A study of reactivity control by metallic hydrides for Accelerator Driven System

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Abstract. In an operation cycle of Accelerator Driven System (ADS), effective multiplication factor (*keff*) largely varies with the burn up of fuel. The ADS is available to keep the core power be constant by changing the proton beam intensity. However, it is not good for an accelerator and high beam intensity results in the irradiation damage. In this study, we have investigated a method for controlling the *keff* by using a control rod of the metallic hydride (*HfH1.3*) which is expected to have longer life than an original B_4C control rod of a fast reactor. For the core, burnup swing during an operation cycle, control rod worth for various locations of the control rods, core characteristic of the ADS core with the control rods were analyzed. As the result, it is found that the control rod of *HfH1.3* has large worth enough to suppress the burnup swing. By using three control rods, it is confirmed that the operation of the ADS core with the constant *keff* is possible.

1. Introduction

The Accelerator Driven System (ADS) proposed by Japan Atomic Energy Agency (JAEA) is a hybrid system that consists of a high intensity proton accelerator, a spallation target and a sub critical core. The thermal power of the ADS is 800MWth. The energy and the intensity of the proton beam is 1.5GeV and 20～30mA. The ADS employs Lead-Bismuth Eutectic (LBE) for the spallation target and the coolant. In the ADS, the effective multiplication factor (*keff*) largely varies during the operation with the burnup of fuel. The ADS is available to keep the core power be constant by changing the proton beam intensity. However, it is not good for an accelerator to increase the proton beam intensity largely and the high beam intensity results in the irradiation damage of the reactor structures such as the beam window. Therefore, it is valuable for ADS to suppress the *keff* during the operation cycle.

We have investigated a method for controlling the *keff* by using a control rod. In this study, for the control rod, we suppose the metallic hydride (*HfH1.3*) which is expected to have longer life than an original B_4C control rod of a fast reactor. Section 2 of this paper summarizes the ADS core and the control rod of *HfH1.3*. The calculation method is presented in Section 3. Section 4 describes about the method and the results for calculating the number and the location of the control rods required to suppress the variation of *keff* in an operation cycle. Section 5 explains about the analysis of the operation plan of the control rods for maintaining the constant *keff* (0.95) during an operation cycle. Finally, the characteristics of the ADS core with the control rods are studied and the results are presented in Section 6.

2. ADS core and Control rod

2.1. ADS core proposed by JAEA

The ADS proposed by JAEA is shown in FIG.1. Main parameters are shown in TABLE.1. The burnup cycle is 600 EFPD. The initial fuel composition of MA and Pu is MA:Pu = 60:40. For the reprocessing at the end of cycle, it is supposed that Fission Product (FP) is removed and MA is added for compensating the MA amount consumed in each cycle.

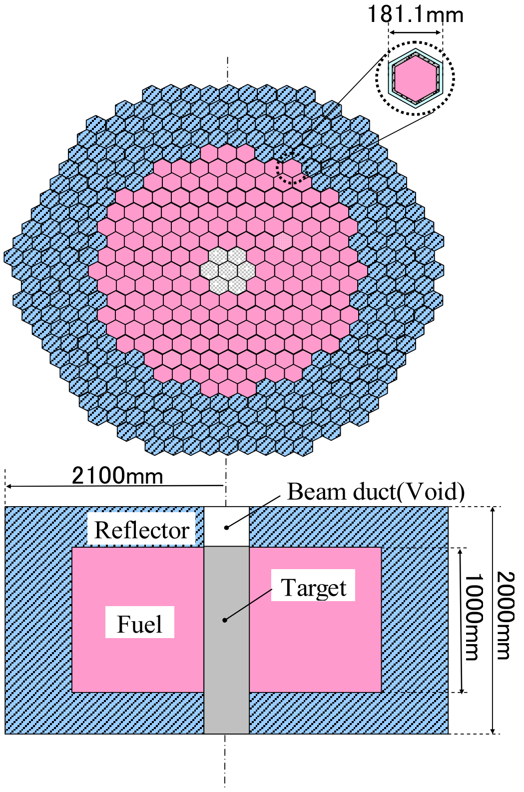


FIG. 1. ADS core proposed by JAEA

TABLE. 1. Main parameters of ADS core proposed by JAEA[3][4]

Core specification		
Thermal power	800	[MWt]
Multiplication factor	0.95	
Equivalent core height/daimeter	1.00/2.50	[m]
Equivalent target height /diameter	1.50/0.50	[m]
Core fuel composition	(60%MA+40%PU)+ZrN	
Target & Coolant material	Pb-Bi(LBE)	
Proton beam energy	1.5	[GeV]
Fuel pin & Assembly		
Fuel assembly lattice pitch	181.1	[mm]
Number of fuel pin /assembly	169	
Fuel pin outer diameter	9.29	[mm]
Fuel pin pitch	13.94	[mm]
Fuel pin height	1000	[mm]
Fuel pellet diameter	8.13	[mm]
Pb-Bi bomd thickness	0.22	[mm]
Cladding thickness	0.36	[mm]
Coolant specification		
Coolant temperature (in / out)	603/703	[K]
Coolant velocity	2	[m/s]
Coolant pressure	1	[Mpa]
Coolant flow rate	$1.98\text{x}10^{8}$	[kg/h]

2.2. Control rod

The control rod is *HfH1.3* which has been being researched [1][2]. FIG.2 shows the layout of the control rod. TABLE.2 shows the main parameters of the control rod.

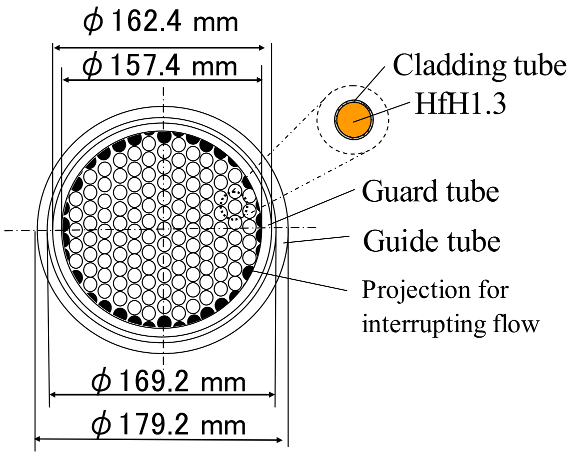


FIG. 2. The contorl rod (HfH1.3) design

TABLE. 2. Main parameters of the control rod (HfH1.3)

Main parameter of absorber		
Absorber material	HfH1.3	
A number of absorber rod	121	
Absorber diameter	10	mm
Cladding tube outer diameter	11.5	mm
Cladding tube inner diameter	10.22	mm
Cladding tube material	PNC-FMS Steel	
Gap width	0.11	mm
Space between absorber pins	1.3	mm
Absorber pin picth	12.8	mm
P/D	1.11	
Absorber Volume ratio	0.3269	
Guard tube and guide tube material	PNC-FMS Steel	

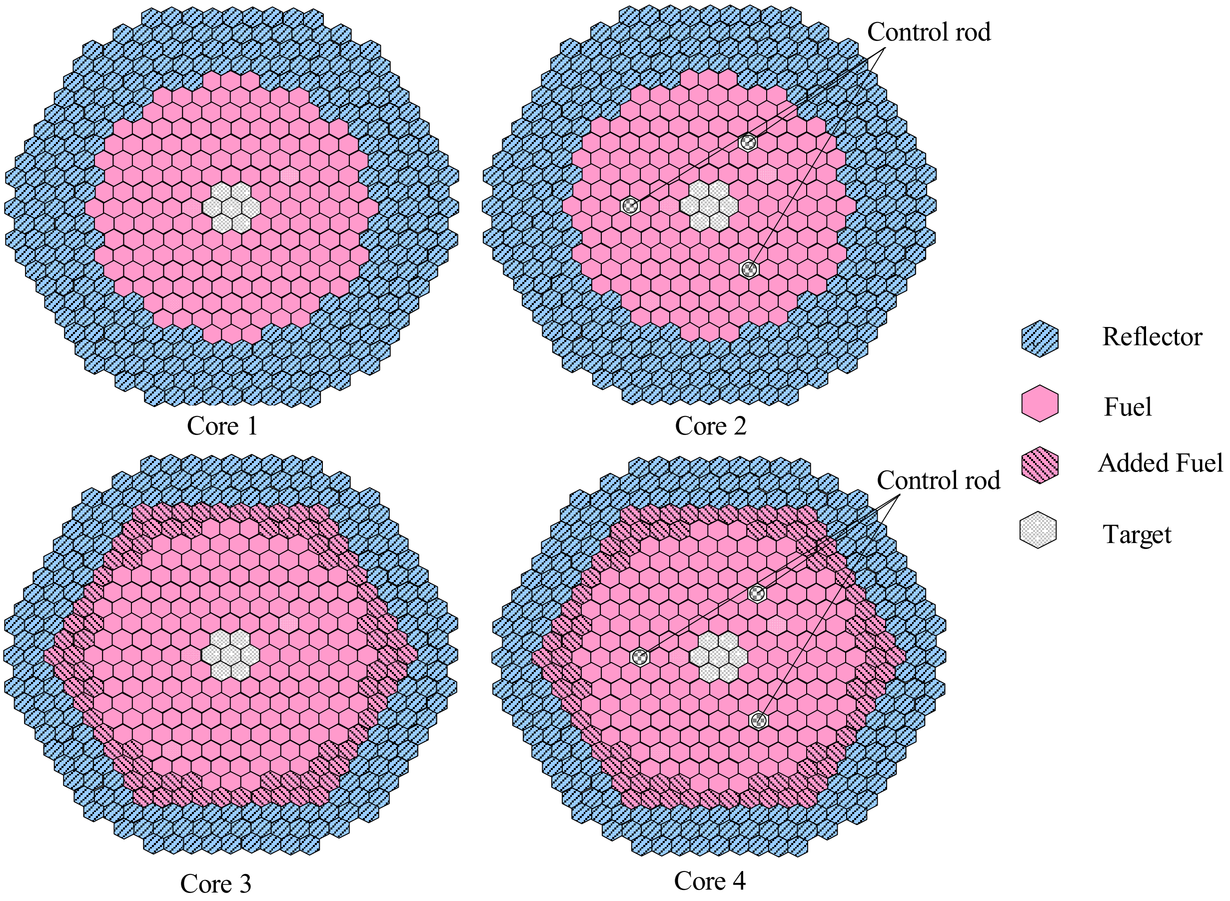
2.3. Four ADS cores adopted

This study considers four kinds of ADS cores. Those are shown in FIG.3. The ADS core proposed by JAEA is Core 1. Core 2 is the modified Core 1 having three control rods of *HfH1.3*. The number and the location of the control rods in Core 2 are determined in Section4.

By enlarging the fuel region of Core 1, the *keff* of Core3 at the end of cycle is increased from about 0.93 to 0.95. TABLE3 shows that the numbers of assemblies of Core 1 and Core 3. The total number of assemblies is maintained. Core 4 is the modified Core 3 having the control rods. Core 4 is prepared for demonstrating to maintain the constant *keff* (0.95) during an operation cycle by using the control rods. Other core parameters such as the height of core and the compositions of the materials are common among the four cores.

TABLE.3. Numbers of each assemblies in Core 1 and Core 3

	Core1	Core3
Target	7	7
Fuel	180	264
Reflector	264	180
Total	451	451



Core 1 Core 2

Core 3 Core 4

FIG. 3. ADS core design for calculation

3 Calculations

3.1. Code and nuclear data

MVP and MVP-BRUN [5] are used and JENDL3-3 [6] is adopted. The calculation for *keff* is performed by MVP code. The history is 2 million (4000x50). The statistical error is within 0.05%. For the burnup calculation, MVP-BURN is employed by dividing one burnup cycle of 600days to 7 steps, that is, one burnup step is 100 days. The history is 1 million (20000x50) in each step. The statistical error is also within 0.05%.

3.2. Outline of calculation

In the calculation, the ADS core is divided into four regions as shown in the FIG.1. The four regions are the fuel region, the reflector region, the target region and the beam duct region. Each region is homogenized in the calculation, that is, the fuel region consists of the fuel material (MA+Pu), the cladding tube (HT-9) and the coolant (Pb-Bi). The reflector region is composed of the reflector material (SUS316) and the coolant (Pb-Bi). The target region is fully filled with the target material (Pb-Bi). The beam duct region is void. On the other hand, the control rod is treated heterogeneously as it is FIG.2. For the partially inserted control rod, it is supposed that the lower region of the control rod is filled with the coolant. In this study, the calculations are performed by the eigenvalue calculation.

3.3. Reactivity swing

The reactivity swing is defined by the following equation.

$$\Delta\rho_{siwng} = \frac{1}{k_{BOE}} - \frac{1}{k_{EOC}}$$

Here, $\Delta\rho_{siwng}$: reactivity swing,

k_{BOC} : *keff* of initial burn up cycle,

k_{EOC} : *keff* of end of burn up cycle,

3.4. Void reactivity

In this study, the void reactivity is calculated from the *keff*s for the core with the void fractions of 0% and 100% void of the fuel region.[7][8]

$$\Delta\rho_{Void} = \frac{1}{k_{0\%Void}} - \frac{1}{k_{100\%Void}}$$

Here, $\Delta\rho_{Void}$: void reactivity,

$k_{0\%Void}$: *keff* of 0% void fraction,

$k_{100\%Void}$: *keff* of 0% void fraction

4 Number and location of control rod

4.1. Reactivity swing

The reactivity swing of the ADS core is investigated. In this study, the reactivity swing of Core 1 is calculated. In addition, another ADS core having 0.97 of *keff* is considered in order to check the effect of the initial *keff*. The additional core is prepared by changing the Pu composition. The Core1_C1 shows the *keff* variation for Core1 itself. The Core1_C2 shows the result for the modified Core 1 with the initial *keff* of 0.97. Those are shown in FIG.4. Each reactivity swings are shown in TABLE.4. It is found that the reactivity swing of the ADS core is about 3%dk/k'k for both.

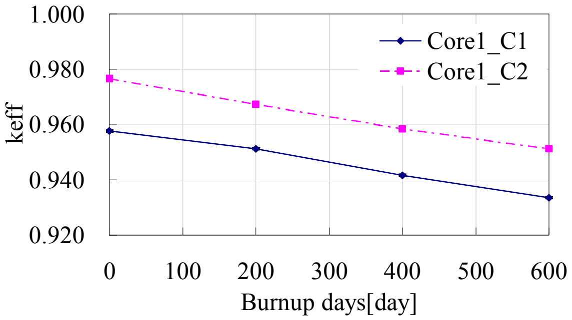


FIG. 4. Variation of keff for Core 1 of different fuel composition

TABLE. 4. Reactivity swing for Core 1 of different fuel composition

	Core1_C1	Core1_C2
Reactivity swing (%Δk/k'k)	2.704±0.063	2.745±0.055

4.2. Number of control rod required

The number of control rod required is investigated by changing the location of the control rod in the core as shown in FIG.5. For each location, the reactivity worth of one control rod is derived. The result is shown in TABLE.5. As the result, the reactivity worth is varied by the location from 0.1 to 0.9 %dk/k'k. It is confirmed that the reactivity swing of 3%dk/k'k is compensated by several control rods if the control rod is placed from Region 1 to 4.

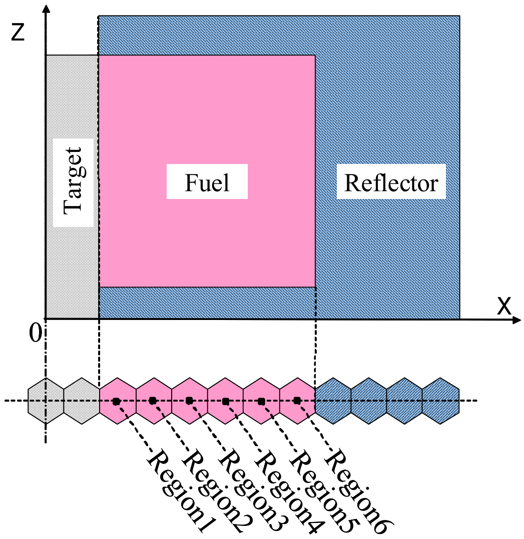


FIG. 5. Region definition on Core 1 (x-z cross section diagram)

TABLE. 5. Reactivity worth of a HfH1.3 control rod loaded to Core 1

	Reactivity worth [-%Δk/k'k]	Error[%Δk/k'k]
Resion 1	0.877	0.039
Resion 2	0.779	0.040
Resion 3	0.660	0.041
Resion 4	0.452	0.047
Resion 5	0.277	0.041
Resion 6	0.075	0.045

4.3. Determination of number and location of control rod

For determining the number and the location of the control rods, we analyses the reactivity worth for the cores in which various numbers and locations of the control rods are located. In the analysis, the different locations from Region 1 to 5 (FIG.5) and the different numbers of 2, 3, 4 and 6 are supposed. The example of the cores is shown in FIG3, that is, Core 2 with three control rods at Region5. The results are shown in the FIG.6.

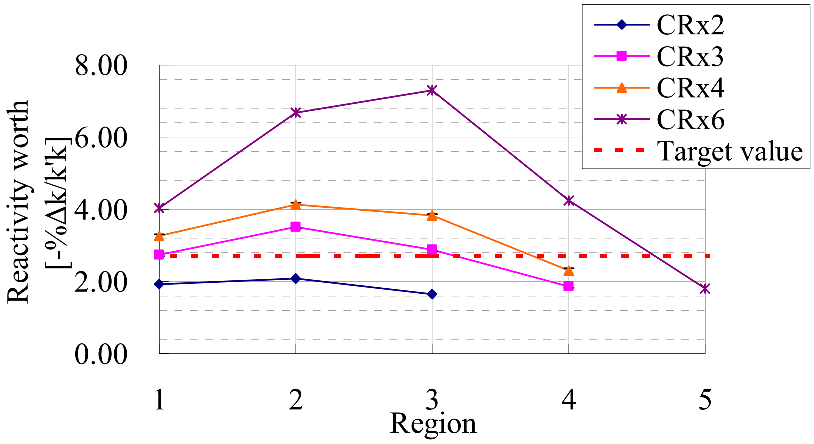


FIG. 6.Reactivity worth of several control rods in Core 1

4.4. Summary

In this chapter, we calculated the reactivity swing of the ADS core and investigated the number and the location of the control rod to suppress the reactivity swing. As the result, it is found that the reactivity swing of the ADS core is about 3%dk/k'k and several control rods of *HfH1.3* is enough to control the reactivity swing. Considering those results, we selected that the number is three and the location is Region 5. The core is shown in FIG.3.

5 ADS core with constant *keff* during burnup cycle

5.1. Varying of *keff* during burnup cycle

In this study, we aim the ADS core with the constant *keff* of 0.95 during the operation cycle. Therefore, Core 3 is prepared by changing the number of fuels from Core 1 (the original ADS core by JAEA). Core3 is the core with the *keff* of 0.95 at the end of cycle. Core4 is the modified Core 3 having three control rods which are determined above. The analysis is performed for Core 4 in this and the next Chapter.

The variation of *keff* for Core4 during the cycle is shown in FIG.6 and TABLE.6 with the results of Core1_C1 (See FIG.4), which is described once again. The reactivity worth of the control rod is shown in TABLE.7. Here, Core4_CR-all-out is the core4 that pulled out three control rods of *HfH1.3*.

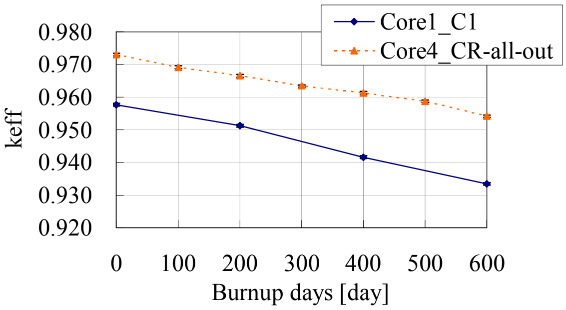


FIG. 6. Variation of keff for Core 4 and Core1

TABLE.6. Comparison of reactivity swing between Core 1 and Core 4

	Core_C1	Core4_CR-all-out
Reactivity swing (%Δk/k'k)	2.704±0.063	2.038±0.056

TABLE.7. Reactivity worth of control rods loaded to Core 4

	Reactivity worth [-%Δk/k'k]	Error [%Δk/k'k]
HfH1.3x3 in Core 4	2.174	0.039

5.2. Operation plan of control rod

The insertion depth of the control rods is determined to make *keff* be 0.95 at each burn up steps. The results are shown in FIG.7 and FIG.8. It is found that the *keff* of Core 4 is 0.95 during the cycle by changing the insertion depth of the control rods shown in the FIG.8.

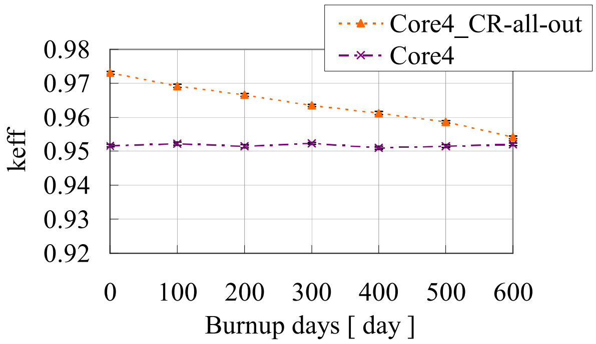


FIG. 7. Variation of keff for Core 4

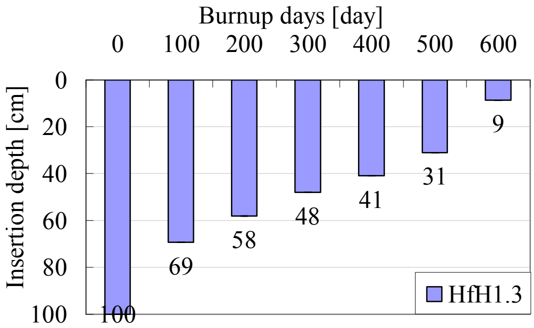


FIG.8. Insertion depth for HfH1.3 control rod

5.4. Summary

In this chapter, the flattering of *keff* is investigated by considering the core with the *keff* of 0.95 at the end of cycle. For the core, the variation of *keff* and the reactivity swing are calculated. As the result, it is shown that the reactivity swing of the ADS can be compensated by using the three control rods. It is confirmed for the ADS core that the *keff* possible to keep it be constant by the few control rod. .

6. Void reactivity

Considering Core 1, Core3 and Core 4, the void reactivity is analyzed. The results at the beginning of cycle (BOC) and the end of cycle (EOC) are shown in the TABLE.9 and TABLE.10.

TABLE.9. Void reactivity in BOC

	Core1	Core3	Core4	Core4_CR-all-out
keff (void 0%)	0.953	0.980	0.953	0.973
keff (void 100%)	0.976	1.017	0.983	1.010
Void reactivity(%⊿k/k)	2.491±0.052	3.733±0.047	3.139±0.050	3.702±0.039

TABLE.10. Void reactivity in EOC

	Core1	Core3	Core4	Core4_CR-all-out
keff (void 0%)	0.934	0.958	0.955	0.957
keff (void 100%)	0.950	0.991	0.988	0.989
Void reactivity(%⊿k/k)	1.847±0.069	3.473±0.036	3.477±0.067	3.369±0.072

It is shown that the void reactivity of Core 4 is larger than that of Core 1 since the core is enlarged (TABLE.9). But, by comparing the void reactivity of the Core 3 with that of the Core4 (TABLE.9), it confirmed that the void reactivity does not increase by using the control rods. The results for Core3 and Core4, Core4_CR-all-out in the TABLE.10 are almost the same since all cases have no control rods. It is additionally remarked that all the *keff*s of the ADS with the 100% void is subcritical as shown in the TABLE.9 and TABLE.10.

7. Future tasks

In this study, the calculations are performed by the eigenvalue calculation. The fixed source calculation is required for accurate consideration about the ADS. Furthermore, since the control rod supposed here is developed for a fast reactor with Na, the thermal-hydraulic calculations considering Pb-Bi is needed. Recently, we have developed ADSE [9] (Advanced Dynamics calculation code system for Subcritical system with External neutron source) in which the source calculation and the consideration of Pb-Bi are available. We intend to study such the future tasks.

Appendix 1: Reference

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