Neutronics of YALINA-Booster Subcritical Assembly for ADS Studies

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Abstract. The minimization and the elimination policy of highly enriched uranium (HEU) use has been an important part of the international non-proliferation activities for many years. This paper examines the Accelerator Driven Systems (ADS) performance changes due to the reduction of the uranium enrichment of the utilized nuclear fuels. The changes of the YALINA-Booster neutronics parameters resulting from the replacement of the 90% enriched metallic uranium fuel by 36% enriched uranium oxide fuel in the inner part of the fast zone have been investigated.

1. Introduction

Driven subcritical systems by spallation neutron sources are recently considered for power production and transmutation of radiotoxic isotopes from nuclear power plants [1]. One of the most important issues in starting and operating these ADS is reactivity control in spite of its safe behavior because it cannot reach a critical state [1]. The YALINA facility has been constructed to study the neutronics behavior of these systems including the kinetics performance and the transmutation of radioactive waste [2, 3]. It consists of two subcritical assemblies YALINA-Booster and YALINA-Thermal driven by high-intensity neutron generator. The facility is equipped with different experimental capabilities and support systems.

Monitoring the system subcriticality during operation is a vital issue and the main question is how it should be performed [1]. The experimental and analytical investigations for monitoring the subcriticality level during the fuel loading and start up, as well as the transmutation rates of the long-lived radioactive nuclides, have been started with the use of the original configuration of YALINA-Booster assembly. The original configuration has metallic uranium with 90% enrichment and uranium oxide with 36% enrichment in the booster zone and uranium oxide with 10% enrichment in the thermal zone [4]. These studies have been continued with the new configuration of YALINA-Booster, which replaces the 90% enriched fuel in the inner part of fast zone with uranium oxide with 36% enrichment. The results from the two configurations are presented and compared in this paper.

2. YALINA-Booster Design and Parameters

The YALINA-Booster subcritical assembly has been constructed at the Joint Institute for Power and Nuclear Research – Sosny (JIPNR), National Academy of Sciences of Belarus shown in *FIG. 1*. It is a zero power subcritical facility driven by external neutron sources. It is designed to have fast and thermal neutron spectra in one configuration and to achieve the highest possible neutron flux density [2-4].

It operates with $k_{eff} < 0.98$ under all conditions for safety considerations. The design and the material content of the assembly eliminate all the possibility for k_{eff} to exceed this specified value. Hypothetical accidents conditions during the fuel loading, operation, and maintenance have been carefully analyzed and documented in the safety evaluation section of the Facility Project Report. The subcritical assembly is driven by an external neutron source generated from a deuteron accelerator with deuterium or tritium target, or ^{252}Cf spontaneous fission source. The original YALINA-Booster configuration has metallic uranium fuel with 90% enrichment in the inner fast zone while the new configuration replaces this fuel with uranium oxide fuel with 36% enrichment. The fast zone of the new configuration is loaded by 695 36%-enrichment uranium oxide fuel rods. In order to increase k_{eff} to its original value, extra 44 uranium oxide fuel rods with 10% enrichment were loaded into the thermal zone of the assembly. The interface between the fast and thermal zones, which provides a one-directional coupling between the two zones, remains unchanged as will as the reflector zone and the experimental channels as shown in *FIG. 1.*

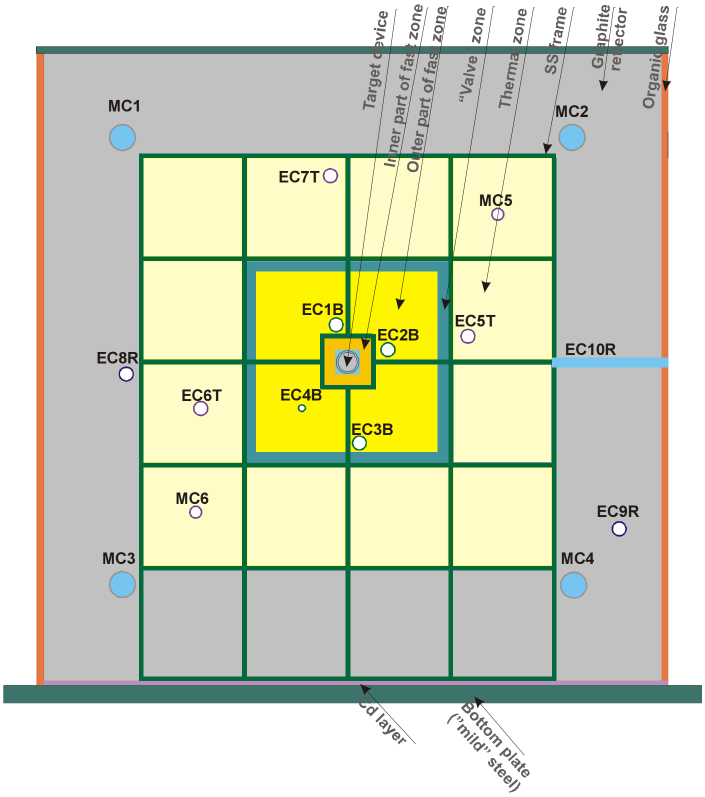

FIG 1. Cross section view of YALINA-Booster assembly displaying EC1B-EC4B experimental channels of the fast zone; EC5T-EC7T experimental channels of the thermal zone; EC8R-EC10R experimental channels of the reflector, MC5 and MC6 measuring channels of the thermal zone; and MC1-MC4 measuring channels of the reflector.

3. Measuring Instruments and Methods

The instruments used in the YALINA-Booster experimental campaign consists of ^{3}He-detectors (CANBERRA type) with different sizes, fission chambers, time analyzer, and dedicated data acquisition system. The fission chambers have different sizes and sensitivities to measure fission rate distributions in experimental channels of the fast and thermal zones. [2]. Pulsed Neutron Source (PNS) methods have been utilized to measure the neutron multiplication factor.

4. Reactivity measurements during the fuel loading and start up

During the fuel loading and the start up of YALINA-Booster assembly, a special emphasis was placed on the subcriticality level measurement by different experimental methods and techniques. The first set of the experimental data was obtained from the original YALINA-Booster configuration to demonstrate the applicability of the PNS area method for reactivity measurements. This approach defines number of fuel rods in thermal zone of the assembly to achieve the desired reactivity. In all the measurements, the neutron detectors were positioned in the fast and the thermal zones of the assembly. The second set of experimental data has been obtained from the new YALINA-Booster configuration. In this configuration, the 90% enriched metallic uranium fuel was replaced with 36% enriched uranium oxide fuel and extra 10% enriched uranium oxide fuel rods were added to the thermal zone.

FIG. 2 shows the change of counting rates from small size ^{3}He-detectors located in MC5 and MC6 measurement channels as a function of time during the loading of the 36% fuel rods in the inner part of the fast zone. The green line represents the starting point for loading the fuels in the inner part of the fast zone. At the starting point the assembly has the 36% enriched uranium oxide loaded in the outer part of the fast zone. The interface and the thermal zones of the original configuration were kept without any change during the loading of the inner part of the fast zone.

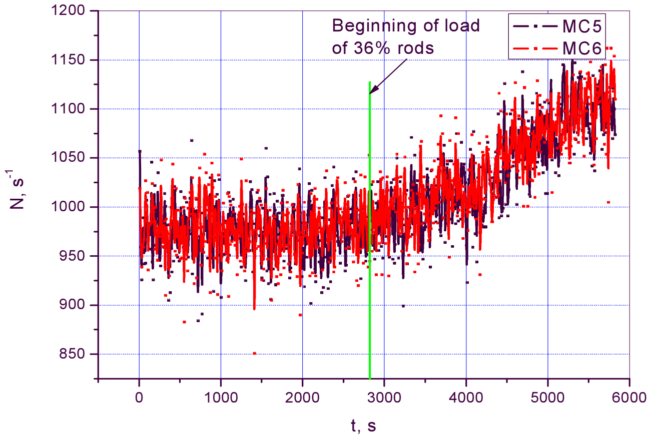

FIG. 2 ^{3}He detectors counting rates as a function of time in the MC5 and MC6 measurement channels of the thermal zone during the loading of the 36% enriched uranium oxide fuel in the inner part of the fast zone.

At the end of the loading process of the inner part of the fast zone, the counting rate increased slightly as shown in *FIG 2*. Such small change indicates that the inner part of fast zone has a small contribution to the total reactivity of the assembly. After the loading of the inner part of the fast zone was completed, extra EK-10 fuel rods was loaded in the thermal zone to achieve the desired reactivity. FIG 3 shows the reciprocal of the counting rates as a function of the total number of the fuel rods in the thermal zone. The obtained counting rates from the MC5 and MC6 measurement channels are similar as shown in *FIG. 3*.

5. PNS measurements

PNS experiments were performed with ^{3}He detectors and a fast data acquisition system. The ^{3}He detector was placed at the center of the EC5T or EC6T experimental channel. At these locations, the counting rates are high, which minimize the statistical errors in the experimental data. The area method used the experimental data to obtain the reactivity of the subcritical assembly. The delayed neutron fraction was obtained from MCNP calculation. The effective neutron multiplication factor of the assembly was calculated from the following equation using the experimental reactivity value and the calculated delayed neutron fraction.

$$k_{eff} = \frac{1}{1 - \left[\frac{\rho}{\beta_{eff}}\right]^{\exp} \beta_{eff}^{MCNP}}.$$

The effective neutron multiplication factors were obtained by the PNS method during the loading of the EK-10 fuel rods in the thermal zone with pulsed D-T neutron source and ^{3}He detectors located in EC5T or EC6T experimental channels as shown in *Fig.4*. The results from the two channels show an excellent agreement.

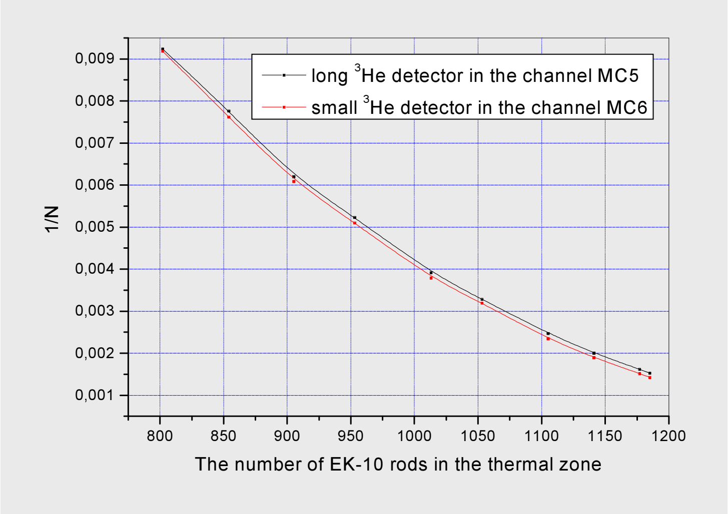

FIG. 3. The reciprocal of the counting rates from MC5 MC6 measurement channels as a function of the number of EK-10 fuel rods in the thermal zone after completing the fuel loading of the fast zone.

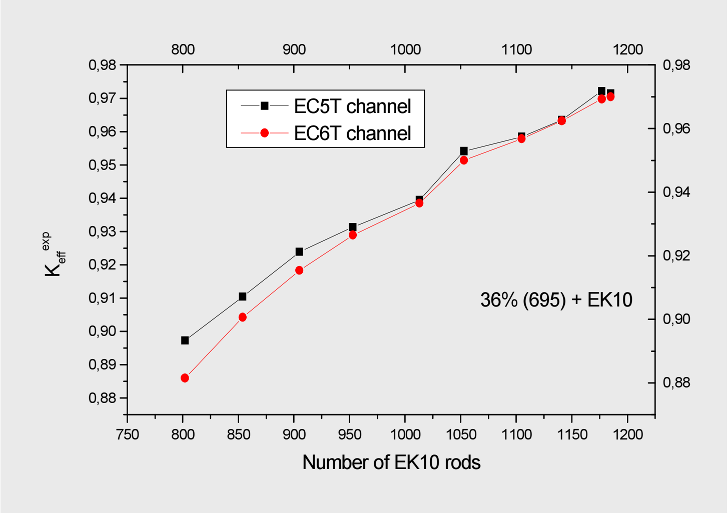

FIG. 4. Neutron multiplication factor measured by ^{3}He detectors in experimental channels EC5T and EC6T versus number of EK-10 fuel rods loaded into thermal zone.

Extra 44 EK-10 fuel rods are required in the thermal zone of the new configuration for the effective multiplication factor ~0.975. In the new configuration, the total number of fuel rods in the fast zone with 36% enriched uranium oxide is 695 and the total number of EK-10 fuel rods in thermal zone is 1185.

The effective neutron multiplication factor of the new configuration of YALINA-Booster assembly is 0.971 (ρ_{exp} = 3.94$ and β_{eff} = 0.00765) using the area method and the corresponding calculated value with MCNP is 0.973. No spatial correction was applied to the experimental values.

6. Time dependent reaction rate measuremnts

The counting rate as function of time due to 5 µs D-T neutron pulse from the KHT-31 fission chamber and the small size ^{3}He detector located in the experimental channels EC1B-EC3B of fast zone are shown in *Fig. 6*. Similar results from the experimental channels of the thermal zone and the reflector are shown in *FIG. 7* due to 10 µs D-D neutron pulse.

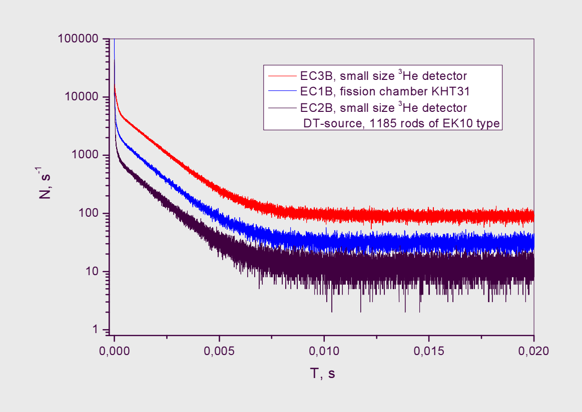

FIG. 6. Counting rates in the experimental channels of the fast zone as a function of time due to 5 µs D-T neutron pulse measured with the KHT-31 fission chamber and the small-size ^{3}He detector.

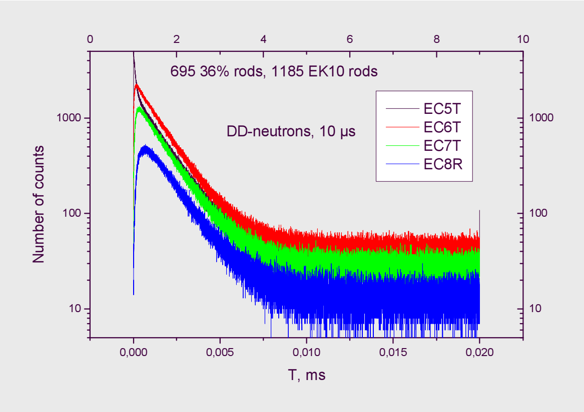

FIG. 7. Counting rates in the experimental channels of the thermal zone and the reflector as a function of time due to 10 µs D-D neutron pulse measured with the KHT-31 fission chamber and the small-size ^{3}He detector.

7. Neutronics characteristics of the original and the new YALINA-Booster configurations

The neutronics characteristics of the two YALINA-Booster configurations have been determined. The effective neutron multiplication factors of the two configurations as a function of the number of fuel rods loaded into thermal zone are shown *FIG. 8*. The new configuration utilized more fuel rods in the thermal zone to achieve the same effective neutron multiplication of the original configuration.

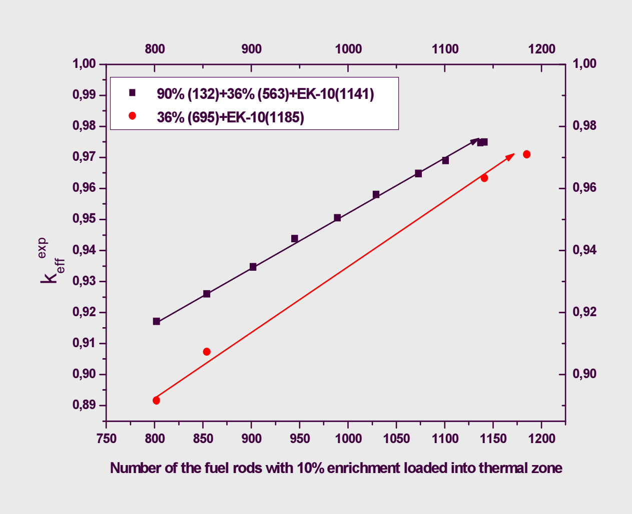

FIG. 8. The effective neutron multiplication factors as a function of the number of EK-10 fuel rods loaded into thermal zone of the original and the new configurations of YALINA-Booster.

FIGs 9 and 10 show the small-size ^{3}He detector counting rate along the EC3B and EC5T experimental channels from the original and the new configurations of YALINA-Booster. The comparison of the cadmium ratios along the experimental channels EC1B and EC2B is displayed in *FIG. 11*. The replacement of the 90% enriched metallic uranium fuel of the inner part of the fast zone leads to softens the neutron spectrum in the experimental channel EC1B and it has no impact on the spectra in the EC2B and EC3B channels.

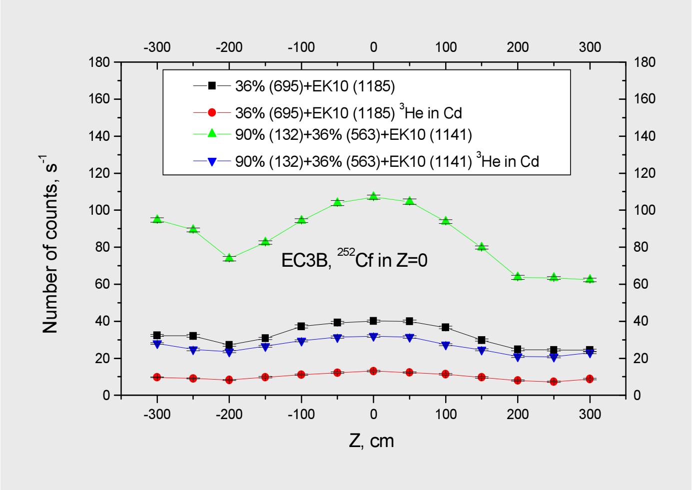

FIG. 9. The ^{3}He detector counting rate along the EC3B experimental channel from the two configurations of YALINA-Booster.

8. Comparison of the “reference” YALINA-Booster configuration performance with that of a new configuration. MCNP calculation

The results of MCNP simulation for calculating the effective neutron multiplication factor as a function of the ^{235}U mass for the two configurations of YALINA Booster are shown in *FIG. 12*. The new configuration uses more ^{235}U to get the same neutronics performance, which can be changed by optimizing the new configuration.

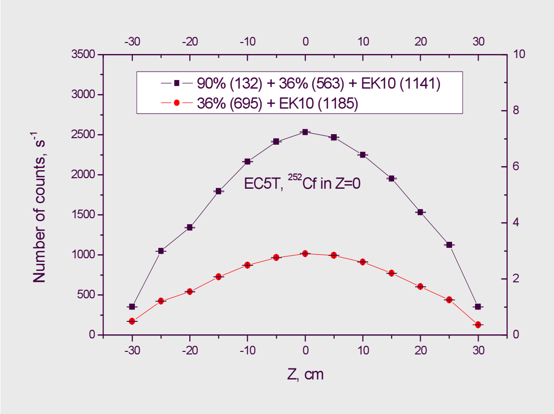

FIG. 10. The ^{3}He detector counting rate along the EC5T experimental channel from the two configurations of YALINA-Booster.

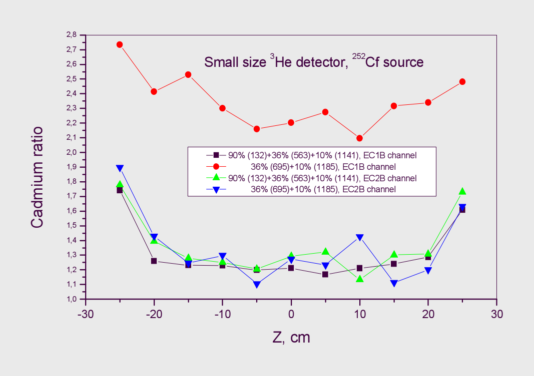

FIG. 11. The cadmium ratios along the EC1B and EC2B experimental channels from the two configurations of YALINA-Booster.

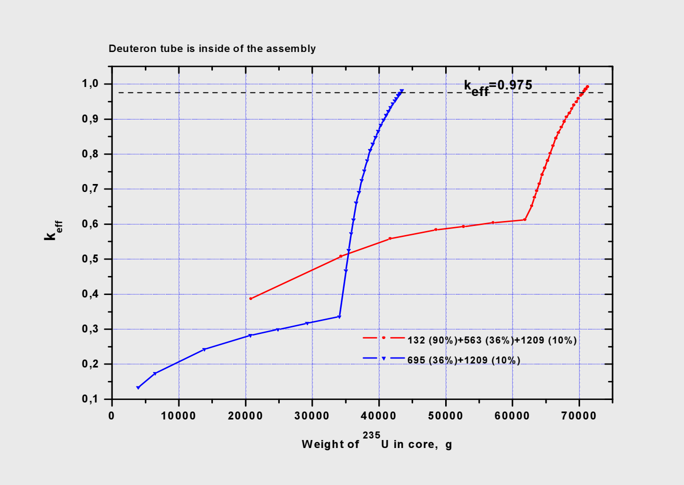

FIG. 12. The effective neutron multiplication factors as a function of the ^{235}U mass loaded for the two configurations of YALINA-Booster.

9. Conclusions

The YALINA-Booster assembly is designed for performing ADS experimental studies. The experimental data are used to benchmark and validate methods and computer codes for designing and licensing ADS by external neutron sources. YALINA-Booster experiments performed during the conversion of the inner part of the fast zone to use nuclear fuel with reduced uranium enrichment reached the following conclusions:

- The reaction rate measurements in the different experimental channels performed during the fuel loading confirmed the validity of the selected procedure to load and start up the YALINA-Booster facility.
- The experimental results obtained by the use of PNS area method improves as the effective multiplication factor exceeds 0.8. The delayed neutron fraction value is used based on calculations but it needs experimental verification.
- The discrepancy between the experimental (PNS method) and calculated effective multiplication factor is less than 0.5% without eliminating the spatial effects.
- The kinetic parameters (neutron generation time, effective fraction of delayed neutrons, etc.) did not change and their values are defined by the thermal zone.
- Replacement of the 90% enriched metallic uranium fuel of the inner part of the fast zone by 36 % enriched uranium oxide fuel reduces the contribution of fast zone to the total reactivity of the assembly, softening the neutron spectrum in the inner part of the fast zone. The neutron spectrum of the thermal zone remains unchanged.

Acknowledgement

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