Subcriticality Measurements in Accelerator-Driven System at Kyoto University Critical Assembly

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Abstract. At the Kyoto University Critical Assembly A-core, subcriticality measurement experiments in the Accelerator-Driven System with 14 MeV neutrons and ^{252}Cf neutron source were carried out using several methods: Feynman-α; Rossi-α; Neutron source multiplication; Pulsed neutron methods. In these subcriticality benchmark problems, these facts demonstrated experimentally that the dependence of subcriticality on the detector and the neutron source positions was found, and that the measurement precision varied both in accordance with the degree of subcriticality and each measurement technique.

1. Introduction

Subcriticality measurements in Accelerator-Driven System (ADS) at Kyoto University Critical Assembly (KUCA) ([1], [2]). are described in this paper. The Kyoto University Research Reactor Institute is going ahead with an innovative research project on ADS using a Fixed Field Alternating Gradient (FFAG) accelerator ([3], [4]). The goal of the research project is to demonstrate the basic feasibility of ADS as a next-generation neutron source using KUCA coupled with a newly developed variable energy FFAG accelerator. The ADS experiments using the FFAG accelerator started in February 2009. At the ADS with the FFAG accelerator, on 4th March 2009, the high-energy neutrons generated by nuclear reactions with 100MeV proton beams of a few pA intensity in a tungsten target was successfully injected into a solid-moderated and -reflected core (A-core) in thermal neutron field of KUCA.

Prior to the ADS experiments with 100 MeV protons, the ADS experiments with 14 MeV neutrons, which is generated by a conventional pulsed neutron generator ([5]) of the Cockcroft-Walton type accelerator, had been conducted in KUCA, including subcriticality, neutron multiplication, reaction rate distribution, neutron spectrum, neutron decay constant. Among these reactor physics parameters, an exact measurement of subcriticality is an interesting issue in the ADS studies. At the KUCA A-core, subcriticality measurement experiments in the ADS with 14 MeV neutrons and ^{252}Cf neutron source were carried out by using several methods: Feynman-α; Rossi-α; Neutron source multiplication; Pulsed neutron methods. In these subcriticality benchmark problems, these facts were experimentally demonstrated that the dependence of subcriticality on the detector and the source positions was found, and that the measurement precision varied both in accordance with the degree of subcriticality and each measurement technique.

2. KUCA Experimental Settings

2.1. KUCA Core Configuration

KUCA comprises solid-moderated and -reflected type-A and -B cores, and a water-moderated and -reflected type-C core. In the present series of experiments, the solid-moderated and -

reflected type-A core was combined with a Cockcroft-Walton type pulsed neutron generator installed at KUCA.

The A-core (A3/8"P36EU(3)) configuration used for measuring the subcriticality measurements shown in Figure 1 (Reference core). The A-core was constructed of a combination of 21 fuel rods that were loaded on the grid plate. The materials used in the critical assemblies were always in the form of rectangular parallelepipe, normally 2" sq. with thickness ranging between 1/16" and 2". The upper and lower parts of the fuel region were polyethylene reflector layers of more than 50cm long, as shown in Figure 2. The fuel rod, a highly enriched uranium-aluminum (U-Al) alloy, consisted of 36 cells of polyethylene plates 1/8" and 1/4" thick, and a U-Al plate 1/16" thick and 2" sq. The functional height of the core was approximately 40cm.

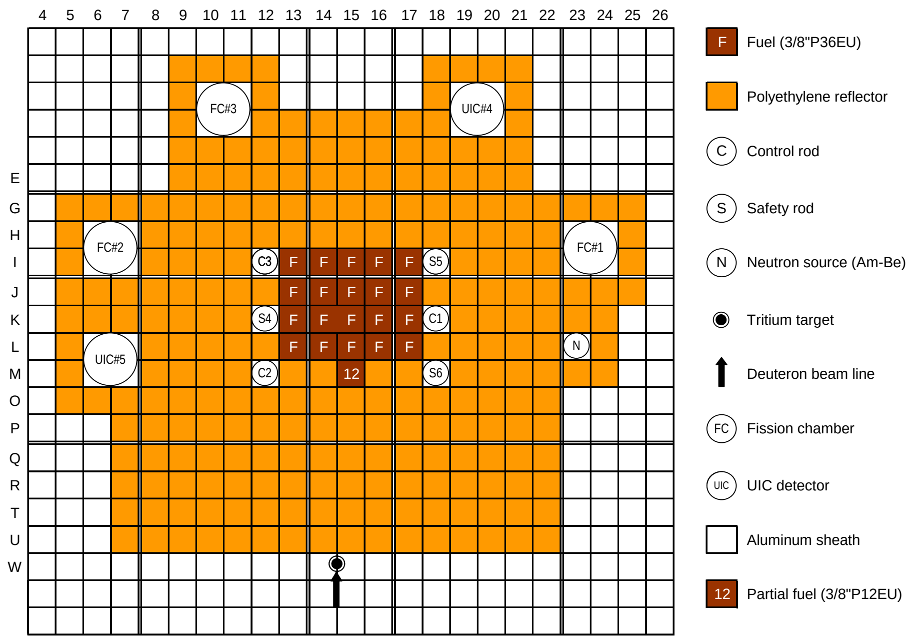

Figure 1. KUCA core configuration of ADS experiments (Reference core)

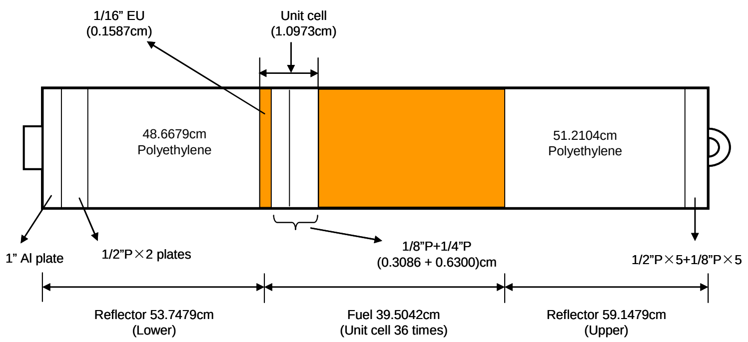

Figure 2. Composition of normal fuel "F" shown in Figure 1

2.2. Neutron Guide and Beam Duct

In KUCA, a tritium target is located outside the core, and the neutron guide and the beam duct were installed in the polyethylene reflector region, as shown in Figure 3 (Neutron guide core). The main purpose of installing the neutron guide and the beam duct was to direct the highest number possible of the high-energy neutrons generated in the target region to the center of the core.

For shielding the high-energy neutrons around the target region and thermal neutrons moderated in the reflector region, the neutron shield comprises several materials inserted into the core: the iron (Fe) for shielding the high-energy neutrons generated in the target region by inelastic scattering reactions; the polyethylene containing 10wt% boron (Polyethylene + boron (10wt%)) for shielding the thermal neutrons moderated by absorption reactions in the reflector region; the beam duct for directing collimated high-energy neutrons, by streaming effect, to the core region. And, SV assembly was composed of one $5.08 \times 5.08 \times 5.08\ cm^3$ center void and 32 fuel unit cells,

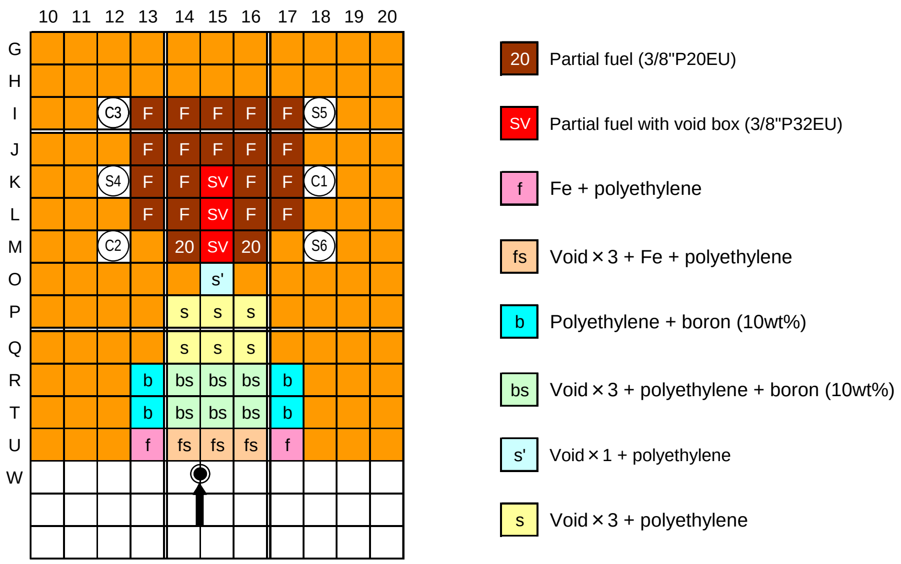

Figure 3. KUCA core configuration of ADS experiments (Neutron guide core)

3. Subcriticality Measurements using External Neutron Sources

3.1. Neutron Noise Methods

The KUCA A-core configuration by neutron noise methods ([6]): Feyman-α method; Rossi-α method is shown in Figure 4. The subcriticality measurements were conducted using four 1/2"ϕ BF_3 detectors at several positions and 14 MeV neutrons by D-T reaction in pulsed neutron generator were injected into the KUCA A-core with pulsed period of 1, 10 and 20 ms. The results of the subcriticality were revealed in Table I. The reference value of subcriticality was evaluated by pulsed neutron method. The measured evaluation by Feynman-α method varied two methodologies: stochastic and deterministic ones on the basis of one-point reactor approximation. Note that the calculated values of β_{eff} and l are 7.627×10^{-3} and 4.304×10^{-5} (sec), respectively, in this core.

As shown in Table I, α-values by Feyman-α and Rossi-α methods showed good agreement with that of reference within the relative difference of 7%, and in cases of 1 and 10 ms, it was found to be as the same tendency as in 20 ms. These facts demonstrated that both Feyman-α and Rossi-α methods get fairly reliable about subcriticality measurement even for an external source of D-T accelerator.

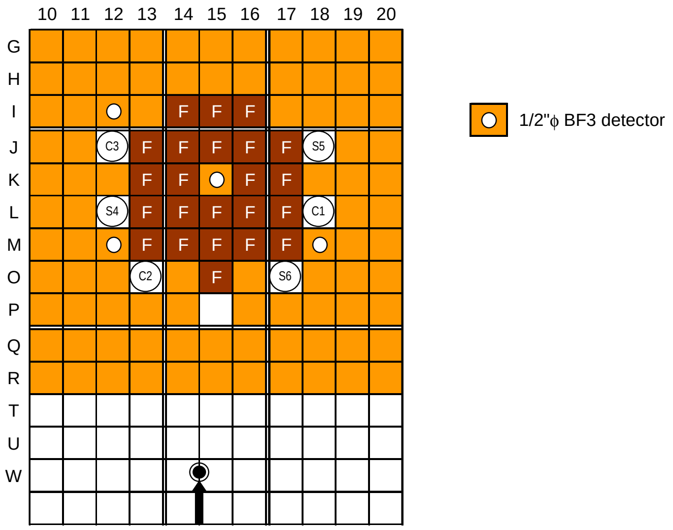

Figure 4. KUCA core configuration of subcriticality measurement experiments by neutron noise methods

Table I Measured subcriticality (%Δk/k) using neutron noise method (pulsed period 20 (ms))

Case	Subcriticality (%Δk/k)	Reference α (1/sec)	Feynman* α (1/sec)	Feynman** α (1/sec)	Rossi (1/sec)
I-1	0.50±0.01	266±2	253±1	285±1	263±1
I-2	0.99±0.01	369±3	373±2	383±1	368±2
I-3	1.58±0.02	494±3	495±3	508±1	500±5
II-4	2.07±0.02	598±4	601±4	631±2	599±7

*: Stochastic method, **: Deterministic method, (Provided from Dr. Y. Kitamura of JAEA, Japan)

3.2. Neutron Source Multiplication Method

Top view of the KUCA A-core configuration by neutron source multiplication method ([7]) (NSM method) is shown in Figure 5. The experiments were carried out at the neutron guide core, and the subcriticality measurements were conducted using four 1/2”ϕ BF_3 detectors at several positions and ^{252}Cf neutron source as an external source at the positions (15, K), (16, M) and (16, O). The results of the subcriticality were revealed in Table II. Subcriticality was obtained by inserting all control and safety rods into the core, and was deduced experimentally by the combination of reactivity worth of each rod by rod drop method and its calibration curve by positive period method. The results of subcriticality measurement by NSM method were observed in the position dependence on both BF_3 detectors and ^{252}Cf source positions, while the accuracy of comparison with the reference and measured results by the detectors was found in relative difference of about 20% at maximum.

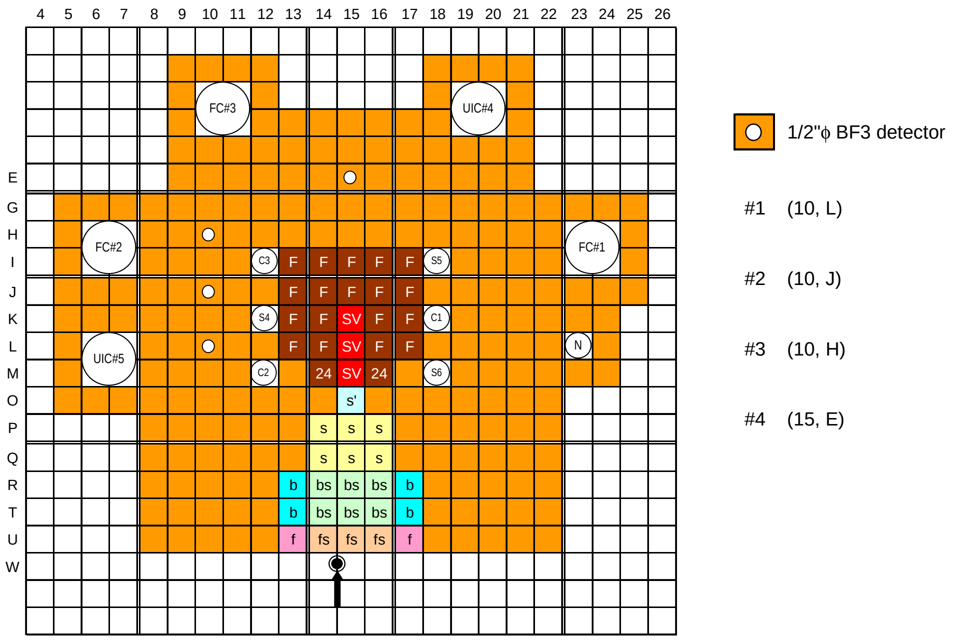

Figure 5. KUCA core configuration of subcriticality measurement experiments by NSM method

Table II Measured subcriticality using neutron source multiplication method at each detector position shown in Fig. 5

Source position	Reference (%Δk/k)	(10, L)	(10, J)	(10, H)	(15, E)	FC#1	FC#2	FC#3
(15, K)	1.64 (0.02)	1.75 (0.02)	1.50 (0.02)	1.59 (0.02)	1.30 (0.01)	1.76 (0.02)	1.67 (0.02)	1.58 (0.02)
(16, M)		1.96 (0.02)	1.83 (0.02)	1.59 (0.02)	1.49 (0.01)	1.71 (0.02)	1.68 (0.02)	1.57 (0.02)
(16, O)		1.93 (0.02)	1.85 (0.02)	1.61 (0.02)	1.54 (0.01)	1.76 (0.02)	1.70 (0.02)	1.59 (0.02)

( ): Error of subcriticality (%Δk/k)

3.3 Pulsed Neutron Method

The principle of the optical fiber neutron detector ([8], [9]) is to have neutrons interact with a neutron converter material. The reaction product can then produce photons in a scintillating material which is extracted through plastic optical fiber, multiplied into a photo-multiplier and converted to electrical signals. In the present experiments, detectors were formed by a mixture of lithium-6 (^{6}Li) enriched LiF and ZnS(Ag) scintillator pasted at the tip of a 1 mm diameter plastic optical fiber. ^{6}Li was selected for its large ^{6}Li(n, t)^{4}He cross section for thermal neutrons. The main advantages of the optical fiber neutron detector are not only its relative simplicity and low building cost, but also its very small size, which allows it to be used in small cores such as those in KUCA with negligible perturbation. The drawbacks include low sensibility because of very small quantity of reacting material and the treatment of the signal required to remove as much as possible of the noise from γ-ray interferences without losing too much of the valuable signal. A schema of the detection settings and size references is shown in Figure 6. Levels of the thermal neutron flux in the measurements were between 10^6 to 10^4 *n*/*sec*/cm^2, for the duration of irradiation in hours.

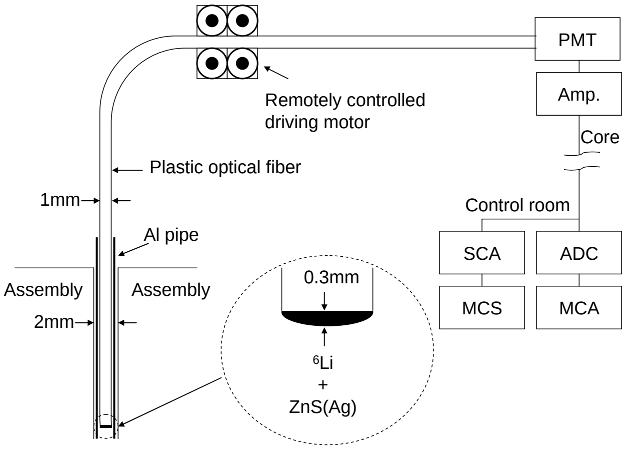

Figure 6. Schema of an optical fiber detection system

To provide information on detector position dependency of the measurements, each core was set with three detectors: Fiber #1 in the fuel region, Fiber #2 in the boundary region between the standard and partial fuel assemblies, and Fiber #3 in the neutron guide region (Figure 7). Moreover, another fiber with a ThO_2 scintillator being fission reactive to the high-energy neutrons was used as a monitor of source intensity of 14 MeV neutrons. The quantity of neutron converter and scintillating material, in the order of milligram, cannot be made identical for all detectors and, thus, precludes making absolute comparison between count rates. A representative selection of the experimental results of the subcriticalities ([10], [11], [12]) is shown in Table III for each detector. Although better for small subcriticality, an overall 10% in relative error with MCNP was taken into account for a comparison of the subcriticalities. For a comparison between the detectors, remarkably Fiber #1 appeared little affected by the increase in the subcriticality, with the discrepancy being within 7% even for the largest subcriticality, while Fibers #2 and #3 reached about 30%.

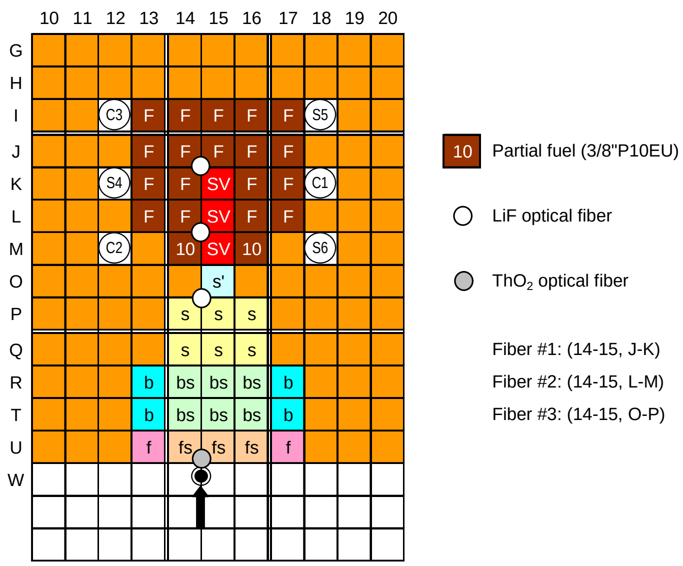

Figure 7. KUCA core configuration of subcriticality measurement experiments by pulsed neutron method

Table III Measured subcriticality using pulsed neutron method at each optical fiber detector position shown in Fig. 7

	Subcriticality (%Δk/k)			
Case	MCNP	Fiber #1	Fiber #2	Fiber #3
III-1	0.97±0.03	0.99±0.01	0.96±0.01	0.99±0.01
III-2	1.83±0.03	1.88±0.02	2.15±0.02	1.78±0.02
III-3	2.55±0.03	2.55±0.03	3.12±0.03	2.42±0.02
III-4	3.45±0.03	3.40±0.03	3.25±0.03	3.63±0.04
III-5	4.15±0.03	4.49±0.04	4.00±0.04	4.60±0.05
III-6	6.24±0.03	5.89±0.06	6.54±0.07	6.87±0.07
III-7	6.76±0.03	6.59±0.07	10.01±0.10	7.56±0.08
III-8	7.41±0.03	7.55±0.08	8.18±0.08	8.64±0.09
III-9	10.38±0.03	10.24±0.10	12.28±0.12	11.93±0.12

4. Concluding Remarks

At the KUCA A-core, subcriticality measurement experiments in the ADS with 14 MeV neutrons were carried out by using several methods: Feynman-α; Rossi-α; Neutron source multiplication; Pulsed neutron methods. In these subcriticality benchmark problems, these facts demonstrated experimentally that the dependence of subcriticality on the detector and the neutron source positions was found, and that the measurement precision varied both in accordance with the degree of subcriticality and each measurement technique.

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