Nuclear Engineering and Design 240 (2010) 3645–3653

Contents lists available at ScienceDirect

Nuclear Engineering and Design

journal homepage: www.elsevier.com/locate/nucengdes

Finding the best fuel assemblies shuffling scheme of ADS for MA transmutation using Dynamic Programming

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ARTICLE INFO

Article history:
Received 8 January 2010
Received in revised form 2 July 2010
Accepted 6 July 2010

ABSTRACT

Dynamic Programming is applied to find the best shuffling scheme of ADS, which consists of 54 fuel assemblies and a spallation target of Pb–Bi, and the best scheme is successfully found under different constraints of power peaking factor. In the present problem the average transmutation ratio of MA is maximized under the constraints for effective neutron multiplication factor, discharged fuel burn-up, and power peaking factor.

The obtained results show the best fuel shuffling scheme consists of initial unique shuffling pattern and succeeding repetitive patterns for all cases. The repetitive pattern is unique for each constraint of power peaking factor, the best shuffling scheme changes sensitively for the change of constraints. For most best shuffling schemes, fresh fuel is loaded into the 2nd inner row of fuel region, and finally discharged from the inner or outer region because of the constraint of power peaking factor.

1. Introduction

Several countries recently promote research and development of accelerator-driven system (ADS) to reduce the burden for conditioning and disposal of the high-level radioactive waste (HLW) by transmuting minor actinide (MA) [1]. The ADS is a hybrid system that consists of a high intensity accelerator, a spallation target and a subcritical reactor. In usual ADS designs [2,3], spallation neutrons are supplied at the center of its core. In most designs lead–bismuth eutectic (LBE) is used as a spallation target, which is also used as a coolant.

This kind of ADS generally has a higher power peak than critical reactors because of its strong neutron source at the center. The power peak may cause the violation of temperature limit of the fuel cladding tubes. Therefore, it is important to flatten the power density distribution.

The ADS is a subcritical reactor system and considered safe for a reactivity-initiated accident by an enough reactivity margin. On the other hand, it is necessary to adjust a power level of the accelerator for supplementing the subcriticality of ADS. The larger *k*-eff is better from economical viewpoint since the larger power can be obtained even for smaller accelerator power, though its safety margin becomes smaller.

In the previous research for ADS by Japan Atomic Energy Agency (JAEA) [3], the subcritical core is composed of several regions and each region has different fuel composition in order to make the power density distribution flat. In this case, it is necessary to fabricate many kinds of fuel pellets. The fabrication of the ADS fuel is difficult because main component of this fuel is MA and Pu. The multiregion design using various fuel compositions is a burden for ADS operation.

In the present study the multiregion design using fuel shuffling is adopted to solve this problem. It is expected that the fuel shuffling can make the power distribution flat and transmute MA effectively by using only one kind of fuel composition. However, the investigation of the ADS fuel shuffling has been hardly done. Therefore in this study we try to find the best fuel shuffling scheme for hexagonal small ADS and investigate regularity of this scheme. There are a lot of patterns of how to shuffle fuels, so the total number of calculation cases becomes huge for finding the best scheme. In this study the Dynamic Programming [4] which can reduce the amount of calculation is introduced.

2. Methodology

2.1. ADS plant

The proton beam from the linac accelerator is introduced to the Pb–Bi target from the top of the ADS through the beam duct. The beam window is positioned at the same level as the top of the active core. Design parameters are shown in Table 1 and Fig. 1, which are based on the JAEA design (reference).

The core consists of 54 fuel assemblies. In this study a 30° rotational symmetric calculation model is used in neutronics

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doi:10.1016/j.nucengdes.2010.07.008

Table 1
Characteristic of base ADS.

Plant	Thermal power	470 MWth
	Coolant	Pb–Bi
	Structure	SUS316
Proton accelerator	Type	Linac
	Energy	1.5 GeV
	Target material	Pb–Bi
Fuel	Composition	(Pu + MA)N + ZrN[a]
	PuN weight ratio[b]	29.2%
	ZrN weight ratio[c]	37.2%
	Theoretical density	14.32 g/cm^3
	Pellet density	90%TD
	Smear density	85%TD
	Fuel pin diameter	7.65 mm
	Thickness of cladding tube	0.5 mm
	Fuel pin pitch	11.48 mm
	Active height	1000 mm
	Gas plenum height	1000 mm

[a] Nitride is 100% ^{15}N.
[b] PuN weight ratio to (Pu + MA)N
[c] ZrN weight ratio to (Pu + MA)N + ZrN.

calculation, and 7 fuel assemblies are considered for fuel shuffling. The region of each fuel is numbered as Region 1 to Region 7, from inner region to outer region as shown in Fig. 2.

2.2. Fuel cycle

The fresh fuel is composed of 62.8% (MA + Pu)N, which is a mixture of 70.8% MA nitride (MAN) and 29.2% Pu nitride (PuN), and

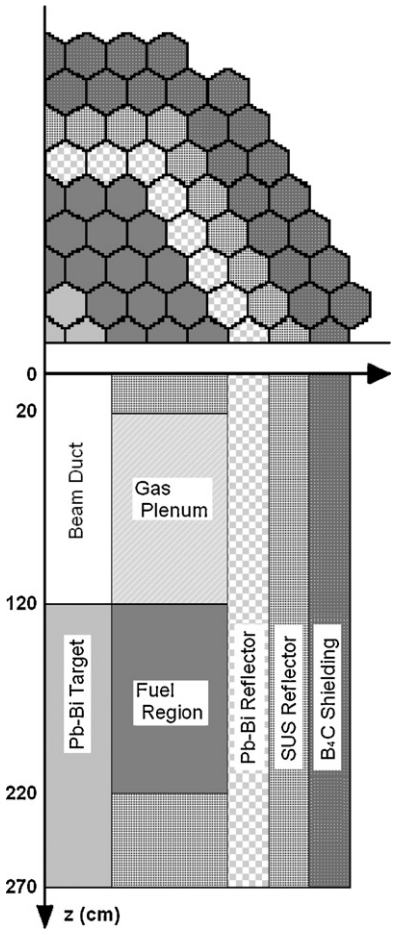

Fig. 1. Arrangement of base ADS assemblies and R-Z model for the cylindrical model.

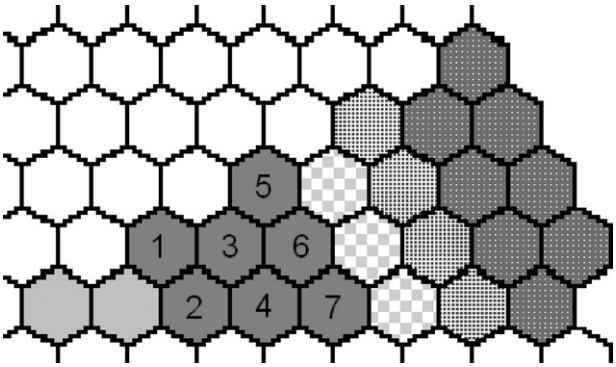

Fig. 2. Fuel region number for fuel shuffling.

37.2% Zr nitride (ZrN) in weight basis. ZrN is inert matrix which should be mixed into the fuel to reduce the power density. The compositions of MA and Pu as shown in Table 2 are assumed considering following reprocessing scheme. The spent PWR fuel of 45GWd/t burn-up is reprocessed after 7 years cooling, and MA and Pu are recovered. Before fabrication of the ADS fuel, additional 3-year period after recovery of MA and Pu is assumed. In the realistic ADS operation the multi-recycling of MA should be considered, but this point is not considered for this preliminary study.

One cycle length of the operation is set 1 year. After the operation of 300 days, all fuels are discharged. These fuels are called as old fuel. After that, the old fuels are shuffled and reloaded or replaced by the fresh fuels. This operation time is based on the LWR operation time. In the present paper we will find the best shuffling scheme for different operation time of ADS.

2.3. Calculation codes

The transport calculation for neutrons above 10 MeV was performed by using the continuous energy Monte Carlo calculation code, MCNPX [5]. An original code system was made for the present study for the diffusion calculation of neutron below 10 MeV, the burn-up of fuel based on one-group cross section, and the fuel shuffling calculation. The cell neutronics calculation is performed by using SRAC2006 [6]. JENDL-3.3 [7] was used as the nuclear data library. The details of fuel shuffling calculation are described in Section 2.4.

2.4. Calculation method

2.4.1. Fuel shuffling and burn-up

The fuel cycle including shuffling scheme is illustrated in Fig. 3. The box surrounded by single line represents fuel shuffling, and

Table 2
Isotopic composition of MA and Pu (wt%).

Isotope	MA	Pu
^{234}U		0.04
^{236}U		0.01
^{237}Np	49.65	
^{238}Pu		2.38
^{239}Pu		54.47
^{240}Pu		24.19
^{241}Pu		10.85
^{242}Pu		6.96
^{241}Am	32.10	1.09
^{242m}Am	0.06	
^{243}Am	13.37	
^{243}Cm	0.03	
^{244}Cm	4.04	
^{245}Cm	0.39	
^{246}Cm	0.04	