Research on Accelerator Driven Subcritical Reactor at Kyoto University Critical Assembly (KUCA)

Cheol Ho Pyeon, Tsuyoshi Misawa, Hironobu Unesaki, Chihiro Ichihara and Kaichiro Mishima

Nuclear Engineering Science Division, Research Reactor Institute, Kyoto University
Asashiro-nishi, Kumatori-cho, Sennan-gun, Osaka 590-0494, Japan
pyeon@kuca.rri.kyoto-u.ac.jp

At KURRI, a new project for research on ADS is now in progress where a new ring type accelerator based on the up-to-date FFAG technology is constructed, and protons with arbitrary energy up to 150MeV could be generated and high-energy neutrons could be injected into a core of KUCA. KUCA is a thermal or epi-thermal reactor which uses enriched uranium fuel plates and polyethylene plates as moderator, and its core configuration or neutron spectrum can be easily changed. The accelerator system is now under construction and new experiments with 150MeV protons on ADS will be stared within FY2007.

Prior to starting the ADSR experiment with 150MeV protons, basic research on ADSR with 14MeV neutrons has been performed in combination with a Cockcroft-Walton type accelerator, which was already equipped inside the KUCA building and produces pulsed neutrons by a D-T reaction. The following experiments have been carried out so far: subcriticality measurement by pulsed neutron methods, neutron noise analysis such as new Feynman-alpha method with a pulsed neutron source to measure subcriticality, reaction rate distribution measurement by foil activation method in a subcritical core, fast neutron spectrum measurement inside the core by the unfolding method, and so on. The experimental analyses were executed by a deterministic method using an SN transport code and Monte Carlo code.

I. INTRODUCTION

The Research Reactor Institute of Kyoto University (KURRI) is going ahead with a research project (Ref. 1) on an Accelerator Driven Subcritical Reactor (ADSR) using the Fixed Field Alternating Gradient (FFAG) accelerator (Ref. 2). The FFAG accelerator, which is a synchrotron-type accelerator, was developed in the High Energy Accelerator Research Organization (KEK) of Japan. The goal of the research project is to demonstrate the basic feasibility of an ADSR as a next generation neutron source multiplication system using the Kyoto University Critical Assembly (KUCA) coupled with a newly developed variable energy FFAG accelerator. In the ADSR experiments with 150MeV protons starting within FY2007, high-energy neutrons generated by nuclear reactions with 150MeV proton beam in a tungsten target will be injected into a solid-moderated and -reflected core (A-core) in the thermal or epi-thermal neutron field of the KUCA.

Prior to operation of the FFAG accelerator, it is inevitable to evaluate neutronic characteristics for the ADSR of the KUCA and to establish measurement techniques for several neutronic parameters in the ADSR with 150MeV protons. For these purposes, a series of experiments in the ADSR with 14MeV neutrons by D-T reactions with a Cockcroft-Walton type accelerator had been carried out at the KUCA A-core. In the experiments, several neutronic parameters had been measured: neutron multiplication (Ref. 3), neutron decay constant (Ref. 4), reaction rate distribution (Ref. 5), neutron spectrum (Ref. 6) and subcriticality (Ref. 7). The numerical analyses for the experiments had been executed by using Monte Carlo calculation code MCNP-4C2 coupling with nuclear data libraries: ENDF/B-VI.2 and JENDL-3.3. Through the analyses, very important and valuable results have been obtained for neutronic characteristics in the ADSR with 14MeV neutrons. After completing the examinations of the FFAG accelerator, ADSR experiments with 150MeV protons are planned by using the FFAG accelerator including experiments topics using the 14MeV pulsed neutrons: γ-ray spectrum detection at the target and in the core region, power monitoring of the core during beam current change and control rod movement. Moreover, these experiments could be possibly carried out in several neutron spectra and γ-ray fields using cores consisting of several kinds of fuel and reflectors; highly enriched uranium, thorium fuel and natural uranium; polyethylene and graphite.

The Accelerator Driven System (ADS) benchmark problems in the KUCA are based on both the 14MeV neutrons generated from a pulsed neutron generator and 150MeV protons generated from the FFAG accelerator. Among the benchmark problems, the valuable and important information on the reaction rate distribution, the neutron decay constant, subcriticality measurement by pulsed neutron and source multiplication methods is described in this paper. The KUCA A-core configuration and the ADS benchmark problems are presented in Sec. II; the results of experiments and analyses by MCNP-4C2 code with ENDF/B-VI.2 and JENDL-3.3, in Sec. III, and the summary of the study in Sec. IV.

II. ADSR IN KUCA

II.A. KUCA A-core Configuration

The KUCA comprises solid-moderated and -reflected type-A and -B cores, and a water-moderated and -reflected type-C core. In the series of ADSR experiments with 14MeV neutrons, the solid-moderated and -reflected type-A core was combined with a Cockcroft-Walton type pulsed neutron generator installed at the KUCA. The materials used in 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 more than 500mm long. 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 400mm.

The present configuration of the ADSR at KUCA is a slightly different from several other ADS systems, because a target is located outside the core. In the experiments, therefore, neutron guides composed of several shielding materials and a beam duct (void) were installed in the polyethylene reflector region, as shown in Fig. 1. The main purpose of installing the neutron guide was to direct the highest number possible of the high-energy neutrons generated at the target to the center of the core. For shielding the high-energy and thermal neutrons, collimator comprises several materials inserted into the core, iron (Fe) for shielding the high-energy neutrons generated in the target region by inelastic scattering reactions; the polyethylene containing 10% boron (Polyethylene + boron (10%)) for shielding the thermal neutrons, moderated by absorption reactions, in the reflector region; beam duct for directing collimated high-energy neutrons, by streaming effect, to the core region. Note that a new target of the ADSR with the FFAG accelerator will be also placed outside the A-core, and that the neuron guide will be installed from the target region to the center of the core.

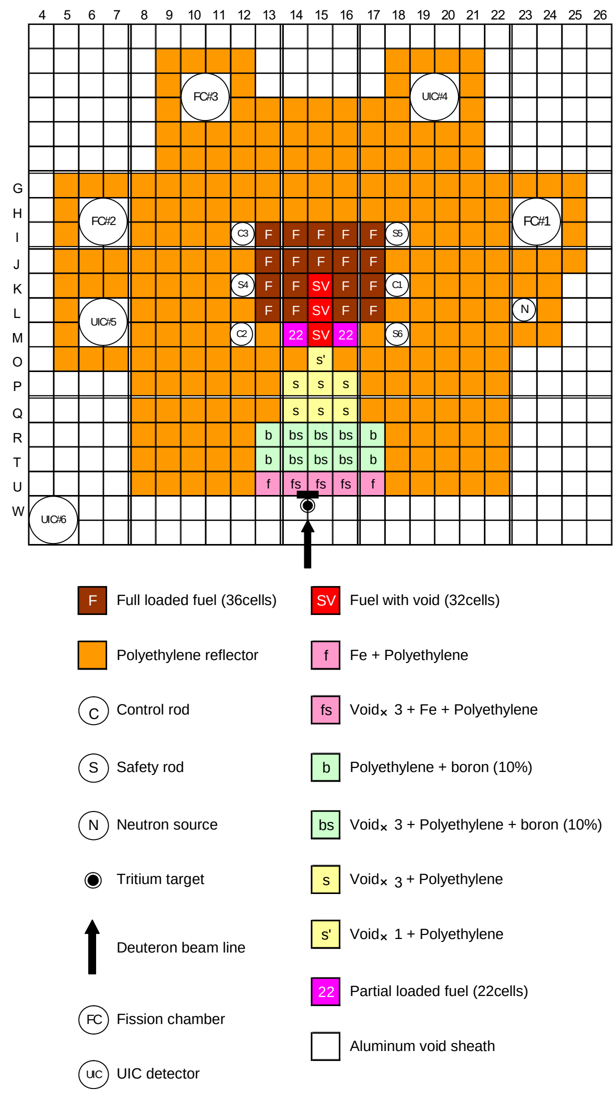

Fig. 1. Core configuration of ADSR experiments with 14MeV neutrons at KUCA A-core.

II.B. 14MeV pulsed Neutron Generator

The pulsed neutron generator was combined with the A-core, where 14MeV pulsed neutrons were injected into the subcritical system through the polyethylene reflector. In the experiments, the deuteron beam (accelerated up to 160keV in beam energy, 0.5mA in beam current, 10μs in pulse width and 500Hz in pulse repetition rate) was led to the tritium target located outside the polyethylene reflector. At the pulsed neutron generator, the beam peak intensity is about 6.5mA for a pulse width of up to 100μs, and the repetition rate varies from a few Hz to 30kHz, providing up to 1×10^8 *n*/s. The main characteristics of the KUCA pulsed neutron generator are shown in Table I.

Table I. Main characteristics of KUCA pulsed neutron generator.

Deuteron beam energy (keV)	300 (Maximum)
Beam current (mA)	6.5 (Maximum)
Pulse repetition rate (Hz)	0.1 – 30,000
Pulse width (μs)	0.3 – 100
Spot size (mmϕ)	25
Duty ratio (%)	1 (Maximum)

In the ADSR with 150MeV protons, all of the ion beta, booster and main accelerator is composed of the FFAG accelerators, and the maximum power of the A-core and maximum neutron yield could be 100W and 1×10^{10} neutrons/s, respectively, when 150MeV protons generated from the FFAG accelerator are injected onto the tungsten target. The main characteristics of the FFAG accelerator are indicated in Table II. Maximum beam current of the FFAG accelerator at the target is 1μA and the average is 1nA.

Table II. Main characteristics of FFAG accelerator.

Number of sectors	12
Proton energy	2.5 – 150MeV
Repetition rate	120Hz
Pulsed width	60ns
Beam current	1μA (Max.), 1nA (Ave.)
Rf frequency	1.5 – 4.6MHz
Field index	7.5
Closed orbit radius	4.4 – 5.3m

III. RESULTS AND DISCUSSION

III.A. Reaction Rate Distribution

The experiments were carried out in the subcritical state by using the pulsed neutron generator. The reaction rate distribution was then measured by the foil activation method. The subcritical state was acquired by inserting the control or safety rods, or both, up to the lower limit in the critical state. The experimental error of reactivity measurement was estimated to be less than 10%. Indium (In) wire 1.5mmϕ in diameter and 60cm long was set in the axial center position of (16,17–J,W) along the vertical shown in Fig. 1, for measuring the reaction rate distribution

As shown in Fig. 2, these results showed that the effects of the neutron guide were clearly exerted in both the neutron shield and the fuel regions. Moreover, from the results of the reaction rates in Cases 3 and 4, it was considered that the window size of the beam duct in Case 4 was more effective in the SV fuel region than in Case 3. Therefore, an optimized combination of the neutron shield and the size of the beam duct in Case 4 was made to direct efficiently the high-energy neutrons to the fuel region. Thus, the installation of the neutron guide was valid for directing the high-energy neutrons to the fuel region, and the pattern of the neutron guide and the beam duct shown in Case 4 was experimentally appropriate for the purpose of the installation of the neutron guide and the beam duct, as demonstrated by the comparison between the results of the reaction rate distributions.

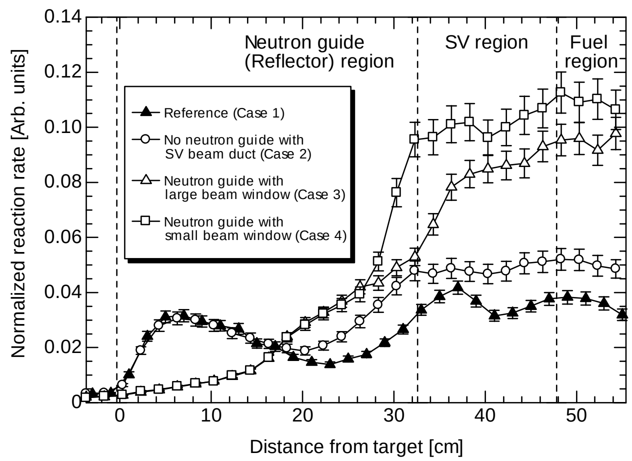

Fig. 2. Measured reaction rate distributions obtained from ADSR experiments with 14MeV neutrons.

III.B. Neutron Decay Constant

The principle of the optical fiber neutron (Refs. 7 and 8) detector is to have neutrons interact with a neutron converter material whose reaction products then produce photons in a scintillating material which can be extracted through plastic optical fiber, multiplied into a photo-multiplier and converted to an electrical signal. In the present experiments, detectors were formed by a mixture of ^{6}Li enriched LiF and ZnS(Ag) scintillator pasted at the tip of a 1mm diameter plastic optical fiber. ^{6}Li was selected for its large ^{6}Li(n,t)^{4}He cross section with thermal neutrons, which were of interest.

The main advantages of optical fiber neutron detectors are not only their relative simplicity and low cost, but also their extremely small size, which allow them to be used in small cores such as the KUCA with negligible perturbation. Disadvantages include low sensitivity due to the extreme small quantity of reacting material, and signal treatment required to remove as much as possible the noise from γ-ray interferences, but without loosing too much of the valuable signal. Fig. 3 gives a schematic view of the detection setting and size references. To establish the detector time response, the arc pulse of the accelerator was used as trigger signal for the Multi Channel Analyzer to obtain a final result equivalent to the response to a single pulse. Levels of thermal neutron flux considered in the present measurements were between 10^6 to 10^4 n/cm^2/s, for irradiation times on the order of hours. Fig. 4 shows the comparison of spatial dependence on neutron decay obtained by the optical fiber detector system set in both core and reflector regions.

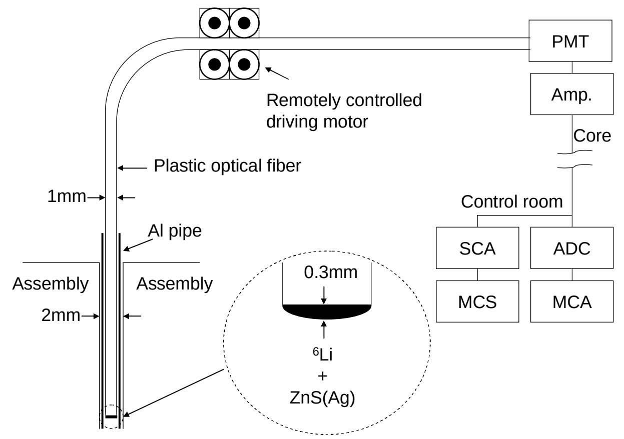

Fig. 3. Schematic view of the optical fiber detector system utilized in measurement of the neutron decay constant and subcriticality by the pulsed neutron method.

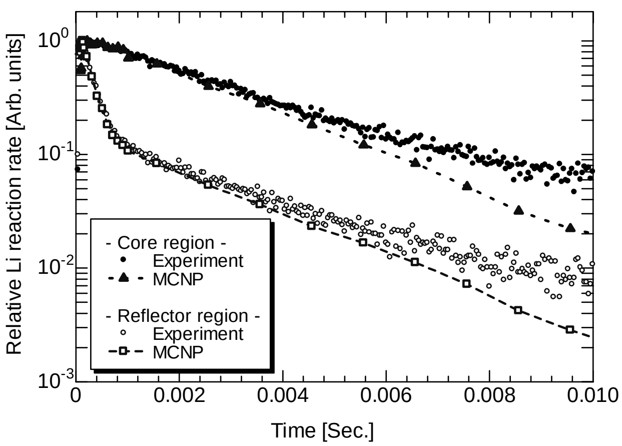

Fig. 4. Comparison of spatial dependence on neutron decay obtained by the optical fiber detector system set in both core and reflector regions.

Calculations were conducted using the Monte Carlos code MCNP-4C2 and the JENDL-3.3 nuclear data library. Note that as such calculations are known to tend to overestimate effective multiplication factors, before conducting source calculations, reactivity adjustment were considered: the density of the fuel was artificially reduced by 5%. This adjustment was estimated in the reflected core such that critical state calculation gives a k_{eff} equivalent to 1 (in effect 0.99985±0.00025). In the case of the neutron guided cores, a separate reduction factor of 3.5% was used as well for comparison.

For dynamic calculations, time tallies were taken at the equivalent detector position, without the actual inclusion of the detector in the calculation geometry. Point detectors were considered (with a 1mm diameter sphere of exclusion) as well as a volume flux tally in 5cm long 1mm in diameter cylindrical volume centered at the detector position; this in order to estimate the validity of the use of point detector tally and the optimization of calculation time.

For axial neutron flux distributions, 2cm long 1mm in diameter volumes were tallied at the detector positions to reconstruct the measurement results. In addition, to monitor the validity of the integral flux distribution to represent the neutron multiplication, it has been compared to the total neutron production from the core.

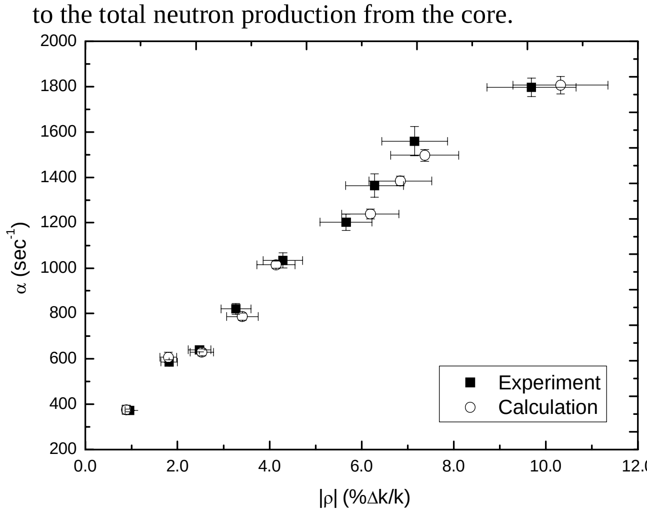

Fig. 5. Comparison of measured and calculated relation between subcriticality by the pulsed neutron method and neutron decay constant.

Considering the dependency of the prompt neutron decay constant with subcriticality, Fig. 5 shows the measurements and calculations results for a BF_3 detector set in the position of (14, 15 – M, O) shown in Fig. 1. In the case of Fig. 5, measurements, though underestimating the subcriticality, tended to give a relatively good evaluation of the prompt neutron decay constant. However, it was found to present a little underestimation of the prompt neutron decay constant for subcriticality higher than 7%. The linear variation of the prompt neutron decay constant with subcriticality was followed for all subcriticalities, and without visible variation due to the neutron guide.

It is finally notable that the calculation results alone did not present the variations between detector positions nor the effect of the neutron guide. The presented results allowed some estimation of the relative effects among the various parameters susceptible to influence the measurement of subcriticality by the neutron pulse technique and prompt neutron decay constant. Although the same value of the delayed neutron fraction had been used for the area ratio method, the results from the detectors allowed evaluation of the variation of the delayed neutron fraction to be at most of the order of the uncertainty over the subcriticality. The neutron guide effect on the spectrum was visible only in the center of the core, which was very counter intuitive; as one would expect the detectors to be affected as they are closer to the neutron source. Those results demonstrate experimentally the relatively small contribution of the variation of the delayed neutron fraction and spectrum variation induced by the neutron guide on the position dependency of the measurement.

Given the calculation results showing no variation between detectors nor core geometry variations, and the validation of those calculation results by the measurements, the remaining possible influences on position dependency of subcriticality by pulse neutron method and prompt decay constant can be seen as experimental causes.

III.C. Measurement of Subcriticality by Source Multiplication Method with Higher-Mode

In the Neutron Source Multiplication (NSM) method with higher-mode flux, the neutron count of detector N_0 at position of x is expressed as follow:

$$N_0 = \left\{ -\frac{\varphi_0^+(x_0)}{\Delta\rho}\varphi_0(x) + \sum_{i=1}^{N} \frac{\varphi_i^+(x_0)}{\frac{1}{\lambda_i} - 1 - \Delta\rho}\varphi_i(x) \right\} \varepsilon S \quad , \qquad (1)$$

where φ_i and φ_i^+ indicates i-th λ-mode flux and i-th mode adjoint flux, respectively. λ_i is i-th mode eigenvalue (i=0, N), N is maximum number of expansion modes, $\Delta\rho$ is reactivity, ε is detector efficiency, S is source intensity, and x_0 is source position. This equation can be derived from the neutron balance equation with an external neutron source in the subcritical system caused by perturbation, which is assumed uniformly over reactor core.

The value of εS can be determined by Eq. (1), when the neutron count of the detector is measured in a known subcritical state, and higher-mode fluxes and eigenvalues in an unperturbed system are known beforehand through calculations. And, subcriticality can be obtained numerically by solving Eq. (1), when the neutron count of the detector is measured in other unknown subcritical states. The results of subcriticality measurements in the KUCA neutron guided core in Fig. 1 are shown in Table III.

Table III. Comparison between subcriticalities with ordinary and high-mode neutron source multiplication methods.

	FC#1 [%$\Delta k/k$]	FC#2 [%$\Delta k/k$]	FC#3 [%$\Delta k/k$]	Reference [%$\Delta k/k$]
Higher-mode	-1.70 (3.80)	-1.62 (-1.09)	-1.54 (-5.97)	-1.64
Ordinary	-1.76 (7.17)	-1.67 (1.93)	-1.58 (-3.41)	
Higher-mode	-1.72 (3.67)	-1.62 (-2.36)	-1.52 (-8.38)	-1.66
Ordinary	-1.71 (2.78)	-1.68 (1.39)	-1.57 (-5.52)	
Higher-mode	-10.43 (61.75)	-10.07 (56.17)	-4.60 (-28.66)	-6.45
Ordinary	-13.54 (109.92)	-12.94 (100.69)	-5.15 (-20.19)	

( ): Relative difference between reference and source multiplication methods.

In the case of small subcriticality, the results by the NSM method with higher-mode agreed with reference values, some results by the NSM method with higher-mode were worse than those by the ordinary NSM method. It was found that the accuracy of the results by the NSM method with higher-mode was not different from that by the ordinary NSM method. The dependency of the ^{252}Cf position was observed between the results in the positions (15, N) and (16, O) or (16, M) shown in Fig. 1. The void region would cause the dependency. In the case of large subcriticality, the accuracy of the results by the NSM method with higher-mode is better than that by the ordinary NSM method, however, the accuracy of the results by both higher-mode and ordinary NSM methods was not good. And the detector position dependency in the results by the NSM method with higher-mode was not decreased well.

The void region existed in the core and emitted neutrons from the ^{252}Cf streamed along the void region. Therefore, the ^{252}Cf would not behave like a point source. To measure subcriticality accurately in the core like this experiment, it is expected that the external neutron source position should be considered well in solving Eq. (1). For example, the external neutron source position is considered such as inner surface of the void. In the present analyses, since the higher-mode calculations were performed by two-dimensional calculations, it is also expected to expand the higher-mode calculation into three-dimensional and multi-energy-group calculations.

IV. CONCLUSIONS

A series of ADS experiments were carried out at KUCA A-core by using a 14MeV pulsed neutron generator to evaluate neutronic characteristics in the subcritical system. Through the ADS experiments with 14MeV neutrons, the experiments and analyses by

MCNP-4C2 with ENDF/B-VI.2 and JENDL-3.3 revealed the following:

1. The reaction rate distributions by In wire demonstrated that the installation of the neutron guide and the beam duct was valid for directing the high-energy neutrons to the fuel region.
2. The configuration of the measured reaction rate distributions in the subcritical system can be reconstructed well by fixed source calculations based on the combined use of MCNP-4C2 and ENDF/B-VI.2.
3. Optical fiber detectors have been estimated to be promising for reactivity and prompt neutron decay constant evaluation by the pulsed neutron method and integral flux measurements at KUCA. Position dependency of dynamic measurement was observed with subcriticality larger than 8.0%$\Delta k/k$.
4. The subcriticalities by the NSM method with higher-mode were measured accurately, and the detector position dependency on the subcriticalities by the NSM method with higher-mode was decreased compared with that by the ordinary NSM method. In addition, the effect for changing in the positions of the external neutron source is also smaller in the NSM method with higher-mode than the ordinary NSM method.
5. In the core installed neutron guide, a large discrepancy was observed between the measured subcriticalities of these experimental results by both higher-mode and ordinary NSM methods and reference values.

In the future, it is expected that the basic research activity of ADS with 150MeV protons could progress on the basis of these ADS benchmark problems with 14MeV neutrons in the KUCA, especially neutronic characteristics in terms of reactor physics.

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