Nuclear Engineering and Design 338 (2018) 284–289

Contents lists available at ScienceDirect

Nuclear Engineering and Design

journal homepage: www.elsevier.com/locate/nucengdes

Reactivity measurement at VENUS-II during control rods drop based on inverse kinetics method

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ARTICLE INFO

Keywords:
Subcriticality monitoring
Inverse kinetics method
Control rod worth
Spatial correction factor

ABSTRACT

Feasibility of subcriticality monitoring with a digital reactivity meter based on inverse kinetics method has been investigated at the lead-based zero power reactor VENUS-II. A series of control rod drop experiments have been carried out in this work. The subcriticality before and after the rod drop were estimated considering the effect of external neutron source. The control rod worth was also extracted from the rod drop experiments. The measurement results exhibited obvious spatial dependence induced by the control rod insertion, and they could be corrected by correction factors calculated with MCNP code. The corrected values of control rod worth were found to be consistent with the reference ones predetermined at critical condition. Moreover, this method could also provide real time subcriticality without any correction when the detectors were placed at appropriate positions at slightly subcritical state. Based on these measurements, it has been proved that the digital reactivity meter could be a useful tool for continuous reactivity monitoring in the operation of ADS in future.

1. Introduction

China Initiative Accelerator Driven System (CIADS) (Fu et al., 2011) is a strategic program authorized in 2011 for improving the utilization of nuclear resources and transmuting minor actinides. It consists of a subcritical reactor with an external source provided by a high intensity accelerator through spallation reaction (Vandeplassche et al., 2012; Gudowski, 1999; Kadi and Revol, 2001). In the operation of an ADS facility, the subcritical reactivity monitoring is of great significance for safety reasons. Hence, a lead-based zero power reactor VENUS-II has been built at China Institute of Atomic Energy (CIAE), in Beijing, China, which aims at a better understanding of the subcriticality monitoring techniques and the physics phenomena of subcritical reactor.

In the past decades, several techniques have been applied to determine the reactivity of a subcritical system, such as the Feynman-α method (Tonoike et al., 2003; Degweker, 2000; Ceder, 2003), the neutron source multiplication method (Misawa et al., 2003; Tsuji, 2003) and pulsed neutron source (PNS) technique (Berglof, 2010; Soule, 2004; Pyeon, 2017; Pyeon, 2017; Persson, 2005), which have been conducted at different subcritical facilities to investigate neutron characteristics of ADS. These experimental benchmarks would play an important role for the numerical verification of subcriticality on-line monitoring. Recently, the PNS method has been conducted using the Kyoto University Critical Assembly (KUCA) to investigate the applicability for on-line subcriticality measurement, and it has been shown that this method was feasible for on-line subcriticality monitoring for deep subcritical conditions (Iwamoto, 2017). However, the high-energy accelerator has to work at pulsed mode for PNS on-line reactivity monitoring technique, which is not intended to be the normal mode of operation of an industrial ADS, such as continuous or quasi-continuous mode. Furthermore, researchers have also studied the current-to-flux method at the subcritical facility YALINA-Booster (Becares and Villamarin, 2013). Although the current-to-flux method is promising for on-line reactivity monitoring, it has been applied only to monitor the relative change in the reactivity. On the other hand, the inverse kinetics method (Jammes et al., 2007) is universally used for continuous monitoring of the effective neutron multiplication factor (k_{eff}) for commercial pressurized water reactors (PWRs). In order to develop and verify a continuous reactivity monitoring technique for ADS, it is necessary to investigate the feasibility of subcriticality monitoring using

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https://doi.org/10.1016/j.nucengdes.2018.08.019
Received 31 January 2018; Received in revised form 11 August 2018; Accepted 20 August 2018
Available online 31 August 2018

the inverse kinetics method. Prior to this work, some research groups have verified the applicability of a digital reactivity meter for the continuous subcriticality measurement with external neutron source using the inverse kinetics method (Shimazu, 1987; Shimazu, 2014). With the application of an adequate filter, the inverse kinetics based reactivity meter has a sufficient capability to reduce reactivity fluctuation even under noisy conditions.

Generally, the commonly used digital reactivity meter can't be directly applied to subcriticality monitoring because it ignores the effect of external neutron source which plays an important role in a subcritical system. If the initial system reactivity, ρ_0, and the stable neutron signal, n_0, have been predetermined with a reasonable accuracy, we could estimate the effective neutron source strength by ρ_0 and n_0. Details are described in Section 2. Moreover, the inverse kinetics equation is derived from one-point reactor kinetics theory which assumes that the shape of the neutron flux distribution is unchanged during the reactivity fluctuation. However, this assumption is not always adapt to different subcritical conditions, which leads to the necessity that the measurement results must be corrected taking into account of the effect of the neutron flux distribution change. In addition, to avoid criticality accident, it is very important to study the reactivity monitoring technique under slight subcritical state, for example $k_{eff} = 0.99$.

The main purpose of this paper is to examine experimentally the feasibility of inverse kinetics method under subcritical conditions, and investigate the detector position dependency for continuous reactivity monitoring, which could provide useful advices about the location of reactivity monitors for the industrial operation of ADS. An alternative derivation of the inverse kinetics equation considering the external neutron source (Trkov, 1992; Trkov, 1995) is exhibited based on one-point reactor kinetics in Section 2. The lead-based zero power reactor VENUS-II and experimental details are briefly described in Section 3. In Section 4, the subcriticality during the control rods drop procedure are presented, and the control rods worth is extracted. Additionally, the measurement results are corrected by the spatial factors calculated with Monte Carlo neutron transport code MCNP (Briesmeister, 1986).

2. Inverse kinetics method

A reactivity meter is based on measuring the power of the reactor to calculate the dynamic reactivity, $\rho(t)$, through the inverse kinetics equation. The algorithm used in the digital reactivity meter is derived from the one-point reactor kinetics model with the external neutron source:

$$\frac{dn(t)}{dt} = \frac{\rho(t) - \beta}{\Lambda} \times n(t) + \sum_{i=1}^{6} \lambda_i C_i(t) + s \tag{1}$$

$$\frac{dC_i(t)}{dt} = \frac{\beta_i}{\Lambda} \times n(t) - \lambda_i C_i(t), \tag{2}$$

where the symbol $n(t)$ denotes the neutron flux level, $C_i(t)$ the concentration of precursor of delayed neutrons for i-th group and s the effective source strength. β_i and λ_i are the effective delayed neutron fraction and the relative precursor effective decay constant respectively, and Λ is the effective neutron generation time, while $\rho(t)$ denotes the reactivity.

Solving the Eqs. (1) and (2) for $\rho(t)$, one obtains the following inverse kinetics equation:

$$\frac{\rho(t)}{\beta} = 1 + \frac{\Lambda}{\beta}\frac{dn(t)}{n(t)dt} - \sum_{i=1}^{6} \frac{\lambda_i \beta_i}{n(t)\beta} \int_0^t n(\tau) e^{-\lambda_i (t-\tau)} d\tau - \frac{\Lambda s}{\beta n(t)} \tag{3}$$

It is obvious that the reactivity, $\rho(t)$, could be determined through the flux level n(t) while the parameters about delayed neutrons are all known. The effective source strength in Eq. (3) is assumed as a constant, and it can't be measured directly. Fortunately, if the reactor is working at a known initial steady state ρ_0, corresponding to the steady counting rate n_0 of neutron detector, the source strength s could be derived from Eqs. (1) and (2) as (Shimazu, 2005):

$$s = -\frac{n_0 \rho_0}{\Lambda} \tag{4}$$

Therefore, once the initial steady state ρ_0 and n_0 were determined exactly, the subcritical reactivity, $\rho(t)$, could be estimated by $n(t)$ using Eq. (5):

$$\frac{\rho(t)}{\beta} = 1 + \frac{\Lambda}{\beta}\frac{dn(t)}{n(t)dt} - \sum_{i=1}^{6} \frac{\lambda_i \beta_i}{n(t)\beta} \int_0^t n(\tau) e^{-\lambda_i (t-\tau)} d\tau + \frac{n_0 \rho_0}{\beta n(t)} \tag{5}$$

To evaluate the $\rho(t)$ data, the kinetics parameters like Λ and β_i must be known beforehand. These parameters could be determined through the Monte Carlo neutron transport code MCNP with ENDF/B-VII.0 nuclear library. The calculation results of these parameters with statistical error (1σ) are summarized in Table 1.

Table 1
Six-group delayed neutron parameters and Λ calculated with MCNP code and ENDF/B-VII library for VENUS-II reactor.

Group	$\lambda_{eff,i}(s^{-1})$	$\beta_{eff,i}$	$\Lambda(\mu s)$
1	0.01249 ± 0.00001	0.00025 ± 0.00002	
2	0.03180 ± 0.00001	0.00117 ± 0.00006	
3	0.10946 ± 0.00001	0.00121 ± 0.00005	
4	0.31742 ± 0.00002	0.00322 ± 0.00009	135.02 ± 1.48
5	1.3529 ± 0.00007	0.00105 ± 0.00005	
6	8.6682 ± 0.00348	0.00030 ± 0.00003	
β_{eff}		0.00719 ± 0.00013	

3. Experimental setup

3.1. The VENUS-II reactor (Ke et al., 2015)

A schematic view of the lead-based zero power reactor VENUS-II is presented in Fig. 1. Two kinds of fuel rods with different enrichment are loaded to this assembly: 90 wt% U-235 enrichment metal uranium pellets with stainless steel clad and 20 wt% U-235 enrichment U_3O_8 powder with Zr clad. The active length of fuel rods is 400 mm. The fuel rods arrangement is that the central four rings are 90 wt% fuel rods, and outer eight rings are 20 wt% fuel rods. They are all implanted in a lead matrix in concentric cycles. The area outside lead body is thermal zone with maximum loading of 380 20 wt% fuel rods in three concentric rings, and polyethylene is around the fuel from bottom to top, acting as moderator. Inside the lead body is the spallation target zone. An effective reflector system is utilized to reduce the neutron leakage. At the top of 90wt% enrichment fuel rods, beryllium metal is used as the reflector. The polyethylene block is used as the top reflector for 20wt% enrichment fuel rods. The bottom and side reflector are graphite blocks with the density of 1.87 g/cm^3. This facility offers great flexibility in core loading patterns, which allows different levels of subcriticality by adding or removing fuel rods conveniently.

Four control rods are used. Two of them are assigned as safety rods for reactor scram, and the others are assigned as adjust rods for the adjustment of reactivity. They are all symmetrically located in the tubes in the graphite reflector as shown in Fig. 1. Safety rods are made of boron carbide (B_4C), while for the adjust rods cadmium (Cd) is used. They can be moved vertically from 0 cm (fully inserted) to 108 cm (fully extracted). The safety rod is designed for the introduction of large negative reactivity (about −1100 pcm) while the small changes of reactivity (−245 pcm) can be achieved using the adjust rod. The reference reactivity worth of control rods has been predetermined by the positive period method and the rod drop method.

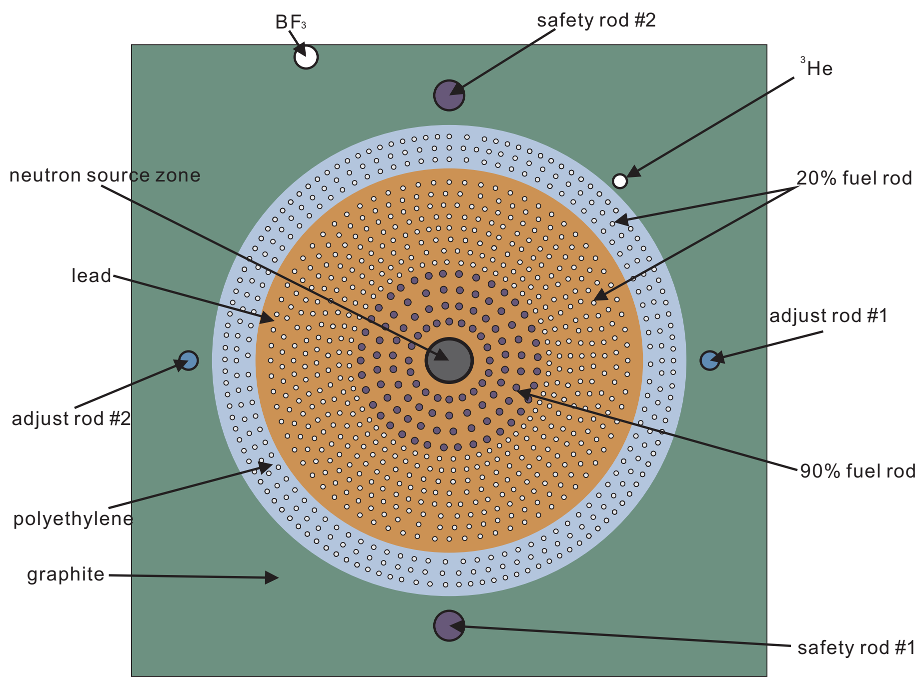

Fig. 1. Schematic of the lead-based zero power reactor VENUS-II.

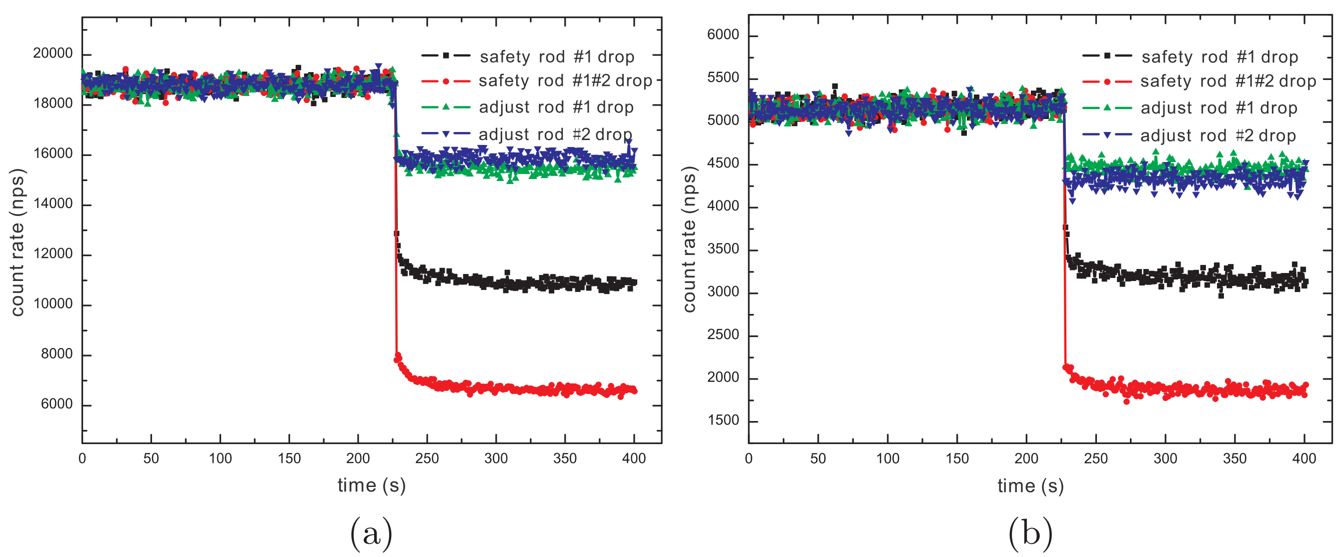

Fig. 2. The modified count rates of the ^{3}He detector (a) and BF_3 detector (b) for different control rods insertion campaign.

3.2. Rod drop experiments

The measurement of subcritical reactivity using the new digital reactivity meter relies on the count rate of one detector driven by the constant external neutron source. For this purpose, a ^{252}Cf neutron source is placed at the target zone. During this experiment, the VENUS-II core is equipped with two neutron detectors (^{3}He and BF_3 proportional counters) at different positions working in pulse mode. Each proportional counter is connected to a high voltage power supply and its output pulse is shaped by an amplifier-threshold discriminator (ORTEC 590A) delivering Transistor Transistor Logic (TTL) pulses. The digital signal is counted through NI PXIe-6614 Counter/Timer Module which is operated by running dedicated LabView program. The time resolution of reactivity monitoring is 1s. The detector threshold is selected to remove the useless signal due to gamma-rays and electric noise. The background count rate recorded for one hour is 0.2 counts/s. Electronics, bias voltage and detector thresholds are maintained unchanged throughout the experimental measurements.

At a slightly subcritical state, the count rate of ^{3}He detector is expected to be so high that the effect of dead time of neutron detector can not be neglected. Meanwhile, the BF_3 detector is free from the effect of dead time due to its location far away from the core. The dead time of ^{3}He detector has been predetermined as $2\mu s$ by comparing the count rate of ^{3}He detector with BF_3 detector whose count rate is not be affected by the dead time.

To verify the capability of the digital reactivity meter to measure the reactivity during a fast variation in the subcriticality of the core, a series of measurements have been performed in the VENUS-II by inserting the control rods. The experiments were carried out in the subcritical configuration that the reactivity of VENUS-II was loaded as $\rho_0 = -1310$ pcm with control rods all out of the core. The initial counting rate n_0 of detectors was measured after the ^{252}Cf neutron source has been introduced in the core for about 10 min. Hence, the effective source strength can be replaced by ρ_0 and n_0 using Eq. (4). In

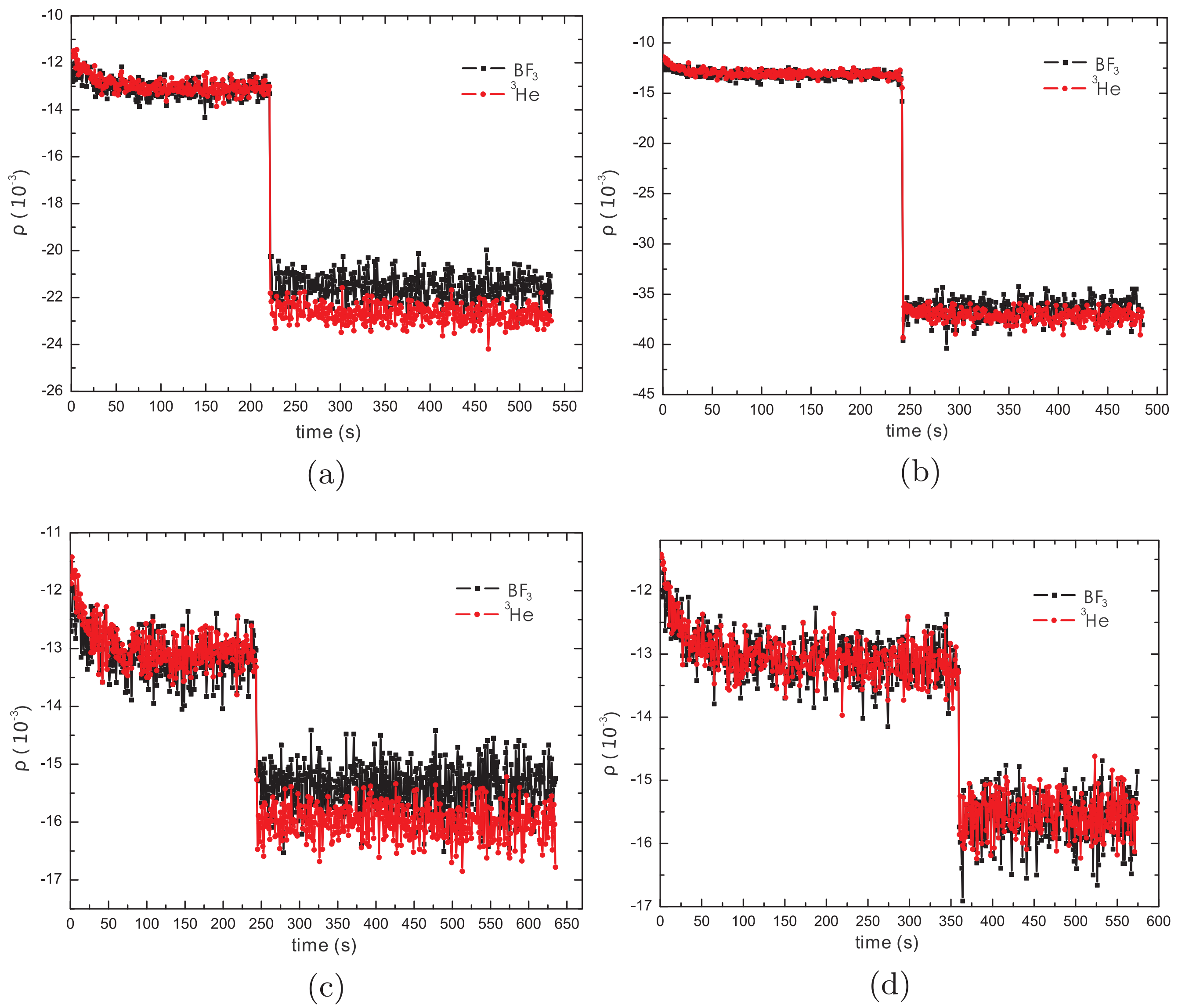

Fig. 3. Reactivity monitoring using ^{3}He and BF_3 detectors for control rods insertion experiments. The initial reactivity $\rho_0 = -1310$ pcm was assumed to be known. (a) Reactivity monitoring of safety rod #1 drop; (b) reactivity monitoring of safety rod #1 and #2 drop; (c) reactivity monitoring of adjust rod #1 drop; (d) reactivity monitoring of adjust rod #2 drop.

Table 2
The reactivity worth monitored and analyzed through the inverse kinetics method, where the relative errors are computed in regard to the reference reactivity measured at critical condition.

Control rod	ρ (pcm)		Reactivity worth (pcm)		Reference reactivity worth (pcm)
	^{3}He	BF_3	^{3}He (relative error)	BF_3 (relative error)	
Safety rod #1	−2267 ± 40	−2155 ± 58	−957 ± 40(13%)	−845 ± 58(23%)	−1100 ± 30
Safety rods #1#2	−3714 ± 62	−3655 ± 97	−2404 ± 62(9%)	−2345 ± 97(6%)	−2200 ± 39
Adjust rod #1	−1599 ± 30	−1540 ± 40	−289 ± 30(18%)	−230 ± 40(6%)	−245 ± 10
Adjust rod #2	−1553 ± 30	−1560 ± 41	−243 ± 30(1%)	-250 ± 41(2%)	-245 ± 9

this work, four series of rod drop experiments have been performed:

(1) safety rod #1 was inserted instantly at the reference state;
(2) safety rods #1 and #2 were inserted simultaneously at the reference state;
(3) adjust rod #1 was inserted instantly at the reference state;
(4) adjust rod #2 was inserted instantly at the reference state;

Considering the effect of dead time, the count rates of ^{3}He detector and BF_3 detector for different control rods insertion campaign are presented in Fig. 2.

Table 3
The spatial correction factors for different rod drop experiments.

Control rod	$f(r_d)$	
	^{3}He (statistical error)	BF_3 (statistical error)
Safety rod #1	0.956(0.12%)	0.928(0.19%)
Safety rods #1#2	1.045(0.14%)	1.075(0.22%)
Adjust rod #1	1.016(0.13%)	0.997(0.16%)
Adjust rod #2	1.004(0.14%)	1.003(0.12%)

4. Results and discussion

4.1. Result of control rods drop

The subcriticality before and after the rod drop was estimated by solving the Eq. (5) using the corrected count rates of both ^{3}He and BF_3 detectors. The calculated results are shown in Fig. 3.

In the beginning, the estimated subcriticality is changed along with time in Fig. 3, although the reactor is working under a steady state. This phenomenon is probably induced by the time-integration before t = 0 of delayed neutron term in Eq. (5). The experimental results of different detectors would tend to be stabilized (−1310 pcm) after about 100 s. Then the monitored subcriticality drop quickly following the prompt insertion of control rods. The reactivity worth of control rods could be obtained by subtracting the reactivity of initial steady condition (−1310 pcm) from the reactivity after the rod drop.

Table 2 presents the extracted results of control rods worth detected by ^{3}He detector and BF_3 detector. As seen from this table, there are obvious deviations between the results of monitors. Meanwhile, the estimated results are also compared with the reference ones measured at critical condition, and the relative errors range from 1% to 23%. These differences might be caused by the change of neutron flux shape before and after the insertion of control rod. Hence, the measured results should be corrected for the spatial dependence reasons.

4.2. Spatial correction

While deriving the one-point reactor kinetics equation from the neutron transport theory, one assumes that the neutron flux density distribution, $\phi(r, E, t)$, could be described as the product of a flux shape function, $\varphi(r, E, t)$, and an amplitude function $n(t)$:

$$\phi(r, E, t) = n(t) \times \varphi(r, E, t) \tag{6}$$

The reactivity monitoring in a subcritical condition using the digital reactivity meter must satisfy the limitation that the flux shape function, $\varphi(r, E, t)$, is unchanged. However, when the system reactivity is changed by inserting the control rod, the neutron flux density close to the control rods drops more quickly compared with the ones away from the control rods. The neutron flux shape function, $\varphi(r, E, t)$, is also changed with the control rods drop. Thus the direct application of Eq. (5) to subcriticality measurement would cause some errors. Two spatial effects should be considered during the procedure of control rods drop. One is static spatial effect induced by the transient redistribution of prompt neutron, and the other is dynamic spatial effect which is caused by the change of delayed neutron distribution. It has been proved that the static spatial effect plays the dominated role compared with the dynamic spatial effect (Yuan, 2013). Therefore, we introduce a static spatial effect correction factor, $f(r_d)$, to correct the measurement results. In this paper, we assume that the flux shape function for the initial steady state is $\varphi_0(r, E, t)$, while the flux shape function after the completely insertion of control rod is $\varphi_1(r, E, t)$. Then the $f(r_d)$ is defined as the ratio of the shape function before and after the control rods insertion:

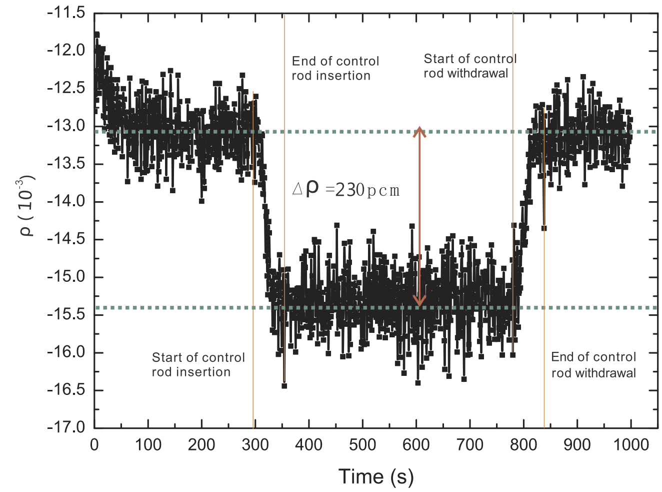

Fig. 4. The monitored subcriticality using BF_3 detector when the adjust rod #1 was inserted and withdrawn slowly.

$$f(r_d) = \varphi_0(r_d, E, t)/\varphi_1(r_d, E, t), \tag{7}$$

where r_d denotes the location for ^{3}He detector or BF_3 detector, and $\varphi(r_d, E, t)$ can be regarded as the flux distribution normalized with the total neutrons. Once the geometry and the material composition of the VENUS-II reactor have been determined, the standard fixed source calculations of MCNP can provide the estimations of flux shape function.

The measured count rate of detectors for different locations should be corrected by multiplying this shape factor $f(r_d)$:

$$N_{mod} = f(r_d) \times N_{meas} \tag{8}$$

N_{meas} and N_{mod} are measured count rate and the modified count rate, respectively.

The position dependent correction factors for ^{3}He detector and BF_3 detector have been calculated by the Monte Carlo code MCNP with ENDF/B-VII.0 nuclear library, and the calculation results were listed in Table 3. The subcriticality corrected by spatial correction factors is shown in Table 4, and it's obvious that the measured control rods worth for different detectors are all coincident with the reference ones when the reactor is operating at subcritical condition of −1310 pcm.

The spatial factors of both detectors don't deviate much from 1 for the adjust rod drop experiments as shown in Table 3, which is caused by the fact that the dissimilarity of the neutron flux shape before and after the adjust rod insertion is smaller compared with the safety rod

Table 4
The corrected reactivity worth considering the change of the flux shape.

Control rod	$\rho_{corrected}$ (pcm)		Corrected reactivity worth (pcm)	
	^{3}He	BF_3	^{3}He (relative error)	BF_3 (relative error)
Safety rod #1	−2371 ± 39	−2322 ± 58	−1061 ± 39(3%)	−1012 ± 58(8%)
Safety rods #1#2	−3554 ± 54	−3400 ± 82	−2244 ± 54(2%)	−2090 ± 82(5%)
Adjust rod #1	−1573 ± 27	−1543 ± 38	−263 ± 27(7%)	−234 ± 38(4%)
Adjust rod #2	−1541 ± 27	−1549 ± 39	−237 ± 27(3%)	−246 ± 39(0.4%)

insertion experiments. In addition, some spatial factors are approximately equal to 1 for the entirety drop of adjust rod #1 or #2. This can be explained by the fact that the positions of these detectors are rather far away from the inserted adjust rod and rather protected from the modification of the neutron flux shape caused by rod movement.

The measured results reveal that the inverse kinetics method could be used for the measurement of reactivity perturbation accurately without any corrections when the detector is located at an appropriate position far from the external source and adjust rods. Fig. 4 presents the continuous monitoring of subcriticality using BF_3 detector when the adjust rod #1 was inserted and then withdrawn slowly. It indicates that the inverse kinetics method could be an alternative tool for subcriticality monitoring of CIADS in the future, and it is mainly applied to monitor the small reactivity perturbation of subcritical systems.

5. Summary

In order to verify the feasibility of the digital reactivity meter based on the inverse kinetics equation for on-line reactivity monitoring at subcritical condition in the framework of program CIADS, we have performed several control rod drop experiments at the lead-based zero power reactor VENUS-II. The measurement results of ^{3}He detector and BF_3 detector exhibit consistent values for different rod drop experiments, while the count rates of both detectors were corrected by spatial factors calculated using MCNP code with ENDF/B-VII.0 nuclear library. In addition, if the subcriticality was changed by inserting the adjust rods, the problem of spatial effect could be ignored when the detectors are placed at positions where the flux shape remain unchanged. As described above, if k_{eff} of the reactor was around 0.99, the proposed method could be directly used for subcriticality monitoring.

In conclusion, the inverse kinetics method is re-confirmed to be appropriate to measure control rod worth at subcritical level, and it will contribute to the development of on-line subcriticality monitoring technique in future. Further research on the inverse kinetics method has been planned for more subcritical conditions and different reactors.

Acknowledgments

We thank the support of operation staff at VENUS-II reactor. This work was supported by National Natural Science Foundation (11575267, 11775284, 11575289, 11605258, 91426301) and Strategic Priority Research Program of the Chinese Academy of Sciences (XDA03030300).

References

Becares, V., Villamarin, D., et al., 2013. Validation of ADS reactivity monitoring techniques in the Yalina-Booster subcritical assembly. Ann. Nucl. Energy 53, 331–341. https://doi.org/10.1016/j.anucene.2012.10.001.

Berglof, C., et al., 2010. Spatial and source multiplication effects on the area ratio reactivity determination method in a strongly heterogeneous subcritical system. Nucl. Sci. Eng. 166, 134–144. https://doi.org/10.13182/NSE09-87.

Briesmeister, J.F., et al., 1986. MCNP-A General Monte Carlo Code for Neutron and Photon Transport, LA-7596-M, Rev. 2.

Ceder, M., et al., 2003. Analytical solution for the Feynman-Alpha formula for ADS with pulsed neutron sources. Progr. Nucl. Energy 43, 429–436.

Degweker, S.B., et al., 2000. Some variants of the Feynman alpha method in critical and accelerator driven subcritical systems. Ann. Nucl. Energy 27, 1245–1257. https://doi.org/10.1016/S0306-4549(00)00006-2.

Fu, S., et al., 2011. Chinese plan for ADS and CSNS. In: Proceedings of SRF2011. Chicago. pp. 977–982.

Gudowski, W., et al., 1999. Accelerator driven transmutation projects. Nucl. Phys. A 654n, 436–457. https://doi.org/10.1016/S0375-9474(99)00269-9.

Iwamoto, H., et al., 2017. On-line subcriticality measurement using a pulsed spallation neutron source. J. Nucl. Sci. Technol. 54, 432–443. https://doi.org/10.1080/00223131.2016.1274687.

Jammes, C., et al. Experimental Results of the RACE-ISU International Collaboration on ADS. In: Int. Conf. AccApp'07.

Kadi, Y., Revol, J.P., et al., 2001. Design of an accelerator driven system for the destruction of nuclear waste. In: Workshop on Hybrid Nuclear System for Energy Production, Utilisation of Actinides Transmutation of Long Lived Radioactive Waste, pp. 83–132.

Ke, G.T., et al., 2015. YBS: the Critical Assembly for ADS Experimental Research. In: CIAE, Proceedings of the Reactor Physics Asia 2015(RPHA15) Conference. Jeju, Korea.

Misawa, T., et al. Measurement of subcriticality by higher mode source multiplication method. In: Proceedings of the International Conference on Nuclear Critical Safety (ICNC2003).

Persson, C.M., et al., 2005. Analysis of reactivity determination methods in the subcritical experiment Yalina. Nucl. Instrum. Methods Phys. Res. Sect. A 554, 374–383. https://doi.org/10.1016/j.nima.2005.07.058.

Pyeon, C.H., et al., 2017. Benchmarks of subcriticality in accelerator-driven system at Kyoto University Critical Assembly. Nucl. Eng. Technol. 49, 1234–1239. https://doi.org/10.1016/j.net.2017.06.012.

Pyeon, C.H., et al., 2017. Experimental benchmarks on kinetic parameters in accelerator-driven system with 100 MeV protons at Kyoto University Critical Assembly. Ann. Nucl. Energy 105, 346–354. https://doi.org/10.1016/j.anucene.2017.03.030.

Shimazu, Y., et al., 1987. Development of a compact digital reactivity meter and a reactor physics data processor. Nucl. Technol. 77, 247–254. https://doi.org/10.13182/NT87-A33964.

Shimazu, Y., et al., 2005. Some technical issues on continuous subcriticality monitoring by a digital reactivity meter during criticality approach. J. Nucl. Sci. Technol. 42, 515–524. https://doi.org/10.1080/18811248.2004.9726418.

Shimazu, Y., et al., 2014. A simple procedure to estimate reactivity with good noise filtering characteristics. Ann. Nucl. Energy 73, 392–397. https://doi.org/10.1016/j.anucene.2014.07.005.

Soule, R., et al., 2004. Neutronic studies in support of accelerator-driven systems: the MUSE experiments in the MASURCA facility. Nucl. Sci. Eng. 148, 124–152. https://doi.org/10.13182/NSE01-13C.

Tonoike, K., et al. Real Time Alpha Value Measurement With Feynman-α Method Utilizing Time Series Data Acquisition on Low Enriched Uranium System. JAERI-Conf 2003-019.

Trkov, Andrej, et al., 1992. Reactivity measurements in a close-to-critical TRIGA reactor using a digital reactivity meter. Kerntechnik 57, 296–300.

Trkov, Andrej, et al., 1995. Application of the Rod-Insertion Method for control rod worth measurements in research reactors. Kerntechnik 60, 255–261.

Tsuji, M., et al., 2003. Subcriticality measurement by neutron source multiplication method with a fundamental mode extraction. J. Nucl. Sci. Technol. 40, 158–169. https://doi.org/10.1080/18811248.2003.9715346.

Vandeplassche, D., et al., 2012. Accelerator Driven Systems, Proc. IPAC 2012 Conf. New Orleans, US. pp. 977–982.

Yuan, A.M., 2013. Research on spatial effect based on point reactor model (Doctoral thesis). Harbin Engineering University.