistical accuracy, from which the number of fast and delayed neutrons can be calculated.

Instrumentally, to register the SCA response, an electronic system with double gating of neutron yield from SCA is used. Each external neutron pulse corresponds to a strobe at the beginning of the neutron pulse (repetition rate 20 Hz) and the same pulse triggers the gating system for measuring the neutron yield from the SCA. The strobing period can be selected in the range from 1 μs to 100 μs. Based on experimental experience, a strobing period of 5 μs was selected.

So, the total number of registered neutrons in SCA pulse response N_{tot} is measured by summarizing the number of registered neutrons during the measuring session.

For the subcritical assembly, the fast neutron output completely ceases during the decay time of 25 ms after the external neutron pulse. The number of delayed neutrons in the neutron response of the subcritical assembly N_d after the decay of the prompt neutron output under quasistatic equilibrium conditions remains constant until the next electron pulse that is 50 ms for our case. To determine the number of delayed neutrons N_d after the initial external neutron pulses one should count the number of neutrons between each 25th and 50th ms of the measurement session and double it, since the number of delayed neutrons between 0 and 25 ms after the initial pulse is the same as between 25 and 50 ms.

Total number of prompt neutrons N_p is determined as the difference between the total number of neutrons N_{tot} in response and the number of delayed neutrons N_d:

$$N_p = N_{tot} - N_d. \quad (3)$$

Fig. 6 shows pulse responses of SCA to external neutron pulse for each stage of FAs loading. The comparison of experimental pulse of SCA response and the one obtained by simulation with MCNP 6.2 code is given in Fig. 7 at loading of 37 FAs. Values of reactivity ρ measured with the area ratio method at each step of the FAs loading averaged on three measuring channels are shown in Fig. 8.

After the 37 FAs loading into the core the averaged on three measuring channels value of k_{eff} is 0.943 ± 0.01%.

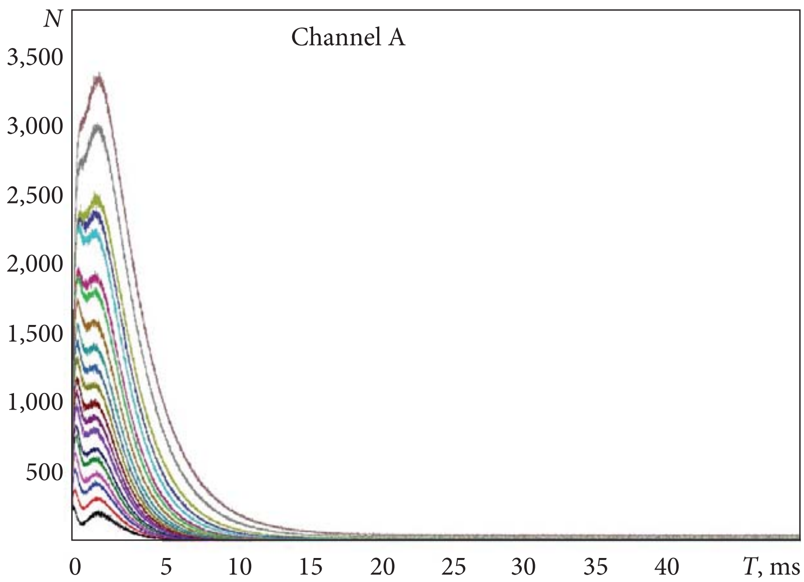

Fig. 6. SCA impulse responses to an external neutron pulse for each stage of loading measured on one of the measurement channels

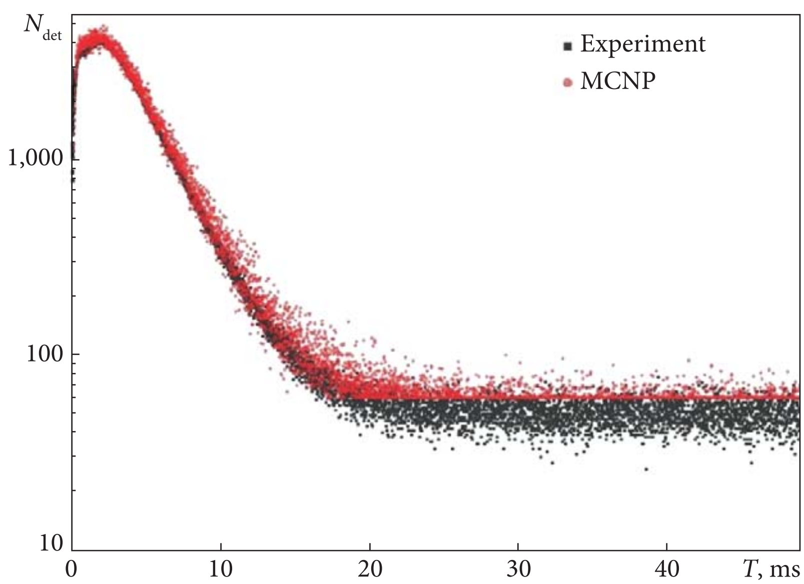

Fig. 7. Pulse response of neutron detector, measured and simulated for the loading of 37 FAs into the core

Spatial correction. For an adequate estimation of the reactivity ρ with the area ratio method, it is necessary to take into account the spatial correction of the measurements due to location of the neutron detectors [10]:

$$f = \frac{\rho_{crit}}{\rho_{scr}}, \tag{4}$$

$$\rho_{cor} = f \cdot \rho_{exp}, \tag{5}$$

where ρ_{crit} is the calculated reactivity value obtained as a result of modeling using the MCNP code in the criticality mode, ρ_{src} is the calculated value of reactivity in the source mode, ρ_{exp} is the reactivity value experimentally measured by the area ratio method, f is the spatial correction factor, which excludes the dependence of the measured value at each neutron detector location, ρ_{cor} is the corrected reactivity value.

Table 3 shows the results of spatial correction simulation for CFUF34 neutron detectors. The simulations were performed when the contributions of the prompt neutrons N_p and delayed neutrons N_d to the whole number of counting can be separated.

Experimental results for k_{eff} measurements. After loading of 37 FAs the number of recorded neutrons released from SCA is increased in $M = 1/(1 — k_{eff})$ times in comparison with the number of neutrons released from SCA without FAs. Estimates from k_{eff} measurement results give the following results for the increase of the neutron yield:

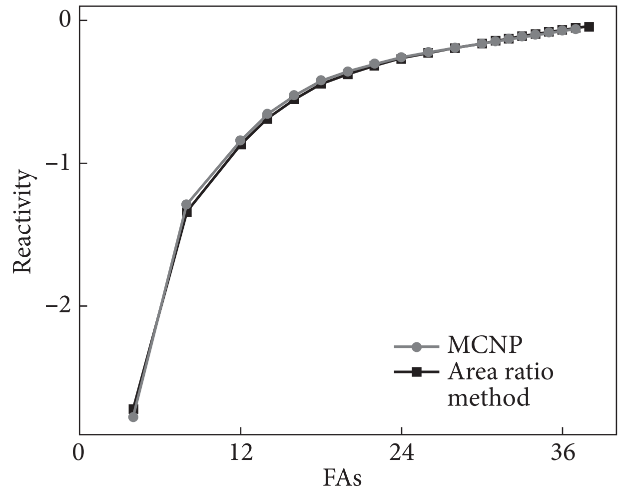

Fig. 8. Comparisons of the reactivity ρ of the core at each step of FAs loading measured with the area ratio method and MCNP simulation results

k_{eff} measured by the area ratio method gives increase of the neutron yield in 17.4 times;

k_{eff} measured by the multiplication method gives increase of the neutron yield in 23.9 times.

The results of k_{eff} value simulations with MCNP 6.2 code for referent parameters of the FAs and results of k_{eff} measurements with multiplication, area ratio methods and taking into account spatial correction are summarized in Table 4.

Fig. 9 shows the value of k_{eff} simulated with MCNP 6.2 code and measured by different methods and averaged over three measurement channels for each fuel loading step in the core.

As one can see, the measurement results of the area ratio method are in a good agreement with MCNP 6.2 simulation results.

The data of Table 4 show a systematic overrun of k_{eff} values measured with multiplication method over k_{eff} measured with area ratio method and MCNP 6.2 simulation results. Herewith, the value of overrun is ~ 1,5% at 37 loaded FAs and increases with 12 loaded FAs into the core up to

Table 3. **Accounting for spatial correction for the area ratio method**

FAs	ρ	f	ρ_{cor}
28	−0.1911	1.0487	−0.2004
30	−0.1624	1.0425	−0.1693
31	−0.1453	1.0251	−0.1490
32	−0.129	1.0231	−0.1320
33	−0.1137	1.0332	−0.1175
34	−0.0993	1.0190	−0.1012
35	−0.0849	1.0084	−0.0856
36	−0.0718	1.0162	−0.0730
37	−0.0607	1.0247	−0.0622

Note. f — average values of the spatial correction factors for CFUF34.

~ 4 %. Such difference in measured values of k_{eff} can be caused by difference in efficiency of neutron registration generated by the target and ^{235}U fission neutrons because of essential difference of neutron energy spectrum. For this reason, it can be argued that k_{eff} values obtained with multiplication measurements have systematic excesses. To eliminate this natural disadvantage of the multiplicative measurement method, it is necessary to approximate the energy spectrum of external neutrons to the spectrum of ^{235}U fission neutrons. It can be supposed, that (*d,d*) reaction can be used as primary reaction for the external primary neutron generation.

In addition, the results of area ratio method are systematically slightly higher than simulation results of MCNP 6.2 code. But the value of overrun with 37 FAs loaded to the core are less than 1 %. The spatial reactivity correction does not lead to a closer match between the results and the simulation.

Preparation of the facility pilot operation. The physical start-up program envisages verification and development of the on-line monitoring methodology of SCA reactivity for the next stage of the facility operation — pilot operation of the SNF "Neutron Source". The pilot operation stage provides for an increase in the electron beam power up to 100 kW with a corresponding increase in the neutron flux yield in the SCA. To ensure the realization of the pilot operation stage of the facility, the following studies were carried out:

▪ starting from 28 FAs loading to the facility core the CFUF54 detectors with 10^{-5} were put in operation;

▪ tests of on-line method of reactivity monitoring with use of neutron flux to electron beam current ratio were carried out using SNF "Neutron source" equipment.

Table 4. **The results of k_{eff} simulations with MCNP 6.2 code for referent values of FAs parameters and k_{eff} measurement results with multiplication and area ratio methods**

FAs	MCNP	Multiplication method	Area ratio method	Area ratio method with spatial correction
4	0.26854	0.3113	0.2646	—
8	0.42698	0.4837	0.4367	—
12	0.5352	0.5891	0.5426	—
14	0.59216	0.6438	0.6027	—
16	0.64486	0.6961	0.6555	—
18	0.6932	0.7449	0.7037	—
20	0.72727	0.7732	0.7366	—
22	0.75933	0.8149	0.7665	—
24	0.78961	0.8249	0.7953	—
26	0.81427	0.8467	0.8183	—
28	0.83751	0.8688	0.8394	0.8331
30	0.86007	0.8868	0.8601	0.8552
31	0.87376	0.8995	0.8731	0.8704
32	0.88674	0.9082	0.8857	0.8834
33	0.90005	0.9202	0.8982	0.8949
34	0.91257	0.9299	0.9096	0.9081
35	0.92525	0.9392	0.9217	0.9211
36	0.93713	0.9474	0.9331	0.9320
37	0.94748	0.9577	0.9428	0.9414

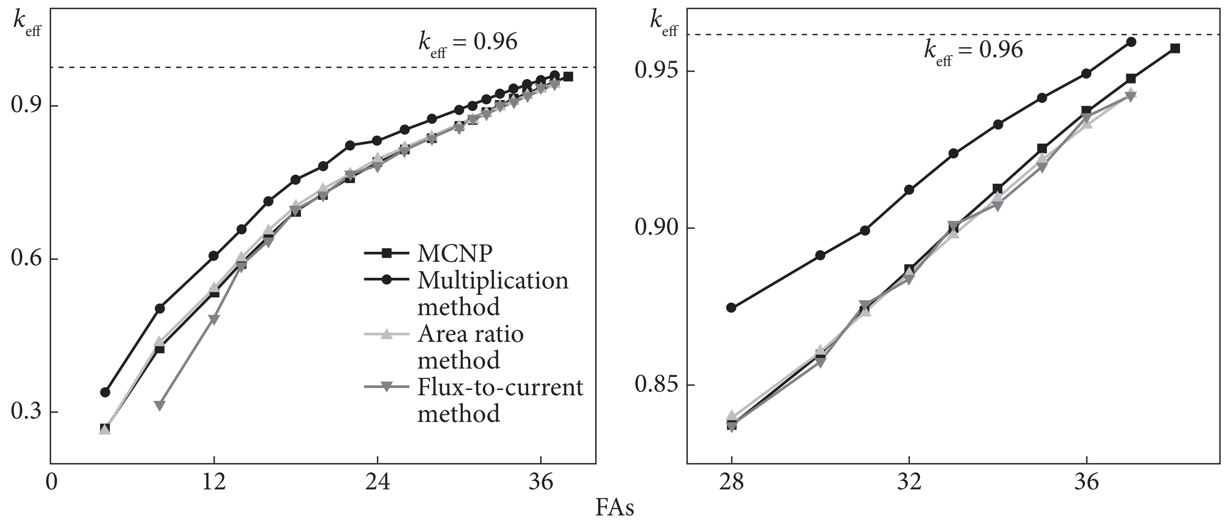

Fig. 9. k_{eff} values of MCNP 6.2 simulation results for referent parameters of FAs and experimental measurement results for different measurement methods

Using CFUF54 detectors. Starting with 28 FAs loaded into the SCA core, the number of neutrons registered by the CFUF54 detectors became large enough to provide acceptable statistics and measurement accuracy. Therefore, simultaneous measurements with CFUF34 detectors were performed with CFUF54 detectors with a sensitivity of 10^{-5}.

Before the measurements, the discrimination curves of CFUF54 detectors were measured. Taking into account the absence of detector manufacturer recommendations concerning discrimination voltage value of the CFUF54 detectors, the discrimination voltages were set in accordance with number of registered neutrons, that should be in 10^2 times less than for next CFUF34 detectors. The discrimination voltage values for the detectors were chosen to be 0.64 V, 0.69 V and 0.63 V.

The results of k_{eff} and reactivity measurements with area ratio method with CFUF54 in compare with the CFUF34 detector measurement results are presented in Table 5. As it can be seen from the data, the results of CFUF34 and CFUF54 measurements agree well.

Table 5. **Experimental data on the effective neutron multiplication factor k_{eff} and reactivity ρ obtained by the area ratio method for detectors CFUF34 and CFUF54**

FAs	CFUF34		CFUF54	
	k_{eff}	ρ	k_{eff}	ρ
28	0.8395	−0.1911	0.8255	−0.2114
30	0.8603	−0.1624	0.8602	−0.1625
31	0.8732	−0.1453	0.8744	−0.1436
32	0.8857	−0.129	0.8848	−0.1302
33	0.8979	−0.1137	0.8976	−0.1141
34	0.9097	−0.0993	0.9099	−0.0991
35	0.9218	−0.0849	0.922	−0.0846
36	0.933	−0.0718	0.9328	−0.072
37	0.9428	−0.0607	0.9429	−0.0606

Using the flux-to-current ratio method. During the step-by-step loading of FAs into the SCA core the system reactivity control method by the ratio of neutron flux to current was tested [10]:

$$\rho_i = \rho_{\text{ref}} \frac{\Phi_{\text{ref}} / I_{\text{ref}}}{\Phi_i / I_i}, \tag{4}$$

where ρ_{ref} is the reactivity reference value measured by area ratio method, Φ_{ref} is the measured reference value of neutron flux, I_{ref} is the measured current reference value of the linear accelerator-driver, Φ_i is the measured current value of neutron flux, I_i is the measured current value of linear accelerator current.

To determine the SCA reactivity by the ratio of neutron flux to electron current, results of reactivity measurement by area ratio method with CFUF34 detectors were used as reference

Table 6. **Averaged on three measuring channels reactivity ρ measured with flux to current ratio method and calculated for different reference values of ρ_{ref}, Φ_{ref}, I_{ref}**

FAs	MCNP	Averaged ρ with area ratio	Averaged ρ with flux to current ratio values			
			i–1 ref	*i*–2 ref	*i*–3 ref	*i*–4 ref
28	−0.19402	−0.1911	−0.194	−0.199	−0.212	−0.214
30	−0.1627	−0.1624	−0.166	−0.169	−0.173	−0.184
31	−0.14448	−0.1453	−0.142	−0.145	−0.147	−0.151
32	−0.12773	−0.129	−0.131	−0.128	−0.131	−0.133
33	−0.11105	−0.1137	−0.110	−0.112	−0.109	−0.111
34	−0.09581	−0.0993	−0.102	−0.098	−0.100	−0.097
35	−0.08079	−0.0849	−0.090	−0.092	−0.089	−0.090
36	−0.06709	−0.0718	−0.068	−0.072	−0.073	−0.071
37	−0.05543	−0.0607	−0.061	−0.057	−0.061	−0.062

Table 7. **Efficiencies of the FAs in the core**

FAs	MCNP		Multiplication method			Area ratio method			Flux-to-current ratio method		
	ρ	Δρ	ρ	Δρ	%	ρ	Δρ	%	ρ	Δρ	%
31	−0.1445	1820	−0.1120	1000	−22.49	−0.1453	1710	0.55	−0.1420	2430	−1.73
32	−0.1277	1680	−0.0963	1570	−24.59	−0.1290	1630	1.02	−0.1313	1070	2.82
33	−0.1111	1660	−0.0827	1360	−25.56	−0.1137	1530	2.34	−0.1100	2130	−0.99
34	−0.0958	1530	−0.0717	1100	−25.16	−0.0993	1440	3.65	−0.1017	830	6.16
35	−0.0808	1500	−0.0620	970	−23.27	−0.0849	1440	5.07	−0.0873	1440	8.04
36	−0.0671	1370	−0.0533	870	−20.57	−0.0718	1310	7.00	−0.0690	1830	2.83
37	−0.0554	1170	−0.0423	1100	−23.65	−0.0607	1110	9.57	−0.0613	770	10.65

Note. Δρ is integral efficiency of one FA, pcm; % is deviation of experimental efficiency from calculated value $\left(\frac{\rho_{\text{exp}}}{\rho_{\text{MCNP}}} - 1\right) \cdot 100$, %.

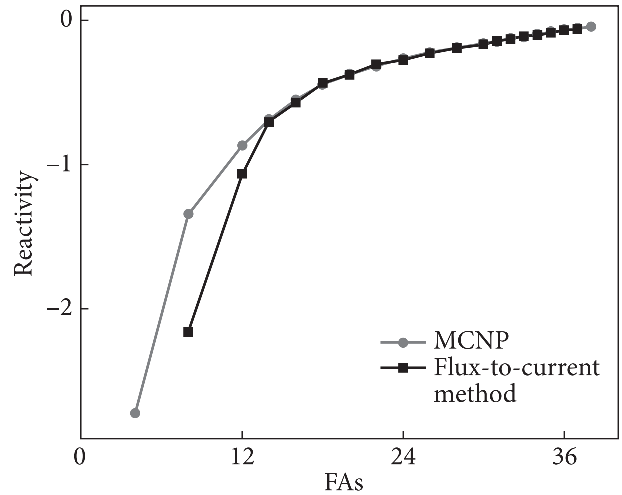

Fig. 10. Comparisons of the reactivity ρ of the core at each step of FAs loading measured with the flux-to-current ratio method and MCNP simulation results

values. At i-th step of FAs loading, the reactivity value at the previous (i–1)-th loading step was selected as reference value. The reactivity value at each loading step was determined as the average value of all three CFUF34 detectors.

The on-line reactivity monitoring method was tested starting with 28 FAs loaded into the plant core with CFUF54 detectors in the same manner.

Fig. 10 shows on-line reactivity monitoring results with CFUF34 detectors with neutron flux to electron beam current ratio starting from the 8 FAs loaded in the core.

On-line method of reactivity monitoring with neutron flux to electron beam current was tested starting from 28 loaded FAs up to 37 FAs loaded to the core when I_{ref} and Φ_{ref} were chosen after reactivity measurements with i–1, i–2, i–3 and i–4 FAs. Results are presented in Table 6. As can be seen, the measurement results are in good agreement with the direct reactivity measurements. To ensure sufficient statistical reliability of the method, the number of electrons that reached the target and the registered number of neutrons for all measurement sessions were used. Taking into account the measurement results, it can be stated that the on-line method of reactivity control by neutron flux to electron beam current can be used at the stage of pilot operation of the SNF "Neutron Source".

Table 7 shows the values of reactivity efficiency Δρ, obtained as a result of single loading of the FAs in the core. Based on the data analysis, it can be stated that the area ratio method and the flux-current method estimate the "weight" of one FA closer to the calculated value compared to the multiplication method.

On the base of simulation and experimental results obtained by different methods the value of k_{eff} increasing due to loading of 38th FA into the core can be estimated. Thus, the forthcoming value of k_{eff} is 0.950—0.952, and reactivity ρ after 38th FA loading is about −0.05. Such values provide safe loading of the 38th FA into the core.

Conclusions. In accordance with the program of physical start-up of SNF "Neutron Source" the following studies were performed:

- 37 FAs of WWR-M2 type were loaded into the SCA core;
- values of the effective neutron multiplication factor k_{eff} of the SCA core at all stages of FAs loading were obtained by multiplication method;
- values of reactivity ρ of the SCA core at all stages of FAs loading were obtained by area ratio method.

The measured neutron-physical characteristics of the SCA core are in satisfactory agreement with the modeling calculations performed with the MCNP 6.2 software code and the SCA design characteristics.

Pre-calculated corrections for neutron detector positions improve the agreement between the experimental results for k_{eff} and the calculated model values using the MCNP 6.2 program code.

The performed simulations of reactivity ρ (as well as effective neutron multiplication factor k_{eff}) of the SCA core using MCNP 6.2 software code and the values of these parameters measured by the area ratio method show the possibility to load 38 FAs into the SCA core with ensuring the nuclear safety criteria $k_{eff} \leq 0.98$.

Together with the studies mandatory for the physical start-up of SNF "Neutron Source", the following studies were performed to support the work at the next stage of the facility life cycle "pilot and industrious operation":

▪ method of on-line monitoring of reactivity ρ of SCA core by measured neutron flux to electron current ratio was tested and the possibility of using this method at the next stage of the facility life cycle "pilot and industrious operation" was shown;

▪ at final stages of FAs loading into the SCA core (starting from 28 FAs) CFUF54 detectors with neutron registration efficiency 10^{-5} were also used, and the results of reactivity ρ measurements by CFUF54 detectors are in satisfactory agreement with CFUF34 detectors.

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ДОСЛІДЖЕННЯ НЕЙТРОННО-ФІЗИЧНИХ ХАРАКТЕРИСТИК ЯДЕРНОЇ ПІДКРИТИЧНОЇ УСТАНОВКИ "ДЖЕРЕЛО НЕЙТРОНІВ" ННЦ ХФТІ В ПРОЦЕСІ ФІЗИЧНОГО ПУСКУ

Національний науковий центр "Харківський фізико-технічний інститут" спільно з Аргонською національною лабораторією розробив, спроєктував і побудував ядерну підкритичну установку "Джерело нейтронів, засноване на підкритичній збірці, що керується лінійним прискорювачем електронів". У статті наведено основні результати, одержані під час фізичного пуску установки, відповідною програмою якого було передбачено поетапне завантаження тепловидільних збірок до активної зони підкритичної збірки з подальшим вимірюванням її нейтронно-фізичних характеристик. Загалом до активної зони підкритичної збірки завантажено 37 тепловидільних збірок типу ВВР-М2. Після кожного кроку завантаження було виміряно значення ефективного коефіцієнта розмноження нейтронів k_{eff} та реактивності ρ підкритичної збірки методами зворотного множення і відношення площ. Додатково апробовано метод моніторингу реактивності ρ підкритичної збірки за відношенням нейтронного потоку до електронного струму. Дослідження виконано під час роботи прискорювача з енергією електронного пучка 100 МеВ, тривалістю електронного імпульсу 2,7 мкс, частотою наповнення імпульсу 20 Гц і імпульсним струмом пучка ≤ 40 мА. Експериментально визначені характеристики активної зони підкритичної збірки порівняно з модельними розрахунками, виконаними за допомогою коду MCNP 6.2 та бібліотеки ядерних даних ENDF/B-VII.0. Одержані результати проаналізовано з точки зору забезпечення ядерної безпеки на наступному етапі введення установки в експлуатацію — її дослідно-промислового використання.

Ключові слова: *ядерна підкритична установка, джерело нейтронів, фізичний пуск, ефективний коефіцієнт розмноження нейтронів, реактивність.*