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EXPERIMENTAL STUDY ON ACCELERATOR DRIVEN SUBCRITICAL REACTOR BY USING THE KYOTO UNIVERSITY CRITICAL ASSEMBLY (KUCA)

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ABSTRACT

A series of basic experiments for an accelerator driven subcritical reactor (ADSR) has been performed at the Kyoto University Critical Assembly (KUCA) by combining a critical assembly with a Cockcroft-Walton type accelerator in view of a future plan to establish a new neutron source for research. Fourteen MeV neutrons were injected into a subcritical system through the polyethylene reflector. By varying subcriticality, the neutron multiplication and the prompt neutron decay constant as well as the subcriticality were measured mainly by an optical fiber detector system. Calculations were executed by a continuous energy Monte Carlo code MVP on the basis of JENDL-3.2 to examine the accuracy of neutronics design for the ADSR at the present stage. A large discrepancy was observed between the measured subcriticality and the calculated one mainly because of an inadequate evaluation of ^{235}U nuclear data compiled in JENDL-3.2, which leads to a large difference among the measured and calculated nuclear parameters of the ADSR. Through the present study, it was strongly recognized that the present tools for the neutronics design calculation of ADSR are not accurate enough especially to predict the neutron multiplication in the ADSR. Although the accuracy of k_{eff} calculation is becoming better and better in the current neutronics design tools for nuclear reactors, one should be careful that the neutron multiplication in the ADSR does not depend on k_{eff} itself, but approximately on $1/(1-k_{\mathrm{eff}})$.

1. INTRODUCTION

A series of basic experiments for an accelerator driven subcritical reactor (ADSR) has been officially launched from the financial year 2000 at the Kyoto University Critical Assembly (KUCA) as a joint use program among Japanese universities[1] in view of a future plan in Kyoto University Research Reactor Institute (KURRI)[2]. A final goal of the future plan in KURRI is to establish a next generation neutron

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source as a substitute for the current Kyoto University Reactor (KUR) of 5 MW established in 1964 by introducing a synergetic system of the research reactor and particle accelerators. The main purpose of the present experiments was to study on the neutron multiplication and the neutron decay properties in the ADSR, which are considered to be essential for the research use of a new neutron source.

By combining a critical assembly with a Cockcroft-Walton type accelerator, 14 MeV pulsed neutrons were injected through the polyethylene reflector into a subcritical system, where the highly enriched uranium fuel was loaded in combination with the polyethylene moderator. By varying subcriticality systematically, the neutron multiplication and the prompt neutron decay constant as well as the subcriticality were measured mainly by an optical fiber detector system[3] developed through the KUCA experiments.

Calculations were executed by a continuous energy Monte Carlo code MVP[4] developed in Japan Atomic Energy Research Institute (JAERI) on the basis of JENDL-3.2[5] to examine the accuracy of neutronics design for the ADSR at the present stage.

2. EXPERIMENTAL

In the present series of experiments, a solid moderator core among the three cores (A, B and C) of the KUCA was combined with a pulsed neutron generator of the Cockcroft-Walton type installed in the KUCA. Figure 1 shows an image of the KUCA ADSR experiment.

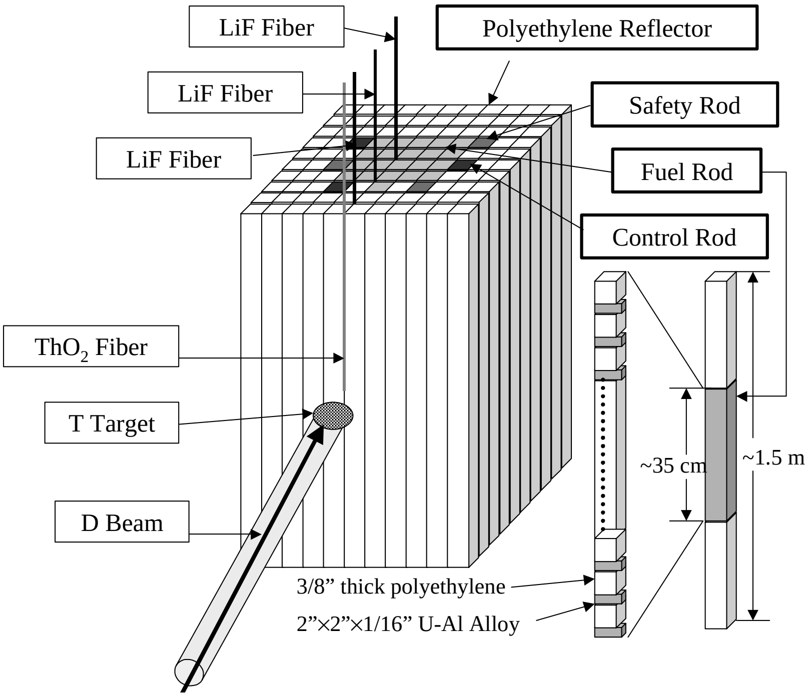

Figure 1. Image of the KUCA ADSR Experiment.

A polyethylene moderated and reflected core loaded with 93% enriched uranium-aluminum (U-Al) alloy fuel was assembled at the A-core position. The fuel rod was consisted of polyethylene and U-Al plates of 5.08 cm × 5.08 cm (2” × 2”) square with the upper and lower polyethylene reflector of more than 50 cm, respectively. The active height of the core was approximately 35 cm. The neutron spectrum of the core can be varied by changing combination of approximately 1.6 mm (1/16”) thick U-Al plates and approximately 3.2 mm (1/8”) thick polyethylene plates piled up in the fuel rod.

The deuteron beam accelerated up to around 200 keV was led to a tritium target located outside the polyethylene reflector to generate 14 MeV pulsed neutrons. These pulsed neutrons were injected through a layer of the polyethylene reflector into the assembly maintained at the subcritical state.

An optical fiber detector system was utilized to measure both the neutron flux distribution and the behavior of neutron decay; a mixture of ^{6}Li enriched LiF and ZnS(Ag) scintillator was pasted on one end of a plastic optical fiber of 1 mm in diameter with the instant adhesive. The LiF detector of approximately 2 mm in diameter with cladding was inserted into an Al tube settled in a narrow air gap of approximately 3 mm in diameter surrounded by corners of 4 fuel rods. A fiber detector of ThO_2 in place of LiF was employed for monitoring generated 14 MeV neutrons.

For the measurement of neutron flux distribution, the LiF fiber detector settled in the vicinity of the central core region was 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 flux distribution. The relative value of neutron multiplication was deduced from the ratio of the spatially integrated neutron counts of the LiF detector to the total neutron counts of the ThO_2 detector during a period of traversing LiF detector in the core region.

On the other hand, LiF detectors were settled at several positions on the mid-plane of the core for the measurement of neutron decay behavior. The arc pulse of accelerator was used as a trigger signal to start the accumulation of neutron count data in the MCS unit. The prompt neutron decay constant was obtained through the least square fitting of measured data to an exponential function.

Experiments were carried out by varying the subcriticality with adjusting the stroke of the control rod insertion or the number of fuel rods loaded in the core. The subcriticality was measured by the rod drop method or the area ratio method of the pulsed neutron technique.

3. ANALYSIS BY USING MVP CODE

The analysis of the experiment described above was executed by using a continuous energy Monte Carlo code MVP on the basis of the JENDL-3.2 library. The eigenvalue calculation was executed to obtain the subcriticality, while the fixed source calculation was done to obtain values of the neutron multiplication and the prompt neutron decay constant. The experimental geometry was explicitly modeled in the MVP calculation, where the number of typical neutron histories was 1,000,000.

To obtain the value of neutron multiplication, one should obtain the absolute number of neutrons S injected into the subcritical core, since the neutron multiplication M in the ADSR can be expressed as

$$M = {(S+F)}\big/{S} \quad , \tag{1}$$

where F corresponds to the number of neutrons generated by the fission chain reactions.

It is not very easy, however, to calculate S for the present series of KUCA ADSR experiments, since neutrons were injected into the subcritical core through the polyethylene layer of reflector. To obtain the value of S, an absolute absorber was introduced in place of the fuel plate loaded in the core, and the number of these absorption reactions was counted by an additional fixed source calculation.

The axial neutron flux distribution in the fuel rod located at the center of the core was calculated by assuming the continuous injection of 14 MeV neutrons into the subcritical assembly. The reason is that it is very difficult to obtain the neutron flux distribution at the same location as that of the LiF detector of 1 mm in diameter, since the statistical error becomes large in the Monte Carlo calculation.

By using the time-dependent option of MVP, the decay behavior of neutrons at the several regions in the subcritical assembly was calculated after the injection of 14 MeV neutrons. To obtain the prompt neutron decay constants, the calculated neutron decay curve in a period from 0.4 to 2 ms was fitted to an exponential curve by using the method of least squares. Note that the time-dependent behavior of delayed neutrons was not taken into account in the MVP calculation.

4. RESULTS AND DISCUSSION

Table I shows the comparison among the measured and calculated subcriticalities for cores used in the measurement of neutron flux distribution. Note that the atomic number density of ^{235}U was reduced by 6.5 % in the Calculation-II in order to attain good agreement between the measured and calculated results, while that was preserved in the Calculation-I. Note that the experimental error was estimated to be less than 10 %, and the statistical error in the calculation was approximately 0.1 %Δk/k.

Table I. Comparison among subcriticalities ρ obtained by the measurement and calculations

Case	Measurement ρ_{exp} (%Δk/k)	Calculation-I $\rho_{\mathrm{cal\text{-}I}}$ (%Δk/k)	Calculation-II $\rho_{\mathrm{cal\text{-}II}}$ (%Δk/k)
1	-0.41	+0.9	-0.4
2	-1.10	+0.2	-1.1
3	-2.27	-1.0	-2.3
4	-4.03	-2.1	-3.5

A large discrepancy between ρ_{exp} and $\rho_{\mathrm{cal\text{-}I}}$ comes mainly from the inadequate evaluation of ^{235}U capture cross sections in the resonance energy region.[6] Since the fixed source calculation can be executed only for the subcritical system, results shown in Table I indicate that one can not conduct any neutronics design study of ADSR loaded with highly enriched uranium fuel by using the combination of MVP and JENDL-3.2, especially when k_{eff} of the subcritical system becomes close to unity. It also indicates that the calculated value of neutron multiplication M becomes inaccurate because M is approximately proportional to $1/(1-k_{\mathrm{eff}})$.

Hereafter, all calculations in the present study were executed by using the reduced atomic number density employed in the Calculation-II for convenience' sake to facilitate the comparison between the measured and calculated parameters.

Figure 2 shows a comparison between the measured and calculated values of the neutron multiplication M. A solid line in this figure corresponds to $1/(1-k_{\mathrm{eff}})$, and the measured and calculated values are normalized to the solid line at ρ_{exp}=-1.10 %Δk/k as relative values. One can easily find that the measured and calculated values of M are approximately proportional to the value of $1/(1-k_{\mathrm{eff}})$; this fact is consistent with the principle of the source multiplication method employed for the subcriticality measurement in the reactor physics experiment.

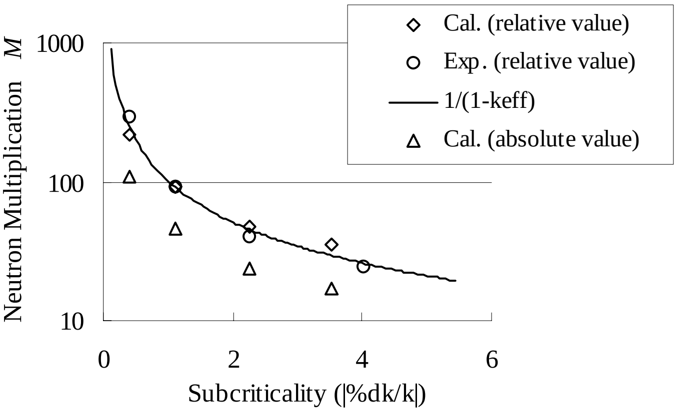

Figure 2. Comparison between the measured and calculated neutron multiplication *M*.

The absolute value of M ($M_{\text{cal-abs}}$) obtained through the fixed source calculation is also shown in Figure 2. It is found that a large difference exists between values of $M_{\text{cal-abs}}$ obtained by the fixed source calculation and $1/(1-k_{\text{eff}})$ based on the eigenvalue calculation. This fact demonstrates that the fixed source calculation is inevitable for the neutronics design of the ADSR.

Figure 3 shows a comparison between the measured and calculated prompt neutron decay constants α. From this figure, one can find that two lines obtained by the least square fitting for the measured and calculated results are approximately parallel with each other. This fact indicates that the reduction in ^{235}U atomic number density acts actually as a correction not only for M but also for α.

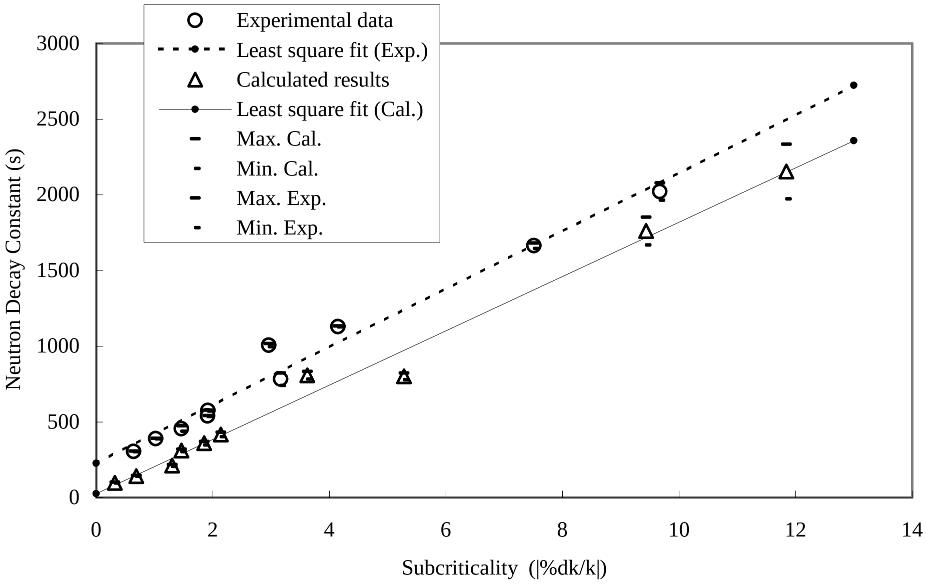

Figure 3. Comparison between the measured and calculated prompt neutron decay constants α.

By taking into account that the time behavior of delayed neutrons was not considered in the present MVP calculation, the agreement between the measured and calculated values of α is fairly good, since one can make correction in consideration of the following equation

$$\alpha = \left(\beta_{eff} - \rho\right) \Big/ \Lambda \quad , \tag{2}$$

where β_{eff} is the effective delayed neutron fraction and Λ is the neutron generation time.

For the neutronics design of the ADSR, it will be inevitable to utilize more and more accurate nuclear data than the current ones to evaluate accurately the nuclear characteristics of ADSR, and to take into account the behavior of delayed neutrons in the time-dependent option of the Monte Carlo code.

CONCLUSIONS

A series of the KUCA experiments has been carried out to examine the nuclear characteristics of ADSR. A large discrepancy was observed between the measured subcriticality and the calculated one mainly because of the inadequate evaluation of ^{235}U nuclear data in JENDL-3.2, which leads to a large difference among the measured and calculated nuclear parameters in the ADSR.

Through the present study, it was strongly recognized that the present tools for the neutronics design calculation of ADSR is not accurate enough especially to predict the neutron multiplication in the ADSR. Although the accuracy of k_{eff} calculation is becoming better and better in the current neutronics design tools for nuclear reactors, one should be careful that the neutron multiplication in the ADSR does not depend on k_{eff} itself, but approximately on $1/(1-k_{\text{eff}})$.

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