M&C 2017 - International Conference on Mathematics & Computational Methods Applied to Nuclear Science & Engineering, Jeju, Korea, April 16-20, 2017, on USB (2017)

Benchmarks of Subcriticality in Accelerator-Driven System at Kyoto University Critical Assembly

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Abstract - *Basic research on the accelerator-driven system is conducted with the combined use of ^{235}U-loaded core (the Kyoto University Critical Assembly) and the accelerators (100 MeV protons and 14 MeV neutrons). The results of experimental subcriticality are presented with a wide range of subcriticality level between near critical and 10000 pcm, as obtained by the measurement methods.*

I. INTRODUCTION

The experimental studies on the accelerator-driven system (ADS) are being conducted for the basic research of analyses of kinetic parameters with the combined use of ^{235}U-loaded core at the Kyoto University Critical Assembly (KUCA) and the fixed-field alternating gradient (FFAG; 100 MeV protons and heavy metal target) accelerator. The ADS experiments with spallation neutrons (ADS-P) [1], which are obtained by the combination of 100 MeV protons and heavy metal target, were carried out to investigate the neutronic characteristics of ADS, and the kinetic parameters were accurately analyzed through the measurements and the Monte Carlo simulations. In previous studies [2]-[4], neutronics of ADS had been experimentally examined by combining the KUCA core and 14 MeV neutrons generated by the deuterium-tritium (D-T) reactions, in order to confirm the measurement methodology of subcriticality. Focusing on actual ADS experimental facilities, measurement of kinetic parameters was conducted in ^{235}U-fueled core for investigating the characteristics [5] of lead-bismuth (Pb-Bi) target and the effects [6] of neutron spectrum made locally by Pb-Bi zone, with the spallation neutrons (100 MeV protons and Pb-Bi target), although Pb-Bi is selected as the materials of coolant in fast neutron spectrum core and target for generation of spallation neutrons. In the thorium-232 (^{232}Th)-loaded ADS experiments [7]-[8] with 14 MeV (ADS-DT) or spallation neutrons, characteristics of kinetic parameters were investigated by varying neutron spectrum under a deep subcriticality level. Through a series of ADS experiments at KUCA, experimental benchmarks of subcriticality were provided as follows: ^{235}U-loaded ADS with 14 MeV neutrons [9]; ^{235}U-fueled and Pb-Bi-zoned ADS with spallation neutrons [6]; ^{232}Th-loaded ADS with 14 MeV or spallation neutrons [10]. In this paper, several experimental results of subcriticality measurement were presented with a wide range of subcriticality level between near critical and 10000 pcm, as obtained by the pulsed neutron source (PNS) method, the Feynman-α method and the neutron source multiplication (NSM) method.

II. 235-U-FUELED ADS-DT EXPERIMENTS

The ADS experiments with 14 MeV neutrons were carried out in the A-core (Fig. 1) comprising a highly-enriched uranium (HEU) fuel and a polyethylene moderator. The fuel assembly "F" (3/8"P36EU) is composed of 36 unit cells, and upper and lower polyethylene blocks are about 500 and 630 mm long, respectively, in an aluminum (Al) sheath 54×54×1524 mm. Numeral "12" (3/8"P12EU) corresponds to the number of fuel plates in the partial fuel assembly used for reaching critical mass.

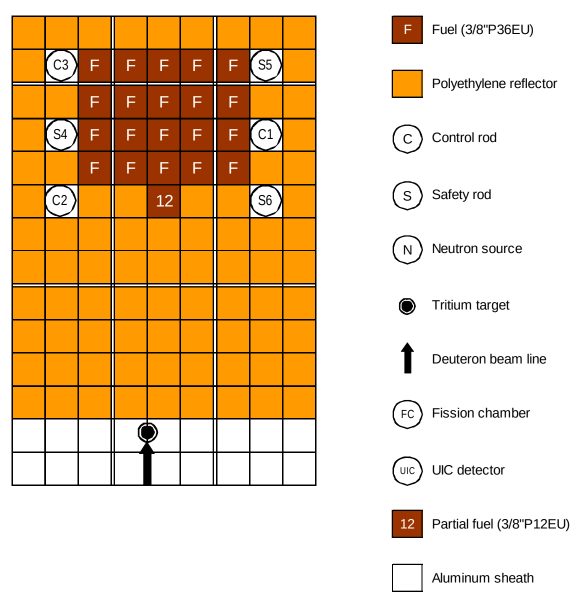

Fig. 1. Top view of core configuration in ^{235}U-loaded (A3/8"P36EU(3)) ADS-DT experiments (Ref. [3]).

Subcriticality was attained by full insertion of control and safety rods, and the substitution of fuel assemblies for polyethylene ones. At KUCA, the subcriticality was deduced experimentally with the combination of the worth of control (C1, C2 and C3) and safety (S4, S5 and S6) rods by the rod drop method and its calibration curve by the positive period method. Furthermore, in case of fuel substitution, the subcriticality was numerically obtained by the MCNP6.1 [13] code with the JENDL-4.0 [14] library, because the reactivities of control and safety rods were varied by the substitution of fuel assembly rods for polyethylene ones. In ^{235}U-loaded ADS experiments with 14 MeV neutrons, subcriticality was obtained by the PNS method, the Feynman-α method and the NSM method, ranging between 1000 and 10000 pcm.

III. 235-U-FUELED ADS-P EXPERIMENTS

For the Pb-Bi target studies [5], influences of different external neutron source on core characteristics were carefully monitored: with the use of tungsten (W), solid two-layer (tungsten-beryllium: W-Be) and Pb-Bi (44.5% Pb and 55.5% Bi) targets (Core target location; Fig. 2), subcriticality was different from those with the W target (reference target at KUCA), ranging between 1360 and 4902 pcm. Here, the high-energy neutrons (Fig. 3) generated by the neutron yield at the location of the target were attained by the injection of 100 MeV protons onto these targets. Also, kinetic parameters of the prompt neutron decay constant and subcriticality were experimentally estimated, when the external neutron source was varied by the kind of solid target used. As shown in Table I, the BF_3 #1 detector revealed good accuracy of subcriticality. From these results, the actual influence of the source target emphasized the importance of the experimental analyses of kinetic parameters, such as the subcriticality.

Table I. Experimental results in subcriticality [pcm] by the PNS method (Ref. [5])

Target	BF_3 #1	BF_3 #2	Optical fiber
W	4944 ± 78	6386 ± 101	6228 ± 99
W-Be	5004 ± 83	7050 ± 114	4929 ± 77
Pb-Bi	4903 ± 77	6356 ± 92	4912 ± 74

(Reference: ρ_{MCNP} = 4902 pcm; β_{eff} = 807 pcm; Λ = 3.050E-05 s)

The ADS experiments (Fig. 4) were carried out in the ^{235}U fueled and Pb-Bi-zoned core [6], under the subcritical state ranging between 1160 and 11556 pcm. Also, measurement of the prompt neutron decay constant and the subcriticality was conducted by the PNS method and the Feynman-α method with the use of optical fiber detectors. Numerical calculations were performed by MCNP6.1 with JENDL-4.0 for transport and JENDL/HE-2007 [15] for high-energy protons and spallation neutrons.

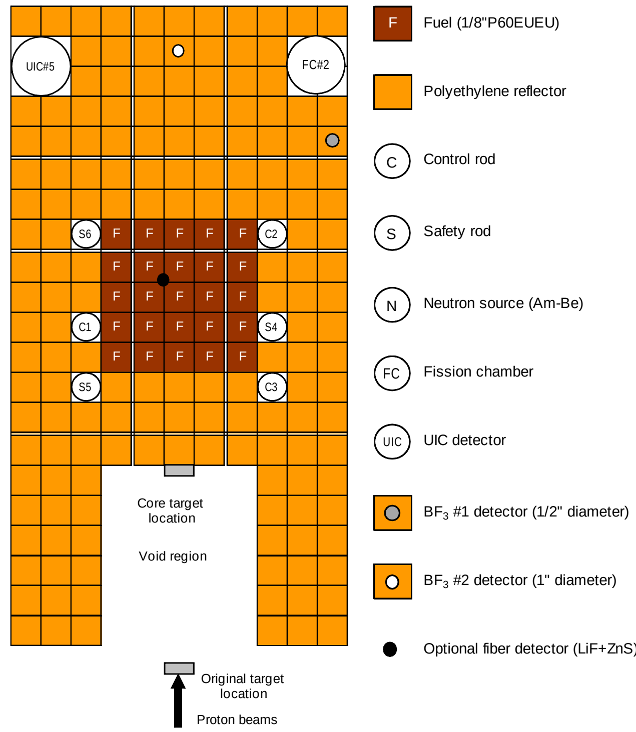

Fig. 2. Top view of ^{235}U-loaded (A1/8"P60EUEU(3)) core in ADS-P experiments (Ref. [5]).

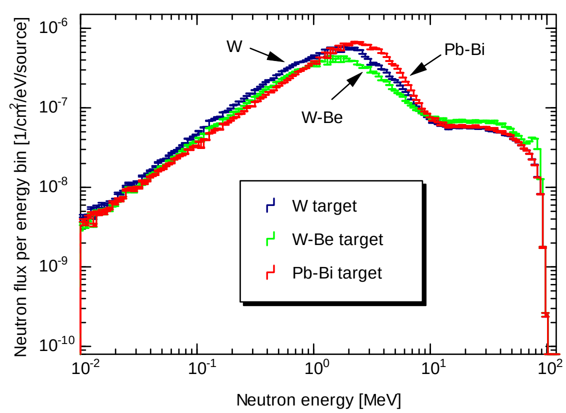

Fig. 3. Comparison between neutron spectra with the use of W, W-Be and Pb-Bi targets (Ref. [5]).

As shown in Table II, the measured subcriticality by the Feynman-α method showed good agreement with the calculated one, with an error around 10% in the C/E (calculation/experiment) value, in the subcriticality ranging between 1160 and 4812 pcm, at the locations of Fibers #1 and #2. Additionally, in a comparison between Fibers #1 and #2, the spatial effects on subcriticality by the Feynman-α method were found to be attributable to placing the fiber detectors at different locations. At the locations of Fibers #1 and #2, with subcriticality ranging between 9895 and 11556 pcm, the deeper the subcriticality, the less accurate were the experimental results of measurements by the Feynman-α methods. The reason for this tendency was considered to be the effect of spallation neutrons on the neutron flux becoming greater with the increased subcriticality.

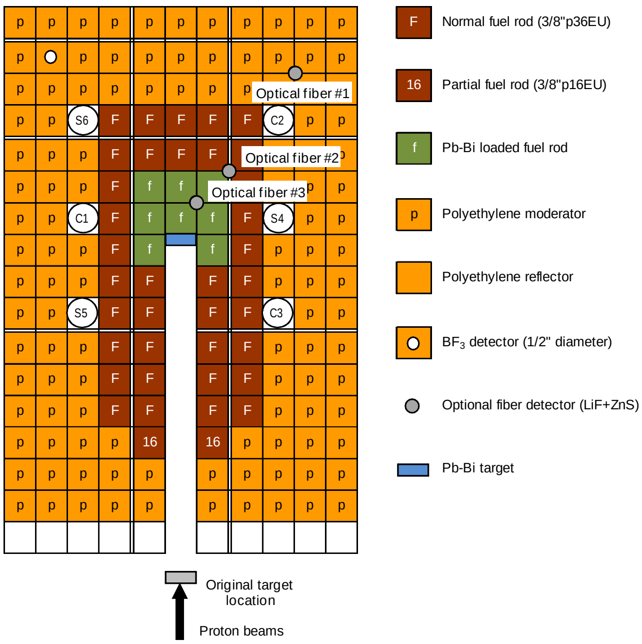

Fig. 4. Top view of ^{235}U fueled and Pb-Bi-zoned core in ADS-P experiments (Ref. [6]).

Table II. Experimental results in subcriticality [pcm] by the Feynman-α method (Ref. [6])

ρ [pcm]	Fiber #1	Fiber #2	Fiber #3
1160±5	1491±57 (0.87±0.03)	1283±36 (0.90±0.03)	2445±105 (0.47±0.02)
1684±6	2024±28 (0.83±0.01)	1814±24 (0.93±0.01)	3250±41 (0.52±0.01)
2483±6	2881±15 (0.86±0.01)	2677±11 (0.93±0.01)	4203±29 (0.59±0.01)
4812±6	4336±38 (1.11±0.01)	4384±35 (1.10±0.01)	5740±77 (0.84±0.01)
9895±6	8087±61 (1.22±0.01)	8316±50 (1.19±0.01)	10110±113 (0.98±0.01)
11556±6	9633±88 (1.20±0.01)	10175±68 (1.14±0.01)	12096±150 (0.96±0.01)

Bracket means the C/E (calculation/experiment) value.

As a consequence, the discrepancy between the experiments and the calculations indentified as the limitation of the applicability of the measurement method to an increased subcriticality level of over or about 10000 pcm.

For Fiber #3, a large influence on spallation neutrons was observed, although the Feynman-α method showed very good agreement in 9895 and 11556 pcm. Neutron noise data are assumed to be dominant over the Poisson distribution, demonstrating that the effect of spallation neutrons becomes stronger with the deep subcriticality.

IV. 232-TH-LOADED ADS-DT AND ADS–P EXPERIMENTS

In the ^{232}Th-loaded ADS experiments (Fig. 5; 14 MeV neutrons), subcriticality in dollar units was deduced by the PNS method with the use of prompt and delayed neutron components shown in Fig. 6, and experimentally evaluated according to the kind of external neutron source (14 MeV and spallation neutrons) and the location of neutron detection shown in Table III.

As is well known, these results revealed subcriticality dependence on both the kind of external neutron source (neutron spectrum) and the location of neutron detection (spatial effects), although the value of subcriticality was theoretically unchanged, regardless of the external neutron source and the location of the detector. Nonetheless, special attention was paid to the conversion coefficient (β_{eff}) of subcriticality in dollar units into one in pcm units, and β_{eff} was estimated to be 849 pcm by the diffusion-based calculations (SRAC-CITATION) in 3-dimentional and 107-energy-group. Consequently, the experimental results showed that the subcriticality in pcm units for 14 MeV neutrons was different from that for spallation neutrons; remarkably, the discrepancy was also observed between the experiments and calculations shown in Table IV.

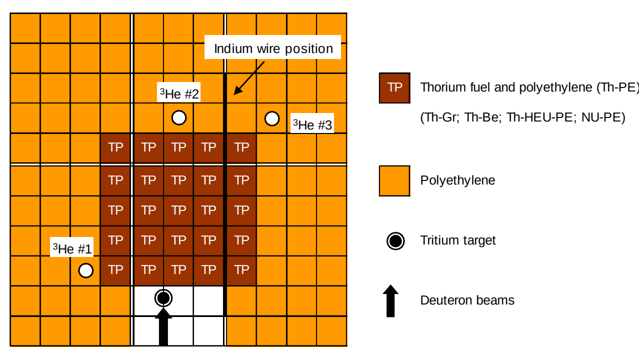

Fig. 5. Top view of ^{232}Th-loaded ADS-DT core (Th-HEU-PE) (Ref. [7]).

Emphasis was placed on the deduction of subcriticality in pcm units to obtain the conversion coefficient according to the kind of external neutron source, since the neutron spectrum of the external neutron source has mostly varied by bombarding at the target and differently affected the neutron flux distribution. Furthermore, objective neutron flux distributions in the experiments are almost different from neutron flux distribution in fundamental mode by the calculations, because the neutron flux distributions in fundamental mode by the eigenvalue calculations are not assumed to be in the existence of external neutron source.

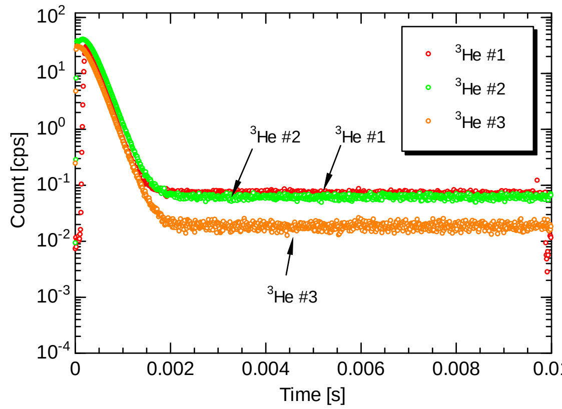

Fig. 6. Measured prompt and delayed neutron behaviors obtained from ^{232}Th-loaded ADS-DT experiments (Th-HEU-PE) (Ref. [7]).

Table III. Measured results in subcriticality [$] by the PNS method (Ref. [7])

Source	^{3}He #1	^{3}He #2	^{3}He #3
14 MeV neutrons	12.36 ± 0.51	29.70 ± 0.03	61.28 ± 0.09
Spallation neutrons	31.19 ± 0.15	26.00 ± 0.10	43.14 ± 0.24

Table IV. Measured and calculated results of deduced k_{eff} (Ref. [7])

Calculation (MCNP)	External neutron source	Experiment (^{3}He #3)
0.5876	14 MeV neutrons	0.6577
	Spallation neutrons	0.7319

In the ADS experiments, it is very important to evaluate numerically kinetic parameters, including the effective delayed neutron fraction, the prompt neutron generation time and the prompt neutron lifetime, in order to deduce the subcriticality by several measurement techniques under the existence of the external neutron source and to make a comparison between the experiments and calculations. Namely, in the ADS experiments, it could be desirable to evaluate the importance functions for obtaining the fundamental-mode kinetic parameters with external neutron source. Lying behind the above view is the assumption that the kinetic parameters could be necessarily evaluated by the fixed source problem, in cases of the ADS experiments with external neutron source. Moreover, the effect of the neutron spectrum at the target on the deduction of subcriticality in pcm units could be satisfactorily estimated by the numerical simulations of β_{eff}: the numerical methodology of β_{eff} needs to be suggested in the fixed source problem.

V. CONCLUDING REMARKS

In the ADS experiments with 14 MeV or spallation neutrons, the measurement of kinetic parameters was conducted by both the PNS and Feynman-α methods, under subcriticality ranging between near critical and 11556 pcm. The results confirmed the validity of the prompt neutron decay constant and the subcriticality in dollar units through the deduction of kinetic parameters. Conventional research questions remained, however, regarding ADS experiments with both 14 MeV and spallation neutrons, as well as the spatial effects, neutron spectrum and subcriticality measurement methods. The experimental benchmarks of subcriticality obtained by ADS experiments are expected to play an important role in theoretical and numerical studies with respect to the spatial effects, neutron spectrum and subcriticality measurement methods. In further studies, the experimental benchmarks could be conducive to the numerical verification of subcriticality on-line monitoring, to the analysis of subcriticality uncertainty and to the deterministic approach to kinetic parameters.

ACKNOWLEDGMENTS

This work is supported under the project of *Basic Research for Nuclear Transmutation Techniques by Accelerator-Driven System*, a Special Research Program funded by Chubu Electric Power Co., Inc. The authors are grateful to all the staff at KUCA and to the FFAG accelerator group for their assistance during the experiments.

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