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Original Article

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 by combining ^{235}U-fueled and ^{232}Th-loaded cores in the Kyoto University Critical Assembly with the pulsed neutron generator (14 MeV neutrons) and the proton beam accelerator (100 MeV protons with a heavy metal target). The results of experimental subcriticality are presented with a wide range of subcriticality level between near critical and 10,000 pcm, as obtained by the pulsed neutron source method, the Feynman-α method, and the neutron source multiplication method.

1. Introduction

With the combined use of the uranium-235 (^{235}U)-fueled core at the Kyoto University Critical Assembly (KUCA) and the fixed-field alternating gradient (FFAG; 100 MeV protons) accelerator, experimental studies on accelerator-driven systems (ADS) are being conducted as basic research into kinetic parameters. ADS experiments with spallation neutrons (ADS-P) [1], which are obtained by combination of 100 MeV protons and a heavy metal target, were successfully carried out to investigate the neutron characteristics of ADS; the kinetic parameters were accurately analyzed through measurements and Monte Carlo simulations.

In previous studies [2–4], in order to confirm the measurement methodology of subcriticality, the neutronics of ADS was experimentally examined by combining the KUCA core and 14 MeV neutrons generated by deuterium–tritium (D–T) reactions. Focusing on actual ADS experimental facilities, measurement of kinetic parameters was interestingly conducted in the ^{235}U-fueled core to investigate the characteristics [5] of a lead–bismuth (Pb–Bi) target and the effects [6] of a neutron spectrum made locally by Pb–Bi zone, with the spallation neutrons (100 MeV protons and Pb–Bi target). It is currently planned at actual ADS experimental facilities for Pb–Bi to be used as a coolant material for a fast neutron spectrum core and a 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 studied by varying the neutron spectrum at levels under the deep subcriticality level.

Through a series of ADS experiments at KUCA, experimental benchmarks of subcriticality were provided for the following cores: ^{235}U-fueled ADS core with 14 MeV neutrons [9]; ^{235}U-fueled and Pb–Bi-zoned ADS core with spallation neutrons [6]; ^{232}Th-loaded ADS core with 14 MeV or spallation neutrons [10]. In this paper, several experimental subcriticality measurements results are presented, having a wide range of subcriticality levels between near critical and 10,000 pcm; results were obtained by the pulsed neutron source (PNS) method, the Feynman-α method, and the neutron source multiplication (NSM) method.

2. ^{235}U-fueled ADS-DT experiments

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 reflector. The fuel assembly "F" (3/8"P36EU) is composed of 36 unit cells; upper and lower polyethylene blocks are about 500 and 630 mm long, respectively, in an aluminum (Al) sheath (54 × 54 × 1,524 mm). Numeral "12" (3/8"P12EU)

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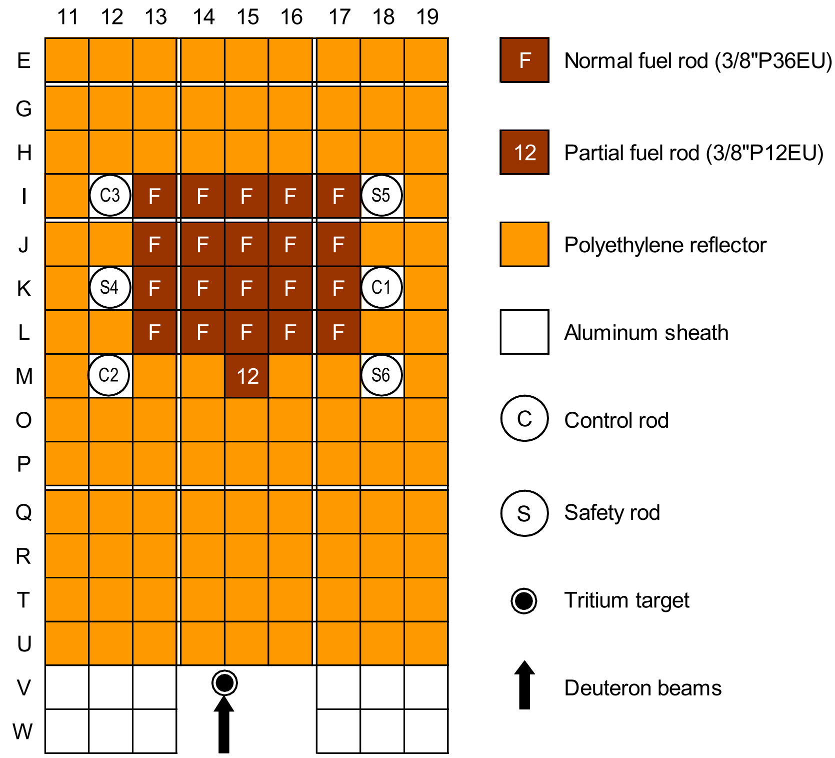

Fig. 1. Top view of ^{235}U-fueled core configuration (A3/8″P36EU(3)) in ADS-DT experiments [2,3,9]. ADS-DT, accelerator-driven system with deuterium and tritium.

corresponds to the number of fuel plates in the partial fuel assembly used to reach critical mass.

Subcriticality was attained by full insertion of control and safety rods, and with the substitution of fuel assemblies for polyethylene ones. At KUCA, using the rod drop method, subcriticality was deduced experimentally by a combination of the worth of the control (C1, C2, and C3) and safety (S4, S5, and S6) rods; the calibration curve was determined using the positive period method. Furthermore, in the case of fuel substitution, because the reactivities of the control and safety rods varied with the substitution of fuel assembly rods for polyethylene ones, subcriticality was numerically obtained using the MCNP6.1 [11] code with the JENDL-4.0 [12] library. In the ^{235}U-fueled ADS experiments with 14 MeV neutrons, subcriticality was obtained using the PNS method, the Feynman-α method, and the NSM method, showing values between 1,000 and 10,000 pcm. Detailed experimental results of subcriticality using the PNS method, the Feynman-α method, and the NSM method were provided in references [2,3,9].

3. ^{235}U-fueled ADS-P experiments

For the Pb–Bi target studies [5], the influences of different external neutron sources on the core characteristics were carefully monitored: with the use of tungsten (W; reference target in KUCA), solid two-layer [tungsten–beryllium (W–Be)], and Pb–Bi (44.5% Pb and 55.5% Bi) targets [location of core target (15, H) in Fig. 2], subcriticality was varied mainly by substitution of fuel rods for polyethylene ones, with values ranging between 1,360 and 4,902 pcm. Here, 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, the kinetic parameters of 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 1, the BF_3 #1 detector revealed fairly good accuracy of subcriticality by the PNS method, in the case of 4,902 pcm. From these results, the actual influence of the external neutron source (neutron spectrum) emphasized the importance of experimental analyses of kinetic parameters, such as the subcriticality, in addition to the detector position dependency.

ADS experiments (Fig. 4) were carried out in the ^{235}U-fueled and Pb–Bi-zoned core [6] under a subcritical state ranging between 1,160 and 11,556 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 [13] for high-energy protons and spallation neutrons. As shown in Table 2, the subcriticality measured with the Feynman-α method showed good agreement with the calculated one, with an error of about 10% in the C/E (calculation/experiment) value, in the subcriticality ranging between 1,160 and 4,812 pcm, at the locations of fibers #1 and #2. Additionally, in a comparison between fibers #1 and #2, the effects of detector position dependency on subcriticality, obtained by the Feynman-α method, were found to be attributable to placing the optical fiber detectors at different locations. At the locations of fibers #1 and #2, with subcriticality ranging between 9,895 and 11,556 pcm, the deeper the subcriticality was, the less accurate the experimental results were for the measurements by the Feynman-α method. The reason for this tendency was considered to be the effect of spallation neutrons on the neutron flux becoming larger with the deep subcriticality. As a consequence, the discrepancy between the experiments and the calculations was identified as a limitation of the applicability of the measurement method to a deep subcriticality level of about or over 10,000 pcm. For fiber #3, a large influence on spallation neutrons was observed, although the Feynman-α method showed very good agreement for subcriticalities of 9,895 and 11,556 pcm. This tendency was thought to

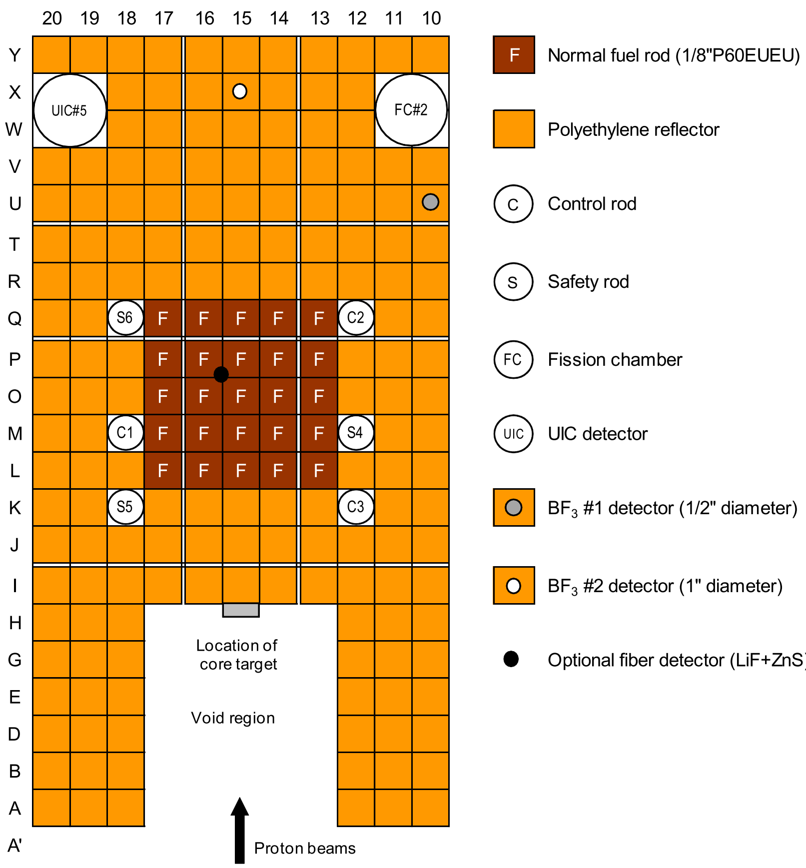

Fig. 2. Top view of ^{235}U-fueled core configuration (A1/8″P60EUEU(3))in ADS-P experiments [5]. ADS-P, accelerator-driven system with proton; BF_3, boron-trifluoride; UIC, uncompensated ionization chamber.

be caused by the fact that neutron noise data are assumed to be dominant over the Poisson distribution, demonstrating that the effect of spallation neutrons becomes stronger with deep subcriticality.

4. ^{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

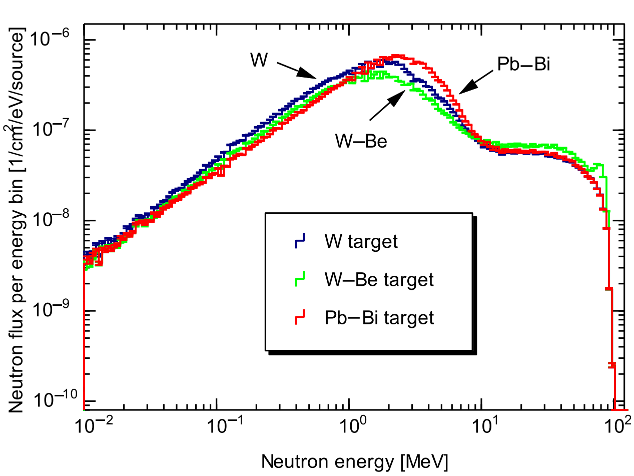

Fig. 3. Comparison between neutron spectra with the use of W, W–Be, and Pb–Bi targets in ADS-P experiments [5]. ADS-P, accelerator-driven system with proton; Pb–Bi, lead–bismuth; W, tungsten; W–Be, tungsten–beryllium.

Fig. 6. Subcriticality was then experimentally evaluated according to the kind of external neutron source (14 MeV and spallation neutrons) and the location of neutron detection, shown in Table 3. Detailed experimental results were shown in reference [10], when fuel components were varied with the combined use of Th, HEU, natural uranium (NU), polyethylene (PE), graphite (Gr), and beryllium (Be).

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), as shown in Table 3, although the value of subcriticality was theoretically unchanged regardless of external neutron source or location of the detector. Nonetheless, special attention was paid to the conversion coefficient (β_{eff}) used to convert subcriticality in dollar units into subcriticality in pcm units; using diffusion-based calculations (SRAC-CITATION [14]) in the three-dimensional and 107 energy group, β_{eff} was estimated to be 849 pcm. Consequently, the

Table 1
Results of subcriticality (pcm) measured using pulsed neutron source (PNS) method at locations of BF_3 #1 (10, U), BF_3 #2 (15, X), and optical fiber (16-15, O-P) shown in Fig. 2.

Target	BF_3 #1	BF_3 #2	Optical fiber
W	4,944 ± 78	6,386 ± 101	6,228 ± 99
W–Be	5,004 ± 83	7,050 ± 114	4,929 ± 77
Pb–Bi	4,903 ± 77	6,356 ± 92	4,912 ± 74

$\rho_{MCNP} = 4{,}902$ pcm; $\beta_{eff} = 807$ pcm; $\Lambda = 3.050 \times 10^{-5}$ s by MCNP6.1 with JENDL-4.0.
Note. From: "Neutron characteristics of solid targets in accelerator-driven system with 100 MeV protons at Kyoto University Critical Assembly," by C.H. Pyeon, H. Nakano, M. Yamanaka, T. Yagi, T. Misawa, 2015, *Nucl. Technol.*, *192*, p. 181–190. [5]. Copyright 2015, *American Nuclear Society*. With permission.

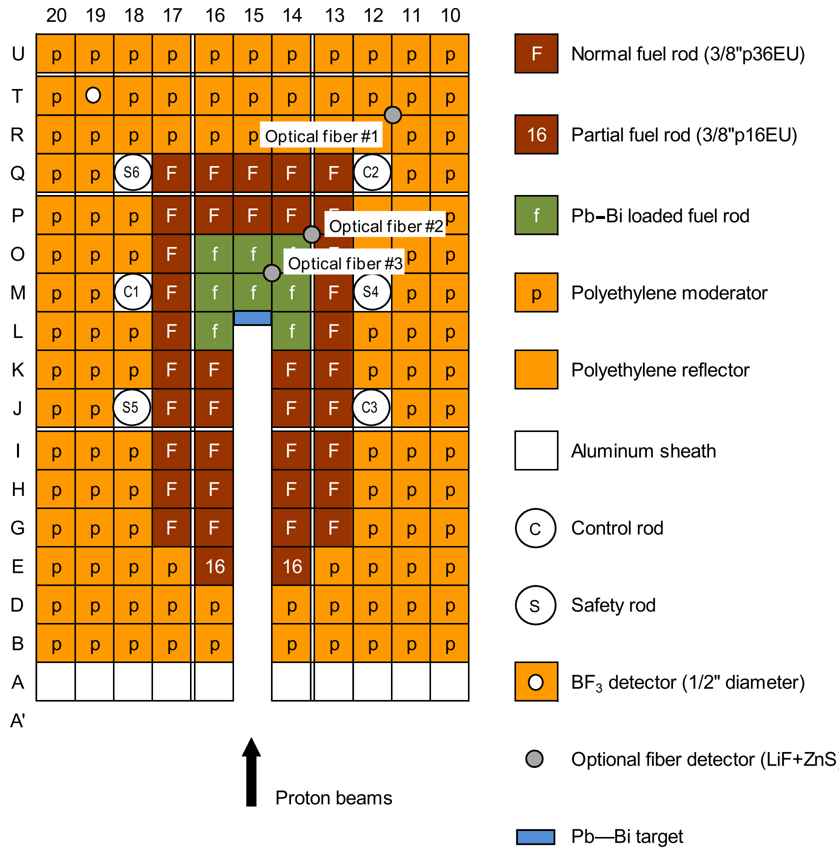

Fig. 4. Top vie– of [235]U-fueled and Pb–Bi-zoned core configuration in ADS-P experiments [6]. ADS-P, accelerator-driven system with proton; LiF, lithium-fluoride; Pb–Bi, lead–bismuth; ZnS, zinc sulfide.

Table 2
Comparison between subcriticalities (pcm) of reference and those obtained by Feynman-α method.

Reference	Fiber #1	Fiber #2	Fiber #3
1,160 ± 5	1,491 ± 57 (0.87 ± 0.03)	1,283 ± 36 (0.90 ± 0.03)	2,445 ± 105 (0.47 ± 0.02)
1,684 ± 6	2,024 ± 28 (0.83 ± 0.01)	1,814 ± 24 (0.93 ± 0.01)	3,250 ± 41 (0.52 ± 0.01)
2,483 ± 6	2,881 ± 15 (0.86 ± 0.01)	2,677 ± 11 (0.93 ± 0.01)	4,203 ± 29 (0.59 ± 0.01)
4,812 ± 6	4,336 ± 38 (1.11 ± 0.01)	4,384 ± 35 (1.10 ± 0.01)	5,740 ± 77 (0.84 ± 0.01)
9,895 ± 6	8,087 ± 61 (1.22 ± 0.01)	8,316 ± 50 (1.19 ± 0.01)	10,110 ± 113 (0.98 ± 0.01)
11,556 ± 6	9,633 ± 88 (1.20 ± 0.01)	10,175 ± 68 (1.14 ± 0.01)	12,096 ± 150 (0.96 ± 0.01)

Enclosed in brackets are the C/E (calculation/experiment) values.
Note. From: "Experimental benchmarks on kinetic parameters in accelerator-driven system with 100 MeV protons at Kyoto University Critical Assembly," by C.H. Pyeon, M. Yamanaka, T. Endo, W.F.G. van Rooijen, G. Chiba, 2017, *Ann. Nucl. Energy*, *105*, p. 346–354. Copyright 2017, *Elsevier*. With permission.

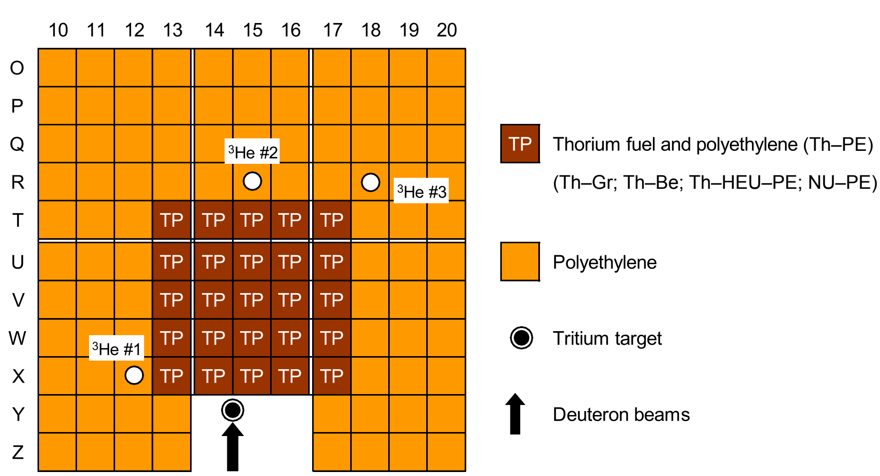

Fig. 5. Top view of [232]Th-loaded core configuration (Th–PE) in ADS-DT experiments [7, 10]. ADS-DT, accelerator-driven system with deuterium and tritium; [3]He, helium-3; NU–PE, natural uranium and polyethylene; PE, polyethylene; Th–Be, thorium and beryllium; Th–Gr, thorium and graphite; Th-HEU-PE, thorium and highly-enriched uranium.

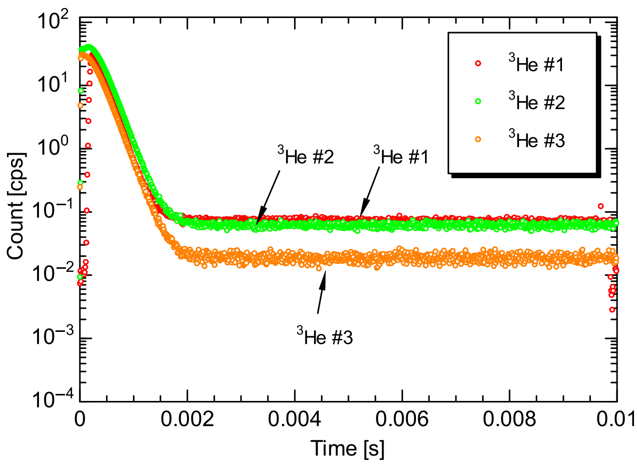

Fig. 6. Measured prompt and delayed neutron behaviors obtained from ^{232}Th-loaded ADS-DT experiments (Th-HEU-PE) [7]. ADS-DT, accelerator-driven system with deuterium and tritium; cps, counts per second; ^{3}He, helium-3; HEU, highly enriched uranium; PE, polyethylene.

Table 3
Results of subcriticality ($) measured using the pulsed neutron source (PNS) method.

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

Note. From "Mockup experiments on the thorium-loaded accelerator-driven system in the Kyoto University Critical Assembly," C.H. Pyeon, T. Yagi, K. Sukawa, Y. Yamaguchi, T. Misawa, 2014, *Nucl. Sci. Eng.*, *177*, p. 156–168. Copyright 2014, *American Nuclear Society*. With permission.

experimental results showed that the subcriticality in pcm units for 14 MeV neutrons was different from that for spallation neutrons; remarkably, this discrepancy was also observed between the experiments and the calculations, as shown in Table 4.

To obtain the conversion coefficient according to the kind of external neutron source, emphasis was placed on the deduction of subcriticality in pcm units, because the neutron spectrum of an external neutron source can vary considerably according to the bombarding of the target and the effects of neutron flux distribution. Furthermore, objective values of neutron flux distribution in experiments are almost always different from the neutron flux distribution in fundamental mode determined by calculations, because the neutron flux distributions in fundamental mode, found using eigenvalue calculations, do not assume the existence of an external neutron source.

To make a comparison between the ADS experiments and the calculations, and to deduce subcriticality via several measurement techniques under the existence of an external neutron source, it is very important to numerically evaluate the kinetic parameters, including the effective delayed neutron fraction, the prompt neutron generation time, and the prompt neutron lifetime. That is,

Table 4
Measured and calculated results for deduced k_{eff}.

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

Note. From "Mockup experiments on the thorium-loaded accelerator-driven system in the Kyoto University Critical Assembly," C.H. Pyeon, T. Yagi, K. Sukawa, Y. Yamaguchi, T. Misawa, 2014, *Nucl. Sci. Eng.*, *177*, p. 156–168. Copyright 2014, *American Nuclear Society*. With permission.

in the ADS experiments, it is desirable to evaluate the importance functions for obtaining the fundamental-mode kinetic parameters with an external neutron source. Lying behind the above view, in cases of ADS experiments with an external neutron source, is the assumption that the kinetic parameters can necessarily be evaluated using the fixed source problem. Moreover, the effect of the neutron spectrum at the target on the deduction of subcriticality in pcm units can be satisfactorily estimated by numerical simulations of β_{eff}: the numerical methodology of β_{eff} needs to be suggested in the fixed source problem.

5. Concluding remarks

In ADS experiments with 14 MeV and spallation neutrons, under subcriticality ranging between near critical and 11,556 pcm, measurement of the kinetic parameters was conducted by the PNS method, the Feynman-α method, and the NSM method. Through a comparison between measured and calculated results of kinetic parameters, the results confirmed the validity of the prompt neutron decay constant and the subcriticality in dollar units. Conventional research questions remain, however, regarding ADS experiments with both 14 MeV and spallation neutrons, including the effects of detector position dependency, 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 detector position dependency, the neutron spectrum, and the subcriticality measurement methods. In further studies, these experimental benchmarks will be conductive to numerical verification of subcriticality online monitoring, to the analysis of subcriticality uncertainty, and to a deterministic approach to kinetic parameters.

Conflicts of interest

No conflict

Acknowledgments

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