Present State of Accelerator Driven Subcritical Reactor (ADSR) Project in Kyoto University Research Reactor Institute (KURRI)

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Abstract

The Kyoto University Research Reactor Institute (KURRI) has a plan to operate the Accelerator Driven Subcritical Reactor (ADSR) by using the Fixed Field Alternating Gradient (FFAG) accelerator, which is a synchrotron-type accelerator developed in the High Energy Accelerator Research Organization (KEK) of Japan. In this ADSR, high-energy neutrons generated by interaction of 150MeV proton beam with heavy metal will be injected into a solid-moderated and -reflected thermal core (A-core) of the Kyoto University Critical Assembly (KUCA) in the KURRI. At the A-core, a series of preliminary experiments had been carried out for examination of neutronic characteristics in the ADSR by using 14MeV pulsed neutron generator combined with the A-core. The static and dynamic parameters were evaluated in the subcritical systems: neutron multiplication, neutron decay constant, reaction rate distribution, neutron spectrum and subcriticality. The numerical analyses for the experiments had been executed by using Monte Carlo calculation code MCNP-4C3 coupling with nuclear data libraries: ENDF/B-VI.2 and JENDL-3.3. From the comparison between the experiments and the calculations, it was obtained with the results very important and valuable for a new ADSR with the FFAG accelerator. After the injection by the FFAG accelerator, both new experiments and numerical simulations could be conducted for the high-energy neutrons generated by 150MeV proton beam.

KEYWORDS: KUCA, ADSR, Pulsed Neutron Generator, FFAG Accelerator, Neutronic characteristics, Monte Carlo Analyses

1. Introduction

The Kyoto University Research Reactor Institute (KURRI) has a plan [1] to operate the Accelerator Driven Subcritical Reactor (ADSR) by using the Fixed Field Alternating Gradient (FFAG) accelerator [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 plan is to establish a next generation neutron source in the KURRI. A new accelerator will be attached to the Kyoto University Critical Assembly (KUCA) on August, 2006, and high-energy neutrons generated by interaction of

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high-energy proton beam of 150MeV with heavy metal, such as Tungsten (W), will be injected into a solid-moderated and -reflected thermal core (A-core) of the KUCA with highly enriched uranium fuel on September, 2006. Before operating 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. For these purposes, a series of preliminary experiments in the ADSR with 14MeV pulsed neutron generator [3] by D-T reactions at a Cockcroft-Walton type accelerator had been carried out in several subcriticality systems at the KUCA A-core. In the experiments, several neutronic parameters had been measured: neutron multiplication [4], neutron decay constant [4], reaction rate distribution[5], neutron spectrum [6] and subcriticality [7]. The numerical analyses for the experiments had been executed by using Monte Carlo calculation code MCNP-4C3 [8] coupling with nuclear data libraries: ENDF/B-VI.2 and JENDL-3.3.

The FFAG accelerator, the KUCA A-core configuration and ADSR benchmark problem are presented in Sec. 2; the results of experiments and analyses by MCNP-4C3 in Sec. 3, and the conclusion of the study in Sec. 4.

2. ADSR in KUCA

2.1 FFAG Accelerator

The conceptual image of the ADSR in the KURRI is shown in Fig. 1. In this ADSR system, all ion beta, booster and main accelerator are composed of the FFAG accelerators, and maximum power of the A-core and maximum neutron yield are 100W and 1×10^{11} *n*/s, respectively. The main characteristics of the FFAG accelerator are indicated in Table 1. Maximum beam current of the FFAG accelerator at the target is 1μA and average one is 1nA.

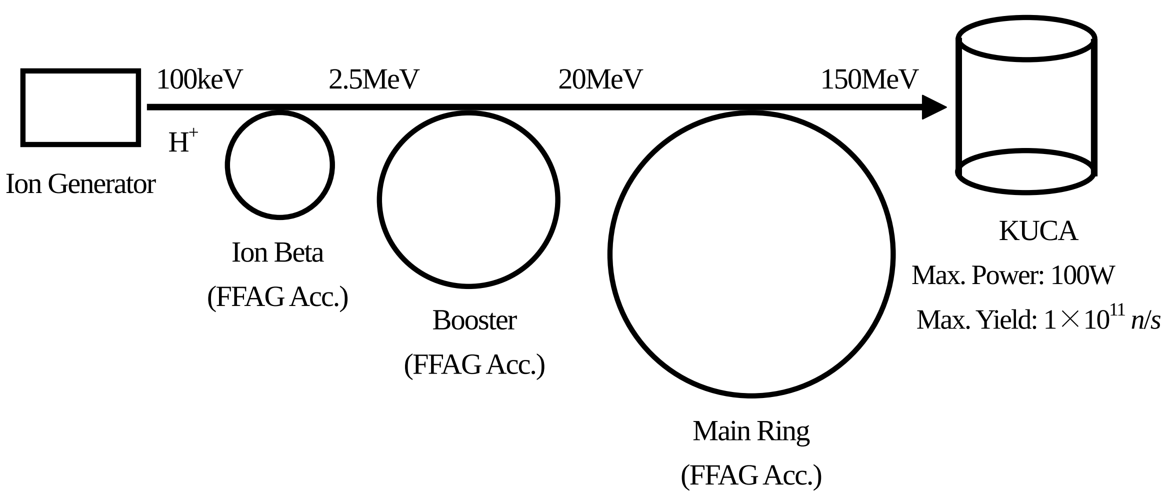

Figure 1: Conceptual image of ADSR with FFAG accelerators in KURRI.

Table 1: 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

2.2 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 present series of experiments, 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 of more than 50cm long, as shown in Fig. 2. The fuel rod, a 93% 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.

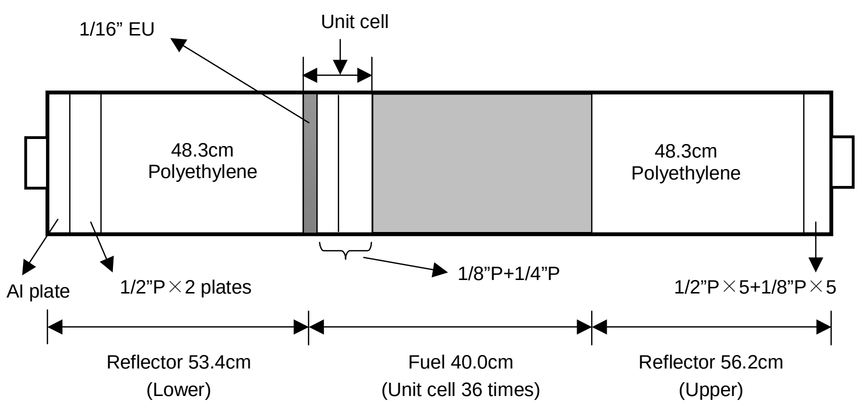

Figure 2: Fall sideways view of configuration of fuel rod of A3/8”P36EU(3) in KUCA A-core (EU: Enriched uranium, Al: Aluminum, P: Polyethylene).

The present configuration of the ADSR at KUCA is a slightly different from several ADSR systems, because a target is located outside the core. In the experiments, therefore, collimator and beam duct were installed in the polyethylene reflector region, as shown in Fig. 3. The main purpose of installing the collimator 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 and thermal neutrons, the collimator comprises several materials inserted into the core, 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; the beam duct (void) for directing collimated high-energy neutrons, by streaming effect, to the core region. Note that a new target of the ADSR system with the FFAG accelerator will be also placed outside the A-core, and that collimator and beam duct be installed in target region to the center of the core.

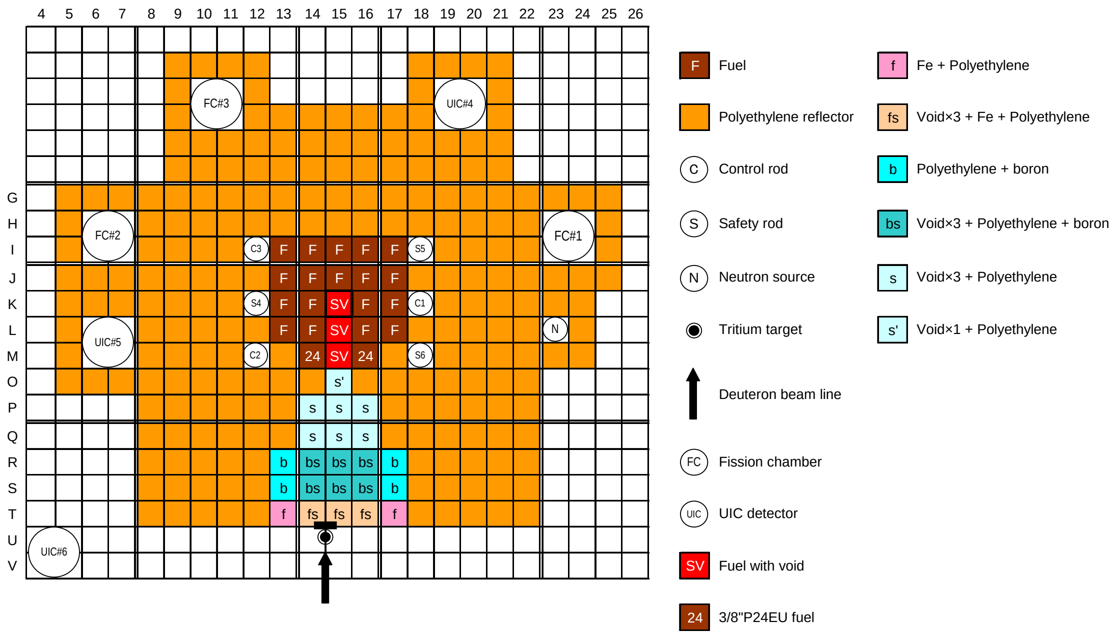

Figure 3: Top view of configuration of A-core experiments with collimator and beam duct.

2.3 ADSR Benchmark Problem

The KUCA is equipped with these following cores coupling several kinds of fuel and reflectors:

- Polyethylene moderated and reflected core with highly enriched uranium fuel,
- Graphite moderated and reflected core with thorium fuel,
- (Polyethylene + Graphite) moderated and reflected core with (thorium + natural uranium) fuel,
- Neutronic decoupling core modeling large size core.

After introducing the FFAG accelerator, reactor physics experiments for the ADSR are planned at a next stage as follows:

- Measurement of subcriticality by pulsed neutron method, neutron noise method and source multiplication method,
- Measurement of reaction rate distribution in the core by foil activation method and optical fiber detection system,
- Measurement of neutron spectrum by foil activation method and organic scintillator,
- Evaluation of neutron multiplication characteristics ($M = S/1 - k_{eff}$),
- γ-rays spectrum detection at the target and in the core region,
- Power monitoring of the core in case of beam current change or moving control rods,
- Optimization of collimator and beam duct installed in the A-core.

Both new experiments and numerical simulations could be conducted for the high-energy neutrons obtained by 150MeV proton beam generated in the FFAG accelerator, on the basis of the important and valuable information obtained in the preliminary experiments by using 14MeV pulsed neutron generator. At the next stage, several benchmark experiments could be opened not only to Japan but also to other countries in the future. On the other hand, these benchmark problems are positioned as basic research for ADSR system development and nuclear transmutation technology in corporation with international collaboration research program [9] published by J-PARC project of JAEA in February 2006.

3. Results and Discussion

3.1 Neutron Multiplication and Neutron Decay Constant Experiments

The optical fiber detector system was utilized to measure both reaction rate distribution and neutron decay behavior; a mixture of ^{6}Li enriched LiF and ZnS (Ag) scintillator was pasted on one end of a plastic optical fiber of 1mm in diameter with the instant adhesive. The LiF fiber detectors of approximately 2mm in diameter with cladding were inserted into an Al tube settled in a narrow air gap of approximately 3mm in diameter surrounded by corners of 4 fuel or reflector rods.

For the measurement of the reaction rate distribution, the LiF fiber detectors set in the vicinity of the central core region were traversed inside the Al tube along the axial direction with a uniform speed to facilitate the conversion from the time-dependent neutron counts accumulated in the multi-channel scalar (MCS) unit to the reaction rate distribution. The relative value of neutron multiplication was deduced from the ratio of the spatially integrated neutron counts of the LiF detector, as shown in Fig. 5. Moreover, the LiF detectors were set at several positions shown in Fig. 4 and the result of the measurement of the neutron decay behavior was obtained as shown in Fig. 6.

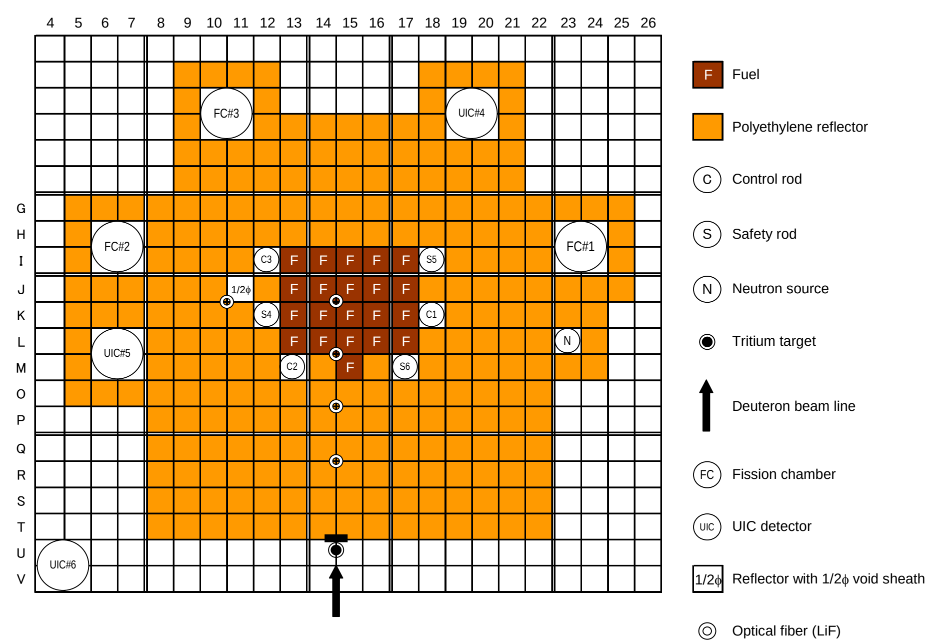

Figure 4: Top view of configuration of A-core neutron multiplication and neutron decay constant experiments.

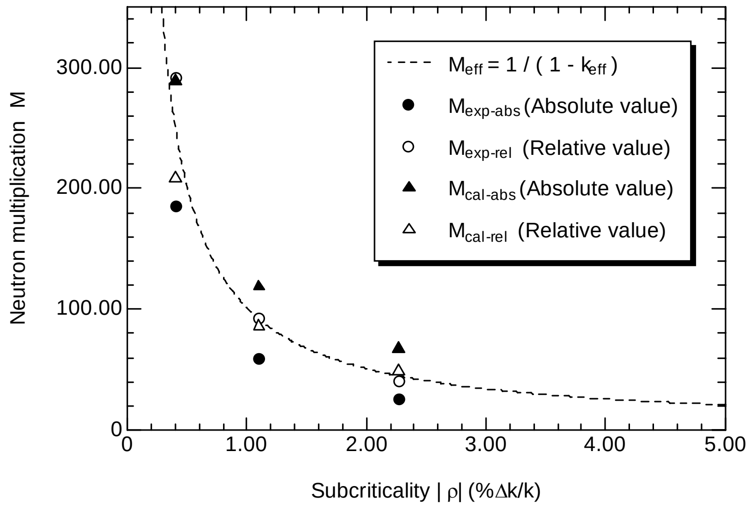

Figure 5: Comparison between measured and calculated results of neutron multiplication.

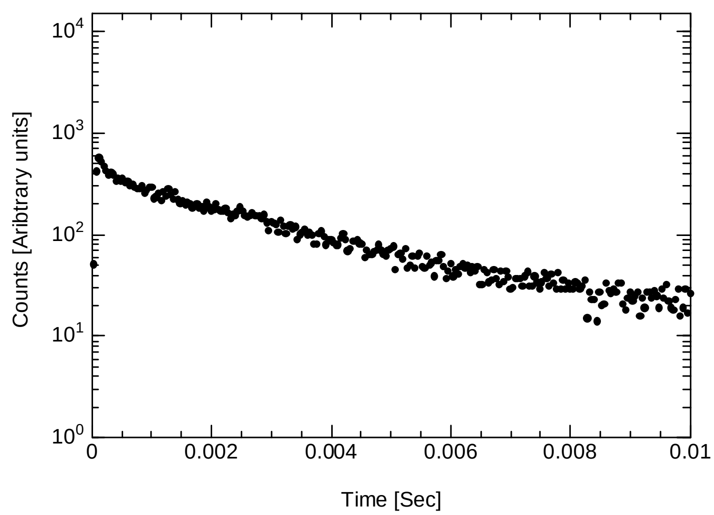

Figure 6: Measured result of neutron decay behavior obtained by optical fiber detection system.

3.2 Reaction Rate Distribution and Neutron Spectrum Experiments

The experimental results of the reaction rate distribution obtained by In wire emitted from ^{115}In(n,γ)^{116m}In reactions are given for the subcriticalities of about 0.7 to 0.9%Δk/k, as shown in Fig. 7. The reaction rate distributions of collimator cores decreased to a greater extent than that of no collimator core in the collimator (reflector) region; inversely, it increased about two times in Streaming Void (SV) and the fuel regions. These results show that the effects of the collimator and the beam duct were clearly exerted in the collimator and the fuel regions, respectively. Therefore, an optimized combination of shielding materials of the collimator and the size of the beam duct was made to efficiently direct the collimated neutrons to the fuel region. Thus, the installation of the collimator and the beam duct was valid for directing the high-energy neutrons to the fuel region, and the pattern of the collimator and the beam duct shown in Fig. 1 was experimentally appropriate for the purpose of the installation, as demonstrated by the comparison between the results of the reaction rate distributions. A comparison between the measured and the calculated reaction rate distributions for the cores used in Fig. 1 demonstrated that the approximate configuration of the measured reaction rate distribution is valid by the fixed source calculation based on the combined use of MCNP-4C3 and JENDL-3.3 shown in Fig. 8.

As shown in Table 3, the experimental results obtained by foil activation method demonstrated that the reaction rates were relatively smaller below half to one-tenth at position (15, K) with the collimator and the beam duct than those in the target region. Through the installation of the collimator and the beam duct, relative evaluation of directing the high-energy neutrons to the center of the core was observed in the measurement of the neutron spectrum by the multi-foil activation method.

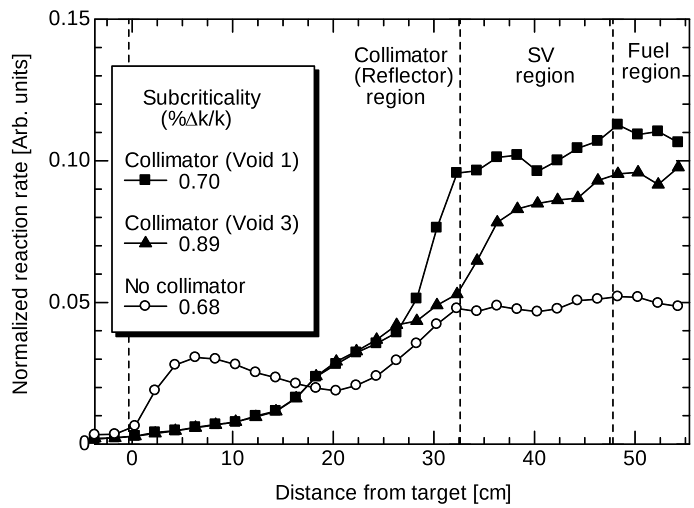

Figure 7: Measured reaction rate distributions by In wire along the vertical (16,17-J,V) shown in Fig. 1.

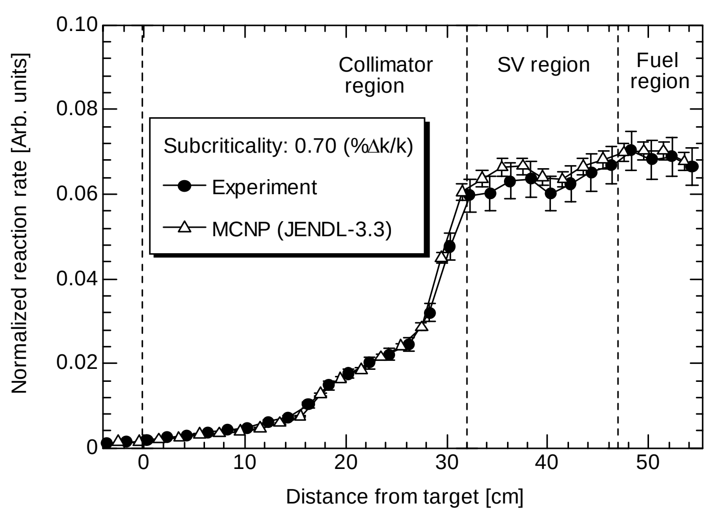

Figure 8: Comparison between measured and calculated reaction rate distributions shown in Fig. 1.

Table 2: Reaction rates of irradiation foils normalized by another irradiated In foil placed at target.

Irradiation position		Target	(15, K) With Collimator
Reaction	Threshold (MeV)	Reaction rate	Reaction rate
^{115}In (n, n') ^{115m}In	0.32	2.66×10^{-1}	5.71×10^{-2}
^{60}Ni (n, p) ^{60}Co	2.08	1.00	5.38×10^{-3}
^{56}Fe (n, p) ^{56}Mn	2.97	2.96×10^{3}	9.50×10^{2}
^{27}Al (n, α) ^{24}Na	3.25	4.84×10^{-1}	4.14×10^{-2}
^{24}Mg (n, p) ^{24}Na	4.93	9.83×10^{-2}	5.71×10^{-2}
^{127}I (n, 2n) ^{126}I	9.22	4.55	
^{58}Ni (n, 2n) ^{57}Ni	12.43	8.26×10^{-2}	5.70×10^{-3}

3.3 Subcriticality Measurements

The subcriticality experiments were carried out by using several methods: pulsed neutron method, neutron noise method (Feynmann-α and Rossi-α methods) and source multiplication method. Through these experiments, it was evaluated with measurement techniques, measurement precision, position dependence on neutron detectors, and so on. A comparison between the measured and the calculated subcriticalities showed that for each core the calculated subcriticality $\rho_{cal\text{-}sub}$ was in good agreement with the measured $\rho_{exp\text{-}sub}$ within relative difference of about 5%, as shown in Table 3. These results demonstrate that exact eigenvalue calculation studies relevant to the reactivity analyses of the ADSR loaded with highly enriched uranium fuel are feasible with the combined use of MCNP-4C3 and ENDF/B-VI.2 or JENDL-3.3. Note that the experimental and the MCNP calculation errors were estimated to be less than 10% and 0.03%Δk/k, respectively.

Table 3: Comparison between measured * and calculated subcriticalities.

JENDL-3.3			ENDF/B-VI.2		
Experiment $\rho_{exp\text{-}sub}$ (%Δk/k)	Calculation $\rho_{cal\text{-}sub}$ (%Δk/k)	Difference (%)	Experiment $\rho_{exp\text{-}sub}$ (%Δk/k)	Calculation $\rho_{cal\text{-}sub}$ (%Δk/k)	Difference (%)
-0.68	-0.69	1.4	-0.68	-0.71	4.8
-0.89	-0.84	5.7	-0.89	-0.86	3.5
-1.34	-1.35	0.3	-1.34	-1.40	3.9
-1.76	-1.71	2.9	-1.76	-1.72	2.4

* : Negative reactivity obtained by combination of rod drop method and control rod calibration curve.

4. Conclusion

A series of preliminary experiments were carried out at KUCA A-core by using 14MeV pulsed neutron generator to evaluate the neutronic characteristics and to establish the measurement techniques in the ADSR. The experiments and analyses by MCNP-4C3 revealed the followings:

1. The optical fiber detection system was experimentally confirmed to be a suitable measurement technique of neutron dynamic characteristics in the ADSR: reaction rate distribution, neutron multiplication and neutron decay constant.
2. The foil activation method was found to be a useful measuring technique for examining the neutronic properties of the ADSR: Reaction rate distribution and neutron spectrum.
3. With the combined use of MCNP-4C3 and ENDF/B-VI.2 or JENDL-3.3, precise eigenvalue calculations can be carried out relevant to the reactivity analyses of the ADSR.
4. Approximately measured reaction rate distribution in the subcritical system can be reconstructed by fixed source calculations based on the combined use of MCNP-4C3 and JENDL-3.3.
5. The effects of the collimator and the beam duct can be validly confirmed through the measurements of reaction rate distribution and neutron spectrum analyses by the foil activation method.

Further studies are needed to examine experimental values against representative subcriticality levels (around k_{eff} = 0.95) of actual ADSR. Based on experimental and numerical techniques obtained in the analyses of the ADSR by using 14MeV pulses neutron generator, new experiments and numerical simulations could be applied for the analyses of the high-energy neutrons generated by 150MeV protons in the FFAG accelerator.

Acknowledgements

The authors extend special thanks to all KUCA staff members for carrying out these experiments and to Mr. Morgan Helvault of Kyoto University for his contribution in executing the computational procedures.

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