

Life Extension of PWR with Coated Particle Fuel By Using Thorium and Plutonium

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I. INTRODUCTION

An innovative concept of PFPWR50 is a smaller PWR than conventional commercial ones with thermal power 50 MW. It provides district-heating service as long periods as possible without on-site refueling. PFPWR50 uses coated particle fuel with cladding of zircaloy. Coated particle fuel, which is used in a high temperature gas reactor (HTGR), has good confining ability of fission products inside the coating. The concept of PFPWR50 can improve the conventional PWR safety and public acceptance to building nuclear reactor at the district. As another advantage, the fuel is fixed by graphite matrix, so that graphite is helpful to reduce the fuel temperature rise in case of loss of coolant accident by its large heat capacity.

UO₂ kernel has been used for the fuel in the previous study,^{1, 2, 3)} but ThO₂-PuO₂ is selected in this study for extending the life of PFPWR50. As is well known, thorium-232 absorbs a neutron to be converted into uranium-233 and it is one of fissile materials. Then it can burn as well as plutonium-239 and plutonium-241. The utilization of the ThO₂-PuO₂ could deal with the uranium shortage in the future. The reason why we use plutonium is to extend the life of PFPWR50 and to utilize plutonium in the spent fuel from conventional PWRs.

The unique feature of PFPWR50 concept is that the excess reactivity is suppressed during a cycle by initially loading burnable poison in the fuel. That could simplify the operation of the reactor and allow eliminating soluble boron system that is one of expensive system, achieving simple design, reducing the cost of the system, and moreover, enhancing the safety of the reactor.

The concept of the coated particle fuel and a fuel rod is shown in **Fig. 1**. The reactor parameters are listed in **Table 1**.

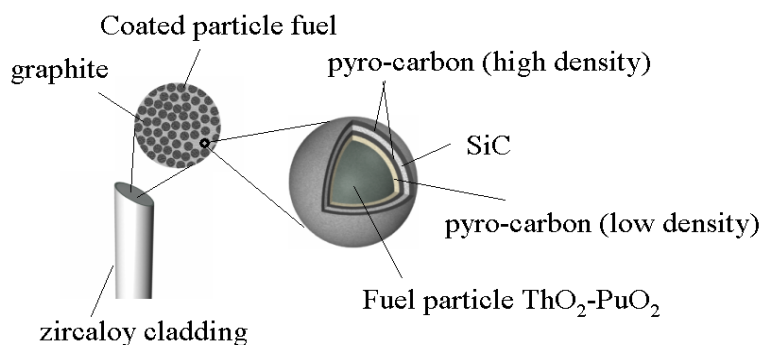


Fig.1 Concept of coated particle fuel and a fuel rod

Table 1 Reactor parameters

Thermal output	50 MW
Core equivalent diameter	~2.4 m
Core height	~1.8 m
Average coolant temperature	~250 °C
Coolant pressure	8.6 MPa
Number of fuel assembly	85
Loading of heavy metal	~4.6 t
Core life	~8.9 EFPY
Average linear heat rate	9.1 kW/m
Fuel	TRISO
Plutonium enrichment	10 wt%
Fissile plutonium enrichment	7.5 wt%
Cladding material	Zircaloy
Lattice type	Hexagonal
Number of rods/Assembly	37
Assembly pitch	21 cm
Fuel rod pitch	34 mm
Fuel rod diameter	29 mm
Cladding thickness	1.5 mm

In the first part of this paper, method of calculation is described briefly, and the second part presents basic parameters and calculation results with some figures.

II. Method of Calculation

The calculation code used is SRAC95,⁴⁾ which is a general-purpose nuclear calculation code system developed by Japan Atomic Energy Research Institute. It consists of various calculation modules for a variety of geometries of a unit cell, fuel assemblies, and a reactor core in 1-dimension to 3-dimensions. We investigated burn-up characteristics by PIJ-module for unit cells, by ASMBURN for fuel assemblies and by COREBN for the reactor core, and all data used are of nuclear data library JENDL-3.2.

A unit cell consists of a fuel rod of spherical particle $\text{ThO}_2\text{-PuO}_2$ coated with thin layers of SiC, graphite, cladding of zircaloy and moderator of light water. PIJ calculates homogenized effective cross sections per regions and burn-up characteristics. However, heterogeneity is not taken into account. Therefore, the comparisons of the results with those by another code (e.g. MVP) are necessary in the future as in reference 5).

As the next calculation step, assemblies are configured using above cell constants and burn-up characteristic is calculated by ASMBURN. It can also generate assembly-wise homogenized cross sections. We propose three types of assemblies, FU-assembly, BP-assembly and GT-assembly. FU-assembly means an assembly containing 37 fuel rods without burnable poison. BP-assembly means an assembly containing the fuel rods with burnable poison; some fuel rods in a FU-assembly are replaced by the fuel rods with burnable poison. GT-assembly means an assembly containing guide tubes for control rods; in the same way as above, 12 fuel rods in a FU-assembly are replaced by guide tubes and some of the other fuel rods are replaced by fuel rods with gadolinia. The reason why fuel rods with gadolinia are loaded in GT-assemblies is that reactivity rises substantially due to the moderator of light water inside the guide tubes.

Those assemblies constitute the core, and burn-up characteristic is calculated

by COREBN. Finally, The loading pattern of assemblies is optimized, which enables to suppress the excess reactivity during a cycle. In this study ‘optimization’ is particularly defined for determining the loading pattern with keeping excess reactivity suppressed. Because the parameters of the core is so many and deeply connected with each other that we cannot optimize all parameters one-by-one.

III. Unit Cell Analysis

The geometry of an unit cell is hexagonal lattice in order to load inventory of the fuel as much as possible. The plane view of an unit cell is shown in **Fig.2**. ThO₂-PuO₂ ratio in a fuel is 9 to 1; thorium isotope is only Thorium-232. Plutonium isotopes are, Plutonium-238, 239, 240, 241 and 242, respectively. The composition vector is that of extracted from spent fuel in a conventional PWR (burn-up at about 35000MWD/t). Their ratios to the total plutonium are 0.02, 0.63, 0.19, 0.12 and 0.04, respectively. Gadolinia is selected as burnable poison loaded in the fuel to obtain effective neutron absorption by its large absorption cross section for harder neutron spectrum. **Figure 3** shows calculation result by PIJ. The burn-up characteristics are compared for the concentrations of gadolinia of 1, 3, 5, 7 and 9 wt% of fuel kernels, respectively. The weight of PuO₂ is kept constant and the balance is adjusted by the weight of ThO₂. In this study, isotope composition of gadolinia is that of natural isotope abundance ratio.

The infinite multiplication factors of the fuels with gadolinia are suppressed at beginning of life (BOL). The infinite multiplication factors with gadolinia converge to that without gadolinia as gadolinia burns. **Figure 4** shows the comparison of neutron spectra in the fuel region of the fuel without gadolinia with one of the conventional PWR. The major difference between the two spectra is that the thermal neutrons ratio is considerably less in fuel without gadolinia than that of conventional PWR, therefore fissions of plutonium occur in the epithermal region. The same is true between PFPWR50 with ThO₂-PuO₂ and one with UO₂. The reactivity coefficients such as void coefficient, Doppler coefficient and moderator temperature coefficient based on the cell calculations are all negative during a cycle, respectively. That indicates the possibility of the core design with safety using the above components.

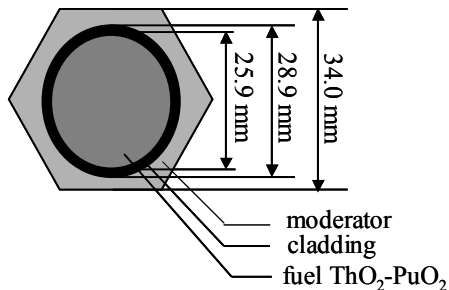


Fig.2 Image of an unit cell

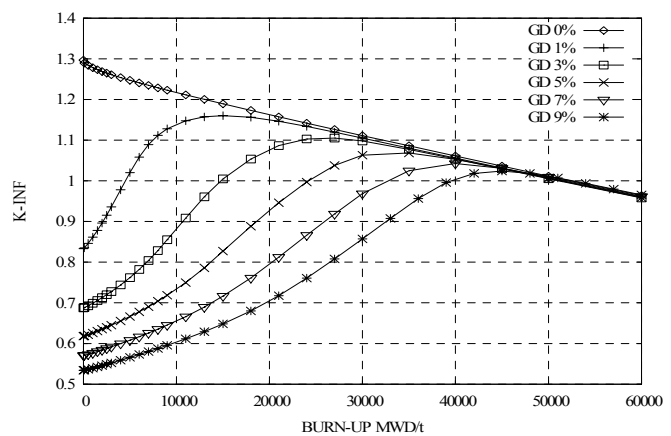


Fig.3 Comparison of burn-up characteristics for unit cell of different concentration of gadolinia

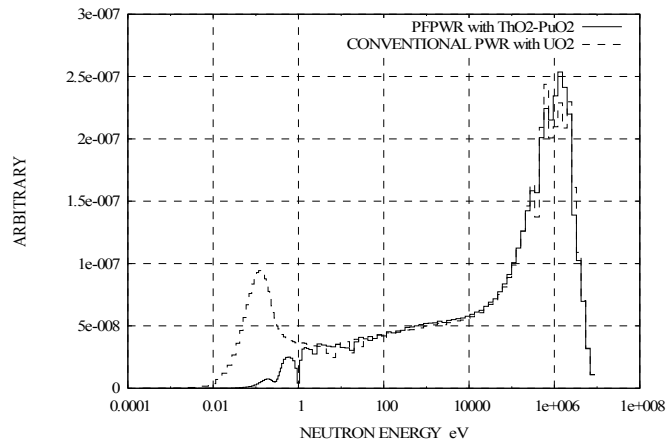


Fig.4 Comparison of neutron spectra for the fuel without gadolinia and one for conventional PWR

IV. Survey of Gadolinia Loading in an Assembly

1. Sensitivity of the Concentration of Gadolinia

As has been previously described, three types of assemblies are prepared. BP-assembly and GT-assembly contain some of the fuel rods with gadolinia (here after, they are called gadolinia-rods). The reactivity of gadolinia in the gadolinia-rods is different for each concentration of gadolinia. For example, the concentrations of gadolinia are parametrically selected as 1, 3, 5, 7 and 9 wt%. The number of gadolinia-rods is selected to be 6 here as shown in **Fig.5**. The burn-up characteristics of those BP-assemblies are shown in **Fig.6**. They are similar to the results from unit cell calculations. It is clear that substantial suppression of the excess reactivity at BOL is impossible by only increasing the concentration of gadolinia in the gadolinia-rods.

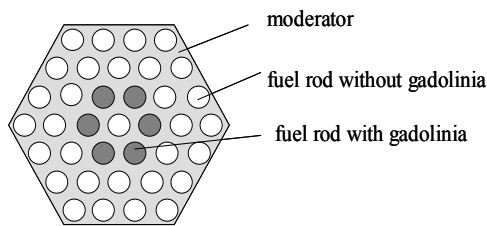


Fig.5 Image of an assembly with 6 gadolinia-rods

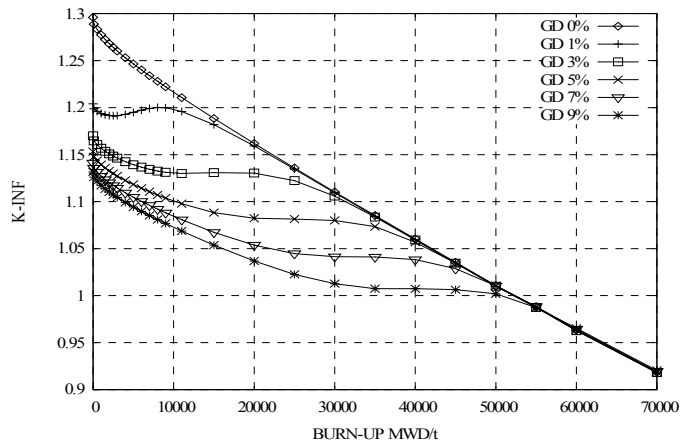


Fig.6 Comparison of burn-up characteristics for the assemblies of different concentration of gadolinia

2. Sensitivity of the Number of the Gadolinia-rods

The reactivity of different number of gadolinia-rods is analyzed with a fixed concentration of gadolinia of 5 wt% in a gadolinia-rod. The numbers of gadolinia-rods in the BP-assemblies are varied as 6, 12 and 18, respectively, as shown in **Fig.7**. **Figure 8** shows that burn-up characteristics are different according to the number of gadolinia-rods. The substantial suppression of the excess reactivity at BOL is possible by increasing the number of gadolinia-rods.

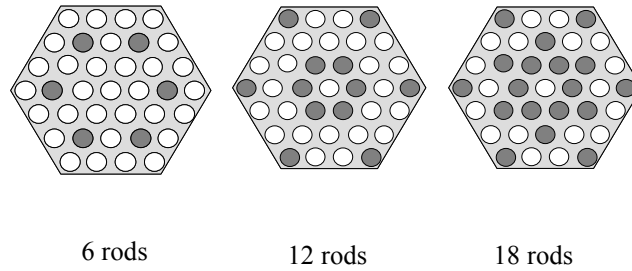


Fig.7 Images of the assemblies with 6, 12, and 18 gadolinia-rods of 5wt%

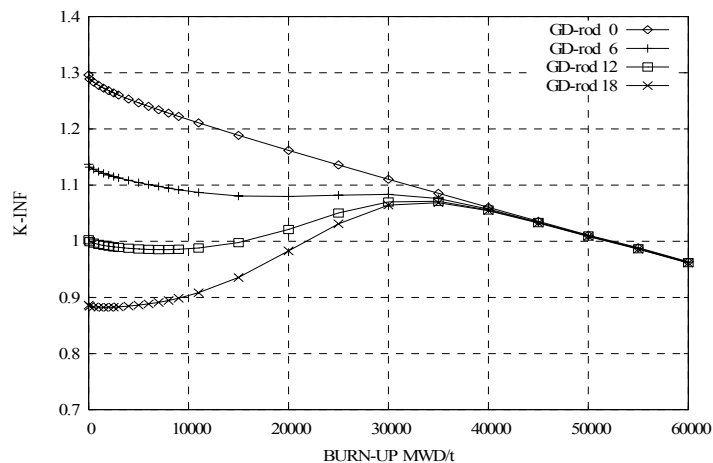


Fig.8 Comparison of burn-up characteristics for the assemblies of different number of gadolinia-rods

3. Sensitivity of the Loading Pattern of Gadolinia-rods

Figure 9 shows different loading patterns of gadolinia-rods in fuel assemblies, and they are named Case-1 and Case-2. The number of gadolinia-rods is fixed to be 12 in both cases. The concentration of gadolinia in the gadolinia-rods is also fixed as 5 wt%. In Case-1, gadolinia-rods are clustered in the center. In contrast, gadolinia-rods are distributed evenly in Case-2. **Figure 10** shows the burn-up characteristics of both cases. The obvious difference is the excess reactivity at BOL. Another difference between both burn-up characteristics is the burning speed of gadolinia. In Case-1, the depletion of

gadolinia is slower than in Case-2. The neutron spectrum at the center of Case-1 assembly becomes harder than that of Case-2. The harder spectrum makes the gadolinia burn slowly. On the other hand, in Case-2 gadolinia burn more rapidly than Case-1. Thus, different loading pattern of gadolinia-rods in an assembly affects the burn-up characteristics.

So far, it is found that the suppression of reactivity swing during a cycle is impossible without selecting the appropriate concentration of gadolinia, number, and loading pattern of gadolinia-rods.

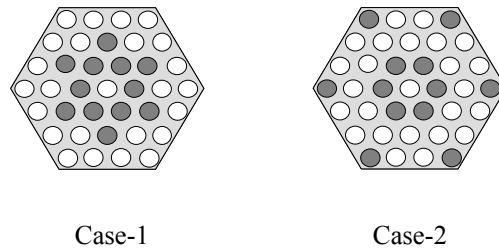


Fig.9 Images of assemblies that have different loading pattern of gadolinia-rods

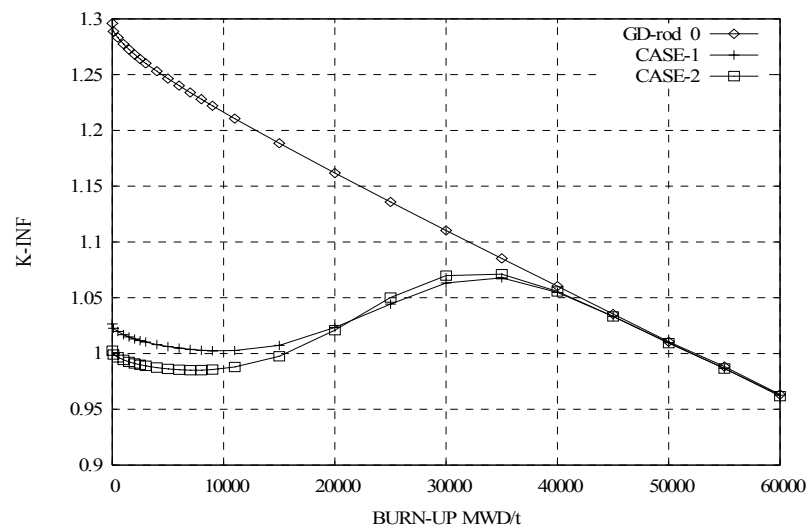


Fig.10 Comparison of burn-up characteristics for the assemblies of different loading pattern

4. Gadolinia Loading in GT-assembly

A GT-assembly has 12 guide tubes of which is filled by light water inside. Therefore, the excess reactivity is larger than that of FU-assembly due to more effective moderation by light water. Loading gadolinia in a GT-assembly is needed because the excess reactivity in any assemblies must be suppressed to some level for the suppression of the excess reactivity in the core. However, excessively loading gadolinia in the GT-assemblies reduces the reactivity worth of control rods in the core when they are inserted. The number of gadolinia-rods should be multiples of 6 as the geometry of

assembly is hexagonal. From the examination based on the fact described above, it is found that the maximum number of gadolinia-rods is 6 to assure the reactivity worth of control rods.

The concentrations of gadolinia and loading patterns of gadolinia-rods in the GT-assemblies should be also determined taking into account the reactivity balance of the whole core. **Figure 11** shows the image of the GT-assembly used in optimized core. As for control rod, it is mentioned in section V.

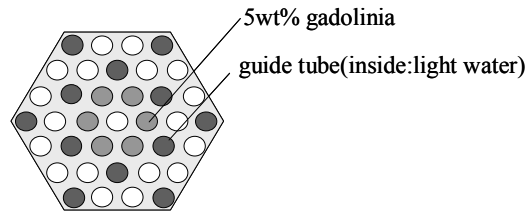


Fig.11 Image of GT-assembly

V. Core Analysis

1. Loading Pattern of Assemblies in the Reactor Core

In this subsection, the burn-up characteristics of different loading pattern of gadolinia in the reactor core are discussed. The reactor core is loaded with various types of assemblies paying attention to the facts below:

- (1) Suppression by increasing concentration of gadolinia is limited.
- (2) The more loading gadolinia-rods, the more obtaining effective suppression.
- (3) Evenly distributing gadolinia in the BP-assemblies causes faster burning of gadolinia and can obtain effective suppression at BOL.
- (4) All GT-assemblies contain 6 gadolinia-rods.
- (5) The inventories of the $\text{ThO}_2\text{-PuO}_2$ in the BP-assemblies and GT-assemblies are less than that of FU-assemblies.

As shown in **Table 1**, 85 assemblies are symmetrically loaded in a reactor core. And the reactor core is surrounded with reflector of light water. The parameters to be determined are so many that the number of gadolinia-rods in a BP-assembly is assumed to be 18 here. **Figure 12** shows different loading patterns of BP-assemblies in the core, and they are named Case-1, Case-2 and Case-3, respectively. Those are typically selected to exhibit the tendencies of the burn-up characteristics with the loading patterns in the core. The concentrations of gadolinia in the gadolinia-rods are different in BP-assemblies in each case (Case-1: 9 wt%, Case-2: 5 wt%, Case-3: 1 wt%). In addition, the number and loading patterns of the BP-assemblies are different (Case-1: clustered in the center, Case-2: distributed evenly, Case-3: distributed all over the core except for GT-assemblies). **Figure 13** shows the burn-up characteristics of those cores. The core life of Case-3 is the longest in spite of the largest number of BP-assemblies. In other words, the core lives of Case-1 and Case-2 are shorter than that of Case-3 although the numbers of BP-assemblies are smaller. When BP-assemblies in Case-1 and Case-2 are increased, the excess reactivity is suppressed as in Case-3. However, it is clear that the core lives become shorter in such cases. The purpose of this study is extension of the core life. Therefore, it is required to increase the number of BP-assemblies but not

increase the concentration of gadolinia in order to suppress the excess reactivity at BOL.

Although the above condition can be satisfied in Case-3, the suppression cannot remain effective during a cycle. Therefore, it is also required to use BP-assemblies with high concentration of gadolinia in the gadolinia-rods. In Case-1 and Case-2, the excess reactivity around MOL is effectively suppressed with small number of BP-assemblies because concentrated gadolinia in a BP-assembly burns slowly as shown in **Fig.6**. In Case-1, the excess reactivity is reduced through a cycle. On the other hand, in Case-2, the variation width of excess reactivity becomes small around and after 15000 MWD/t. As the result, it is found that it is necessary to combine BP-assemblies with different concentration of gadolinia in the gadolinia-rods in order to reduce the width of reactivity swing during a cycle.

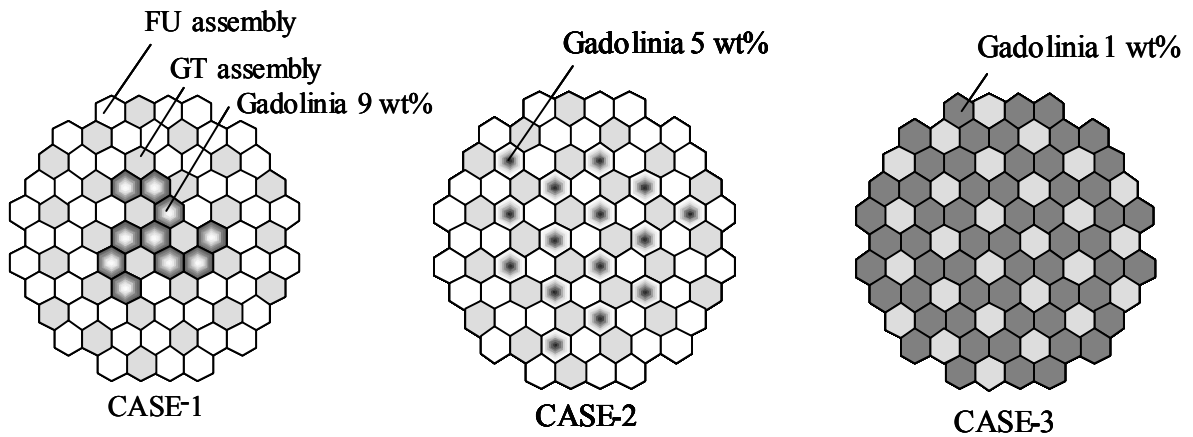


Fig.12 Images of cores with different loading pattern of BP-assemblies

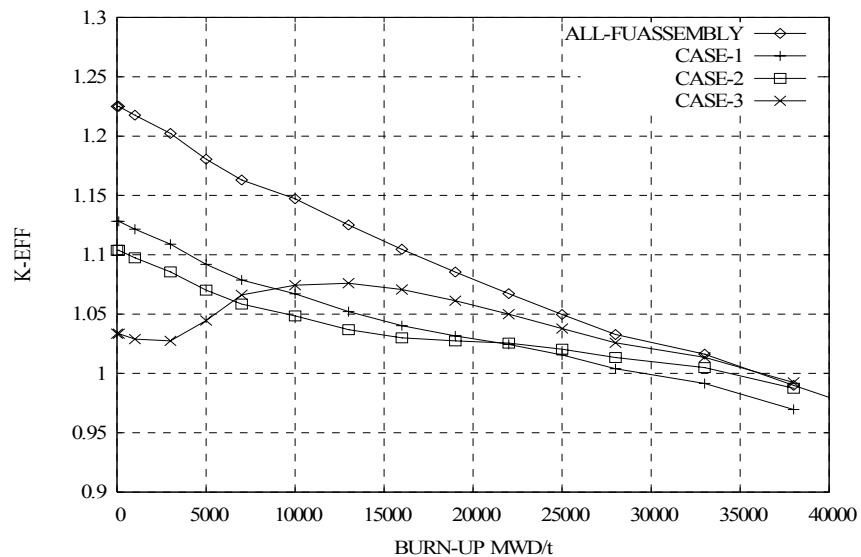


Fig.13 Comparison of burn-up characteristics for cores of different loading pattern

2. Loading Pattern Optimization

We examined burn-up characteristics of various cores with changing the number of BP-assemblies, the number of gadolinia-rods in the BP-assemblies and the concentration of gadolinia. At this point, the most favorable combination of assemblies is such as shown in **Fig.14**. In this loading pattern, 1 wt% gadolinia-rods are loaded as many as possible to suppress the excess reactivity near BOL, and 5 wt% gadolinia-rods are clustered in the center to suppress the reactivity around MOL. The burn-up characteristic of the optimized core is shown in **Fig.15**. The swing of the excess reactivity is slightly remained near BOL and around MOL. It is expected that the swing is completely eliminated when more BP-assemblies of 5 wt% gadolinia-rods are loaded in place of those with 1 wt%. However, the excess reactivity rises around MOL. And when more BP-assemblies of 1 wt% gadolinia-rods are loaded in place of those with 3 or 5 wt%, the excess reactivity rises near BOL and the life of the core becomes shorter. Thus, a certain level of allowance of compromise is necessary. It is also found that using 7 and 9 wt% gadolinia-rods are not favorable from the aspect of extending the life. In this optimized core, some BP-assemblies with 1 wt% gadolinia-rods are replaced by 12 gadolinia-rods with 3 wt % gadolinia. This BP-assembly can suppress the excess reactivity at BOL as well as 1 wt% BP-assembly. And this BP-assembly also contributes to reduce the reactivity swing around MOL due to slower burning of gadolinia.

The core life is approximately 35000 MWD/t, and it corresponds 8.9 equivalent full power years (EFPY). Extending of 1.9 EFPY is achieved from one with UO₂ of 5 wt% enrichment, whose core life is 7 EFPY. In the core in which only FU-assemblies are loaded, the life is approximately 36000 MWD/t because the inventory of the fuel is more than one with gadolinia.

The reactivity coefficients such as void coefficient, Doppler coefficient and moderator temperature coefficient were calculated at each burn-up step. It was confirmed that they were kept negative during a cycle. For example, at BOL, they are –119.4 pcm/%void, -3.40 pcm/K and -15.1 pcm/K, respectively. They are the closest values to zero through the cycle, respectively.

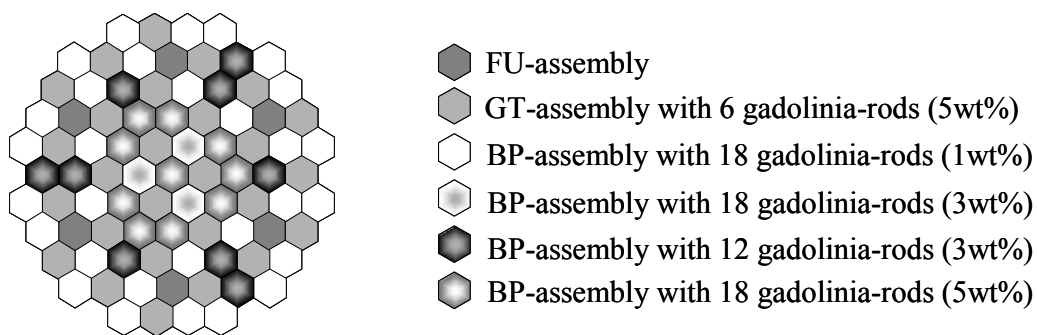


Fig.14 Loading pattern of the optimized core

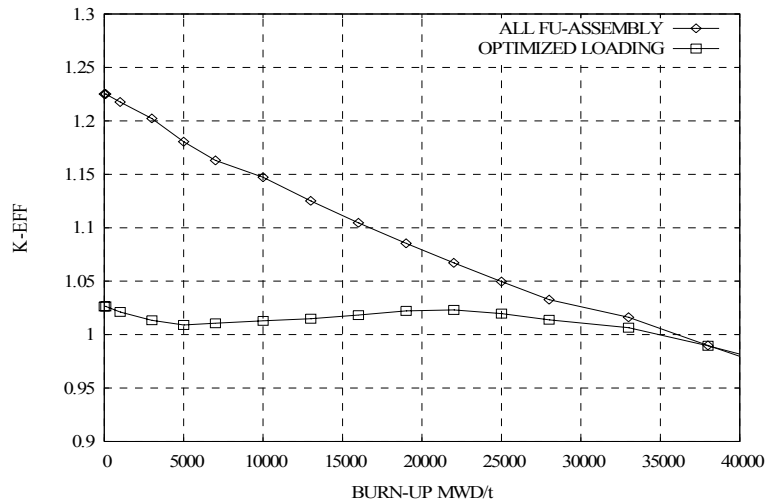


Fig.15 Burn-up characteristic of the optimized core

3. Control Rod Analysis

Each control rods are inserted to guide tubes in GT-assemblies. We have examined various loading patterns of GT-assemblies in order to assure the one rod stuck margin of 1 % $\Delta k/k$ under cold zero power (CZP) condition. In the previous studies, the material of control rod has been boron carbide (B_4C , 90% boron-10), and the minimum number of GT-assemblies required is 24 and/or 31. In accordance with the fact, it has been assumed that the minimum number of GT-assemblies required in this study is about the same as those of previous studies. However, as mentioned above, the neutron spectrum becomes so harder that it is required to use gadolinia as the material of control rod. In the case with only B_4C , subcriticality is not guaranteed even though GT-assemblies are loaded all over the core. The target value of 1 % $\Delta k/k$ is achieved replacing B_4C by gadolinia. It is found that the minimum number of the GT-assemblies required is 27 when the weight ratio of B_4C and gadolinia is 1 to 9.

VI. CONCLUSION

We examined burn-up characteristics of the core to extend the core life of previous study.^{2, 3)} The conclusion is that extending the life of PFPWR50 is possible by using ThO_2 - PuO_2 with suppression of the excess reactivity during a cycle. It is found out that the extension of core life is achieved by combination of at least 6 types of assemblies in which the quantity of gadolinia is different. The extended core life is 8.9 EFPY with one batch operation. The number of control rods required is 27. The reactivity coefficients are all negative during a cycle. On the other hand, some problems still remain. For example, in this study the heterogeneity of the fuel with coated particle fuel and distribution of temperature in the core is not taken into account. The peaking factor for each assembly must be reviewed. Moreover, optimization for thorium utilization and additional extension of the life, though they are contradictory, should be examined. In order to reduce the width of reactivity swing, other combinations of finer concentrations of gadolinia would be necessary. We are going to continue our study for those problems including usage of SiC ceramic cladding.

REFERENCES

1. Y. Shimazu, H. Tochihara, Y. Akiyama, K. Itho, "PWRs Using HTGR Fuel Concept with Cladding for Ultimate Safety," Workshop Proceedings on ARWIF, Chester, UK, Oct., pp235-243 (2001)
2. M. Kauchi, Y. Shimazu, "Optimal Burnable Poison-Loading in a PWR with Carbon Coated Particle Fuel," J. Nucl. Sci. Technol., Vol. 40, No. 1, pp. 22-29 (2003)
3. Y. Shimazu, M. Nagai, "Small PWR with Coated Particle Fuel for District Heating," IAEA-TECDOC-1451, May (2005)
4. K.Okumura, SRAC95, JAERI-Data/Code 96-015, [In Japanese] (1996)
5. M. Nagai, Y. Shimazu, "A study on the Nuclear Characteristics of 50 MWt Particle Fuel Pressurized Water Reactor, PFPWR50," Proc. ICAPP05 (CD-ROM), May15-19, Seoul, KOREA (2005)