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DESIGN STUDY OF FULL SCALE ACCELERATOR DRIVEN SYSTEM (ADS), FOR TRANSMUTING HIGH LEVEL WASTE OF MA/Pu

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ABSTRACT

DESIGN STUDY OF FULL SCALE ACCELERATOR DRIVEN SYSYTEM (ADS), FOR TRANSMUTING HIGH LEVEL WASTE OF MA/PU. The ADS system used in this study consisting of a high intensity proton linear accelerator, a spallation target, and a sub-critical reactor core. The Pb-Bi spallation target is bombarded by high intensity protons coming from the accelerator. The fast neutrons generated from the spallation reaction were used to drive the sub-critical reactor core. In this ADS system, the neutron source is in the center of reactor core region, so that the neutron distribution was concentrated in the center of core region. In this case, the B/T of MA/Pu could be performed effectively in the center of core region. The neutron energy in the outer region of reactor core was decreased due to the moderation of fuel and coolant materials. Such condition gives a chance to perform Burning and/or Transmutation of LLFPs.The basic parameters of this system are shown in the form of neutronic design, neutron spectrum and B/T rate, including other aspects related to the safety operation system. Furthermore, the analysis of the ADS system was accomplished using ATRAS computer code of the Japan Atomic Energy Research Institute, JAERI[1]. Due to the complexity of the reactor calculation codes, the author has carried out only those calculations needed for analyzing the neutronics system and some parameters related to the safety system. Design study of the transmutation system was a full-scale power level system of 657.53 MWt sub-critical reactor for an accelerator-driven transmutation system. The liquid Pb-Bi was used together as the spallation target materials and coolant of the system, because of some advantages of Pb-Bi in the system concerning the comparison with the sodium coolant. Moreover, they have a possibility to achieve a hard neutron energy spectrum, avoid a positive void reactivity coefficient, allow much lower system operating temperatures, and are favorable for safety in the event of coolant leakage. The multiplication factor of sub-critical core design was adjusted exclusively through the high intensity protons beam accelerator at the spallation target. The fuel was assumed to have homogeneous compositions in the form of (MA-Pu) ZrN mixture with ^{15}N enriched. The compositions of Pu and MA were the same with the compositions of UO_2 fuel from 33-GWd/t burn-up in PWRs spent fuel after 5 year cooling. The results have been compared with the spent fuel composition from 45 and 60 GWd/t burn-up in PWRs at the same cooling time. The calculation of the burn-up step was 730 days per one batch reloading by using 4-regions core calculation model. The specific parameters of ADS system used in the calculation are described in Table 1.

Keywords : ADS, Transmutation, Energy, PWRs

INTRODUCTION

ADS system has been studied by many researchers in the several countries such as USA, Japan, France, etc[2]. The recent status of the ADS research in Japan has been realized as a prototype system for transmuting high level waste of MA/Pu and energy generation[3, 4, 5]. There are still some problems should be under taken for designing full scale system such as a problem of MA/Pu performance in the system[6, 7].

In this paper, a design study of the system has been studied and evaluated. Design study of system was a full-scale power level system of 657.53 MWt sub-critical reactor for an accelerator-driven transmutation system. The liquid Pb-Bi was used together as the spallation target materials and coolant of the system, because of some advantages of Pb-Bi in the system concerning the comparison with the sodium coolant[8, 9]. Moreover, they have a possibility to achieve a hard neutron energy spectrum, avoid a positive void reactivity coefficient, allow much lower system operating temperatures, and are favorable for safety in the event of coolant leakage.

The multiplication factor of sub-critical core design was adjusted exclusively through the high intensity protons beam accelerator at the spallation target. The fuel was assumed to have homogeneous compositions in the form of (MA-Pu) ZrN mixture with ^{15}N enriched. The compositions of Pu and MA were the same with the compositions of UO_2 fuel from 33-GWd/t burn-up in PWRs spent fuel after 5 year cooling[10]. The results have been compared with the spent fuel composition from 45 and 60 GWd/t burn-up in PWRs at the same cooling time. The calculation of the burn-up step was 730 days per one batch reloading by using 4-regions core calculation model. The specific parameters of ADS system used in the calculation are described in Table 1.

Nuclides i.e. Pu, Np, Am, and Cm were shown as part of nuclides to be taken into account of the transmutation capability. Table 4 show the initial loading of ADS using the fuel composition from 33, 45, and 60 GWd/t of PWRs spent fuel with 5 years cooling. The calculation results related to the materials inventory for the ADS system are shown in Table 5. The most important parameter related to the transmutation system evaluated here are the transmutation rate and the transmutation ratio. The results of the transmutation rate or capability and transmutation ratio have been calculated using the simple formulation. These calculations have been performed without treating the burn-up and decay chains, for the fuel composition from 33, 45, and 60 GWd/t of PWRs spent fuel with 5 year cooling. The transmutation rate or capability of an ADS system here is defined by the ratio of weight of overall heavy metal (MA) which is burned by fission and/or capture to that of initial loading of heavy metals (MA) per unit time. The definition of the transmutation rate is defined by the ratio of weight of heavy metals (MA) incinerated by fission reaction to that of initial loading of heavy metals (MA) per unit time. This is so because the aim of transmutation is the conversion of long-lived nuclide to short-lived or stable nuclides by fission and/or capture, because there are difficulties for separating the both transmutations.

Transmutation ratio = {difference of inventory between EOC and BOC}/ {Inventory at (BOC) x (cycle time)} (1)

Transmutation rate = {difference of inventory between EOC and BOC}/{EFPY between EOC and BOC) x Thermal power (MWt)} (2)

Note that HM (BOC) and (EOC): heavy metals quantities at the beginning and end of cycle (g/cc), cycle time: equivalent full power year (EFPY) between BOC and EOC, and thermal power (GWt).

Proceeding the R&D on proton ADS was a system that is consists of high intensity proton accelerator, spallation target, and sub-critical core region. Neutrons produced from spallation reaction in liquid Pb-Bi target drove the sub-critical core.

The objectives of the system are to destroy or minimize the long-lived radio-nuclide wastes and to improve the long-term safety assurance in the management of HLW in order to develop the available transmutation system covering the future development and utilization of nuclear power plant. The main long-lived radio-nuclide to be transmuted are actinide isotopes which is consists of Neptunium, Np, Americium, Am, Curium, Cm, and plutonium, Pu from various LWRs spent fuel.

EXPERIMENTAL METHODS

Basic Evaluation

The schematic diagram of the core calculation model of ADS evaluated here is shown in the following Figure 1. The liquid lead-bismuth as spallation target was in the center of core region. The neutrons generated from spallation reactions are used to drive the sub-critical reactor core which consists of MAs+Pu introduced surroundings the target region. In this calculation, the radius of spallation target and fuel in the core regions are set to 25 cm and 122 cm, with the core high was 100 cm, respectively. Thermal power generated in the core was 657.53 MWt with the energy of incident proton was 1.5 GeV.

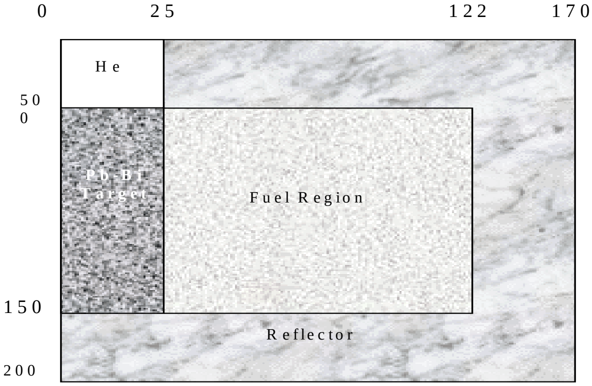

Figure 1. The schematic diagram of core used in the calculation model.

Burn-up Reactivity Swing

The calculation results on the burn-up characteristics for ADS is shown in the following figures. In this calculation, the reactor core was fueled by the fuel composition from 33 GW MOX and UO_2 LWRs spent fuel with 5 years cooling. The basics parameter calculation is shown in Table 1 in which the one batch reloading was 730 days with 3 years refueling. A mean burn-up value is assumed for evaluating the characteristics of burn-up reactivity swing as shown in Figure 2. As the results, it was found that the burn-up reactivity swing (% dk/k) was quite different from using 1 and 4-core region

Table 1. Specific parameters of ADS system used in the calculation using ATRAS codes system:

Parameter	Specification
Thermal Power	800 MWt.
Proton Beam Energy	1500 MW.
Target	
Material	Liquid Lead Bismuth
Duct Height	50 Cm
Diameter	50 Cm
Length	100 Cm
Core	
Height	100 Cm
Diameter	344 Cm
Pin Diameter	0.929 Cm
Pin-Pitch to diameter ratio	1.4 (-)
Fuel	(Pu, MA)N (^{15}N enriched)
Type	40% Pu + 60% MA
Composition	75.16 % ZrN
Inert Matrix	

calculation model. From the results, its may suggested to use the regionwise calculation model instead of the using of one region core calculation.

Table 2. Performance of the burn-up reactivity swing of ADS using 1 and 4-core regions calculation model from the fuel composition of 33 GW MOX and UO_2 PWR spent fuel.

Item	**1-Core Region**		***% Δk/k***
	BOC	**EOEC**	
UO_2	9.80E-01	9.39E-01	4.21E00

EOEC End of Equilibrium Cycle

Neutron Flux Distribution

Configuration of the ADS core design in this neutronic calculation is given by the same configuration with the calculation model from K. Tsujimoto as shown in the Figure 1. The reactor core in this model was divided into the target surrounded by four regions of core and reflector in cylindrical geometry in order to get the smooth region surfaces analyses. The survey parameters of the evaluations are including the spatial dependent of neutron flux distribution in group energy index, corresponding the neutron flux average in maximum eigen value and equal neutron flux average in each core region is shown in the following Figure 2. From the results, it can be seen that the neutron fluxes were mostly in the fast energy region and in the inner side of core region. Then, the transmutation was prescribed by the fast neutron energy region and higher neutron fluxes in the inner side to adhere to an averaged neutron flux distribution in the core region. In other word, the composition of fuel could be arranged using inhomogeneous loading pattern in order to increase the effectiveness of transmutation system.

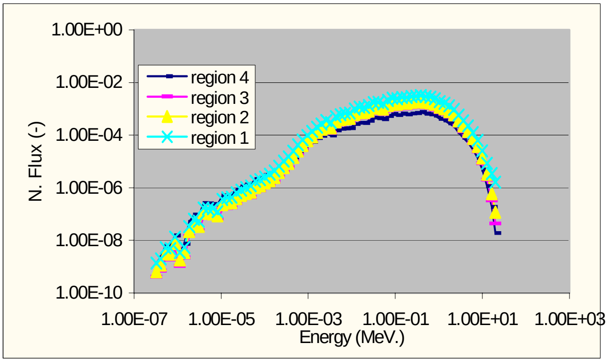

Figure 2. Neutron flux vs energy distribution using the fuel composition of MOX from 33 GW PWR spent fuel, 5 years cooling.

Nuclides Density

Nuclide density from UO_2 fuel composition after recycle is shown in the following Figure 3. The evaluation of the nuclides to be show here such as ^{237}Np, ^{238}Pu, ^{239} Pu, ^{241}Am, and ^{244}Cm. The accumulation were also occurred for the same nuclides such as ^{238} Pu and ^{244}Cm which is mostly from the captures reaction of ^{237}Np and ^{243}Cm. Then the significant decreases were also occurred for the nuclides of ^{237}Np, ^{239}Pu, and ^{241}Am.

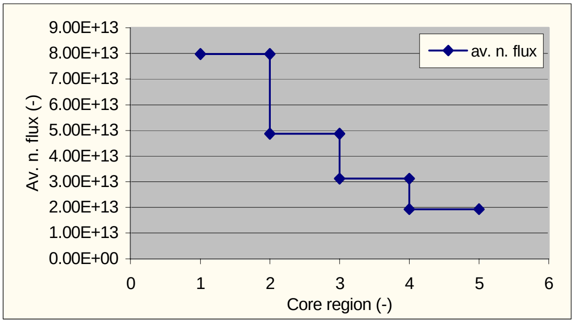

Figure 3. Average neutron flux distribution in each core region using the fuel composition of MOX from 33 GW PWR spent fuel, 5 years cooling.

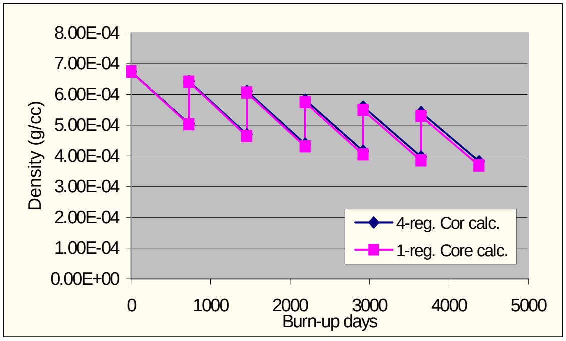

Figure 4. ^{237}Np density along the burn-up days using the fuel composition of UO_2 from 33 GW PWR spent fuel, 5 years cooling.

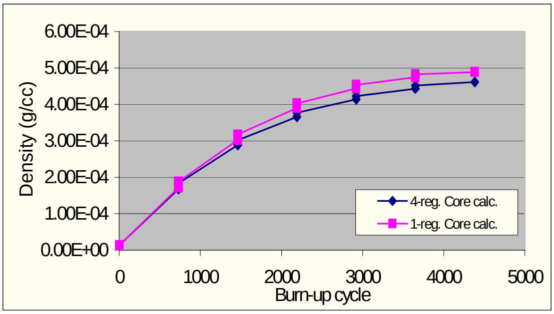

Figure 5. ^{238}Pu density along the burn-up days using the fuel composition of UO_2 from 33 GW PWR spent fuel, 5 years cooling.

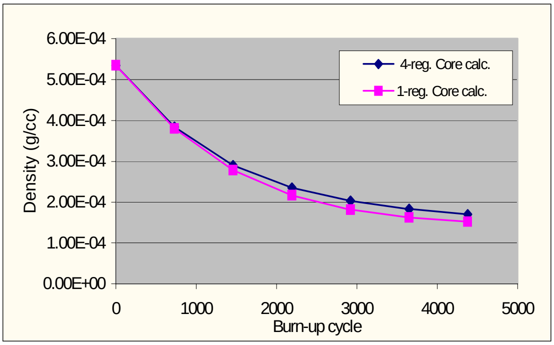

Figure 6. ^{239}Pu density along the burn-up days using the fuel composition of UO_2 from 33 GW PWR spent fuel, 5 years cooling.

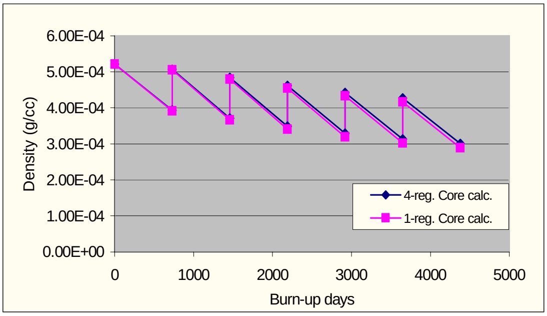

Figure 7. ^{241}Am density along the burn-up days using the fuel composition of UO_2 from 33 GW PWR spent fuel, 5 years cooling.

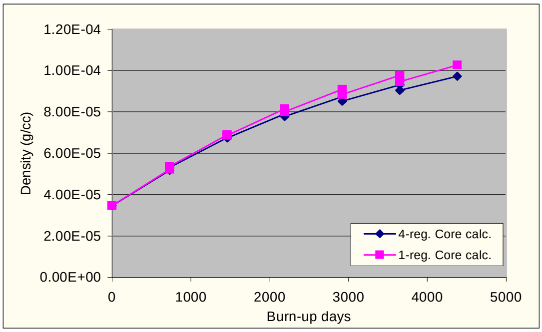

Figure 8. ^{244}Cm density along the burn-up days using the fuel composition of UO_2 from 33 GW PWR spent fuel, 5 years cooling.

Then, the capability of ADS ADS loaded with UO_2 fuel Composition from 33 GW PWR spent fuel, 5 years cooling could be summarized as the following Table 3.

Table 3. Capability of ADS loaded with UO_2 fuel Composition (%).

UO_2 fuel	Transmutation ratio (% / y)	
	HM	MA
1-Region	6.60E+00	1.42E+01
4-Region	6.58E+00	1.36E+01

Inventory

The calculation results of materials inventory for the ADS system are shown in the following Table 6. The important parameter related to the transmutation system evaluated here is the transmutation rate and the transmutation ratio. The results of the transmutation rate and transmutation ratio have been calculated using the simple formulation (1) and (2) bellow. This calculations have been performed without treating the burn-up and decay chains, for the fuel composition from UO_2 of 33, 45, and 60 GWd/t of LWRs spent fuel with 5 years cooling time. The transmutation rate of an ADS system here is defined by the ratio of weight of overall heavy metal (MA) which is burned by fission and/or capture to that of initial loading of heavy metals (MA) per unit time. The definition of the transmutation ratio is defined by the ratio of weight of heavy metals (MA) incinerated by fission reaction to that of initial loading of heavy metals (MA) per unit time. This is because of the aim of transmutation is the conversion of long-lived nuclide to short-lived or stable nuclides by fission and/or capture, because of the difficulties for separating the both transmutation. The formulations of both transmutation rate and transmutation ratio are defined as the equations follow;

Transmutation ratio = {difference of inventory between EOC and BOC}/ {HM at (BOC) x (cycle time)} (3)

Transmutation rate = {difference of inventory between EOC and BOC}/{(cycle time) x Thermal power (MWt)} (4)

Where, HM (BOC) and (EOC): heavy metals quantities at the beginning and end of cycle (g/cc), cycle time: equivalent full power year (EFPY) between BOC and EOC, and thermal power (GWt), (1 cycle length = 600 days and thermal power = 0.8 GWt were used in the present consideration).

The appropriate nuclides density of ADS system using UO_2 composition from 33 GW, 45 GW, and 60 GW PWRs spent fuel with 5 years cooling was performed by the same way as already shown as the appropriate nuclides density for MOX fuel composition. Initial loading of an ADS system using fuel composition from UO_2 of PWRs spent fuel, 5 years cooling are shown in the following Table 4.

Table 4. Initial loading of an ADS system using fuel composition from UO_2 of PWRs spent fuel, 5 years cooling, (DF of RE = 10 %, Y-N = 74.9 %, Pu = 37 %).

Nuclides	Initial loading (g/cc) at BOC*		
	33-GWd/t	**45**-GWd/t	**60**-GWd/t
Uranium			
^{234}U	-	-	-
^{235}U	-	-	-
^{236}U	-	-	-
Plutonium			
^{238}Pu	4.81E-03	7.98E-03	1.23E-02
^{239}Pu	1.92E-01	1.80E-01	1.70E-01
^{240}Pu	7.81E-02	7.98E-02	7.90E-02
^{241}Pu	3.70E-02	3.94E-02	4.08E-02
^{242}Pu	1.75E-02	2.30E-02	2.72E-02
MAs			
^{237}Np	2.75E-01	2.78E-01	2.84E-01
^{238}Np	-	-	-
^{241}Am	2.12E-01	1.81E-01	1.54E-01
^{242m}Am	3.07E-04	3.49E-04	3.84E-04
^{242}Am	3.67E-09	4.17E-09	4.60E-09
^{243}Am	5.86E-02	7.51E-02	8.40E-02
^{242}Cm	4.15E-06	4.72E-06	4.92E-06
^{243}Cm	1.39E-04	2.06E-04	2.60E-04
^{244}Cm	1.41E-02	2.45E-02	3.48E-02
^{245}Cm	9.65E-04	2.17E-03	3.84E-03
^{246}Cm	8.00E-05	2.25E-04	4.64E-04
HM	*8.91E-01*	*8.91E-01*	*8.91E-01*
MA	*5.61E-01*	*5.61E-01*	*5.61E-01*

BOC Beginning of Cycle*

Nuclide densities after the incineration using UO_2 fuel composition are given in Table 5. In this calculations, material distribution i.e. volume fractions, isotope compositions of fuel (fertile and fissile), densities are prescribed in the ADS evaluation design. In this evaluation, several nuclides i.e. Np, Pu, Am, and Cm were shows as part of nuclides to be taken in to account of the transmutation capability. In case of the composition from UO_2 fuel, the capability of ADS could be varied dependently as the initial loading of fuel composition used in the calculations as shown in the Table 5 above.

Table 5**.** Material inventory and mass balance of ADS system using fuel composition from UO_2 of PWRs spent fuel, 5 years cooling, (DF of RE = 10 %, Y-N = 74.9 %, Pu = 37 %).

Nuclides	Inventory (g/cc)					
	33-GWd/t		**45**-GWd/t	**60**-GWd/t		
	BOEC*	EOEC**	BOEC*	EOEC**	BOEC*	EOEC**
U						
^{232}U	5.08E-6	-	4.93E-6	-	4.88E-6	-
^{233}U	-	-	-	-	-	-
^{234}U	3.29E-2	3.12E-2	3.13E-2	2.96E-2	3.03E-2	2.85E-2
^{235}U	4.02E-3	-	3.91E-3	-	3.86E-3	-
^{236}U	9.99E-4	-	1.02E-3	-	1.04E-3	-
Pu						
^{238}Pu	2.12E-1	2.10E-1	2.00E-1	1.98E-1	1.93E-1	1.91E-1
^{239}Pu	5.62E-2	5.54E-2	5.35E-2	5.28E-2	5.19E-2	5.12E-2
^{240}Pu	7.77E-2	7.28E-2	8.75E-2	8.17E-2	9.43E-2	8.79E-2
^{241}Pu	8.52E-3	9.73E-3	9.51E-3	1.10E-2	1.02E-2	1.19E-2
^{242}Pu	4.12E-2	4.20E-2	3.92E-2	3.96E-2	3.73E-2	3.74E-2
Mas						
^{237}Np	2.28E-1	1.70E-1	2.24E-1	1.66E-1	2.24E-1	1.65E-1
^{238}Np	2.02E-4	-	2.04E-4	-	2.07E-4	-
^{241}Am	1.76E-1	1.31E-1	1.48E-1	1.09E-1	1.25E-1	9.22E-2
^{242m}Am	1.33E-2	1.32E-2	1.13E-2	1.11E-2	9.63E-3	9.51E-3
^{243}Am	6.56E-2	5.43E-2	7.85E-2	6.35E-2	8.47E-2	6.78E-2
^{242}Cm	1.10E-4	7.97E-3	9.44E-5	6.86E-3	8.15E-5	5.93E-3
^{243}Cm	7.95E-4	8.11E-4	7.31E-4	7.29E-4	6.72E-4	6.56E-4
^{244}Cm	4.17E-2	4.43E-2	5.61E-2	5.80E-2	6.68E-2	6.75E-2
^{245}Cm	8.82E-3	8.97E-3	1.25E-2	1.24E-2	1.56E-2	1.52E-2
^{246}Cm	1.85E-3	2.11E-3	2.98E-3	3.31E-3	4.19E-3	4.56E-3
^{247}Cm	1.36E-4	-	2.32E-4	-	3.39E-4	-
HM	*9.70E-1*	*8.53E-1*	*9.60E-1*	*8.43E-1*	*9.53E-1*	*8.36E-1*
MA	*5.36E-1*	*4.32E-1*	*5.34E-1*	*4.31E-1*	*5.31E-1*	*4.28E-1*

* *Beginning of Equilibrium Cycle*

** *End of Equilibrium Cycle*

As already mentioned above, that the performance of ADS on the side of burn-up reactivity swing is depending on the initial spent fuel composition. As the calculation results, the initial spent fuel compositions mostly affect the transmutation capability. By using the same equations of (3) and (4), the nominal value of the transmutation rate and transmutation ratio are shown in the following Table 5.

Table 5. Capability of an ADS system using fuel composition from UO_2 of PWRs spent fuel, 5 years cooling, (DF of RE = 10 %, Y-N = 74.9 %, Pu = 37 %).

Items	Initial loading (kg)		Transmutation ratio (% / y)		Transmutation rate (kg /GWy)	
	HM	MA	HM	MA	HM	MA
33 GW	3.99E+06	2.52E+06	7.33	11.78	398.31	353.73
45 GW	3.99E+06	2.52E+06	7.41	11.78	398.35	352.14
60 GW	3.99E+06	2.52E+06	7.47	11.82	398.46	351.66

CONCLUSIONS

1. Considering of the calculation results, the deviations between the using of single and multi-region core calculations were high enough. Then, the consideration of using the regionwise calculation model could become reasonable and suggested to perform the appropriate design evaluation arising from comparison of the former one region calculation model.
2. Burn-up characteristics of an ADS system were mostly depending on the spent fuel compositions such as MOX or UO_2 compositions. These dependencies to the burn-up reactivity swing and the transmutation ratio between the both fuel compositions may come from the differences of the fuel densities and accumulation of several nuclides in MOX fuel rather than UO_2 fuel composition whether by fission or captures.
3. The choice for initial loading of Pu elements could affect to the performance of burn-up reactivity swing. In which, when the initial loading of Pu elements was under or less than 37 %, it could gives the significant effects to the negative burn-up reactivity swing instead of the initial loading of Pu by greater than 37 %. Its mean that the initial loading of Pu elements should be decided at least by 37 %.
4. The composition of initial loading of Pu from MOX spent fuel in each GW burn-up gives the significant effects to the changes of k-eff instead of the using of UO_2 composition. Its mean that the use of MOX spent fuel composition in various GW burn-up should be under taken in to account over the appropriate design requirements considering to the initial Pu loading instead of the use of UO_2 spent fuel composition, and the most interesting is that the both spent fuel compositions from MOX and UO_2 gives the linear effects to the initial value of k-eff.
5. All fuel elements containment introduced in the ADS system was considered as about 4.0 tons of HM (heavy metal). The HM weight

contents in the reactor core could affect the magnitude value of the k-eff in which the value of burn-up reactivity swing (dk/k) was almost the same for each HM weight contents. Then, such as effects could be used as a choice for determine the amount of MA or HM to be transmuted by the appropriate fuel design.

6. Finally, the ADS system could be designed for transmuting the heavy metal or MA elements by the appropriate agreements to the capability of ADS it self with the existing of spent fuel reprocessing demand (such as pyro-chemical process or dry processing etc.).

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