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Neutronic double heterogeneity effect in particle dispersed type inert matrix fuels

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Abstract

Rock-like oxide (ROX) fuel concept is studied in Japan for effective plutonium burning in light water reactors (LWRs). ROX is a heterogeneous fuel, where Pu containing yttria stabilized zirconia (YSZ) particles are dispersed in spinel matrix, and similar to the high temperature gas cooled reactor (HTR) fuel. The effect of such a 'double' heterogeneity (fuel, structure and coolant heterogeneity in reactor core, plus fuel heterogeneity) on HTR neutronic characteristics is important, while the effect was not taken into account in the ROX fueled LWR neutronics calculations. Here, this double heterogeneity effect is estimated for ROX fueled LWR, and compared with the Pu containing YSZ particle fueled HTR. As a result, the heterogeneity effect was negligible in the ROX–LWR system, while it is notable in YSZ–HTR system. The volume fraction of YSZ particle in the fuel region is one of the important parameter to cause the difference.

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1. Introduction

As one of the inert matrix fuel (IMF) concept, Japan Atomic Energy Research Institute (JAERI) has been studying rock-like oxide (ROX) fuel for effective plutonium burning in light water reactors (LWRs) [1]. The fuel contains only small amount of fertile ^{238}U, and much larger Pu burnup rate is achievable than in the usual MOX fueled LWRs. In addition, chemical and geological stability of the fuel matrix makes it possible to dispose the spent ROX fuel directly under geological formations. Plutonium burnup in the ROX–LWR system can be an effective energy cycle option when the excess Pu amount is increasing.

The inert matrix of ROX fuel consists of two phases, yttria stabilized zirconia (YSZ) and spinel. Plutonium is dissolved in YSZ, and form chemically and geologically stable phase. Spinel is used to compensate low thermal conductivity of YSZ. The present promising ROX fuel concept is a particle dispersed type fuel in which YSZ particles of 200–250 μm diameter are dispersed in spinel matrix. Thus ROX fuel is a kind of heterogeneous fuel and the ROX–LWR system has a heterogeneity in the level of fuel, cladding and moderator in the

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reactor core, plus fuel heterogeneity in the YSZ particle and spinel matrix level. Such a 'double' heterogeneity is similar to that in the graphite moderated high temperature gas cooled reactors (HTRs), where the double heterogeneity effect, in comparison with the homogenized fuel model of 'single' heterogeneity, in neutronics calculations is known to be important.

In ROX fuel, although the volumetric fraction of fuel particles is much larger and the diameter of particles is smaller than those in HTR fuel, it is worth confirming the neutron physical double heterogeneity effect of the ROX–LWR system, because ROX fueled LWR design calculations [2,3] were made with homogenized fuel model and the fuel heterogeneity was not taken into account.

In this paper, from the viewpoint of reactor core design, the double heterogeneity effect on the neutronic characteristics of the ROX–LWR system is estimated. Furthermore, the double heterogeneity effect is also estimated here for the Pu containing YSZ particle fueled HTR and compared with ROX–LWR, firstly because the heterogeneity effect is expected to be much larger in HTR than in LWR, and secondly because HTR is also a promising candidate of plutonium burning reactor by using IMF.

If there is a heterogeneity effect on the burnup reactivity change, it means an effect on discharge burnup. In the Pu burning fuel, correct estimation of burnup period is important for correct estimation of Pu transmutation rate. Because of the lack of ^{238}U in IMF, fuel temperature coefficient of reactivity is one of the most important physics parameter in IMF fueled reactors for the safe transient behaviors. For these reasons, the heterogeneity effect of the particle dispersed type IMFs is studied here, on the reactivity and the fuel temperature reactivity effect. The results are compared between LWR and HTR, and the difference is discussed.

2. Calculation model of particle dispersed fuels

Homogeneous fuel cell model is compared with doubly heterogeneous cell model in the LWR and HTR calculations. The both homogeneous and heterogeneous fuel models have the same geometry of the infinite array of the square pin cell based on the conventional 17×17 PWR type assembly, or of spherical cell with a fuel ball (pebble) based on the pebble bed type HTR.

The cell model for LWR is composed of fuel, Zircaloy cladding and H_2O moderator regions. The pin diameter is 0.95 cm. The pin pitch of the equivalent lattice is 1.32 cm, in which the extra water and structural material, such that are in the control rod guide tube area and between the fuel assemblies, are homogenized in the water moderator region. In the homogeneous fuel model, the ROX fuel is homogenized in the region inside of the cladding, while in the doubly heterogeneous model, the heterogeneity of the particle dispersed ROX fuel is taken into consideration together with the pin cell heterogeneity.

In the heterogeneous fuel model, the YSZ particle diameter of 200 μm (0.2 mm) and the packing fraction (volumetric fraction) of YSZ particles in fuel region of 0.4 are assumed, based on the actual particle dispersed ROX fuel for irradiation tests [4].

In the core design calculations of ROX–LWR [2], necessary Pu enrichment was decided to achieve the discharge burnup of 1200 equivalent full power days (EFPD) with the averaged linear heat rate of 18 kW m^{-1}. The discharge burnup corresponds to about 45 MW d kg^{-1} of UO_2 and MOX fuels. In the design calculations, U, Er and Gd were also added in ROX fuel. Uranium additive was incorporated to improve reactivity coefficients of ROX fuel, and Er and Gd to reduce burnup reactivity swing. The additives U, Er and Gd are distributed in the fuel particle together with Pu. As a result, the YSZ phase in the ROX fuel is composed of (Zr, Y)O_2, PuO_2, UO_2, Er_2O_3 and Gd_2O_3. The Pu enrichment and the additives concentrations decided for the homogeneous fuel model are all increased 2.5 ($=0.4^{-1}$) times in the YSZ particle, according to the volume fraction of the particle in the heterogeneous fuel model, to keep the same homogenized fuel composition. Thus, the approximate contents of YSZ particle are 18% PuO_2, 20% UO_2, 2% $ErO_{1.5}$ and 0.1% $GdO_{1.5}$ in molecular fraction. The matrix is totally composed of spinel ($MgAl_2O_4$). Reactor grade Pu and depleted U are used in the calculations. The compositions of Pu and U in weight fraction are respectively 1.6% ^{238}Pu, 58.5% ^{239}Pu, 22.4% ^{240}Pu, 11.2% ^{241}Pu, 5.7% ^{242}Pu and 0.6% ^{241}Am for reactor grade Pu, and 0.2% ^{235}U and 99.8% ^{238}U for depleted U. Temperatures of the fuel in the homogeneous fuel model and the YSZ particle and the spinel matrix in the heterogeneous model are all 900 K, while the cladding and the moderator are assumed to be 600 K.

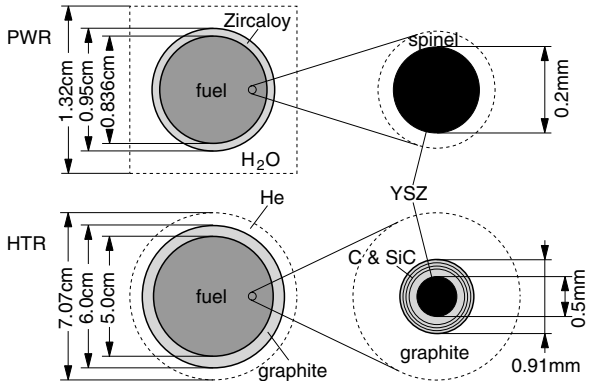

Fig. 1. Particle dispersed fuel cell models of PWR and HTR.

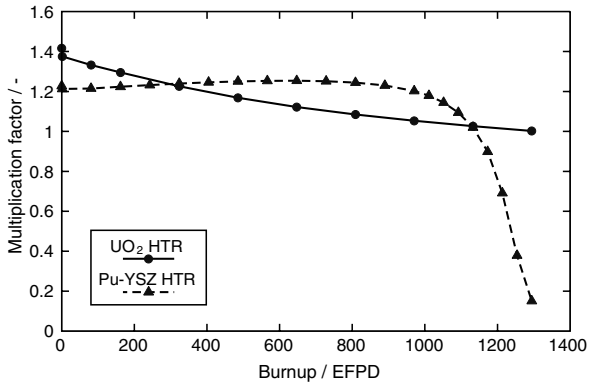

Fig. 2. Burnup dependence of infinite multiplication factors of UO_2 and Pu-YSZ fueled HTR pebble cell.

The PWR fuel cell model is schematically described in Fig. 1, together with the HTR cell model.

The HTR calculation model is based on the specifications of the OECD NEA/NSC benchmark calculation for HTR [5]. The model is for pebble bed type HTR and the spherical fuel pebble consists of the 5 cm diameter fuel region and 0.5 cm thickness graphite shell surrounded by the He coolant region. The outer diameter of the He coolant region is 7.07 cm. In the fuel region, coated fuel particles of 0.91 mm diameter are dispersed in the graphite matrix. The packing fraction of the coated particles in the fuel region is 0.09. The fuel particle consists of the 0.5 mm (500 μm) diameter fuel kernel and the 4 coating layers of low-density carbon, pyrolytic carbon, silicon carbide and again pyro-carbon from inside to outside of the particle. The volume fraction of the fuel kernel in the fuel region is, therefore, only 0.015, and is much smaller than that in the ROX fuel.

The fuel kernel in the current study is composed of YSZ and PuO_2. The content of PuO_2 in the kernel was decided so that the discharge burnup, in terms of EFPD, becomes the same as that in the benchmark specified UO_2 fuel kernel case. In the NEA/NSC benchmark specifications, burnup calculation is to be performed at a constant power of 0.556 kW per UO_2 fueled pebble for 80 MW d kg^{-1}, which corresponds to about 1300 EFPD. As shown in Fig. 2, however, the reactivity of Pu-YSZ fueled HTR pebble does not change linearly with burnup. It is therefore difficult to estimate the discharge burnup of this fuel pebble by the cell burnup calculation. Here, the Pu content in the YSZ fuel kernel was adjusted to obtain the same burnup averaged multiplication factor as the UO_2 fuel case over the burnup period of 1300 EFPD. As a result, the content of PuO_2 was decided to be about 10 molecular % in the fuel kernel. Any additives such as UO_2 and Gd_2O_3 are not considered here, because the temperature reactivity coefficient is negative without additives, as shown in the following section, and there seems no need to suppress excess reactivity throughout the burnup time, as shown in Fig. 2. The same reactor-grade Pu isotope composition is assumed here as in the PWR case. The temperature of all region is 1000 K, as specified in the NEA/NSC benchmark calculation.

Before the heterogeneity effect estimation, the cell burnup calculations were performed to obtain the fuel compositions at the end of burnup life (EOL), both for PWR and HTR cell models of homogenized fuel region by using the fuel compositions given at the beginning of burnup life (BOL). By using the fuel compositions, the heterogeneity effect is calculated both at BOL and EOL. Here, the burnup calculations were made with the deterministic reactor analysis code system SRAC [6] and the nuclear data library based on the evaluated file JENDL-3.3 [7]. For the PWR cell model, burnup calculation was made for 1200 EFPD with the linear heat rate of 18 kW m^{-1}, while for HTR cell model for 1300 EFPD with 0.556 kW per pebble. The cell burnup calculation in Fig. 2 for the estimation of the BOL Pu content in the HTR pebble was also carried out by using the SRAC system. As shown in this figure, the multiplication factor of Pu-YSZ fueled HTR rapidly drops near the end of burnup due to the rapid decrease of fissile isotopes in this fertile free fuel. As a result, the multiplication factor is very small at EOL (1300 EFPD). There seems to be no meaning to estimate the heterogeneity effect at this burnup stage, because the importance of such a

pebble in the reactor core will be very small. Instead of the actual EOL fuel composition, the fuel composition at about 1200 EFPD burnup was evaluated for the heterogeneity effect calculation of HTR. At this burnup time, the multiplication factor is still as large as 0.7.

After obtaining the fuel compositions at EOL, the double heterogeneity effect is estimated by using the continuous energy Monte Carlo code MVP [8] for the particle dispersed type fueled cells both at BOL and at EOL. This code can treat a statistical geometry model in which particles of a fixed diameter can be randomly distributed in specified regions satisfying a given packing fraction. This geometry model, together with the continuous energy Monte Carlo method, is considered to give the most precise results for neutronic characteristics of the doubly heterogeneous fueled system.

The MVP calculations are carried out for 5 000 000 neutron histories in all the cases. The statistical error of the calculated multiplication factors is about 0.02%. The JENDL-3.3 based nuclear data library is used also in the MVP calculations.

3. Double heterogeneity effect on reactivity and fuel temperature coefficient

Multiplication factors and the heterogeneity effects of the Pu inert matrix fueled PWR and HTR calculated with the MVP code are shown in Table 1. Here, $\mathrm{d}k\,k^{-1}_{\mathrm{homo.}}$ is the reactivity change in the heterogeneous fuel cell from the homogeneous fuel case, that is the heterogeneity effect.

As shown in this table, the heterogeneity effects are very small for PWR both at BOL and EOL to be less than $+0.1\%\ \mathrm{d}k\,k^{-1}$. By assuming that the reactivity changes linearly with burnup, these effect corresponds to the only slight increase in discharge burnup of about 4 EFPD, or the Pu transmutation rate of about 0.2%, at around 1200 EFPD.

On the other hand, the heterogeneity effect is large in the HTR cell at BOL to be more than $+6\%\ \mathrm{d}k\,k^{-1}$, and decreases with burnup. The burnup averaged heterogeneity effect is about $+3.4\%\ \mathrm{d}k\,k^{-1}$. As shown in Fig. 2, the reactivity does not change linearly with burnup in this HTR cell, and it is difficult to estimate the corresponding increase in discharge burnup. While, the change in burnup averaged reactivity of $+3.4\%\ \mathrm{d}k\,k^{-1}$ corresponds to the change in Pu content in the fuel kernel by about 4–5%, i.e., the Pu content in the fuel kernel can be reduced from 10% to 9.5–9.6% to achieve the same discharge burnup. This change in the initial Pu content directly affects the Pu transmutation rate, because the Pu transmutation rate is defined as the ratio of transmuted to initial amounts of Pu.

Table 2 compares the temperature reactivity coefficients calculated with homogeneous and heterogeneous fuel models. Here, FTC means the fuel temperature coefficient obtained for the 300 K temperature increase in fuel region, and ITC is the isothermal temperature coefficient calculated for HTR cell obtained for the 300 K temperature increase in all regions of fuel, graphite shell and He coolant. It can be seen in this Table 2 that the temperature coefficients calculated for the heterogeneous fuel model are almost the same as those obtained for the homogeneous fuel model, both in PWR and HTR, both at BOL and EOL. There is found almost no double heterogeneity effect on the temperature coefficient.

The double heterogeneity effect in PWR is found to be much smaller than that in HTR, and is almost negligible. Several reasons of this difference can be assumed here. Firstly, YSZ fuel kernel volume fraction in fuel region is much larger in PWR (0.4) than in HTR (0.015). Secondly, the YSZ fuel kernel diameter in PWR (200 μm) is smaller than in HTR (500 μm). And thirdly, the fraction of neutron absorbing heavy metals in YSZ fuel kernel is larger in PWR (0.4) than in HTR (0.1). But the third one is not assumed to be the reason of the difference in double heterogeneity effect between PWR and

Table 1
Calculated multiplication factor and its double heterogeneity effect $\mathrm{d}k\,k^{-1}_{\mathrm{homo.}}$ in Pu inert matrix fueled PWR and HTR at BOL and EOL

	PWR (BOL)	$\mathrm{d}k\,k^{-1}_{\mathrm{homo.}}$	PWR (EOL)	$\mathrm{d}k\,k^{-1}_{\mathrm{homo.}}$
Homogeneous	$1.1862 \pm 0.02\%$		$0.9623 \pm 0.02\%$	
Heterogeneous	$1.1872 \pm 0.02\%$	$+8 \times 10^{-4}$	$0.9629 \pm 0.02\%$	$+6 \times 10^{-4}$
	HTR (BOL)	$\mathrm{d}k\,k^{-1}_{\mathrm{homo.}}$	HTR (EOL)	$\mathrm{d}k\,k^{-1}_{\mathrm{homo.}}$
Homogeneous	$1.1728 \pm 0.02\%$		$0.7777 \pm 0.01\%$	
Heterogeneous	$1.2475 \pm 0.02\%$	$+6.37 \times 10^{-2}$	$0.7821 \pm 0.01\%$	$+5.7 \times 10^{-3}$

Table 2
Temperature coefficients of reactivity ($dk\ k^{-1}\ K^{-1}$) calculated for the 300 K temperature increase and the double heterogeneity effect in Pu inert matrix fueled PWR and HTR at BOL and EOL

	PWR FTC (BOL)	PWR FTC (EOL)	HTR FTC (BOL)	HTR FTC (EOL)	HTR ITC (BOL)	HTR ITC (EOL)
Homogeneous	-1.9×10^{-5}	-2.5×10^{-5}	-7.8×10^{-5}	-6×10^{-6}	-1.19×10^{-4}	-2.8×10^{-5}
Heterogeneous	-2.0×10^{-5}	-2.4×10^{-5}	-7.6×10^{-5}	-7×10^{-6}	-1.12×10^{-4}	-2.7×10^{-5}

FTC: fuel temperature coefficient, ITC: isothermal temperature coefficient.

HTR, because both in PWR and HTR the heterogeneity effect becomes smaller at EOL than at BOL, and the heavy metal isotopes content is largely reduced at EOL. Here, the effect of these parameters, YSZ kernel volume fraction, YSZ kernel diameter and heavy metal absorber isotopes content in YSZ kernel, are studied in the following section.

4. Comparison of the double heterogeneity effect on reactivity between PWR and HTR

The double heterogeneity effect is compared between Pu inert matrix fueled PWR and HTR in this section, by changing the parameters such as YSZ fuel kernel (particle) volume fraction, YSZ kernel diameter and heavy metal isotopes fraction in YSZ kernel. Here, the heterogeneity effect is compared only on the reactivity, and the temperature coefficient is not discussed, because the heterogeneity effect on temperature coefficient was found to be very small both in PWR and HTR in the previous section.

4.1. Effect of YSZ fuel kernel volume fraction in the fuel region

As already explained in the previous section, the volume fraction of Pu containing YSZ kernel (particle) is very much different between PWR and HTR calculation models. By decreasing the volume fraction of fuel kernel in PWR cell and by increasing it in HTR cell, the double heterogeneity effect on reactivity is calculated as shown in Table 3. The maximum volume fraction of the YSZ kernel in the HTR cell model is 0.12, because the maximum packing fraction of the fuel particle including the coating is 0.74 in the closest packing structure. Therefore the volume fraction of YSZ particle in the PWR cell model is decreased as low as 0.1. The YSZ diameter is 200 μm for PWR and 500 μm for HTR. In the Table 3, the packing fraction of the coated fuel particle p_f in HTR cell model is also shown in the parentheses, together with the volume fraction of YSZ fuel kernel v_f. As shown in Table 3, the heterogeneity effect on reactivity increases with v_f. But there is still a big difference between PWR of $v_f = 0.1$ and HTR of $v_f = 0.09$.

Table 3
Double heterogeneity effect on reactivity $dk\ k^{-1}_{homo.}$ at BOL for different YSZ fuel kernel volume fraction (v_f) in PWR and HTR cell models

v_f	PWR	HTR
0.4	$+8\times10^{-4}$	–
0.2	$+1.3\times10^{-3}$	–
0.1	$+2.0\times10^{-3}$	–
0.09 ($p_f = 0.54$)	–	$+1.14\times10^{-2}$
0.045 ($p_f = 0.27$)	–	$+3.55\times10^{-2}$
0.015 ($p_f = 0.09$)	–	$+6.37\times10^{-2}$

4.2. Effect of YSZ fuel kernel diameter

The effect of YSZ fuel kernel (particle) diameter on the double heterogeneity effect is next studied by increasing the YSZ particle diameter in PWR cell model to 400 and 800 μm, for the cases of $v_f = 0.4$ and 0.1. Unfortunately in HTR cell model, it is geometrically impossible to reduce the YSZ kernel diameter to 200 μm at the same time of keeping coating thickness constant, when the YSZ kernel volume fraction v_f is 0.09.

The calculated results are shown in Table 4. The larger the diameter is, the larger the heterogeneity

Table 4
Double heterogeneity effect on reactivity $dk\ k^{-1}_{homo.}$ at BOL for different YSZ fuel kernel diameter (d) in PWR and HTR cell models

d (μm)	PWR ($v_f = 0.4$)	PWR ($v_f = 0.1$)	HTR ($v_f = 0.09$)
200	$+8\times10^{-4}$	$+2.0\times10^{-3}$	–
400	$+1.0\times10^{-3}$	$+4.8\times10^{-3}$	–
500	–	–	$+1.14\times10^{-2}$
800	$+2.4\times10^{-3}$	$+9.9\times10^{-3}$	–

effect becomes. In the $v_f = 0.4$ case in PWR cell, the diameter effect is not so significant, and the effect becomes larger in the $v_f = 0.1$ case. The volume fraction of the YSZ kernel, therefore, seems to be an important factor for the kernel diameter to cause a significant heterogeneity effect. Even though the heterogeneity effect in PWR is still smaller than that in HTR, it becomes nearly half of that in HTR when the v_f and d values are almost the same each other ($v_f = 0.1$, $d = 400$ μm PWR and $v_f = 0.09$, $d = 500$ μm HTR cases).

4.3. Effect of heavy metal isotopes content in YSZ kernel

Actually, the neutron absorbing heavy metal isotopes content in YSZ kernel is not assumed to be the reason of the heterogeneity effect difference between PWR and HTR, but the calculations were made for PWR and HTR cells with different heavy metals (+Er and Gd for PWR) content in YSZ. The results are summarized in Table 5.

As it is expected, the heterogeneity effect on reactivity increases with heavy metal content HM. In the $v_f = 0.4$ PWR case, however, it seems that the smaller heterogeneity effect is obtained in the HM = 0.8 case than in the HM = 0.4 case. But the difference between these two cases is only about two times of the statistical error of the MVP calculation, and it cannot be said these two values are different each other. It should be rather considered that there is no difference between these two cases. On the other hand in the PWR of $v_f = 0.1$, the clear effect of HM is observed. The volume fraction of YSZ again seems to be an important factor.

The values v_f and HM, in fact, cannot be changed independently in the reactor design study, because the total amount of the heavy isotopes in the fuel cell is already decided to achieve the aiming discharge burnup. The heavy metal amount in the PWR cell was decided in the $v_f = 0.4$ case to be HM = 0.4, and it is necessary in the PWR cell of $v_f = 0.1$ to increase the HM value 4 times to keep the total heavy metal amount in the cell. It is actually impossible to increase the HM value 4 times from 0.4, and it is increased only 2 times to be 0.8 in Table 5. In the same manner, the HM value in the HTR of $v_f = 0.09$ must be 0.17 ($= 6^{-1}$) times of that in HTR of $v_f = 0.015$ to be 0.017. As shown in Table 5, the heterogeneity effect in the PWR of $v_f = 0.1$ becomes $+8.3 \times 10^{-3}$ d$k\,k^{-1}$ when YSZ diameter d is 400 μm and the heavy metal content HM is 0.8. This effect is as large as that of HTR of $v_f = 0.09$ and HM = 0.017 ($+8.7 \times 10^{-3}$ d$k\,k^{-1}$). Of course in this case, 80% of the YSZ particle is composed of Pu and U in PWR, (which no longer is a 'YSZ' particle but can be considered as a MOX particle,) and this heavy metal content is far larger than that in the YSZ kernel in HTR.

5. Discussion and conclusion

Double heterogeneity effect on reactivity and temperature reactivity coefficient was estimated for the particle dispersed type ROX fueled PWR and Pu containing YSZ particle fueled HTR. The heterogeneity effect in PWR is very small both on reactivity and temperature coefficient of reactivity, while there is observed a heterogeneity effect on reactivity in HTR.

This difference in heterogeneity effect between PWR and HTR is further studied by changing the parameters of the YSZ fuel particle volume fraction in fuel region (v_f), the YSZ fuel particle diameter (d) or the heavy metal isotopes content in YSZ particle (HM). As a result, the heterogeneity effect on reactivity is dependent on all the three parameters. However in the case of $v_f = 0.4$, which is the standard value for ROX fuel in PWR, not only the heterogeneity effect itself but also its dependency on d and HM becomes small. The v_f value of 0.4 seems to mean that the YSZ particles are too tightly

Table 5
Double heterogeneity effect on reactivity d$k\,k^{-1}_{\text{homo.}}$ at BOL for different heavy metal isotopes content in YSZ fuel kernel (HM) in PWR and HTR cell models

HM	PWR ($v_f = 0.4$, $d = 200$ μm)	PWR ($v_f = 0.1$, $d = 200$ μm)	PWR ($v_f = 0.1$, $d = 400$ μm)	HTR ($v_f = 0.09$, $d = 500$ μm)
0.017	–	–	–	$+8.7 \times 10^{-3}$
0.1	–	–	–	$+1.14 \times 10^{-2}$
0.4	$+8 \times 10^{-4}$	$+2.0 \times 10^{-3}$	$+4.8 \times 10^{-3}$	–
0.8	$+3 \times 10^{-4}$	$+3.7 \times 10^{-3}$	$+8.3 \times 10^{-3}$	–

packed and not so heterogeneous from the neutronics point of view.

The double heterogeneity effect on reactivity in PWR can be as large as that in HTR, when the YSZ particles are much loosely packed with the volume fraction of $v_f = 0.1$ and the YSZ particle size is as large as 400 μm. But such small YSZ volume fraction and large YSZ particle diameter are not realistic in the actual ROX fuel. When v_f value becomes 0.2 or less, the YSZ particle composition becomes not suitable for the host phase of Pu, because the fraction of YSZ in the particle is only less than 20% to keep the total Pu amount in the cell. In order to keep the YSZ fraction of more than 50% in the particle, v_f should be around 0.4 or more. While the YSZ particle diameter in ROX fuel is optimized in the fuel concept study [1], from the viewpoints of the irradiation damage of the spinel matrix, temperature increase in the YSZ particle and the thermal stress between the YSZ particle and the spinel matrix. From this study, it is difficult to increase the YSZ particle diameter to 400 μm for the actual ROX fuel use in PWR.

From these results obtained on the heterogeneity effect on reactivity and temperature coefficient, it can be concluded that the double heterogeneity effect is negligible for the LWR fueled with particle dispersed type ROX fuel. It can be also considered that the important factor of the cause of this small heterogeneity effect is the tightly packed volume fraction of the YSZ fuel particle in the fuel region. On the other hand in Pu-YSZ fueled HTR, the double heterogeneity effect on reactivity must be taken into consideration for the precise evaluation of the burnup period and the Pu transmutation rate.

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