RESEARCH ON THE ACCELERATOR-DRIVEN SUBCRITICAL REACTOR AT THE KYOTO UNIVERSITY CRITICAL ASSEMBLY (KUCA) WITH AN FFAG PROTON ACCELERATOR

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Abstract

At the Kyoto University Research Reactor Institute (KURRI), a new project for research on the accelerator-driven subcritical reactor (ADS) was started in 2002. For this project, a new ring-type accelerator based on the up-to-date FFAG (fixed field alternating gradient) technology will be under construction through 2005. With this new accelerator, a proton beam having arbitrary energy from 2.5 to 150 MeV will be generated and the proton beam from this accelerator will be introduced into a core at the Kyoto University Critical Assembly (KUCA) in order to generate high-energy neutrons via collision with heavy metal (e.g. tungsten). Before starting this new experiment, basic research on ADS was performed at KUCA, combining a KUCA core with an accelerator to generate 14 MeV neutrons via a D-T reaction and to investigate the nuclear characteristics of a subcritical reactor with an external neutron source.

Introduction

Accelerator-driven subcritical reactors (ADS) have attracted worldwide attention in recent years. ADS have been developed for the purposes of producing energy and transmuting minor actinides and long-lived fission products, as a result of their superior safety characteristics and potential for burning plutonium and other nuclear wastes. It is well-known that the advantage of ADS is the rare chance of energetic reactivity accidents due to its subcritical operation.

At the Kyoto University Research Reactor Institute (KURRI), a new project for research on ADS was started in 2002. For this project, a new ring-type accelerator based on up-to-date FFAG (fixed field alternating gradient) technology will be constructed, which can produce a proton beam of ~1 microampere current with arbitrary energy from 2.5 to 150 MeV. The proton beam from this accelerator will be introduced into the core of the Kyoto University Critical Assembly (KUCA) to induce high-energy neutrons generated by bombarding a heavy metal (e.g. tungsten). This new accelerator system is now under construction and new experiments at KUCA with the FFAG accelerator will begin in 2005 [1-3].

Before beginning the new ADS experiment using an FFAG accelerator, basic research on ADS was performed at KUCA. This involved combining KUCA with a Cockcroft-Walton type accelerator that was already equipped at KUCA. The present study discusses the results of experiments and calculations performed at the KUCA core for the preliminary study on ADS using the present D-T accelerator.

Core configuration

The KUCA A-core, which is a solid moderated core with highly enriched uranium fuels and a polyethylene moderator among the three cores (A, B and C) of KUCA, was combined with a pulsed neutron generator of the Cockcroft-Walton type installed at KUCA. A polyethylene-moderated and reflected core loaded with highly enriched uranium-aluminium (U-Al) alloy fuel was assembled at the A-core position as shown in Figure 1. All the ADS experiments were carried out at this core. As shown in Figure 2, the fuel rod consisted of polyethylene and U-Al plates with upper and lower polyethylene reflectors of more than 50 cm. The active height of the core was ~40 cm. The neutron spectrum of the core could be changed by adjusting the combination of 1.6-mm (1/16-inch) thick U-Al plates and 3.1-mm (1/8-inch) thick polyethylene plates that were piled up in the fuel rod [5].

A pulsed neutron generator run by a Cockcroft-Walton type accelerator was installed at KUCA to accelerate a deuteron beam up to ~300 keV and to make collisions with a tritium target located outside the core (see Figure 2) generate 14 MeV pulsed neutrons via D-T reaction. The pulse frequency could be changed up to 1 kHz depending on the purpose of the experiment. These pulsed neutrons were injected through a layer of the polyethylene reflector into the assembly, which was maintained at subcritical state.

The following experiments have been carried out thus far for the ADS study: (1) subcriticality measurement via the pulsed neutron method or modified source multiplication method, (2) neutron flux distribution measurement using optical fibre detectors or the foil and wire activation method in the subcritical core, (3) neutron spectrum measurement via the irradiated foil unfolding method, (4) neutron noise analysis such as the new variance-to-mean ratio method with pulsed neutron source to measure subcriticality or core properties, and so on. The results of the experiments were analysed with a deterministic method using an SN transport code and Monte Carlo code (e.g. MCNP [4]).

Figure 1. Structure of the KUCA core

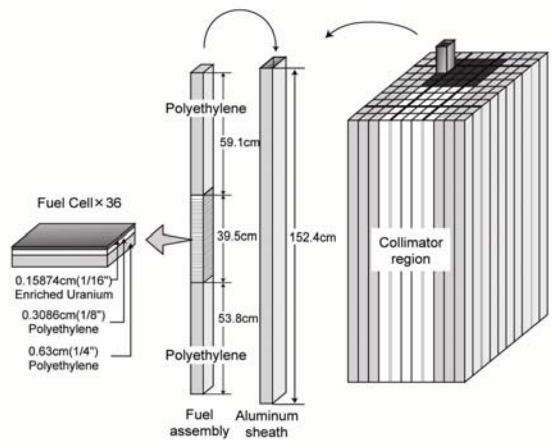
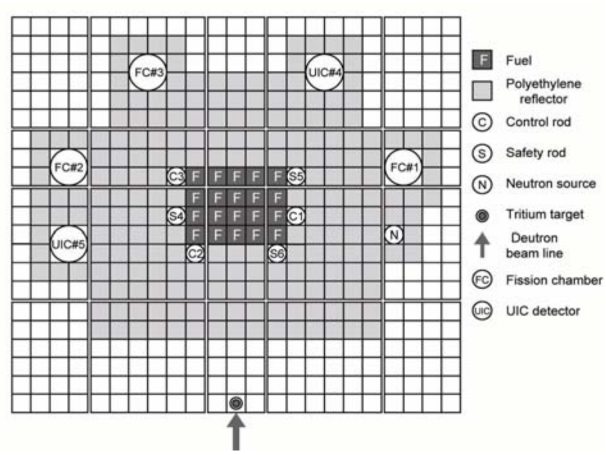


Figure 2. Horizontal core configuration

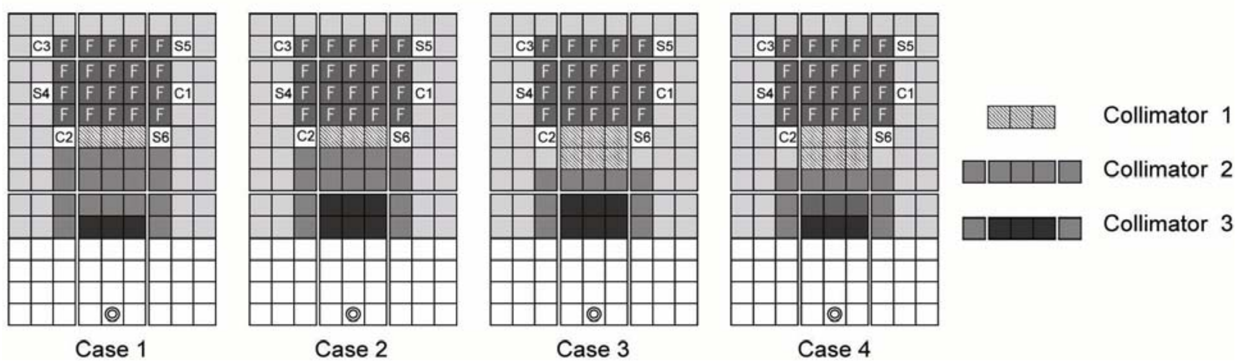


Design of neutron beam collimator

The numerical experiments were carried out at the KUCA combined with the accelerator that generates 14 MeV high-energy neutrons. First, the neutron collimator to introduce high-energy neutrons effectively into the core was designed. The collimators were provided in the polyethylene reflector region, towards the core from the target and at the centre region in the axial direction. As shown in Figure 3, several kinds of assemblies with a beam tube inside were adopted to make up the collimator region – polyethylene, polyethylene with mixture of ^{10}B (to shield thermal neutrons) and iron metal (to shield fast neutrons). These materials were used to moderate the fast neutrons or to absorb the additional neutrons that were moderated around the target region. The installation patterns of collimators in the reflector region are shown in Figure 4. For the numerical simulations using MCNP, attention was paid to neutron multiplication in the core and neutron flux distribution along the neutron guide passage as well as to when collimators were installed in the polyethylene reflector region.

From these analyses, it was concluded that the Figure 3/Case 4 installation pattern of collimators was the best pattern to effectively introduce fast neutrons into the core and to reduce the thermal neutrons that were moderated by the wall of the beam transport tube in the collimator region.

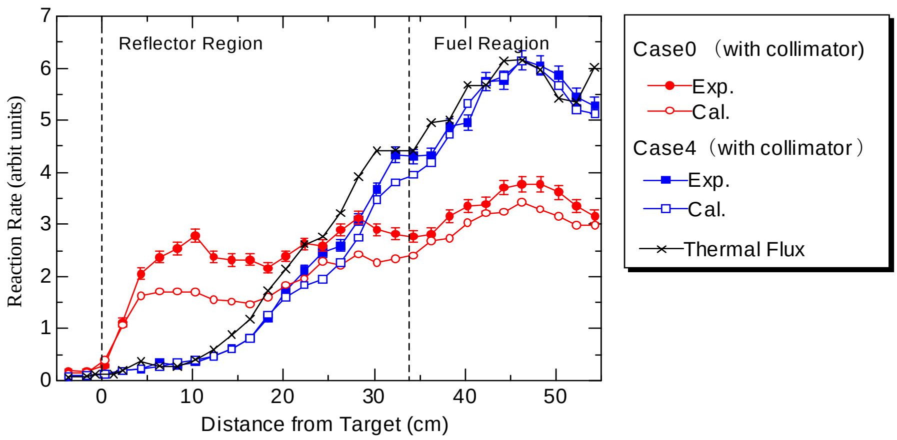
Figure 3. Collimator patterns in the reflector region



Measurement of reaction rate distribution

Since the study of neutron flux distribution in subcritical systems is one of the important topics in ADS design, flux distribution measurements were carried out at the KUCA core with the accelerator. At the KUCA core, gold foils were used for this purpose. However, in a subcritical state, it is difficult to measure the reaction because the reactor power is determined by subcriticality accelerator power and its value is much lower than that of a core in a critical state. To overcome this difficulty, indium (In) wire [measures neutron flux by ^{115}In (n, gamma)^{116m} In reactions] was used in the experiments for the present study. Indium wire of 1.5-mm diameter was set in vertical direction (see Figure 1) along the collimator and the accelerator was operated about three hours to irradiate the wire. Note that the subcriticality of the core was adjusted by the position of control rods, which was about -1% dk/k. After irradiation, the wire was cut into small pieces and the emitted gamma-rays were measured by a pure Ge detector. Figure 4 shows the indium reaction rate distribution with and without the collimator (Figure 3/Case 4) together with the calculated results from the MCNP code. It was found that the reaction rate was accurately measured by this method even in a subcritical state and that the present collimator acted as transporter of neutrons into the fuel region (due to increasing the reaction rate in the fuel region). The calculated results from MCNP agreed well with the measured ones.

Figure 4. Measured reaction rate distribution by indium wire in vertical direction with and without collimator together with calculated results by MCNP



Measurement of reaction rate by fast neutrons

Fast neutrons in the subcritical core were measured by the activation method using threshold detector foils that react with neutrons of higher than threshold energy. Table 1 shows the reaction types used in the present experiments, where 10 threshold reactions were adopted to measure fast neutron reaction. In the experiments, foils were set in the fuel region and in front of the tritium target. They were irradiated about six hours and the emitted gamma-rays were measured by a pure Ge detector. Table 1 shows the results of each reaction rate with and without a collimator (Figure 3/Case 4). It was found that each reaction rate was measured within 10% accuracy by this method even in a subcritical state.

Table 1. Reaction rate of threshold irradiation foils

Reaction Type	Threshold [MeV]	Reaction Rate $[s^{-1}]$ $\times 10^2$ with Collimator		Reaction Rate $[s^{-1}]$ $\times 10^2$ without Collimator	
		Fuel	Target	Fuel	Target
$^{115}In(n,n')^{115m}In$	0.5	3.40	2.20	2.32	2.45
$^{58}Ni(n,p)^{58}Co$	1.9	8.51	10.2	1.79	22.8
$^{64}Zn(n,p)^{64}Cu$	2	9.86	13.0	4.22	11.9
$^{56}Fe(n,p)^{56}Mn$	4.9	5.08	7.40	3.12	8.34
$^{27}Al(n,\alpha)^{24}Na$	4.9	1.40	1.18	0.707	5.54
$^{24}Mg(n,p)^{24}Na$	6	0.505	1.03	0.35	1.24
$^{200}Hg(n,2n)^{199m}Hg$	8.1	0.129	0.300	0.0676	0.323
$^{127}I(n,2n)^{126}I$	9.3	3.21	10.6	1.05	10.7
$^{63}Cu(n,2n)^{62}Cu$	11.9	7.28	26.8	3.23	35.3
$^{58}Ni(n,2n)^{57}Ni$	13	0.567	0.626	0	0.744

Measurement of neutron noise of ADS

For the safe operation of ADS, it is important to detect subcriticality in real-time, and the neutron noise analysis method is one of the appropriate methods for this purpose. A new noise data acquisition system has been developed [6] and was used for these experiments. With the ADS system, neutron counts are fluctuated not only by the effect of chain reaction that is observed in a critical reactor, but also by periodic operation of an external neutron source from the accelerator. Including these effects, a new formulation based on the variance-to-mean ratio method (Feynman-alpha method) was developed.

Figure 5 shows results of measured data by the pulsed neutron method and the variance-to-mean ratio method (Feynman-alpha method) when the repletion period was 0.01 seconds. It was found that measured Y-values agreed well with theoretical values that were obtained by fitting the experimental data. Furthermore, Table 2 shows the results of measured prompt neutron decay constants (alpha values) by these different analysis methods that agreed well. From these results, it was found that subcriticality of the system, which was obtained from the prompt neutron decay constant (alpha value), could be observed in real-time when neutron noise data was obtained during the operation of the ADS.

Figure 5. Measured neutron decay after neutron injection from accelerator (right) and measured Y-values (circles) and fitted lines by Feynman-alpha method (left)

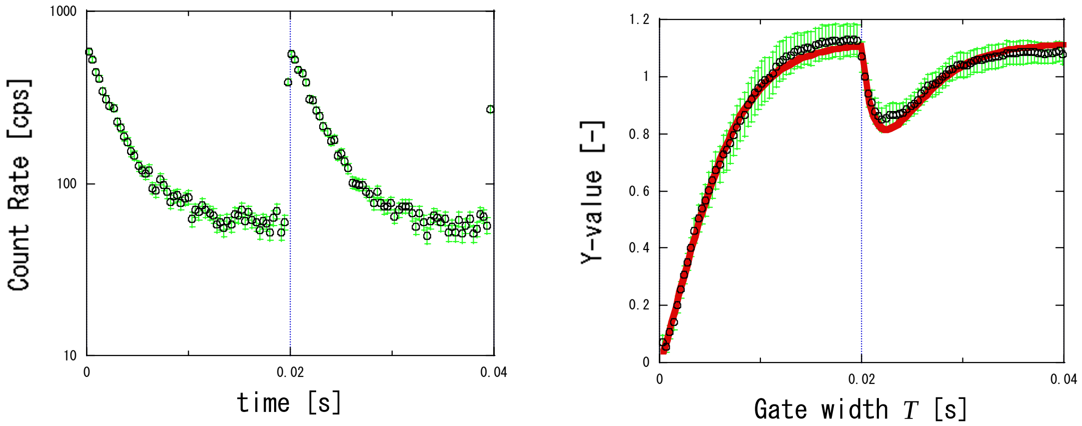


Table 2. Results of measured prompt neutron decay constants (alpha values) by pulsed neutron method and variance-to-mean ratio method

Pulsed neutron method (Area-ratio method)		V-to-variable-M method	Comparison of α -value
$-\rho$ [$]	α_0 [1/s]	α [1/s]	$(\alpha - \alpha_0) / \alpha_0$
1.597 ± 0.012	357.8 ± 0.9	359 ± 16	0.005 ± 0.045

Conclusion

Several experiments were carried out where the KUCA core was combined with a D-T neutron generation accelerator in order to examine the neutron characteristics of an ADS. In the KUCA core, the neutron transport beam collimators were designed and installed in the polyethylene reflector region, towards the core from the target. Using this system, reaction rate measurements in a subcritical system with an accelerator were carried out by the foil activation method, and the results agreed well with the calculated ones. Moreover, to detect the subcriticality of the ADS, a new neutron noise analysis method based on the variance-to-mean ratio method was developed.

Acknowledgements

The authors wish to thank Dr. Y. Kitamura of Nagoya University and Mr. Y. Hirano of Kyoto University for their generous help throughout the present study.

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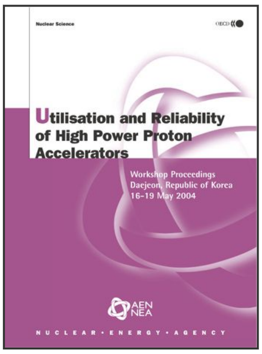
TABLE OF CONTENTS



From:

Utilisation and Reliability of High Power Proton Accelerators

Workshop Proceedings, Daejeon, Republic of Korea, 16-19 May 2004

Access the complete publication at:

https://doi.org/10.1787/9789264013810-en

Please cite this chapter as:

Misawa, Tsuyoshi, *et al.* (2006), "Research on the Accelerator-Driven Subcritical Reactor at the Kyoto University Critical Assembly (KUCA) with an FFAG Proton Accelerator", in OECD/Nuclear Energy Agency, *Utilisation and Reliability of High Power Proton Accelerators: Workshop Proceedings, Daejeon, Republic of Korea, 16-19 May 2004*, OECD Publishing, Paris.

DOI: https://doi.org/10.1787/9789264013810-38-en