Effect of high burn-up and MOX fuel on reprocessing, vitrification and disposal of PWR and BWR spent fuels based on accurate burn-up calculation

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Abstract

To examine the procedures of the reprocessing, the vitrification and the geologic disposal, precise burn-up calculation for high burn-up and MOX fuels has been performed for not only PWR but also BWR by using SWAT and SWAT2 codes which are the integrated burn-up calculation code systems combined with the burn-up calculation code, ORIGEN2, and the transport calculation code, SRAC (the collision probability method) or MVP (the continuous energy Monte Carlo method), respectively. The calculation results shows that all of the evaluated items (heat generation and concentrations of Mo and Pt) largely increase and those significantly effect to the current procedures of the vitrification and the geologic disposal. The calculation result by SWAT2 confirms that the bundle calculation is required for BWR to be discussed about those effects in details, especially for the MOX fuel.

KEYWORDS: High burn-up, MOX fuel, SWAT, SWAT2, waste disposal, waste glass, waste loading, intern storage

1. Introduction

The reprocessing, the vitrification and the geologic disposal for spent nuclear fuels have been scheduled in Japan. In those procedures, there are some regulations for heat generation, Pt concentration and Mo concentration in order to prevent the leakage of fuel waste and to maintain the integrity of waste glass. At the current stage, the regulations have been determined supposing the spent UO_2 fuel from PWR with the burn-up of 28GWd/THM. However, high burn-up fuels up to 70GWd/THM or mixed oxide (MOX) fuels will be employed for improving economic efficiency, for reducing the amount of spent fuel and for recycling the fissile material. Those advanced fuels will affect to the reprocessing, vitrification and disposal procedures and it may require changing the regulations of those procedures.

To examine the effects, the precise analysis is required for nuclide burn-up. The simple burn-up calculation code such as ORIGEN2 [1] is often used, however, such a method is impossible to apply to high burn-up and MOX fuels since the code cannot treat the changes of neutron spectrum during burn-up. To analyze the burn-up of these fuels, advanced calculation codes, SWAT [2] and SWAT2 [3], has been introduced, and the effects of them for reprocessing, the vitrification and geologic disposal have been evaluated for high burn-up and MOX fuels not only of PWR but also of BWR.

In this paper, we describes about SWAT and SWAT2 codes, the items evaluated,

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parameters assumed, then, the PWR results are briefly summarized since those have been published in the reference [4]. After that, the results for the BWR fuels are presented and the effects are discussed.

2. SWAT and SWAT2

In this study, we have introduced the advanced calculation codes. SWAT and SWAT2 which are the integrated burn-up calculation code systems combined with the burn-up calculation code, ORIGEN2, and the transport calculation code, SRAC [5] (the collision probability method) or MVP [6] (the continuous energy Monte Carlo method), respectively. The calculation by SRAC code included in SWAT is suitable to analyze homogeneous fuel assemblies such as PWR. On the other hand, since SWAT is not adequate to apply the analysis to inhomogeneous fuel assemblies such as BWR, SWAT2 is introduced to treat the fuel bundle structure of BWR properly by using the continuous energy Monte Carlo calculation method. The accuracy of SWAT and SWAT2 codes has been evaluated by comparing these calculation results with the result of post irradiation examination (PIE) [7]. The cross section library JENDL3.3 [8] was adopted in the whole calculations.

3. Items evaluated

We have evaluated the effects of the high burn-up and MOX fuels of PWR and BWR on the reprocessing, vitrification and disposal procedures and discussed about the difference between PWR and BWR, the difference between the calculation results by the pin-cell and the assembly of BWR.

In such calculations, the following items were evaluated after the burn-up calculation:

1. Heat generation at vitrifying: In a waste glass, high heat generation causes phase separation, crystallization and crack, which affect the retaining performance of nuclides. A waste glass should satisfy the regulation of 2.3kW per canister.
2. Mo concentration: In the waste glass, Mo makes yellow phase or alkali molybdates, which also affect the retaining performance of nuclides. The concentration of Mo should be under 1.5wt% at vitrifying.
3. Pt concentration: Since Pt is insoluble in the solvent, it sediments in the melter and it forms electrical short circuits, or it makes viscosity higher. Those affect the lifetime and the performance of the melter. The concentration of Pt should be under 1.25wt% at vitrifying.
4. Heat generation at disposing: High heat generation degrades the performance of the artificial buffer. Heat generation of 0.35 kW per canister should be satisfied

4. Parameters assumed

In the calculation of PWR, the fuel assembly type of 17x17 is supposed and the five burn-up exposures of 28, 33, 45, 55 and 70GWd/THM are considered. Corresponding to the five exposures, the five fuel enrichments of 2.6, 3.0, 4.5, 5.3 and 6.5 wt% are adopted, respectively. For the MOX fuels, the plutonium contents are set to 7.0, 8.0, 12.0, 14.0 and 17.0 wt%, respectively.

For the BWR cases, three fuel assembly types of 8x8 (the high burn-up fuel of 28, 33 and 45GWd/THM), 9x9 (the high burn-up fuel of 55 and 70GWd/THM) and 10x10 (the MOX fuel of 70GWd/THM) are considered. The geometric data of fuel assemblies have been presented in Ref. [9]. In the BWR cases, first, the pin-cell fuel model is introduced for the calculation of SWAT. In the same manner with the PWR case, the same five burn-up exposures are considered, and the five enrichments of 2.1, 2.4, 3.8, 4.5 and 6.5 wt% are set respectively. The plutonium contents of the MOX fuel are set to 4.0, 5.0, 8.0, 9.0 and 11.0wt% respectively. In the SWAT calculation, three void cases of 0%, 40% and 70% are considered.

For the BWR cases, the fuel bundle model is also calculated by using SWAT2. The same three fuel assembly types of 8x8, 9x9 and 10x10 are considered, and burn-up exposures are set to 45GWd/THM, 70GWd/THM and 70GWd/THM, respectively. The void of 40% is only considered.

The power densities of the UO_2 fuel or the MOX fuel are 37.0MW/TU and 36.6MW/THM in the case of PWR, are 25.0MW/TU and 25.0 MW/THM in the case of BWR, respectively. After 4 years cooling, 99.5% of U and Pu nuclides are removed at the reprocessing. The total cooling period is set to 100 years.

5. Summary of PWR results

The heat generation of a waste glass linearly increases with burn-up and by changing to MOX. Heat generation of the high burn-up fuel of the 70GWd/THM is 2.3 times larger than that of the burn-up of 28GWd/THM. Heat generation of the MOX fuels is 5.2 times larger than that of the UO_2 fuel with the same exposure. Owing to the increase of heat generation, the number of glass canisters from should be largely increased in order to satisfy the regulation of 2.3kW per glass unit at the procedure of waste loading in the waste glass.

The Mo content, for both the high burn-up UO_2 and MOX fuels, increases linearly with burn-up, even though no significant difference is seen between the UO_2 and MOX fuels. The Mo content of the high burn-up fuel of the 70GWd/THM is 2.5 times larger than that of the burn-up of 28GWd/THM. The content of the MOX fuels also increase at same rates as that of the UO_2 fuel. However, if the regulation of heat generation of 2.3 kW is satisfied, even at the burn-up of 70GWd/THM, the content attains approximately 2wt%, which is the regulation of Mo content in a waste glass.

The Pt content also increases linearly with burn-up for both the high burn-up UO_2 and MOX fuels. The Pt content of the high burn-up fuel of the 70GWd/THM is 2.4 times larger than that of the burn-up of 28GWd/THM. The content of the MOX fuels is 4.0 times larger than that of the UO_2 fuel with the same exposure. However, if the regulation of heat generation of 2.3 kW is satisfied even at the burn-up of 70GWd/THM, the Pt contents satisfy the regulation of 1.25wt% in whole burn-up.

When the regulation of heat generation is satisfied at vitrifying, the heat generation at disposing slightly changes with burn-up. Therefore, the cooling period before disposal increases slightly than about 50 years in whole burn-up of UO_2 fuel, which is the period supposed currently. However, the period should become longer than about 75 years for the MOX fuels, which needs 25 additional years to the period currently supposed.

6. Analysis of BWR by SWAT

The effects of high burn-up and MOX fuel on the reprocessing, vitrification and disposal of BWR spent fuels were evaluated by SWAT as the first step of the analysis by using the pin-cell fuel model.

6.1 Heat generation at vitrification

From the calculation result, it was observed that the heat generation of spent fuel increases linearly with burn-up for UO_2 or MOX fuels. The heat generation of the 70GWd/THM UO_2 fuel is about 2.4 times that of the 28GWd/THM UO_2 fuel. That of 70GWd/THM MOX fuel is about 2.7 times that of the 28GWd/THM UO_2 fuel. This result means that the heat generation of the high burn-up MOX fuel of 70GWd/THM is 5.3 times that of the current UO_2 fuel of 28GWd/THM.

The UO_2 fuel over 50GWd/THM does not satisfy the regulation of 2.3kW/glass unit. For the MOX fuel, the heat generations of all burn-up cases do not satisfy it. From these results, it is clear that the effects of high burn-up or MOX fuels at vitrifying are large.

The number of glass units with 2.3kW per glass unit is shown in Fig 6.1. To satisfy the regulation, i.e. to keep the integrity of a waste glass, the number of glass units have to be 2.4 times current one in the high burn-up UO_2 fuel. The numbers of the 70GWd/THM MOX fuel is 2.7 times larger than that of 28GWd/THM. The numbers of glass units is 5.2 times larger than the current 28GWd/THM UO_2 fuel.

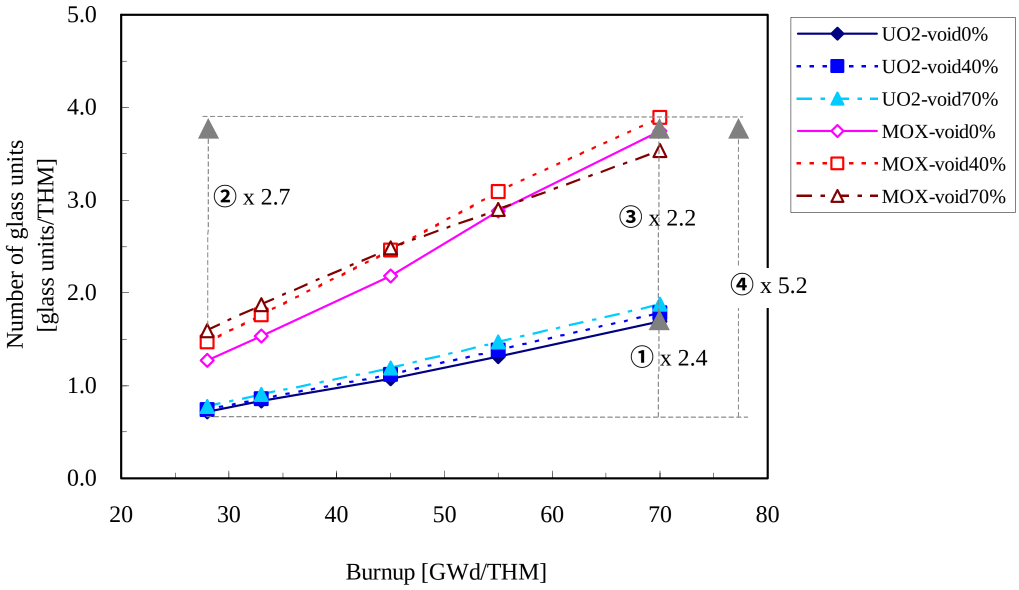


Fig.6.1 The number of glass units per 1 ton of spent fuel (the hypothetical fuel model of BWR) in the case of satisfying 2.3kW per glass unit

6.2 Mo concentration

The Mo content in the spent fuel increases linearly with the burn-up of UO_2 or MOX fuels. The high burn-up UO_2 fuel (70GWd/THM) has 2.5 times larger Mo content than the current UO_2 fuels (28GWd/THM). That of the MOX fuel has almost same Mo content as the UO_2 at the same burn-up, even though it also increases linearly with burn-up. From this result, it is confirmed that the effect of introducing the MOX fuel is small in the term of Mo content.

The Mo content per glass unit at vitrifying when the regulation of the heat generation of 2.3kW per glass unit is satisfied was shown in Fig 6.2. Since the increases of the heat generation per glass unit and the Mo content are almost the same, the effect of the high burn-up and MOX fuel is not so large, assuming that the heat generation is kept under the regulation of 2.3 kW per glass unit.

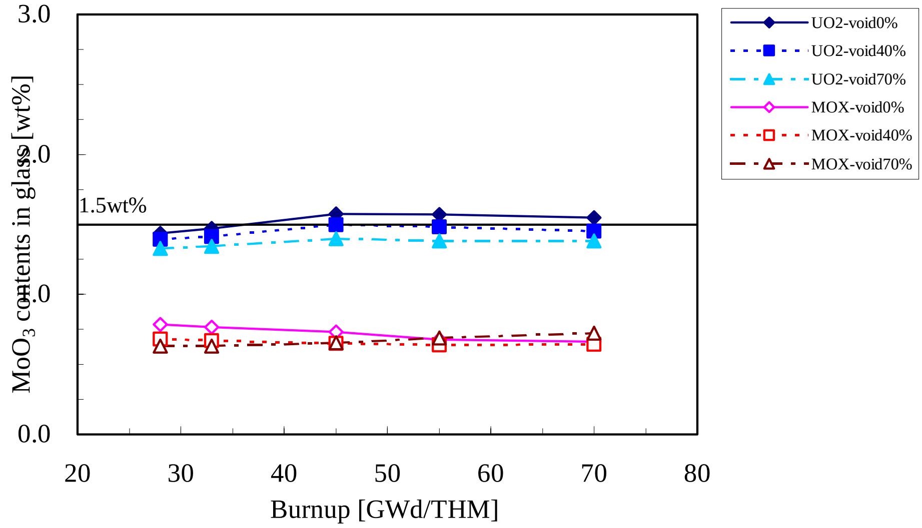


Fig.6.2 The MoO_3 contents in a glass unit (the hypothetical fuel model of BWR)
in the case of satisfying 2.3kW per glass unit heat generation

6.3 Pt concentration

The Pt content also increases linearly with burn-up for the UO_2 or MOX fuels. That of the 70GWd/THM UO_2 fuel is about 2.5 times larger than that of the 28GWd/THM fuel. For the MOX fuel, that of the 70GWd/THM fuel is about 2.6 times larger than that of the 28GWd/THM fuel. Totally, the Pt content of the high burn-up MOX fuel of 70GWd/THM is 3.5 times larger than that of the current UO_2 fuel of 28GWd/THM.

As mentioned at above, also in the case of the Mo content, since the increases of the heat generation per glass unit and the Pt content are almost the same, the effect of the high burn-up and MOX fuel is not so large if the heat generation is kept under the regulation of 2.3 kW per glass unit.

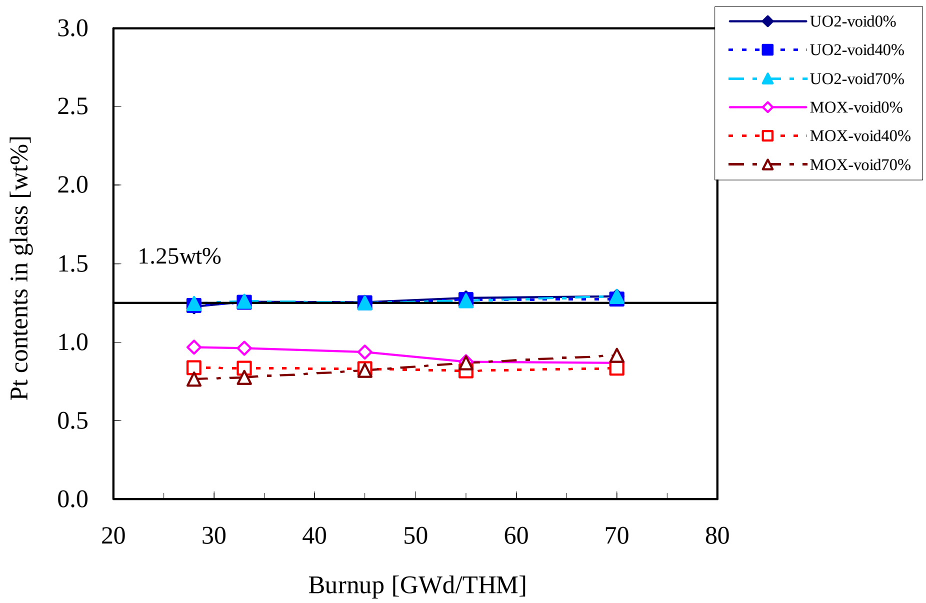
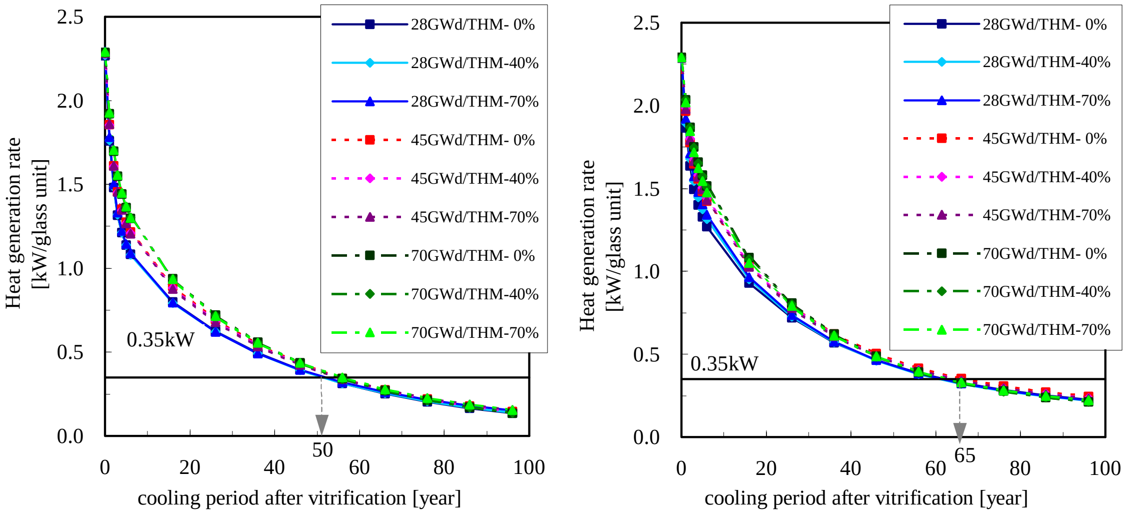


Fig.6.3 The Pt contents in a glass unit (the hypothetical fuel model of BWR)
in the case of satisfying 2.3kW per glass unit heat generation

6.4 Heat generation at disposing

Figure 6.4 shows the change of heat generation of a glass unit with cooling period after vitrification when 2.3kW per glass unit heat generation is satisfied. As shown in the figure, the heat generation does not depend on the burn.

The cooling time required to satisfy the regulation of 0.35kW/glass unit at the disposal is about 50 years for all UO_2 fuels and is 65 years for all MOX fuels. It is found that the cooling period before the disposal does not depend on fuel burn-up or fuel type.



(a) UO_2 fuel (b) MOX fuel

Fig.6.4 The change of heat generation of a glass unit with age (the hypothetical fuel model of BWR) in the case of satisfying 2.3kW per glass unit heat generation

7. Analysis of BWR by SWAT2

In this section, the effects of high burn-up and MOX fuel of BWR spent fuels were evaluated by SWAT2, which can treat the fuel bundle structure. These results have been compared to the results from SWAT; the difference between the pin-cell model and the bundle model has been discussed.

7.1 Heat generation at vitrification

The calculation result of the pin-by-pin heat generation in the fuel bundle is shown in Fig. 7.1. The figure indicates the large variation of the pin-by-pin values.

In the figure, the average value in the bundle and the pin-cell-averaged value by the SWAT calculation are shown. The difference of the bundle between the pin-cell and the bundle is 5.2% and 9.9% in the 8x8 or 9x9 UO_2 fuel assemblies and is 18% in the 10x10 MOX fuel assembly. From this result, it is confirmed that the calculation of the fuel bundle structure is needed in the analysis of the BWR fuel especially in the MOX fuel.

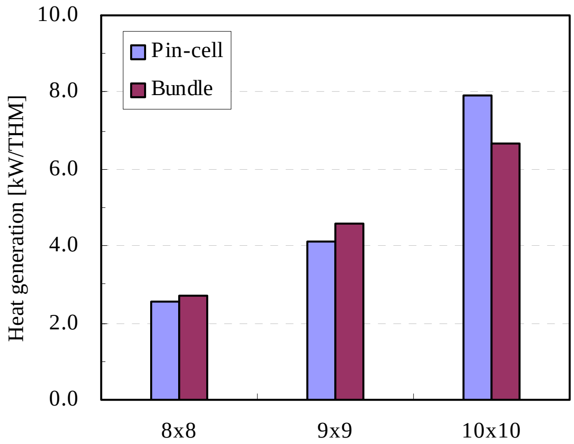
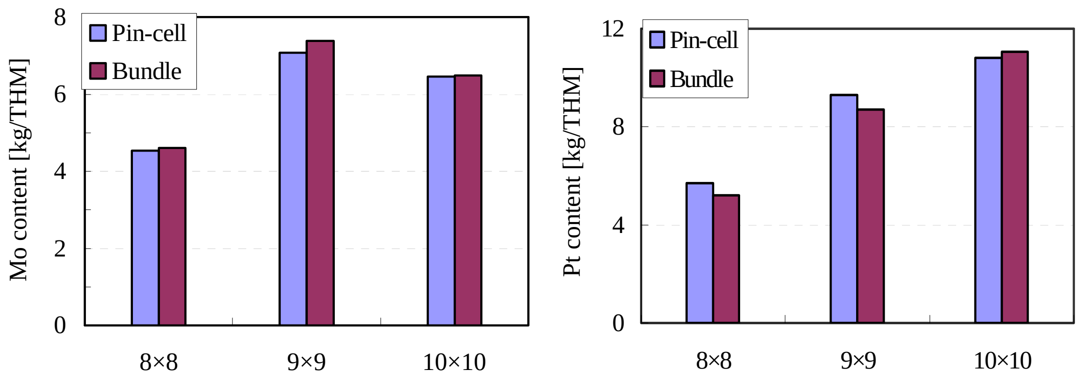


Fig.7.1 Comparison of heat generation of the fuel bundle model with the fuel pin-cell model

7.2 Mo and Pt concentration

Comparison of the Mo and Pt content is shown in Fig 7.2. The differences of the Mo content between the bundle and the pin-cell are under 5% in all fuel assembly types. The differences of the Pt content between the bundle and the pin-cell in 8x8, 9x9 and 10x10 fuel assembly types are 8.3%, 6.7% and 3% respectively. Those content does not largely depend on the fuel bundle structure since the generation of FP nuclides is mostly decided by the exposure.



(a) Mo content (b) Pt content

Fig.7.2 Comparison of the Mo and Pt contents in a glass unit in the fuel bundle model with the fuel pin-cell model

8. Conclusion

The SWAT code has been introduced, as which can treat the change of spectrum for the fuel burn-up. By using SWAT code, the effects of high burn-up and MOX fuels from BWR for the reprocessing, the vitrification and the geologic disposal have been evaluated. From these results, for the high burn-up fuels and the MOX fuels of BWR, it is observed that all of the evaluated items significantly increase. In order to satisfy the regulation, i.e. to keep the integrity of a waste glass, the number of glass units from the 70GWd/THM MOX fuel have to be 5.2 times larger than the current 28GWd/THM UO_2 fuel. The SWAT2 code has been introduced to calculate the fuel bundle structure since BWR has inhomogeneous structure. By using SWAT2 code, the effects of the high burn-up and MOX fuels have been evaluated and the results are compared to the results from the pin-cell calculation. In the heat generation of the MOX spent fuel, the bundle calculation significantly differs from the pin-cell. Considering these results, it is found that the fuel bundle calculation is requires for BWR.

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