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Reactor Physics Study related to Subcriticality of Accelerator Driven System by AESJ/JAERI working party

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Abstract

Under Atomic Energy Society of Japan (AESJ) and Japan Atomic Energy Research Institute (JAERI), a Working Party on Reactor Physics of Accelerator-Driven System (ADS-WP) has been set since March 1999 to review and investigate special subjects related to reactor physics research of Accelerator-Driven System (ADS). In the ADS-WP, the extensive and aggressive activity is being made by 25 professional members in the field of reactor physics in Japan. The ADS is now studying three subjects related to subcriticality of ADS; (1) calculation accuracy of subcriticality on ADS, (2) critical safety issues of ADS, and (3) theoretical review of subcriticality and its measurement methods. This paper describes two topics related to the subjects (1) and (2); one is an analysis of maximum reactivity potentially inserted to a subcritical core and the other is a benchmark proposal for checking calculation accuracy of subcriticality on ADS. The full specification of the calculation benchmark will be supplied by June 2002. Researchers from overseas, especially from Korea, are welcome to join this benchmark.

1. Introduction

Under the Research Committee on Reactor Physics of Atomic Energy Society of Japan (AESJ) and Japan Atomic Energy Research Institute (JAERI), a Working Party on Reactor Physics of Accelerator-Driven System (ADS-WP) has been set since March 1999 to review and investigate special subjects related to reactor physics research of Accelerator Driven System (ADS). In the ADS-WP, the extensive and aggressive activities are being made by 25 professional members in the field of reactor physics in Japan. The ADS is now

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studying three subjects related to subcriticality of ADS; (1) calculation accuracy of subcriticality on ADS, (2) critical safety issues of ADS, and (3) theoretical review of subcriticality and its measurement methods.

The ADS-WP will continue until March 2003 and the activity for all three subjects is being in progress. Therefore, this paper describes two topics related to the two subjects of (1) and (2). Section 2 describes about a benchmark problem based on experiments by three critical assemblies in Japan. In Section 3, an analysis of the maximum reactivity potentially inserted to a subcritical system is described as one of the issues related the critical safety of ADS. Section 4 summarizes this paper.

2. Benchmark for subcriticality on ADS

For checking the accuracy of the calculation of ADS core characteristics, two international benchmarks have held under OECD/NEA. The first one is the benchmark for the whole ADS calculation including the calculation in high energy region over 20 MeV. Therefore, only three laboratories participated. Nevertheless large discrepancies were shown among the three calculation results. After the first benchmark, the second benchmark immediately proposed. To collect more participants, the information (energy, angle space distributions of neutron production) in a spallation neutron source was specified in advance. Although about 10 participants joined the second benchmark, large discrepancies have been still observed.

It is considered that the large discrepancies in the ADS benchmarks are caused by the following three reasons:

(1) Calculation accuracy of subcriticality,
(2) Accuracy of nuclear data of Minor Actinide (MA),
(3) Calculation accuracy of spallation neutron source.

It is difficult to break down the discrepancies to each contribution originated from each reason since the reasons are complexly connected each other in the OECD/NEA benchmark problems. Benchmarks individually suitable for each reason are required to check the ADS calculation accuracy and improve the accuracy.

There is another problem in those OECD/NEA benchmarks. The benchmarks are not based on any experiment data; therefore it is impossible to clarify whether the calculation results of each participant are correct or not. A benchmark based on any experiment data is required. As the third benchmark, OECD/NEA is preparing to propose the benchmark problem based on the experimental results of MUSE-4 at CEA laboratory in Cadarache France.

Considering these situations, we have prepared to propose new benchmark problems, which are based on experiments using Japanese critical assemblies and are concentrated on the point of the calculation accuracy of subcriticality. As the experiments for the new benchmark, the following three facilities are taken into account:

(1) Kyoto University Critical Assembly, Kyoto University (KUCA)
(2) Tank-type Critical Assembly, Japan Atomics Energy Research Institute (TCA)
(3) Fast Critical Assembly, Japan Atomics Energy Research Institute (FCA)

(1) KUCA

KUCA has two types of critical assemblies; one is "C-core" which employs light water moderator and 93%-enriched uranium metal fuel, and the other is "B-core" which uses polyethylene moderator and 93%-enriched U-Al fuel. In KUCA, a series of experiments have performed by using B-core for subcriticality research of ADS. In the experiments, subcriticality has changed parametrically from critical up to -50$ by varying the numbers of fuels from 19 to 6 as shown in Table 1. Figure 1 shows the layout of core and fuel assembly of B-core with 21 fuels.

Table 1 Experiments in KUCA B-core for ADS subcriticality

No. of Fuels	Subcriticality ($)
19	2.32 ±0.02
17	6.40 ±0.08
15	10.9 ±0.2
13	13.4 ±0.2
9	28.2 ±1.1
6	49.4 ±1.0

(2) TCA

TCA is the light water moderated critical assembly with pin-type fuel. The fuel is the oxide fuel of 2.6%-enriched uranium. The core of TCA is shown in Fig.2. In the experiments by using TCA, subcriticalities of some ADS mock-up cores were measured with many experimental methods such as exponential experiment, pulsed-neutron and Feynman - α methods. The subcriticality was ranged from critical to -0.3 dk/k.

(3) FCA

FCA is a critical core with fast neutron spectrum. This facility employs plate type fuel of plutonium and uranium. In this facility, many experiments were made for reactor physics of ADS. In those experiments, the location of Cf252 neutron source was parametrically changed and the neutron flux distribution were measured precisely. The subcriticality was also measured by using many manners as mentioned above. A typical core arrangement of the FCA

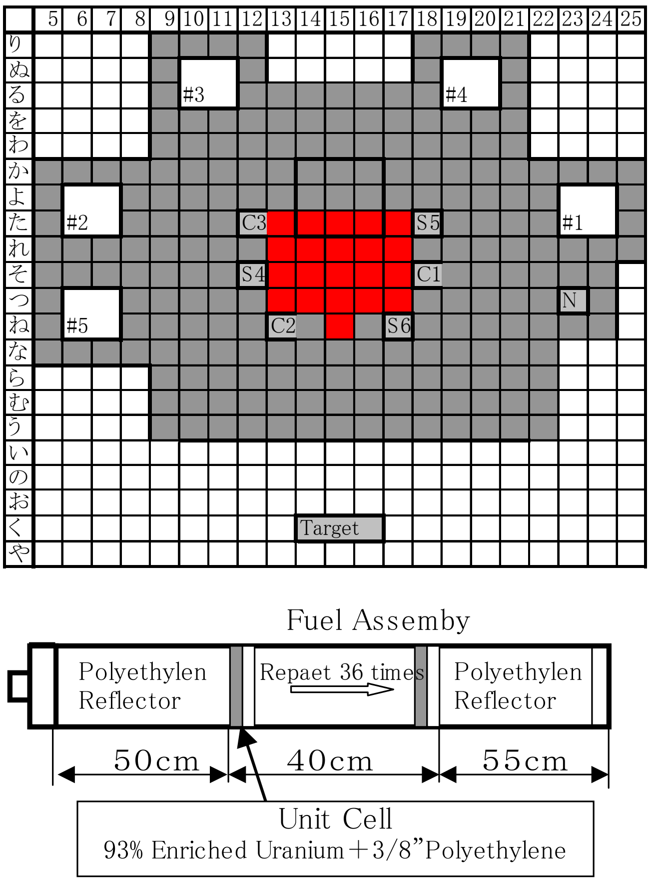

Fig.1. Core and fuel assembly of KUCA

experiments is shown in Fig.3. These experiments will be very valuable for the benchmark of ADS core calculation since usual ADS system is a fast reactor core.

(4) Benchmark problem

Based on the experiments mentioned above, the ADS-WP is now reviewing the experiments and is summarizing the specification benchmark problems, which includes subcriticality up to -50$ and neutron flux distributions for different locations of neutron sources.

This activity of benchmark specification will be done by June 2002 and will be opened for the member of ADS-WP and many researches in overseas

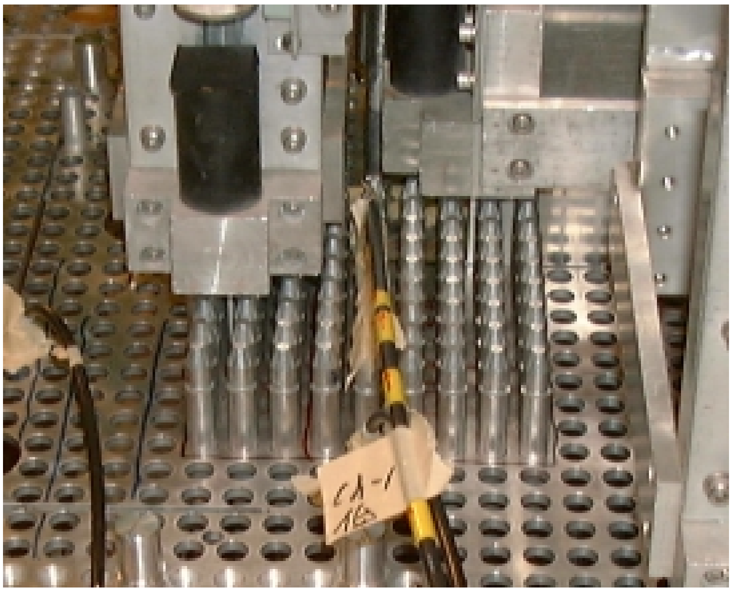

Fig.2. Core Layout of TCA

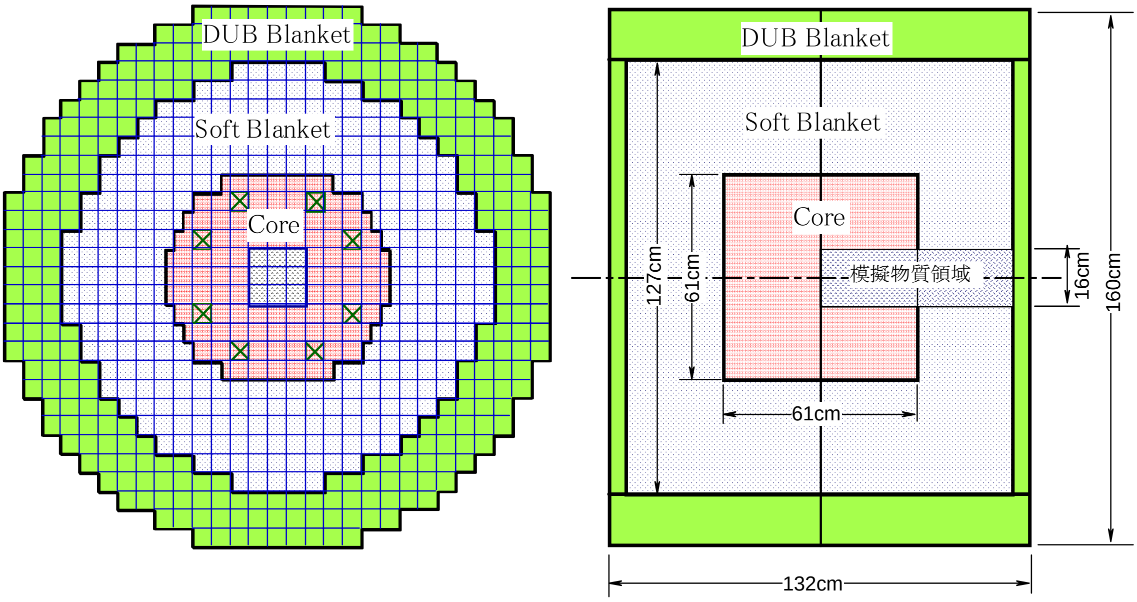

Fig.3. Core Layout of FCA for ADS experiment

3. Critical safety of ADS

Reactor power of an accelerator-driven subcritical reactor can be controlled by beam power from an accelerator. However, beam power does not directly change reactivity. For an accident where positive reactivity is inserted into a core, controlling accelerator is helpless for canceling the inserted reactivity and terminating the accident. The reactivity control of ADS should be studied to avoid any critical accidents in ADS. To examine the control method of ADS, the maximum reactivity, which might be induced into the core of ADS, should be investigated first. In this section, the reactivity insertion to ADS under an accident situation is investigated and the maximum reactivity, which might be potentially inserted to ADS, is evaluated.

Many factors insert reactivity into ADS. Considering core characteristics and accident behavior of Fast Reactor core (FR), which is similar to ADS core, only three factors are major. The three factors are the coolant temperature, the coolant void and the fuel temperature. Under an accident or transient situation, each factor changes. These factors promptly inserts the reactivity into the core accompanied with the core power change. Other factors such as the expansion of the core support are very important for a fast reactor. However, the factors effect with delay after changing the core power. Therefore, those factors are ignored in this study.

The reactivities inserted into the core by the three factors are as follows:

$$\delta\rho_c = \alpha_c \cdot (T_c - T_{c0}) \qquad (1)$$

$$\delta\rho_V = \alpha_V \cdot (V - V_0) \qquad (2)$$

$$\delta\rho_f = \alpha_f \cdot (T_f / T_{f0}) \qquad (3)$$

where

$\delta\rho_c$	:	Reactivity of coolant temperature
$\delta\rho_V$	:	Reactivity of void fraction
$\delta\rho_f$	:	Reactivity of fuel temperature
α_c	:	Reactivity coefficient of coolant temperature
α_V	:	Reactivity coefficient of void fraction
α_f	:	Reactivity coefficient of fuel temperature, i.e., Doppler coefficient
T_c and T_{c0}	:	Coolant temperature and reference coolant temperature
V and V_0	:	Void fraction and reference void fraction
T_f and T_{f0}	:	Fuel temperature and reference fuel temperature

The total reactivity of the three reactivities which is induced into the core is obtained from the following equation:

$$\delta\rho = \delta\rho_c + \delta\rho_v + \delta\rho_f \qquad (4)$$

Under any transients or accidents, the three factors does not change independently. For example, the coolant temperature does not exceed the fuel temperature. The void fraction is always zero when the coolant temperature is under the boiling temperature. Considering these relations of the three factors, we supposed the realistic range of the three factor variations as shown in Table 2. At the same time, we investigated the reactivity insertion at hypothetical cases where the three factors are changed independently without any relation (see Table 2). The reactivity of the hypothetical cases is employed to determine the maximum reactivity after comparing between the maximum reactivities for the realistic and hypothetical cases.

Two typical ADSs were adopted in the present study for investigating the maximum reactivity. One is a Na-cooled ADS (Na-ADS) and the other is Pb-Bi cooled ADS (PbBi-ADS), which have been designed by JAERI. The specifications of the Na-ADS and PbBi-ADS are shown in Table 3 (a) and (b). The core configurations of the both ADS were shown in Fig.4 in R-Z geometry. The Na-ADS is very similar to a FR core with the solid target at the core center. The PbBi-ADS has no solid target and the Pb-Bi coolant works as the target.

Table 2 Variation ranges and relations of coolant void, coolant and fuel temperatures

(a) no void

		V	T_c	T_f
Realistic situation	Temperature increase	$V=0$	$T_c < T_c^{BP}$	$T_f > T_c$
	Temperature decrease	$V=0$	$T_c^{MP} < T_c$	$T_f = T_c$
Hypothetical situation*		$V=0$	Free ($T_c^{MP} < T_c < T_c^{BP}$)	Free ($T_f < T_f^{MP}$)

(b) with void

		V	T_c	T_f
Realistic situation	Temperature increase	$0 < V \le 100$	$T_c = T_c^{BP}$	$T_f > T_c$
	Temperature decrease (=Coolant loss)	$0 < V \le 100$	$T_c^{MP} < T_c$	$T_f = T_c$
Hypothetical situation*		$0 < V \le 100$	Free ($T_c^{MP} < T_c < T_c^{BP}$)	Free ($T_f < T_f^{MP}$)

* No relation among V, T_c and T_f

MP = melting point (temperature), BP = boiling point (temperature)

The reactivity coefficients of the two ADSs were calculated by using the ATRAS code system, which consists of SCALE-4, TWODANT, etc. Four reactivity coefficients, α_c of the core region, α_c of the target region, α_V and α_f, were summarize in Table 3 (a) and (b). The reactivity coefficients of the PbBi-ADS are less negative than those of the Na-ADS. The coolant temperature coefficients for both regions become negative. However, the void coefficient is still positive and that of the core region are rather large (2.1 %dk/k/void). It is remarked for the two ADSs that the void coefficients of the core region are dominant.

Table 3 Specifications of Na cooled ADS and PbBi cooled ADS and their reactivity coefficients

(a) Na cooled ADS

Material	Fuel		(MA90%-Pu10%)-Nitride
	Target		W
	Coolant		Na
	Reflector		SUS
Size	Fuel Region Height		800mm
	Fuel Region Radius		400mm
Reactivity Coefficient	Coolant Temperature	Core	1.48E-05 (dk/k/C)
		Target	6.05E-07 (dk/k/C)
	Fuel Temperature	Core	-7.20E-05 (Tdk/k)
		Target	-7.20E-05 (Tdk/k)
	Void	Core	6.16E-02 (dk/k/V)
		Target	2.87E-03 (dk/k/V)

(b) Pb-Bi cooled ADS

Material	Fuel		(MA60%-Pu40%)-Nitride
	Target		Pb-Bi
	Coolant		Pb-Bi
	Reflector		SUS
Size	Fuel Region Height		850mm
	Fuel Region Radius		900mm
Reactivity Coefficient	Coolant Temperature	Core	7.12E-06 (dk/k/C)
		Target	-1.73E-08 (dk/k/C)
	Fuel Temperature	Core	-3.88E-04 (Tdk/k)
		Target	-1.40E-05 (Tdk/k)
	Void	Core	2.11E-02 (dk/k/V)
		Target	-7.13E-03 (dk/k/V)

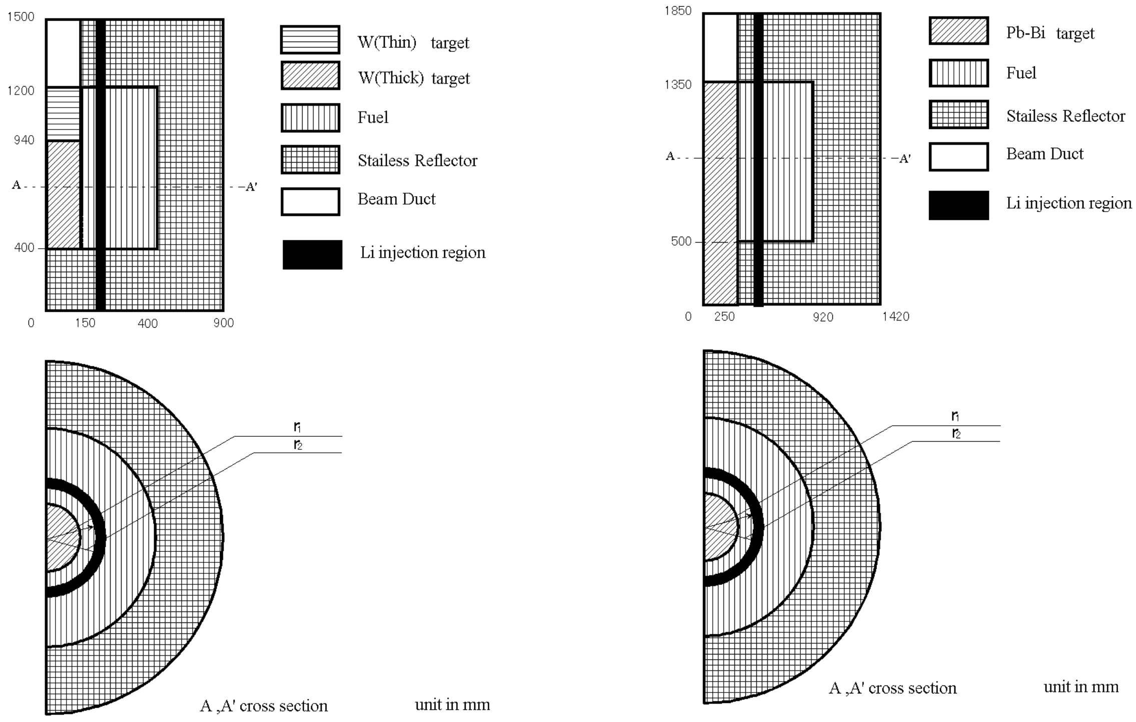

Fig.4. Core configuration in R-Z geometry for Na-ADS (left) and PbBi-ADS (right).

The results of the maximum reactivity for the two are shown in Table 4. For the Na-ADS, since the void reactivity coefficient is very large and is dominant, the total reactivity almost depends on the void fraction in the core region for both the realistic and the hypothetical situations. The maximum reactivity was 6.7%dk for the Na-ADS. The multiplication factor of ADS has been usually set to 0.95. Based on the maximum reactivity (6.7%dk), it can be concluded that the Na-ADS has potential risk of critical accident; therefore, any reactivity control may be installed in the Na-ADS.

On the other hand, the maximum reactivity was about 3.0%dk for the PbBi-ADS. This result is also due to the void fraction of 100% in the core region for both situations. The maximum reactivity of 3.0%dk is not small, however, it is concluded that the PbBi-ADS is safe for all reactivity insertion accidents if 0.95 is ensured during the operation of the PbBi-ADS.

Table 4 Maximum reactivities (%dk) for two ADSs

		Target	Core
Na cooled ADS	No void	0.044	-0.68
	With void	0.33	6.7
Pb-Bi cooled ADS	No void	-0.005	1.0
	With void	0.72	3.0

4. Summary and discussion

Under the Research Committee on Reactor Physics of Atomic Energy Society of Japan (AESJ) and Japan Atomic Energy Research Institute (JAERI), a Working Party on Reactor Physics of Accelerator-Driven System (ADS-WP) has been set since March 1999 to review and investigate special subjects related to reactor physics research of Accelerator Driven System (ADS). In the ADS-WP, the extensive and aggressive activities are being made by 25 professional members in the field of reactor physics in Japan. The ADS is now studying three subjects related to subcriticality of ADS; (1) calculation accuracy of subcriticality on ADS, (2) critical safety issues of ADS, and (3) theoretical review of subcriticality and its measurement methods.

The ADS-WP will continue until March 2003 and the investigation of all three subjects is being in progress. Therefore, this paper described two topics related to the two subjects of (1) and (2): one is the benchmark based on the experiments by the three critical assemblies (KUCA, TCA, FCA) in Japan for checking the calculation accuracy of subcriticality of ADS and, the other is the analysis of the maximum reactivity potentially inserted to a subcritical system as one of the issues related the critical safety of ADS.

The calculation benchmark, which is partly described in this paper, will be fully specified by the end of June, 2002. About 20 participants from Japan will be joined in this calculation benchmark. Participants from overseas, especially from Korea, are welcome to join this benchmark. We hope that many Korean researchers participate the benchmark.