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Core burnup calculation and accidents analyses of a pressurized water reactor partially loaded with rock-like oxide fuel

H. Akie [a,*], Y. Sugo [b], R. Okawa [c]

[a] Japan Atomic Energy Research Institute, 2-4 Shirakata Shirane Tokai-mura, Naka-gun, Ibaraki-ken 319-1195, Japan
[b] Information Technologies Japan Inc., Mito-shi, Ibaraki-ken 310-0803, Japan
[c] The Japan Research Institute Ltd., Chiyoda-ku, Tokyo 102-0082, Japan

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Abstract

A rock-like oxide (ROX) fuel – light water reactor (LWR) burning system has been studied for efficient plutonium transmutation. For the improvement of small negative reactivity coefficients and severe transient behaviors of ROX fueled LWRs, a partial loading core of ROX fuel assemblies with conventional UO_2 assemblies was considered. As a result, although the reactivity coefficients could be improved, the power peaking tends to be large in this heterogeneous core configuration. The reactivity initiated accident (RIA) and loss of coolant accident (LOCA) behaviors were not sufficiently improved. In order to reduce the power peaking, the fuel composition and the assembly design of the ROX fuel were modified. Firstly, erbium burnable poison was added as Er_2O_3 in the ROX fuel to reduce the burnup reactivity swing. Then pin-by-pin Pu enrichment and Er content distributions within the ROX fuel assembly were considered. In addition, the Er content distribution was also considered in the axial direction of the ROX fuel pin. With these modifications, a power peaking factor even lower than the one in a conventional UO_2 fueled core can be obtained. The RIA and LOCA analyses of the modified core have also shown the comparable transient behaviors of ROX partial loading core to those of the UO_2 core.

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1. Introduction

Plutonium rock-like oxide (ROX) fuel with uranium free inert matrix (PuO_2-$(Gd,Y,Zr)O_{2-x}$-$MgAl_2O_4$) in a light water reactor (LWR) burning system has been studied at the Japan Atomic Energy Research Institute (JAERI) for its potential of high plutonium transmutation rate. This type of U-free matrix fuel, however, has smaller reactivity coefficients and a larger burnup reactivity swing than UO_2 and MOX. Due to these characteristics, severe transient behaviors of ROX-LWR core were predicted in a reactivity initiated accident (RIA) and a loss of coolant accident (LOCA) analyses [1].

In order to improve these ROX-LWR core behaviors, a partial loading core concept was studied, where the ROX fuel assemblies are partially charged in a conventional UO_2 core, together with a study on additives in ROX fuel like UO_2, ThO_2 and Er_2O_3. As a result, both partial loading core and addition of UO_2 or ThO_2 were found effective to improve the reactivity coefficients and the accident behaviors of ROX fueled core [1]. In the partial loading core, however, the power peaking factor was very large, and the flattening of power distribution seemed necessary.

In this paper, reduction of the power peaking factor of the ROX fuel partial loading core is studied. After reaching an adequate improvement, accidents analyses are also made to confirm the effect of the power peaking reduction.

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[*] Corresponding author. Tel.: +81-29 282 6939; fax: +81-29 282 6805.
E-mail address: akie@mike.tokai.jaeri.go.jp (H. Akie).

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2. Physics characteristics and transient behaviors of ROX partial loading core

2.1. Core burnup calculation

For the improvement of reactivity coefficients of ROX fuel, two different approaches were considered in the previous work [1]: One is a ROX fuel assemblies partial loading in the UO_2 fueled core and the other are additives like UO_2, ThO_2 or Er_2O_3 in ROX fuel. The core burnup characteristics of the ROX partial loading core were evaluated by using SRAC95 code system [2]. Core burnup calculations based on the diffusion method were performed on the 2-dimensional X–Y geometry model of the 1100 MW electric class PWR with 193 square fuel assemblies of 17×17 type. In the calculation, 3-batch refueling was assumed and the fuel assemblies loading and refueling pattern was decided to give as small core radial power peaking as possible. Along with the 2-dimensional calculations, the burnup dependence of the core axial power profile was evaluated with the 1-dimensional diffusion calculation on slab geometry. In addition, local power peaking within an assembly was also estimated with the assembly burnup calculations.

Table 1 compares the Doppler reactivity coefficient for a fuel temperature change from 900 to 1200 K and the total (radial × axial × local) power peaking factor estimated for weapons-grade Pu (W-Pu) ROX fuel PWR cores without and with the modifications at the beginning of burnup cycle (BOC) [1]. In the original ROX fuel core, the Doppler coefficient has a very small negative value and the power peaking factor is large in comparison with those of conventional UO_2 fueled cores. By adding UO_2 or ThO_2 in ROX fuel, or by considering a 1/3 ROX and 2/3 UO_2 partial loading core, the Doppler coefficient can be largely improved. The power peaking factor in the UO_2 or ThO_2 added ROX fuel core is also improved. Especially with the combination of UO_2 and Er_2O_3 additives (‘15 at.% U(Er) added’ in Table 1), the peaking factor can be reduced as low as that in UO_2 core. While in the partial loading core, the power peaking becomes even larger than that in the original ROX fuel core.

Table 1
Calculated Doppler reactivity coefficient for a fuel temperature change from 900 to 1200 K and power peaking factor of ROX fuel PWR cores at BOC

	Doppler coeff. (pcm K^{-1})	Peaking factor
Weapons-Pu		
Original ROX	−0.33	2.7
15 at.% U(Er) added	−2.0	2.1
24 at.% Th added	−1.9	2.4
1/3ROX + 2/3UO_2	−1.6	2.8
UO_2	−2.5	2.0

2.2. Accident analyses

By using the core characteristics evaluated in the previous section, RIA and LOCA behaviors of 1100 MW electric class PWR were analyzed with EUREKA-2 [3] and RETRAN2 [4] codes, respectively. The both codes perform point kinetics calculations on the reactor model with the hottest and the average channels in a reactor core. In the present calculations, the hottest and the average channels were further divided into 12 axial nodes. The power levels and the axial power profiles of these channels were decided based on the results of the core burnup calculations. In the RIA analysis with the EUREKA code, the reactivity insertion condition was set referring to that of the current UO_2 PWR, and the hot zero power and full power conditions both at BOC and EOC (end of cycle) were analyzed. In the LOCA analysis with the RETRAN code, the plant data and the noding model were based on the 1100 MW electric class conventional PWR analysis, and the cold leg large break LOCA incident was analyzed both at BOC and EOC.

The RIA and LOCA analyses results obtained for the same cases as in Table 1 are shown in Table 2 [1]. In the original ROX fueled core, the maximum fuel enthalpy change in RIA event is far larger than 0.96 MJ kg^{-1}, which is the current UO_2 pin failure condition in RIA. In the UO_2 or ThO_2 added ROX fuel core, the maximum enthalpy increase in RIA becomes less than 0.96 MJ kg^{-1}, while the enthalpy change is still slightly larger than 0.96 MJ kg^{-1} in the partial loading core. In both cases, the enthalpy increases are much larger than in the UO_2 fuel case. However in the pulse irradiation experiments of ROX fuel pins at the Nuclear Safety Research Reactor (NSRR) in JAERI, the failure condition of ROX fuel pin was shown to be almost the same as that of UO_2 fuel pin in terms of volumetric enthalpy [5]. The volumetric enthalpy change is also shown in Table 2. The pin failure condition in this unit will be about

Table 2
Maximum fuel enthalpy change (ΔH) in RIA and peak cladding temperature (T_{PC}) in LOCA of ROX fueled PWR cores

	RIA		LOCA
	ΔH (MJ kg^{-1})	ΔH (GJ m^{-3})	T_{PC} (K)
Weapons-Pu			
Original ROX	$\gg$0.96		>1470
15 at.% U(Er) added	0.81	4.5	1090
24 at.% Th added	0.94	5.2	1240
1/3ROX + 2/3UO_2	1.02	5.7	1240
UO_2	0.39	4.3	1080

10 GJ m^{-3}. Because of the difference in density between ROX and UO_2, the volumetric enthalpy change in $UO_2 + Er_2O_3$ added ROX becomes almost the same as that of UO_2 fuel case. On the other hand in the ROX partial loading core, even though there is a margin to the pin failure condition, the enthalpy change is still larger than that in the UO_2 core.

In the LOCA analysis, the peak cladding temperature in the original ROX fueled core also exceeds the current limitation value of 1470 K (1200 °C). The cladding temperature becomes less than 1470 K in all ROX fuel cores with a modification. The temperature is even as low as that in the UO_2 core in $UO_2 + Er_2O_3$ added ROX fuel core.

From these results, it can be said that the $UO_2 + Er_2O_3$ added ROX fueled core achieved a comparable RIA and LOCA behaviors to those of the UO_2 fueled core, while the ROX fuel partial loading core will not be as 'safe' as the current UO_2 fuel core. The power distribution flattening seems to be the key issue, because the ThO_2 added ROX fuel core also gives larger power peaking factor, higher fuel enthalpy increase in RIA and higher cladding temperature in LOCA than in the UO_2 fueled core.

3. Power distribution flattening in ROX fuel

The inert matrix fuel without containing any fertile nuclides tend to cause very large excess reactivity at the beginning of burnup life (BOL), and hence large burnup reactivity swing when loaded in reactors. In order to suppress this excess reactivity, Gd_2O_3 burnable poison was used in the original ROX fuel. The Gd burnable poison efficiently reduce the excess reactivity at BOL, and loses its effect very quickly with burnup. The excess reactivity of the Gd added fuel is very low at BOL, and becomes the largest at the middle of burnup. As a result in a batch loading core, this burnup reactivity swing causes a large power level mismatch between fuel assemblies at different burnup stages [1]. This is one of the cause of the large peaking factor in the ROX partial loading core.

To avoid this, Er_2O_3 burnable poison can be chosen instead of Gd_2O_3 in ROX fuel. The Er poison has not such large effect on reactivity as Gd in LWR, and gradually burns with burnup. The burnup reactivity swing becomes smooth in comparison with the case with Gd poison. In addition for the reduction of power peaking, Pu enrichment and Er content distributions are considered within a ROX fuel assembly.

3.1. Radial local power distribution within an assembly

Local power peaking within an assembly in the ROX and UO_2 assemblies partial loading system takes place near the gap between ROX and UO_2 assemblies, because of the neutron spectrum difference. Fig. 1 shows the neutron spectrum at BOL and EOL (end of burnup life) for ROX and UO_2 fuel PWR cells. As shown in this figure, the spectrum in UO_2 fuel does not change so much with burnup, while in ROX fuel, the spectrum is very hard at BOL and becomes softer than that in UO_2 at EOL. Consequently at BOL in the region adjacent to the gap between assemblies, thermal neutrons flow from UO_2 into ROX assembly, and at EOL from ROX to UO_2, and cause a power peaking.

For the local power distribution flattening within an assembly, assembly burnup calculations are performed on 4-assembly model of a ROX assembly and 3 UO_2 assemblies based on 17 × 17 type PWR assembly as shown in Fig. 2. Both with weapons- and reactor-grade Pu (R-Pu), the power peak appears at pin 'A' in Fig. 2 at

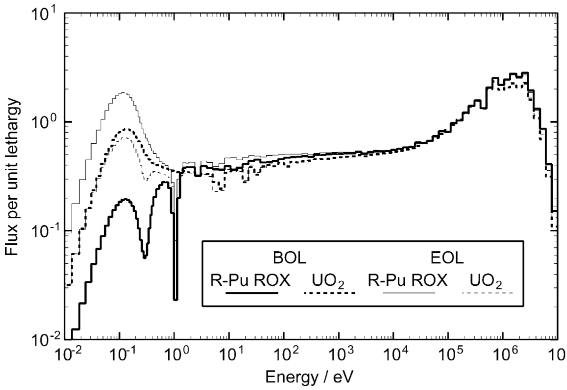

Fig. 1. Energy dependence of neutron flux per absorbed neutron in ROX (reactor-grade Pu) and UO_2 fuels obtained by cell calculation on 17 × 17 type PWR pin cell model (EOL: 1170EFPD = 45 GW d t^{-1} for UO_2).

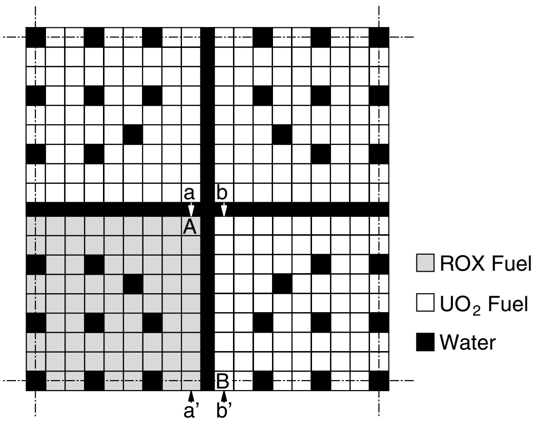

Fig. 2. Four-assembly geometry model of ROX and UO_2 fuels based on 17 × 17 type PWR.

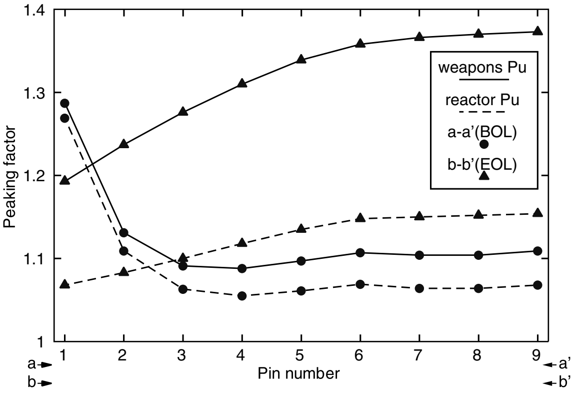

Fig. 3. Pin by pin power peaking factor along gap between ROX and UO_2 assemblies (a-a′: ROX fuel side, b-b′: UO_2 fuel side).

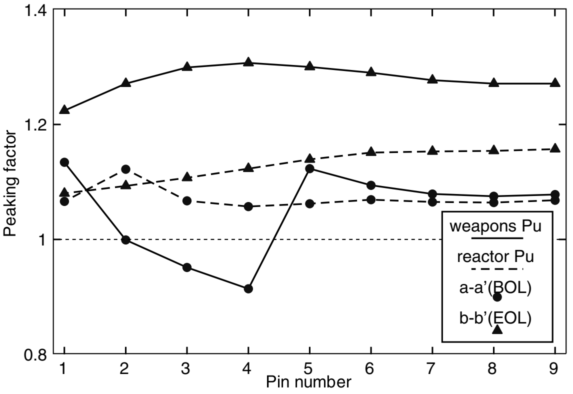

Fig. 4. Improved power distribution by considering pin by pin Pu enrichment and Er concentration distributions.

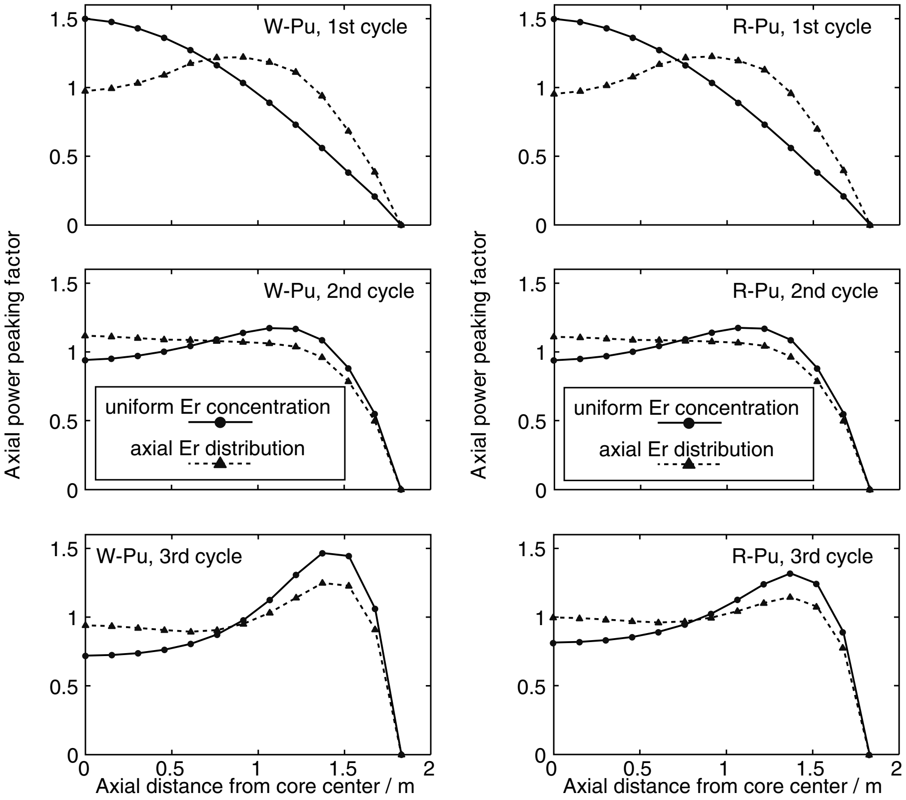

Fig. 5. Axial power distribution with and without axial Er content distribution at the beginning of 1st 2nd and 3rd burnup cycles in weapons and reactor-Pu ROX fuel pins.

BOL, and at pin ‘B’ at EOL. The power distribution along a-a′ line in Fig. 2 at BOL and along b-b′ line at EOL are compared in Fig. 3. The power peak at pin A at BOL is very sharp. While at EOL in W-Pu ROX case, 2 or 3 pins next to pin B have also high power. The power peaking at pin B at EOL is not large for R-Pu ROX case.

For the power peaking reduction, the Pu enrichment at the corner of ROX fuel assembly is reduced and the Er content is increased. The largest power peak usually appears at BOL. In a batch loading core, however, the UO_2 assembly of the first burnup cycle might be loaded next to the ROX assembly at EOL. In the 4-assembly calculation here, it is worth reducing the power peak at pin B in UO_2 assembly at EOL. For this purpose in the W-Pu ROX fuel assembly, the Pu enrichment and Er content are increased in several ROX pins along ROX-UO_2 assembly gap on the other side of pin B. As a result, an example of improved power distributions is shown in Fig. 4. As shown in this figure, for W-Pu case, it is possible to reduce the local peaking factor to less than 1.2 at BOL, and to less than 1.3 at EOL. The local power peaking factor becomes less than 1.2 in the R-Pu system.

3.2. Axial power distribution

It is also tried to flatten axial power distribution by considering Er content distribution in the axial direction of fuel pin. With the assumption of 3-batch refueling, axial power distributions at the beginning of 1st, 2nd and 3rd cycles (BO1C, BO2C and BO3C) with and without Er content distribution are compared in Fig. 5 for W-Pu and R-Pu cases. As can be seen from the figure, it is possible to reduce the power peaking factor to be as low as 1.2.

3.3. Radial power distribution in core and total power peaking

Finally, 2-dimensional core burnup calculation is performed for W-Pu or R-Pu ROX partial loading core model based on 17 × 17 type 1100 MW electric class PWR. In this calculation, core radial power distribution is estimated together with the reactivity coefficients. With the assumption of 3-batch refueling, loading and refueling pattern is surveyed for ROX and UO_2 assemblies at 1st, 2nd and 3rd burnup cycles. In consequence, a core radial power peaking factor of 1.2 is obtained both for W-Pu and R-Pu partial loading cores. The total power peaking (radial × axial × local peaking factors) is 1.7 for the W-Pu core, and 1.8 for the R-Pu core. The estimated core characteristics are summarized in Table 3.

Table 3
Improved Doppler reactivity coefficient and power peaking factor of ROX fuel partial loading PWR cores at BOC in comparison with UO_2 fueled core

	Doppler coeff. (pcm K^{-1})	Peaking factor
1/3ROX(Er) + 2/3UO$_2$		
Weapons-Pu	−1.8	1.7
Reactor-Pu	−1.6	1.8
UO_2	−2.5	2.0

4. Characteristics of improved ROX partial loading core

4.1. RIA and LOCA behaviors

By using the improved power distribution and reactivity coefficients evaluated in Section 3.3, RIA and LOCA analyses are carried out. The results are shown in Table 4. Both for W-Pu and R-Pu ROX partial loading core, the fuel enthalpy increase in RIA and cladding temperature in LOCA are well improved up to levels comparable to UO_2 fueled core ones.

4.2. Fuel temperature under nominal operation condition

The melting temperature of ROX fuel is about 2200 K and very low in comparison with UO_2. The maximum fuel temperature under normal operation condition is also an important parameter in ROX fuel cores. The maximum fuel temperature can be estimated by using the fuel thermal conductivity and the maximum power level of the fuel obtained from the power peaking factor. Fig. 6 shows the radial temperature distribution in a ROX fuel pin and its dependency on the power peaking factor at the peak power position of reactor. The temperature was evaluated [1] by using the fuel thermal conductivity

Table 4
Maximum fuel enthalpy change (ΔH) in RIA and peak cladding temperature (T_{PC}) in LOCA of modified ROX fuel partial loading PWR cores

	RIA		LOCA
	ΔH (MJ kg^{-1})	ΔH (GJ m^{-3})	T_{PC} (K)
1/3ROX(Er) + 2/3UO$_2$			
Weapons-Pu	0.75	4.2	1080
Reactor-Pu	0.79	4.4	1070
UO_2	0.39	4.3	1080

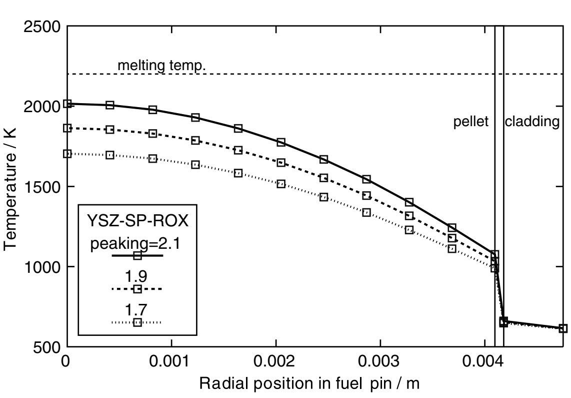

Fig. 6. Temperature of ROX fuel pin at peak power position calculated with different power peaking factors at BOL.

Table 5
Input and transmuted amount ($t\,GW^{-1}$ electrical per 300 d of full power operation) of plutonium in ROX and MOX fueled cores (1170 d discharge burnup, corresponding to 45 $GW\,d\,t^{-1}$ heavy meatlin MOX core)

		Weapons-Pu			Reactor-Pu		
		Input (t)	Transmuted		Input (t)	Transmuted	
			(t)	(%)		(t)	(%)
1/3Zr-ROX + 2/3UO_2	^{239}Pu	0.35	0.26	75	0.35	0.25	73
	Total Pu	0.37	0.16	43	0.59	0.31	53
(in 1/3ROX only)	^{239}Pu	0.35	0.34	99	0.35	0.34	98
	Total Pu	0.37	0.32	85	0.59	0.47	79
Zr-ROX(Er)-UO_2	^{239}Pu	0.93	0.85	92	0.80	0.70	88
	Total Pu	0.99	0.69	69	1.36	0.81	60
Zr-ROX-ThO_2	^{239}Pu	0.97	0.94	97	0.80	0.75	93
	Total Pu	1.03	0.82	79	1.37	0.90	66
MOX (once-through)	^{239}Pu	0.88	0.56	63	0.99	0.44	45
	Total Pu	0.94	0.30	32	1.69	0.41	25
(recycle once)	^{239}Pu	0.76	0.54	71	0.76	0.44	58
	Total Pu	0.81	0.35	43	1.30	0.48	37

ROX results with 2-dimensional core calculations, and MOX results with cell calculations.

measured for the ROX fuel composition of 49 mol% yttria stabilized zirconia (YSZ: $(Zr,Y)O_2$) – 37 mol% spinel (SP: $MgAl_2O_4$) – 14 mol% UO_2 [1]. When the power peaking factor is reduced to as low as 1.7, it is possible to keep the ROX fuel temperature less than about 1700 K, 500 K lower than the melting temperature.

4.3. Plutonium transmutation capability

The transmuted amount (the difference between input and output amount) and the transmutation rate (the ratio of transmuted to input amount) of plutonium per 1 GW electric reactor power per 300 d of equivalent full power operation is shown in Table 5 for ROX fueled PWR cores in comparison with MOX PWR. By adjusting Pu and U enrichments, the discharge burnup of all the cores in this table is set to be about 1170 d with 18 $kW\,m^{-1}$ average linear heat rate, which corresponds to about 45 $GW\,d\,t^{-1}$ heavy metal for MOX.

In the ROX fuel assemblies in the partial loading core, the Pu transmutation rate is extremely high to be 80–85%. This is the advantage of this heterogeneous core when once-through burnup and direct disposal of ROX fuel is considered. Even taking into account the amount of Pu produced in the UO_2 assemblies, total Pu transmutation rate is still larger than that of a MOX fueled core.

5. Conclusion

In order to reduce the large power peaking of the ROX fuel partial loading core, the fuel composition and the assembly design of ROX were modified. Firstly, Er_2O_3 burnable poison, in place of Gd_2O_3, was added in the ROX fuel to improve the burnup reactivity swing. Then pin-by-pin Pu enrichment and Er content distributions within the ROX fuel assembly were considered. In addition, the Er content distribution was also considered in the axial direction of the ROX fuel pin. With these modifications, the total (radial × axial × local) power peaking factor could be reduced as low as 1.7, that is even smaller than the peaking factor of the conventional UO_2 fueled core.

To confirm the effect of the improvement in power distribution, accident analyses were performed. The RIA and LOCA analyses of the core with modified ROX assemblies have shown the comparable transient behaviors of the ROX partial loading core to those of the UO_2 core. The ROX fuel assembly in the partial loading core has a very high Pu transmutation rate, which is an advantage for the once-through Pu disposal.

The flattening of the power distribution discussed here is found effective to improve the characteristics of the ROX fuel partial loading core. From the result, there seems a feasibility of the ROX fuel partial loading core, as well as the full ROX cores with UO_2 or ThO_2 additive.

The Pu and U fuels partial loading core behaviors are actually complex space dependent problems. In this paper, the kinetics analyses are carried out by using point kinetics calculation codes, mainly because of the comparison purpose with the previous work. The space dependent calculations will be important in the next step to further investigate the ROX fuel partial loading core kinetics.

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