Reactor physics experiment for advanced nuclear reactor system at Kyoto University Critical Assembly (KUCA)

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Abstract: Recent activities on reactor physics experiment for advanced nuclear reactor systems using the Kyoto University Critical Assembly (KUCA) are described and reviewed. The activities include 1) benchmark experiments for high burnup next generation reactor fuel, 2) basic experiments on thorium fueled reactor, and 3) experiments on ADS using high-energy proton accelerator and subcritical cores. These experiments are mainly aimed at verification and validation of current methodology for nuclear characteristics design, and also aimed at development of experimental techniques.

Keyword: reactor physics; KUCA; advanced nuclear reactor; thorium; ADS

1 Introduction

A significant revival of nuclear energy use is expected in the near future. Numerous energy demand and supply forecasts show that the importance of nuclear energy will become increasingly important for enhancing energy security and for mitigating the greenhouse gas emission.

The expected increase of nuclear energy is arising the need for enhancement of reliability, safety, efficiency and economy of nuclear energy system in the forthcoming years. This requires not only the safe and reliable operation of current nuclear energy system but also the development of advanced nuclear reactor system with enhanced performance for the next generation.

To meet these requirements and to provide fundamental scientific information for the development of advanced nuclear reactor, the authors are performing a series of experimental studies at the Kyoto University Critical Assembly (KUCA) facility. Among the various studies being performed, the following three activities will be highlighted and described in this article; 1) benchmark experiments for high burnup next generation reactor fuel, 2) basic experiments on thorium fueled reactor, and 3) experiments on ADS using high-energy proton accelerator and subcritical cores. These experiments are mainly aimed at verification and validation of current methodology for nuclear characteristics design, and also aimed at development of experimental techniques.

2 The KUCA facility

KUCA is a multi-core type, thermal spectrum critical assembly dedicated for the fundamental research and education on reactor physics[1]. KUCA consists of one light-water moderated core and two solid-moderated cores, both loaded with highly enriched uranium fuels; a pulsed neutron generator is also attached and could be used in combination with a solid-moderated core. Reactor physics experiments on numerous critical and sub-critical configurations have been hitherto successfully conducted at the KUCA.

The solid moderated cores (A- and B- cores) have been used in the series of experiments described in this article. The schematic view of the fuel elements and the core is shown in Fig.1. The main fuel material for the solid-moderated core is 1/16”-thick highly enriched uranium-aluminum alloy fuel. 1mm-thick natural uranium metal plates were used in combination with highly-enriched fuel plates to alter the average enrichment of the fuel. 1/8"-thick thorium metal plates were used to simulate the fuel composition of thorium-loaded cores.

Received date: August 4, 2010
(Revised date: September 15, 2010)

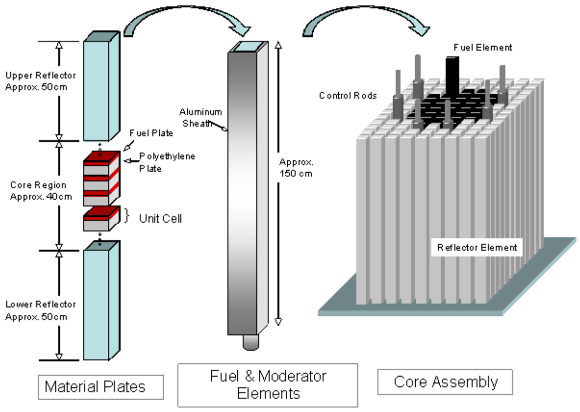

Fig.1 Schematic View of KUCA Solid-Moderated Core and Fuel Elements.

The fuel plates are combined with polyethylene moderator plates to form the unit fuel cell. The total thickness of the polyethylene plates can be varied to change the H/U-235 ratio and consequently the neutron spectrum of the core. The unit fuel cells are then piled up to form the core region of approximately 40 to 45 cm in height. The core region is then sandwiched with lower and upper reflectors, and is stacked into aluminum sheaths to form fuel elements. Finally, the fuel elements are arranged onto a core grid plate to construct the critical core. An example of the actual core is shown in Fig.2.


Fig. 2 Example of the KUCA Solid-Moderated Core (B-core), showing fuel elements, control rods and removable section of the core (in shutdown position).

3 Benchmark experiments for high burnup next generation fuel

3.1 Purpose

Utilization of high-burnup fuel is effective to reduce the number of spent fuel from nuclear power plant. The most straightforward way to realize a high-burnup fuel is to increase the uranium enrichment[2]. However, the current upper limitation of the fuel enrichment is 5wt% in Japan, and the increase of uranium enrichment over 5wt% requires considerable investment in fuel fabrication, transport and storage process, namely, design modification, reconstruction and re-licensing to cope for the possible issues in critical safety. Such investments may be a serious barrier for the introduction of future high-burnup fuels with higher enrichment.

The Erbia bearing Super High-Burnup (Er-SHB) (hereafter referred as "Er-SHB") is an alternate pathway for realizing the high-burnup fuels with higher enrichment[3]. In this concept, low content (>0.2wt%) of erbia (Er_2O_3) is added in the UO_2 powder with high enrichment (>5wt%) immediately after the re-conversion process. The addition of erbia acts to suppress the reactivity of the high-enrichment fuel, so that the criticality safety will be equivalent to the uranium fuel with enrichment of 5wt% or less; this idea for suppressing the reactivity is named as "erbia credit".

The concept of Er-SHB is rather different from the current LWR fuel loaded with erbia as burnable absorber, where erbia is loaded partially in certain fuel rods in the fuel assembly to control in-core power distribution and moderator temperature coefficient. Contrary to such usage, erbia is added in all fuel rods to meet the criticality safety requirements in the Er-SHB fuels.

In order to conduct a comprehensive R&D on the Er-SHB fuel, the authors have launched a three-year development program in 2005 under the support project of Ministry of Economy, Trade and Industry (METI) for Innovative and Viable Nuclear Energy Technologies (IVNET). In this program, various investigations have been carried out to introduce and demonstrate the feasibility of the proposed erbia credit concept. The program[4] covered a wide aspect of the fuel fabrication, such as critical experiments of erbia-loaded thermal spectrum cores, development of uncertainty reduction methodology for neutronics parameters, criticality safety analysis, fabrication test of erbia-bearing fuel pellet, core design of Er-SHB loaded cores, source term estimation for heat load and shielding analysis, and applicability of burnup credit for the Er-SHB fuels.

Among these intensive activities, a series of critical experiments on Erbia-loaded thermal neutron spectrum cores being conducted using the KUCA[5] is described in this section.

3.2 Experiment

In the present experiments, highly-enriched U-Al alloy fuel plates are combined with natural uranium metal, polyethylene and erbia-coated graphite plates (Fig.3) to simulate the design specifications of Er-SHB fuel under various conditions by varying the H/U ratio, average enrichment and erbia content. The Erbia-coated graphite plates consists of graphite plate (1.5mm x 50.8mm x 50.8mm) with engraved surface where erbia is coated with 30 micro meter thickness. The amount of erbia per plate is approximately 0.3 g.

Fig. 3 Erbia-coated graphite plates.

Three critical cores having different H/U ratio, average enrichment and erbia content have been constructed in the present experiment (Table 1).

Table 1 Erbia-loaded KUCA Cores

Core ID*	Averaged Enrichment	H/U-235	Erbia Content
Core 1	5.4%	274	0.3%
Core 2	5.4%	91	0.3%
Core 3	9.6%	48	0.6%

* Precise ID for Core 1: B6/8”P17 EU-NU-EU-NU-Er(3), Core 2: B2/8”P28EU-NU-EU-NU-Er+2/8”P38EU-EU(3), Core 3: B1/8”P40EU-NU-EU-Er+2/8”P38EU-EU(3)

The cell-averaged neutron spectrum of the three cores are shown in Fig.4, together with the currently proposed Er-SHB PWR fuel. A wide range of neutron spectrum is obtained by the three cores; the most well-moderated core has been selected so as to correspond to over-moderated condition anticipated in accidental condition at fuel fabrication process, whereas the other two cores were selected to simulate the neutron spectrum of the currently proposed Er-SHB PWR fuel.

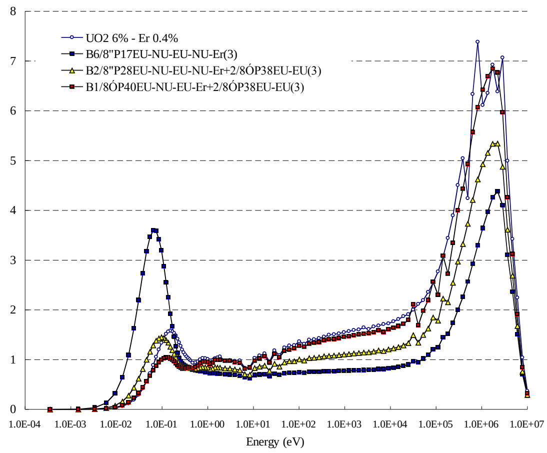

Fig. 4 Neutron spectrum of the cores.

Following the criticality approach experiment, measurement of the erbia sample worth, defined as reactivity induced by replacing erbia plate with graphite plate, have been extensively carried out in this series of experiment.

In the experiment, the erbia-coated graphite plates loaded in the central fuel element are replaced by the graphite plates without erbia coating. This replacement has been made axially from the center of the fuel element and expanding to top and bottom symmetrically; the number of erbia-coated graphite plates is increased in several steps until all the plates in the central fuel element were replaced. The erbia sample worth was defined as reactivity difference caused by the replacement. The erbia sample worth ranged from approximately 0.03% $\Delta k/k$ to 0.16% $\Delta k/k$, and the accuracy of the erbia sample worth measurement, defined as the relative standard deviation, is estimated to be less than 3% for most cases.

The analyses of the erbia sample worth have been performed using reactor analysis system SRAC[6]. JENDL-3.3, ENDF/B-VI.8 and JEFF-3.0 were used as nuclear data libraries. 2-D and 3-D diffusion calculation using CITATION and 2-D transport calculation using TWOTRAN have been performed in the analysis using various energy groups. The calculation results reproduced the experiment within 10% for most cases. Taking into account that the experimental accuracy for erbia sample worth is approximately 3% except for cases with small sample reactivity (i.e. the first cases for each core), it could be generally concluded that significant discrepancy between calculation and measurement could not be observed for erbia sample worth.

These results are expected to be utilized to provide the database for evaluation of erbium cross section uncertainty and improvement of prediction uncertainties of Er-SHB PWR core characteristics using the generalized bias factor method[7, 8], and also as basic benchmark data for integral evaluation of erbia cross section.

4 Basic experiments on thorium fueled reactor

4.1 Purpose

Studies on thorium-based fuel cycle and reactors have emerged in the very early days of reactor study, and extensive studies have been made in the past. Nevertheless, thorium has recently regained a growing interest from nuclear society, including nuclear power companies and fuel fabricators. This is due to the attractive potential of thorium-based fuel cycle, such as its rich natural resource, less possibility of generating TRU wastes and excellent non-proliferation characteristics.

For the reliable design of thorium-based systems, the accuracy of neutron cross section, especially that of 232Th, will be of primary importance. Due to the recent developments in computing environment, the major ambiguity in the predicted nuclear characteristics are now considered to be coming from the ambiguity in the nuclear data. However, compared to the uranium-plutonium fuel cycle, less attention have been paid to the validation of nuclear data related to thorium fuel cycle. For this point of view, a series of critical experiments on thorium fueled thermal spectrum cores are being performed at KUCA[9][10][11] in order to accumulate experimental information on thermal spectrum systems containing thorium.

4.2 Experiments

In the experiment, core parameters such as H/235U ratio and 232Th/235U ratio were systematically varied by changing the number of uranium, thorium and polyethylene plates contained in a unit fuel cell. Seven cores have been constructed as summarized in Table 2, with H/235U ratio ranging from 138 to 316, and 232Th/235U ratio from 12.7 to 19.0. In order to quantitatively describe the neutron spectrum of the core, spectrum index (S.I.), defined here as the ratio of neutron flux below 1eV to total flux (upper energy bound = 10MeV), will be hereafter used and are also shown in Table 2. For each core, criticality, control rod worth, neutron flux distribution and sample worth measurements have been performed. In the following, the results of criticality (k-effective) analysis are summarized.

Table 2 Core specifications

Core ID	H/^{235}U ratio	^{232}Th/^{235}U ratio	S.I.	Core Volume (liter)
B4/8"P24EU-Th-EU-EU(5)	138		0.184	56.8
B6/8"P24EU-Th-EU-EU(3)	211	12.7	0.242	48.8
B3/8"P48EU16Th(3)	316		0.313	58.5
B3/8"P45EU18Th(3)	316	15.2	0.309	65.9
B3/8"P30EU-Th-EU(5)	155		0.191	93.4
B4/8"P17EU-Th-EU(5)	207	19.0	0.230	81.2
B6/8"P17EU-Th-EU(5)	316		0.297	89.1

Analysis of criticality was performed using the continuous energy Monte Carlo code MVP[12] together with JENDL-3.2, JENDL-3.3, ENDF/B-VI.8 and JEFF3.0 cross section libraries. 3,300,000 neutrons have been tracked in a MVP calculation, yielding the statistical error (1 σ) of about 0.05% for k-effective. It was found that C/E values are overestimated by all data libraries used. JENDL-3.2 shows the most significant overestimation of 1.3% to 1.8%, and this overestimation is considerably reduced to 0.6% to 1.0% by the use of JENDL-3.3. However, compared to C/E values of uranium fueled cores of KUCA obtained by JENDL-3.3, the C/E values of uranium / thorium fueled cores are considerably larger as shown in Fig. 5. Thus it could be concluded that the prediction accuracy of JENDL-3.3 for thorium fueled thermal systems still need to be improved.

Among the four libraries, ENDF/B-VI.8 showed the most moderate C/E values with overestimation of 0.4% to 0.6%. JEFF3.0 showed the largest C/E values among the recent libraries (JENDL-3.3, ENDF/B-VI.8 and JEFF3.0), with overestimation of 0.8% to 1.2%. The C/E values become generally larger with increasing ^{232}Th/^{235}U ratio for JENDL libraries and JEFF3.0, but this trend could not be seen in ENDF/B-VI.8. This spread among C/E values of cores with different ^{232}Th/^{235}U ratios were less than 0.3%.

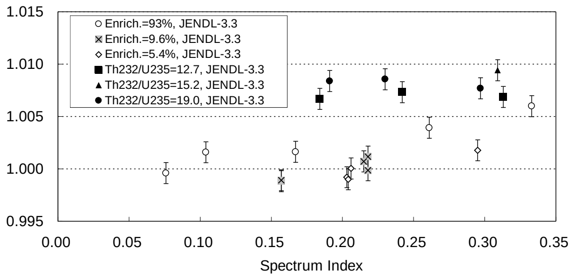

Fig. 5 C/E Values of KUCA Uranium Fueled Cores and Uranium / Thorium Fueled Cores by JENDL-3.3.

It could be concluded that the prediction accuracy of thorium fueled thermal systems have been improved by the use of recent data libraries such as JENDL-3.3 and ENDF/B-VI, but is still inferior to that of the conventional uranium fueled systems. The major cause of this issue is due to the ^{232}Th cross section itself; considerable discrepancy between the ^{232}Th evaluations exist and has been shown to have considerable impact on nuclear characteristics of thorium fueled thermal systems. Among the current evaluated nuclear data libraries, ENDF/B-VI.8 showed the best results in terms of criticality prediction, and thus may be recommended for use in the design studies of thorium fueled thermal systems.

5 Experiments on ADS using high-energy proton accelerator and subcritical cores

5.1 Purpose

The accelerator driven system (ADS) has been developed for producing energy and for transmuting minor actinides and long-lived fission products. The ADS has attracted worldwide attention in recent years because of its superior safety characteristics and potential for burning and incinerating plutonium and nuclear waste, together with the expectation of absence of reactivity accidents.

Experimental study of ADS has been launched at KUCA years ago by using 14 MeV (D,T) pulsed neutron generated by the Cockcroft-Walton type accelerator attached to KUCA A-core[13][14][15]. Based on the rich experience on those experimental study on neutronic characteristics of subcritical system with pulsed neutron source, a series of experiment have been launched using the fixed field alternating gradient (FFAG) accelerator[16] (Fig. 6) and KUCA[17]. The experiments, including the world's first injection of spallation neutrons generated by high-energy proton beams into a reactor core[18], is aimed to conduct a feasibility study on ADS and develop an innovative nuclear reactor for a high-performance transmutation system with a capability of power generation or for a new neutron source for scientific research.

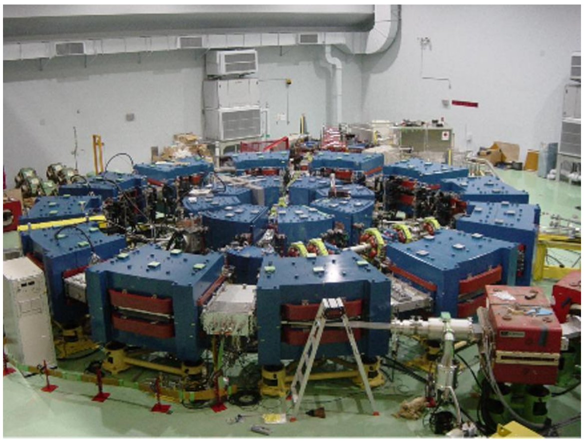

Fig. 6 FFAG accelerator.

5.2 Experiments

5.2.1 Subcritical core

The subcritical core shown in Fig. 7 of thermal neutron system (H/^{235}U ratio of approximately 315) was constructed at the A-core (solid moderated core). The 100 MeV proton beam generated by the FFAG accelerator was transported into KUCA building and was injected onto a tungsten target of 80mm diameter and 10mm thickness placed at the side of the critical assembly. A specially designed neutron guide and beam duct assemblies were used to lead the high-energy neutrons generated at the target into the core fuel region.

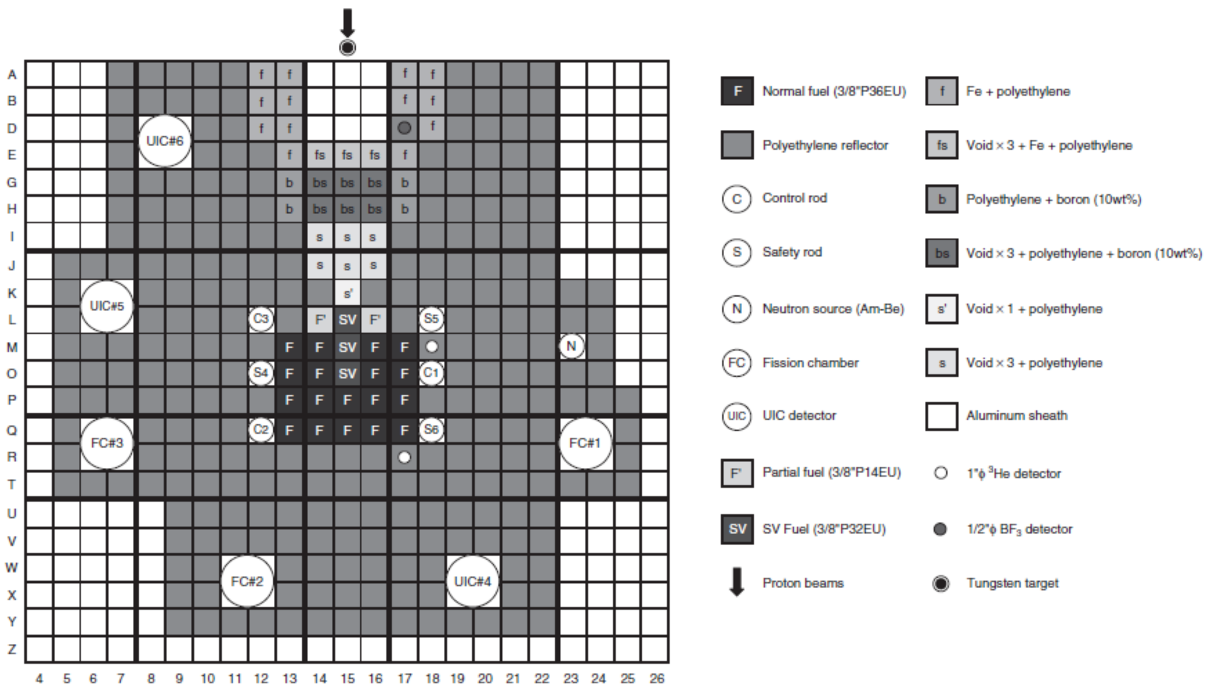

Fig. 7 Core configuration of the ADS experiment.

5.2.2 Prompt neutron decay measurement

As for the first experiment, the prompt neutron decay measurement was performed. The subcriticality of the core has been varied by changing the insertion pattern of the control rods. The time dependence of the detector response at various subcriticality shown in Fig. 8 shows an evident behavior of the prompt and delayed neutron in a subcritical system with pulsed neutron, which indicates that the present neutron multiplication have been caused by the injection of high-energy neutron generated by proton-tungsten spallation reaction. It should be noted that this was the first successful attempt in the world to drive a subcritical core by proton-induced high energy neutron. The subcriticality obtained from the measured detector response using the area method agreed with the experimentally evaluated subcriticality by the rod drop method within 20%.

The thermal neutron flux distribution within the subcritical core was estimated using the $^{115}In(n,\gamma)^{116m}In$ reaction rate distribution by the foil activation method using In wires. An example of the measured reaction rate distribution and calculated reaction rate distribution using MCNPX code is shown in Fig. 9. The measured and calculated values agreed within the statistical error with few exceptional data points and this indicates the validity of the present calculation method.

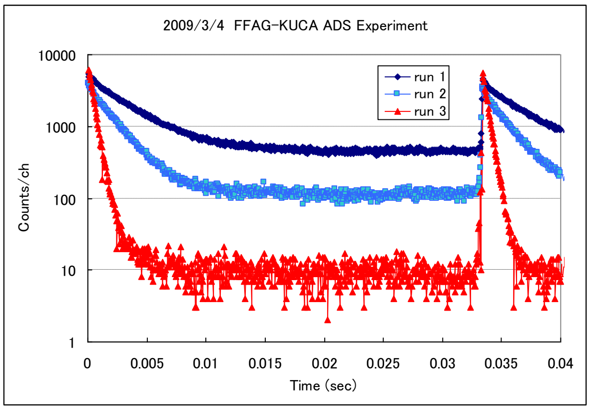

Fig. 8 Detector response of the subcritical core.

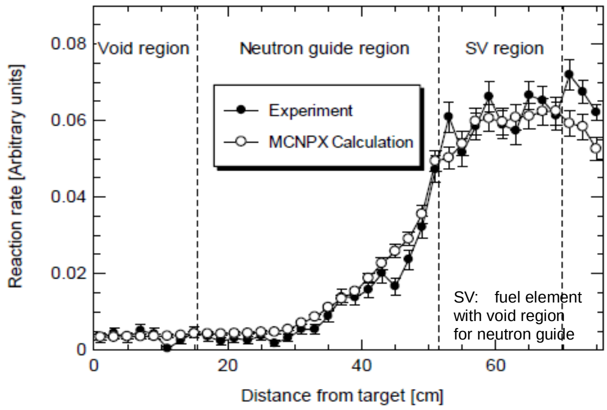

Fig. 9 Comparison of measured and calculated reaction rate distribution.

5.2.3 Core response at the beam trip, beam induction and rapid reactivity insertion

In order to achieve the operational characteristics of ADS under beam perturbation and reactivity insertion, the dynamic behavior of the core response have been measured under the conditions simulating the beam trip, beam induction and the rapid insertion of negative reactivity. Through the experiment, it has confirmed that the present subcritical system is robust to beam perturbation and could safely operated.

5.2.4 Subcriticality and kinetic parameter measurement using pulse train data

The detector response during the beam injection was recorded using digital multichannel data acquisition system as a time-dependent pulse train data. This data was analyzed using pulse neutron method and Feynman-□ method to obtain subcriticality and prompt neutron decay constant. The subcriticality of the system was varied by changing the control rod insertion pattern.

The prompt neutron decay constant deduced from detector response at different position using pulsed neutron method is shown in Table 3 together with calculation results using one-point approximation. The results of Feynman-α method showed good agreement with the pulsed neutron method. The overall trend of increasing decay constant with subcriticality was successfully observed, which justifies the applicability of the present data measurement and analysis method to ADS. On the other hand, the increasing discrepancy between measurement and calculation with increasing subcriticality indicates the necessity of detailed examination of space dependent time behavior of neutron in the system and its interpretation.

Table 3 Prompt neutron decay constants

Subcriticality (%Δk/k)	Det. at M-18	Det. at R-17	Calculation
0.16	204.0	273.0	191.6
1.18	237.3	271.6	403.1
1.63	346.5	337.8	496.4
1.90	396.2	365.2	759.8
2.91	536.8	525.9	857.3

6 Conclusions and future work

The reactor physics experiment for advanced nuclear reactor systems using KUCA are described and reviewed. These experiments, mainly aimed at verification and validation of current methodology for nuclear characteristics design, and also aimed at development of experimental techniques, are currently being continued and expanded to improve the reliability and accuracy of the experimental data. In order to aid the utilization of the experimental data, we are currently compiling and validating the experimental data to be published as international benchmark data such as ICSBEP.

As for the extension of the experiments, various new activities are being conducted or planned as follows;

- investigation on burnable poison materials for design of next generation high burnup fuel,
- critical experiment on thorium fueled cores for expanding the variety of core characteristics,
- enhancement of FFAG beam current and quality to improve the data accuracy of ADS experiments, and
- basic experiment on thorium-loaded ADS cores.

It is expected that a systematic and precise physical data be obtained through these activities, which may be inevitable for the verification and validation of current methodology for nuclear characteristics design of the next generation nuclear reactor system.

Acknowledgement

The authors would like to acknowledge all the technical staffs of KUCA for their generous and significant contribution in performing the experiments. The authors would also like to acknowledge the FFAG accelerator team for their generous and continuous assistance during the ADS experiments. A part of this work was supported by the grant-in-aid from Ministry of Education, Culture, Sports, Science and Technology (MEXT) of Japan.

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