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Subcritical Experiments in Uranium-Fueled Core with Central Test Zone of Tungsten

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To study the basic core characteristics of accelerator-driven systems (ADS), subcritical experiments were carried out in a uranium-fueled core FCA-XXI-1 at the FCA. Subcritical reactivity and axial distributions of ^{235}U-fission rate were measured in subcritical configurations with the central test zone of tungsten for simulating a target region of ADS.

The deterministic calculations by using a conventional fast reactor analysis code system with the JENDL-3.2 nuclear data file resulted in an overestimation of 1~2% for the effective multiplication factor k_{eff} of critical configuration, while the precisely modeled Monte Carlo calculation showed a good accuracy of 0.2%. The subcritical reactivity was measured down to -5%Δk by the modified source multiplication method. The measured reactivity values by out-of-core detectors showed little dependence of source position and agreed with the calculated values within 5%, but those by in-core detectors still showed a spatial dependence on the positions of external source and detectors. The measured distribution of ^{235}U fission rate for each subcritical configuration was well calculated by adjusting effective production cross-sections so that the calculated k_{eff}-value of the reference critical configuration should be consistent with the experimental one.

KEYWORDS: subcritical experiments, Fast Critical Assembly (FCA), uranium-fuel core, subcritical reactivity, axial distribution of 235U fission, source multiplication method, accelerator-driven system (ADS)

1. Introduction

In the design of accelerator-driven systems (ADS), the subcritical reactivity of core is a key parameter to evaluate not only nuclear safety characteristics but also core performance such as neutron multiplication and power distribution. To study the basic core characteristics of subcritical multiplying system driven with an external neutron source, subcritical experiments were carried out at the Fast Critical Assembly (FCA) of Japan Atomic Energy Institute (JAERI). For the first stage of benchmark experiments, we constructed a uranium-fueled core FCA-XXI-1 that is relatively simple in geometry and composition. This paper describes the results of static experiments for subcritical reactivity and axial distribution of ^{235}U fission rate in the core with a central test zone of tungsten for simulating a target region of ADS.

2. Experiments

2.1 Experimental Setup

2.2.1 Core Configuration

The FCA is a split- table type critical assembly consisting of two half assemblies, of which one is fixed and the other is movable. Each half assembly has a lattice structure constructed with 5.52cm-square tubes of stainless steel. Plate-type fuel and other core materials are packed in the stainless steel drawers, which are inserted into the lattice tubes of the assemblies to configure a mockup core.

The FCA-XXI-1 core was constructed as a benchmark of uranium-fueled core so that its composition and geometry were as simple as possible. The core is cylindrical in shape (61cm in diameter and 61cm high), which is surrounded by inner and outer blanket regions, as shown in Fig.1. A fuel drawer is comprised with two regions; one half corresponds to the core region loaded with fuel and the other half to the inner blanket region. The core region has a simple composition consisting of enriched uranium and stainless steel. The inner blanket region consists of depleted uranium dioxide and sodium, and the outer blanket region of only depleted uranium metal. In the subcritical configurations, the central 9 drawers of 3x3 square matrix region (~16cm square) in the fixed half assembly were used as a test zone and an external neutron source of ^{252}Cf was inserted into the center drawer to drive the core.

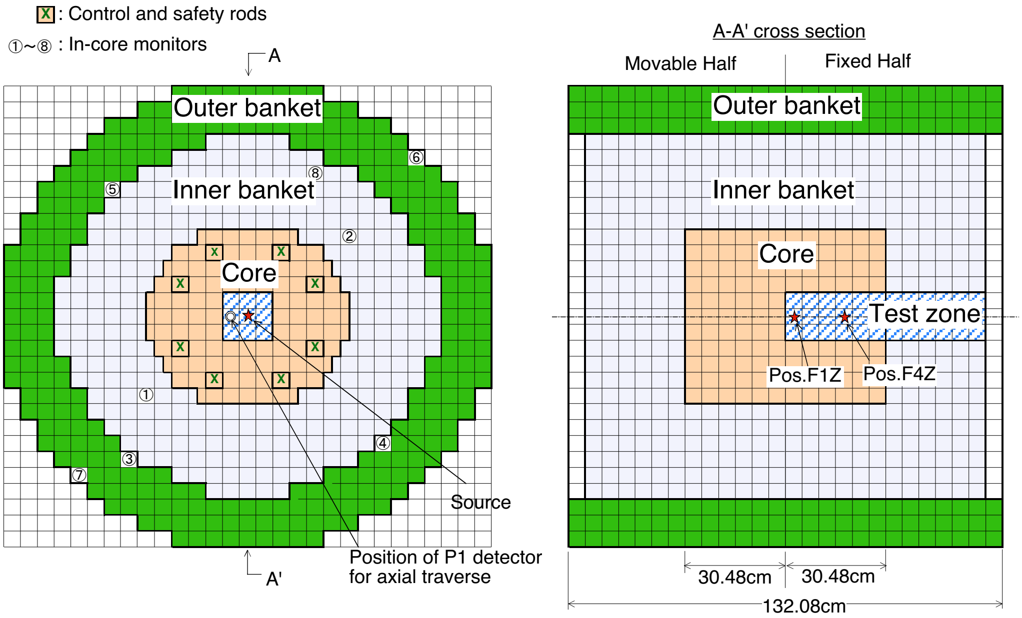


Fig.1 Experimental configuration in FCA XXI-1 core.

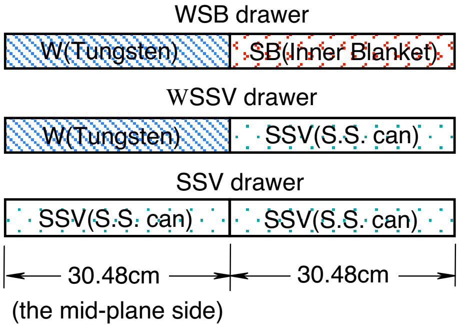


Fig.2 Loading patterns of test drawers.

Table 1 Atomic number density of homogenized material regions (10^{24} atoms/cm^3)

Nuclide	Fuel	Inner Blanket	Outer Blanket	SSV	W
^{235}U	3.73E-3	1.86E-5	8.44E-5		
^{238}U	6.00E-3	9.16E-3	4.02E-2		
H	1.47E-4				
C	1.24E-4				3.19E-5
O	6.42E-5	1.84E-2			
Na		7.66E-3			
Cl					2.71E-6
Cr	1.23E-2	3.12E-3	1.81E-3	4.60E-3	1.81E-3
Mn	6.93E-4	2.29E-4	1.20E-4	3.30E-4	1.20E-4
Fe	4.33E-2	1.12E-2	6.47E-3	1.57E-2	6.47E-3
Ni	5.37E-3	1.41E-3	7.89E-4	2.08E-3	7.89E-4
Mo					1.40E-6
W					5.22E-2

2.2.2 Test Zone

The normal fuel drawers in the test zone were replaced with test drawers for simulating an accelerator target region in ADS. In this series of experiments, three types of test drawers were prepared: WSB, WSSV and SSV drawers. The loading patterns of them are shown in Fig.2. The WSB and WSSV drawers were filled with tungsten plates (5.08cm-square by 0.63cm-thickness) in the corresponding core region, followed by the inner blanket material (SB) and void cans of stainless steel (SSV) respectively. The SSV drawer was entirely filled with void cans. Homogenized atomic number densities in principal regions are given in Table 1.

2.2.3 External Neutron Source

A neutron source of ^{252}Cf (10^8n/s in nominal) was placed on the core axis in the test zone. To examine the effect of source position on reactivity determination and power distribution, experiments were carried out at two different source positions of 2.5cm(F1Z) and 18cm(F4Z) from the mid-plane of assembly.

2.2 Measurement Method

Prior to construct subcritical configurations, the excess reactivity of the reference critical configuration, where the test zone was loaded with normal fuel drawers, was measured using the calibrated control rods to determine the effective multiplication factor (k_{eff}) at critical state. Corrections required for a comparison with calculations were also measured independently for reactivity effects of a change of room temperature, a gap between two half assemblies, in-core monitors and so on.

The subcritical reactivity was measured by the source multiplication method (SM method) and the spatial higher harmonics effect on the count rate was corrected by using the correction factors based on the MSM method [1]. The reactivity of the reference subcritical configuration was adjusted with the calibrated control rods. Twelve neutron detectors were used: four out-of-core monitors of startup channels (fission chambers Ch1 and Ch2) and operation channels (BF_3-ionization chambers Ch5 and Ch6), and eight in-core monitors (fission chambers M1~M8) distributed in the fixed half as shown in Fig.1. Two out-of-core monitors (Ch1 and Ch5) were installed in the movable half and the rest (Ch2 and Ch6) in the fixed half, and all of them were located at an equal distance of 155cm from the core axis.

The fission rate distribution was measured in the test zone using a miniature ^{235}U fission chamber (P1) along an axial experimental channel (1.27cmx2.54cm rectangular cross section), which passed through the two halves in the drawers next to the central ones. The measurement was carried out at least by every 5cm step in the core region.

3. Calculations

An analysis was made in large part using a conventional fast reactor analysis code system of JAERI. The cell calculations were performed with the SLAROM code [2] using the JFS-3 library based on a nuclear data file JENDL-3.2 [3]. In the core calculations, transport codes TWODANT and THREEDANT in the DANTSYS code system [4] was employed with a 70-group structure and a P0-S8 approximation in two-dimensional RZ (2D-RZ) and three-dimensional XYZ (3D-XYZ) models respectively. The reactivity effect of test zone was estimated from forward eigenvalue calculation for each subcritical configuration. The fission rate distribution corresponding to a fission chamber traverse was calculated using infinite fission cross-section for ^{235}U and flux distribution obtained in a fixed-source calculation. For a comparison with the measurement, the calculated k_{eff}-value was corrected for the reactivity effect of anisotropic neutron diffusion due to a plate arrangement in the drawers. This correction was estimated from additional calculations with a diffusion code

CITATION [5] by using isotropic and anisotropic diffusion constants. To exclude the uncertainty of such a correction, a continuous-energy Monte Carlo code MVP [6] was also employed as reference calculations for criticality and reactivity effect. The MVP calculations were made with a precisely modeled geometry using the JENDL-3.2. The effective delayed neutron fraction, β_{eff}, for the reference critical configuration was calculated with the PERKY code [7] using a set of forward and adjoint fluxes obtained by CITATION with a 70-group structure in a three-dimensional XYZ model. The resultant β_{eff}-value of 0.007123 was used to convert the reactivity scale between Δk/k unit in calculations and dollar unit in experiments.

4. Results

4.1 Criticality of reference configuration

The comparison of k_{eff}-values between calculation and experiment is summarized in Table 2. The deterministic calculations overestimated k_{eff} by 1.43% and 1.15% respectively for 2D-RZ and 3D-XYZ models, and the 2D-RZ model was less accurate by 0.3% than the 3D-XYZ model. The precisely modeled calculation by MVP showed a good accuracy of 0.2%.

It is noted that the results of deterministic calculations showed ~3% supercritical for the as-built reference critical configuration without correction for the effect of anisotropy due to a plate type fuel as shown in Table 2. This led to a problem in the fixed source calculation for the flux distribution and the estimation of correction factors for applying the MSM method, as described later.

Table 2 Comparison of k_{eff} values at a critical state between calculation and experiment

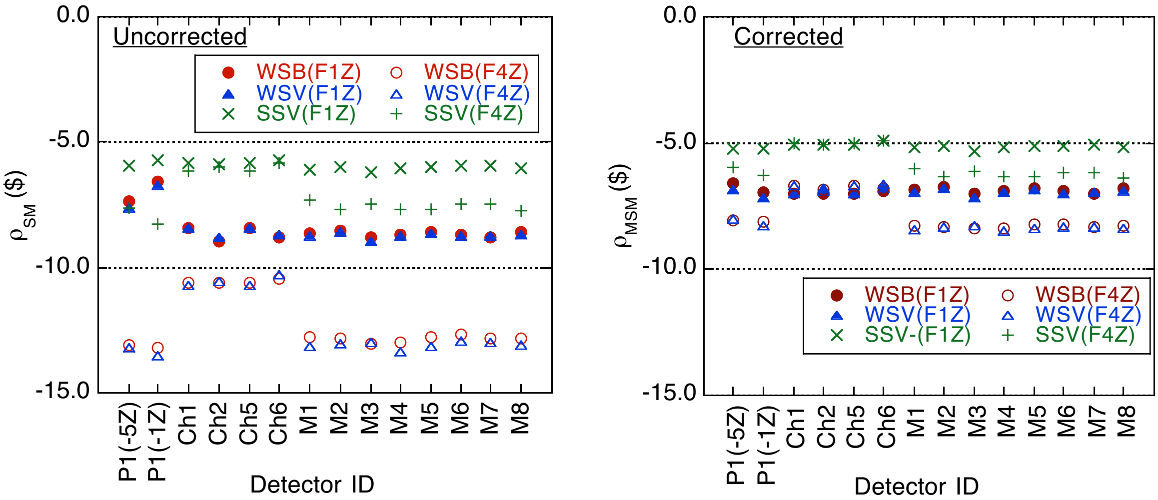
Experiment	for 2D-RZ model	for 3D-XYZ model	for 3D-precise model
k_{eff} measured (E)	1.0051±0.0004	1.0050±0.0004	1.0029±0.0001
Calculation	TWODANT	THREEDANT	MVP
k_{eff} calculated (C)	1.03427	1.03121	1.00470±0.00042
k_{eff} corrected for the effect of anisotropy due to a plate type fuel			
	1.0194	1.0165	-----
C-E (Δk)	0.0143	0.0115	0.0018

* β_{eff}= 0.007123

4.2 Subcritical Reactivity

Figure 3(a) illustrates the detector-to-detector variation of measured subcritical reactivity values by the SM method (uncorrected). This figure also includes the results by P1 detector at axial positions of –2.5cm(-1Z) and –22.5cm(-5Z). As shown in Fig.3(a), the uncorrected values largely depended on the position of external source and detectors. In particular, in the case of a F4Z source position, the results by in-core monitors were 20~50% large in comparison with those in the F1Z case.

The corrected values of measured subcritical reactivity by the MSM method are shown in Fig. 3(b). The correction factors used here were calculated with the 3D-XYZ model using a "adjusted" cross-section set, which will be described later in relation to the analysis of fission rate distribution. In the results for F1Z case, all detectors gave almost the same value. On the other hand, in the case of F4Z the results of in-core detectors of M1~M8 and P1 still differed from those of out-of-core detectors. The results of out-of-core detectors show little dependence of source position and seem to be most reliable. This will be due to that they are far from the external source compared with other in-core detectors. In Table 3, the calculation results are summarized and compared with the average of results by out-of-core detectors. Although the 2D-RZ and 3D-XYZ results for the cases of WSB and WSSV are a few percent large compared with the MVP results, they are consistent for each subcritical configurations and agree well, within 5%, with the measured values for the subcriticalty down to –7$(-5%Δk).



(a) SM method (uncorrected)

(b) MSM method (corrected)

Fig.3 Measurement results of subcritical reactivity by SM method (uncorrected) and MSM method (corrected)

Table 3 Calculation results of subcritical reactivity and a comparison with measured ones

Configuration	WSB		WSSV		SSV	
Source position	F1Z	F4Z	F1Z	F4Z	F1Z	F4Z
Experiment 1)	-7.00±0.05	-6.78±0.07	-6.94±0.09	-6.73±0.07	-5.03±0.07	-4.99±0.07
2D-RZ calc.	-6.771		-6.854		-4.986	
C/E	0.967	0.998	0.987	1.019	0.991	1.000
3D-XYZ calc.	-6.801		-6.887		-4.996	
C/E	0.972	1.003	0.992	1.024	0.993	1.002
MVP calc.	-6.618±0.091		-6.605±0.088		-4.975±0.088	
C/E	0.945	0.976	0.951	0.982	0.989	0.998

1) Average and standard deviation of Ch1, 2, 5 and 6.

4.3 Axial Distribution of ^{235}U Fission Rate

Figure 4 and 5 show typical experimental results of fission rate distribution respectively for the reference and subcritical configurations. In Fig.5, the reactivity (ρ) given for each configuration is the average value of reactivity measured with the four out-of-core detectors.

In the reference subcritical configuration of Fig.4, any effect of the external source on the flux shape was not observed in the shallow subcritical state (-0.10$) with relatively high reactor power of 2W. This means that the flux shape of reference subcritical configuration near critical is well approximated with that of the reference critical state.

When the normal fuel drawers in the test zone are replaced with WSSV or WSB drawers, the reactivity became deep down to -7$ (-5%Δk) with a decreased reactor power, and then a remarkable peak was observed at the source position, as shown in Fig5.

Figure 6(a) shows axial fission rate distributions calculated with a 2D-RZ model, compared with measured ones. The calculated distribution in the reference critical state well agreed with the measured ones. In the subcritical configuration, however, a large discrepancy was seen and a peak near the external source as observed in the measured distributions was not reproduced in the case of F4Z source position. As noted earlier, the present deterministic calculation method overestimated a k_{eff}-value by ~3% for the as-built reference critical configuration, and therefore it could not predict accurately the actual flux shape for each subcritical configuration if nothing was done. This overestimation would force some adjustment of system reactivity in calculations to reproduce the experimental shape. As an approach to solve this problem, effective production cross-sections ($\nu\Sigma_f$) were adjusted so that the calculated k_{eff}-value of the reference critical configuration became equal to an experimental value of unity. The calculation results using the adjusted cross sections are shown in Fig. 6(b). Improvement was much better than expected and a good agreement was obtained between calculation and experiment. The calculation results for each subcritical configuration are shown in Fig.7, which were obtained with a 3D-XYZ model using the adjusted cross-sections. It should be remarked that the 3D-XYZ model showed a slightly sharp peak near the source position, especially in the F4Z case, in comparison with the 2D-RZ model but significant difference was not seen. These analysis results suggest that such an adjustment has practically useful to evaluate flux distribution in a large subcritical configuration and furthermore gives in some measure a validation for the present calculation of a correction factor by the MSM method.

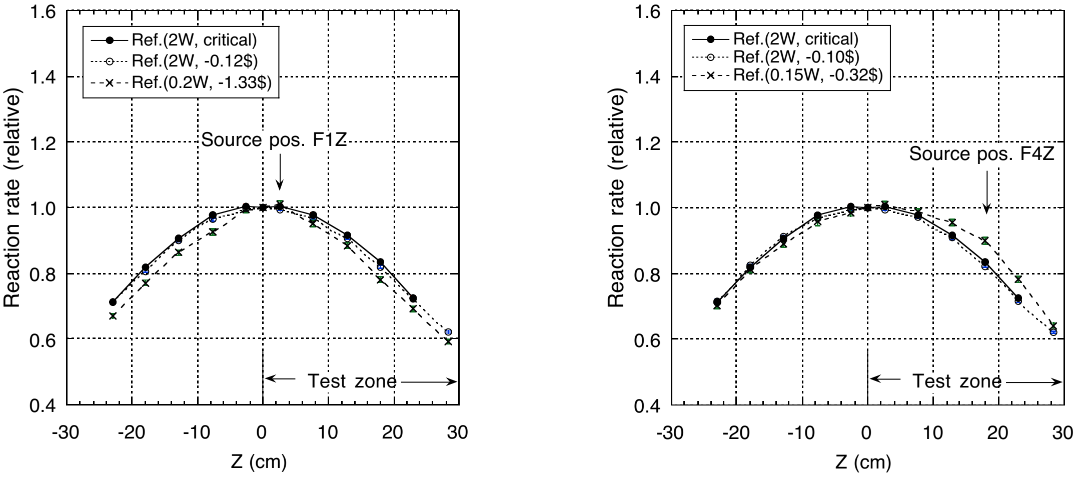


Fig.4 Experimental results of axial fission rate distribution in reference configuration.

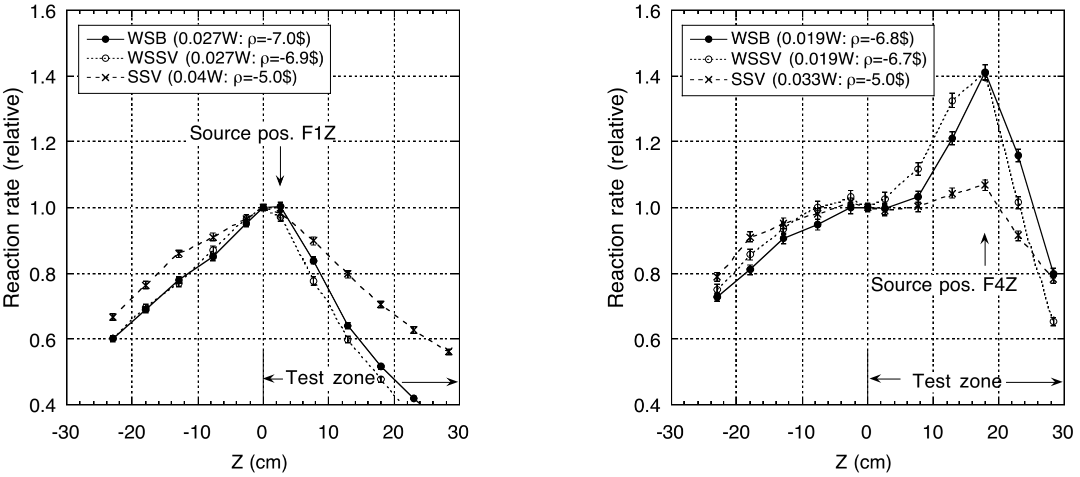
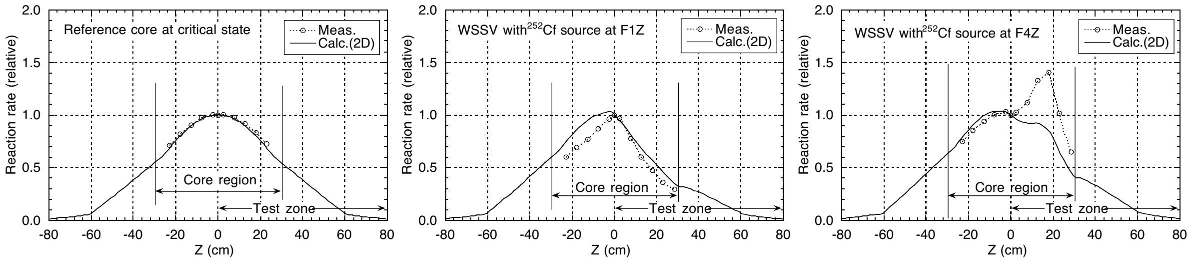
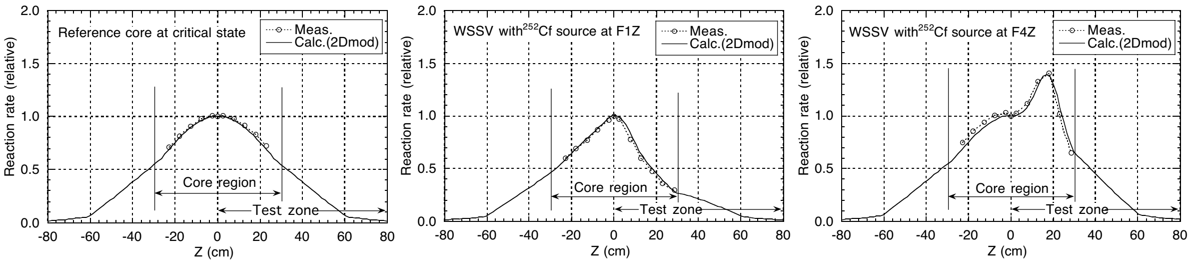


Fig.5 Experimental results of axial fission rate distribution in subcritical

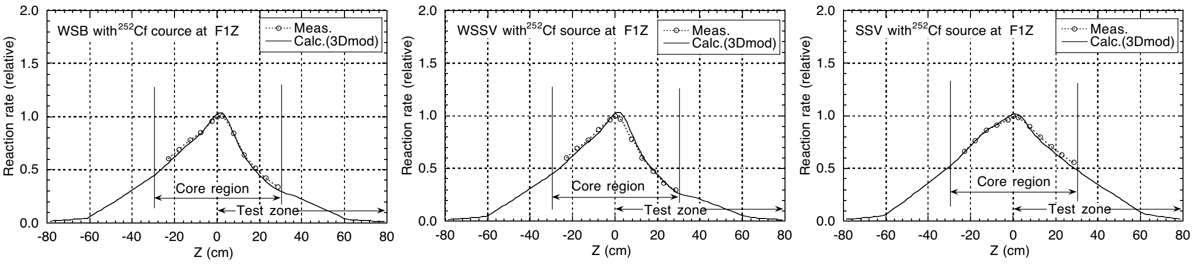


(a) Without adjustment

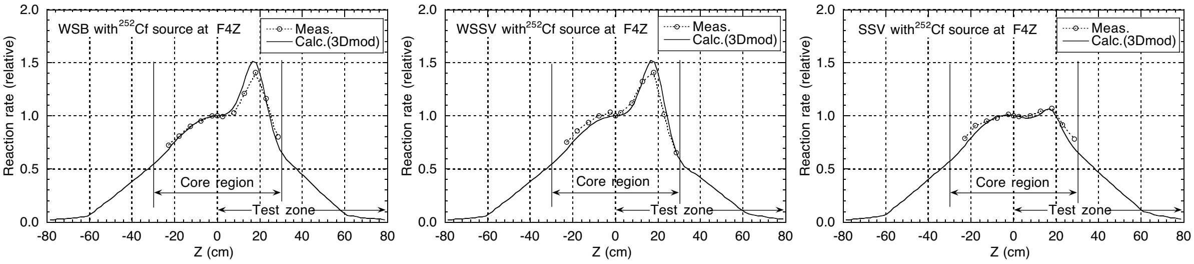


(b) With adjustment

Fig.6 Calculated axial distribution in of ^{235}U fission rate with and without adjustment.



^{252}Cf source at F1Z



^{252}Cf source at F1Z

Fig.7 Comparison of axial distribution between calculation (adjusted) and experiment.

5. Conclusion

Subcritical experiments were carried out in a uranium-fueled core FCA-XXI-1 at the FCA. Subcritical reactivity and axial distributions of ^{235}U-fission rate were measured in subcritical configurations with the central test zone of tungsten for simulating an accelerator target of ADS. The following results were obtained.

- The deterministic calculations overestimated the effective multiplication factor of critical configuration by 1.43% and 1.15% respectively for 2D-RZ and 3D-XYZ models, while the precisely modeled calculation by MVP showed a good accuracy of 0.2%.

- The subcritical reactivity was measured down to -5%Δk by the modified source multiplication method. The measured reactivity values by out-of-core detectors showed little dependence of source position and agreed with the calculated values within 5%, but those by in-core detectors still showed a spatial dependence on the positions of external source and detectors.
- The measured distribution of ^{235}U fission rate for each subcritical configuration was well calculated by adjusting effective production cross-sections so that the calculated k_{eff}-value of the reference critical configuration should be consistent with the experimental one.

The calculation accuracy of absolute k_{eff}-value in a subcritical system is essential for predicting flux distribution that is closely related to the reliability of reactivity measurement through an estimation of correction factor by the MSM method. If a calculated k_{eff}-value at a critical state is too far from a real one, an adjustment of system reactivity is necessary in a subcritical fixed-source calculation. Although in the present study we obtained a significant improvement of the prediction accuracy by adjusting effective production cross-sections, the validity of such an adjustment should be further investigated because it distorts the system neutron balance in nature.

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