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Evaluation of U-Zr Hydride Fuel for a Thorium Fuel Cycle in an RTR Concept

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Abstract

In this paper, we performed a design study of a thorium fueled reactor according to the design concept of the Radkowsky Thorium Reactor (RTR) and evaluated its overall performance. To enhance its performance and alleviate its problems, we introduced a new metallic uranium fuel, uranium-zirconium hydride ($U\text{-}ZrH_{1.6}$), as a seed fuel. For comparison, typical ABB/CE-type PWR based on SYSTEM 80+ and standard RTR-type thorium reactor were also studied. From the results of performance analysis, we could ascertain advantages of RTR-type thorium fueled reactor in proliferation resistance, fuel cycle economics, and back-end fuel cycle. Also, we found that enhancement of proliferation resistance and safer operating conditions may be achieved by using the $U\text{-}ZrH_{1.6}$ fuel in the seed region without additional penalties in comparison with the standard RTR's U-Zr fuel.

I. Introduction

Recently, Radkowsky suggested a thorium fuel cycle, called Radkowsky Thorium Reactor (RTR)[1,2]. This reactor concept means the development of a new thorium fuel cycle which can be adopted to the existing PWR technology. Main design solution of RTR is spatial separation of fissile region and fertile region of the fuel assembly. From this separation, we could overcome some problems of existing thorium reactor concepts such as relatively slow buildup of U^{233}, necessity of spent fuel reprocessing, possible proliferation potential, and so on. However, spatial separation of supercritical fissile part "seed" and subcritical fertile part "blanket" causes stiff power gradient at BOC of the fuel cycle and other technical problems.

In this study, we provide an analysis of the RTR-type thorium reactor to evaluate its overall performance and its technical problems. To compare with a typical PWR, we also studied ABB/CE-type reactor based on SYSTEM 80+. In addition, we proposed[3] to enhance its overall performance and to alleviate its technical problems the use of a new seed fuel, uranium-zirconium hydride[4] ($U\text{-}ZrH_x$), instead of uranium-zirconium (U-Zr) alloy.

We used the cell code system HELIOS[5] and the 2-group diffusion nodal code system AFEN[6] for numerical results. To perform depletion calculation, a link of these two code systems was done using a macro-depletion model.

II. Reactor Design and Calculational Methods

In this work, we performed a comparison study of three different reactor cores, which are ABB/CE type, standard RTR-type, and U-$ZrH_{1.6}$ loaded RTR-type reactor. Except for the use of U-$ZrH_{1.6}$ instead of U-Zr as a seed fuel, the second and third cases have the same design parameters otherwise.

Assembly configuration of ABB/CE type and RTR-type is shown in Fig. 1. Black-marked regions in SBU are waterholes and prepared for guide tubes, control rods, and burnable absorbers. SBU has 17×17 lattice array. Seed region is located in the center of an assembly and has 11×11 lattice array. Volume fraction of the seed region in an assembly is about 40%.

These reactors have the maximum operating power of 3800 MWth. In each core, 241 assemblies are loaded. Operating conditions are assumed to be the same for all cases. Design parameters of the assembly and reactor core are summarized in Table 1.

To assess the characteristics and properties of the fuel assembly and to obtain group constants for core calculation, assembly calculations were performed using HELIOS. In all cases, typical assembly, which has the average power density of the reactor core and average operating condition, was tested. HELIOS calculation was done using 34-group cross section library.

Core calculation was done using AFEN. For depletion calculation, a link of HELIOS and AFEN was done by macro-depletion model. A basic concept of this model is constant burnup during a given time interval. Thus if power distribution of i-1'th burnup step is obtained, we can calculate the burnup distribution of i'th burnup step. From the calculated burnup distribution, we can find the group constants from a lookup-table, which is generated at BOC of each fuel cycle for all types of assemblies. Using these group constants, core calculation of i'th burnup step is performed. Because the blankets of RTR-type reside in the core during ten seed fuel cycles, depletion calculations were performed from cycle 1 to cycle 10 for all cases.

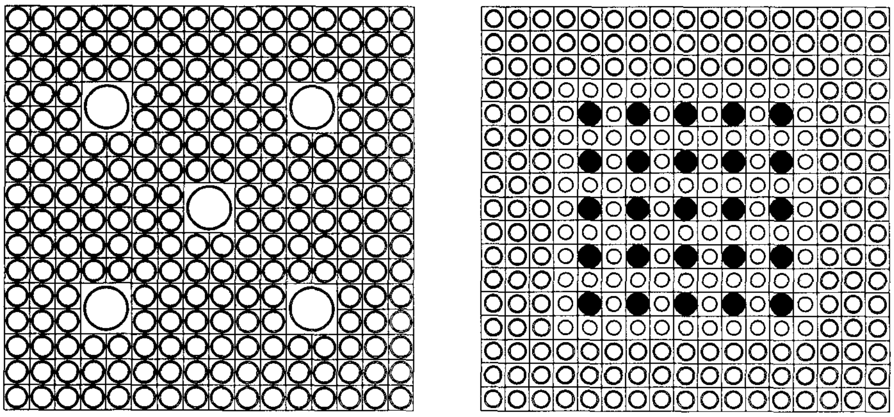

(a) ABB/CE type assembly (b) RTR type assembly - SBU

Fig. 1. Configuration of ABB/CE type assembly and RTR type SBU.

Table 1. Design Parameters of Assembly and Reactor Core

	ABB/CE	RTR-type
Total Power (MWth)	3800	3800
Number of Assemblies	241	241
Operating Temp. (°K)	580	580
Average Power Density (W/g)	40.00	50.348
Number of Fuel Pins per Assembly	236	264
Number of Waterholes per Assembly	5	25
Pin Pitch (cm)	1.28750	1.21176
Fuel Type	UO_2	Seed : U-Zr $U\text{-}ZrH_{1.6}$ Blanket : UO_2 + ThO_2
Fuel Pin OD (cm)	0.84	Seed : 0.72 Blanket : 0.82

Ⅲ. Results of Numerical Estimation

1. Results of Assembly Calculation

Reactivity coefficients of ABB/CE, SBU ($U\text{-}ZrH_{1.6}$), and SBU (U-Zr) are summarized in Table 2. Table 2 indicates that SBU (U-Zr) has more negative MTC than that of others. This fact is not favorable in some accident scenarios. In contrast, SBU ($U\text{-}ZrH_{1.6}$) has a similar MTC value with that of ABB/CE. SBUs have more negative FTC and it is a favorable fact in view that high power density occurs in the seed region. A significant fact in Table 2 is the large difference of boron worth between the two types of assemblies at EOC. From the results, we find that boron worth of SBU is relatively high and increases rapidly as burnup increases. In general, effective multiplication factor of the blanket is related with power production and neutron economics in the blanket, so the use of soluble boron reactivity control is unfavorable for RTR-type reactors.

Pin power peak in an assembly and estimated maximum fuel centerline temperature are given in Table 3 for ABB/CE and SBU ($U\text{-}ZrH_{1.6}$). Although power density in the seed region is relatively high, the results show that there exists sufficient thermal margin because of the metal alloy fuel in the seed region. So, high power density of the seed region and low melting temperature of the seed fuel are not a serious problem in SBU. Low power density of the blanket region and high radiation resistance of ThO_2 may allow for the long residence time of the blanket fuel. However, it should be noted that about 64% of the total power of SBU is generated in the seed region which fills in 40% of SBU. For adequate heat transfer between fuel rods and coolant, power share between the seed and blanket should be controlled in a proper way. Thus power share control is a more important factor than local power peak control in SBU. From this fact, extensive use of burnable absorbers will be required in RTR-type reactors.

Pin-wise power distribution is shown in Fig. 2. While power distribution of ABB/CE type reactor shows almost the same behavior at BOC and EOC, that of SBUs shows power shift from the seed to the blanket as burnup proceeds.

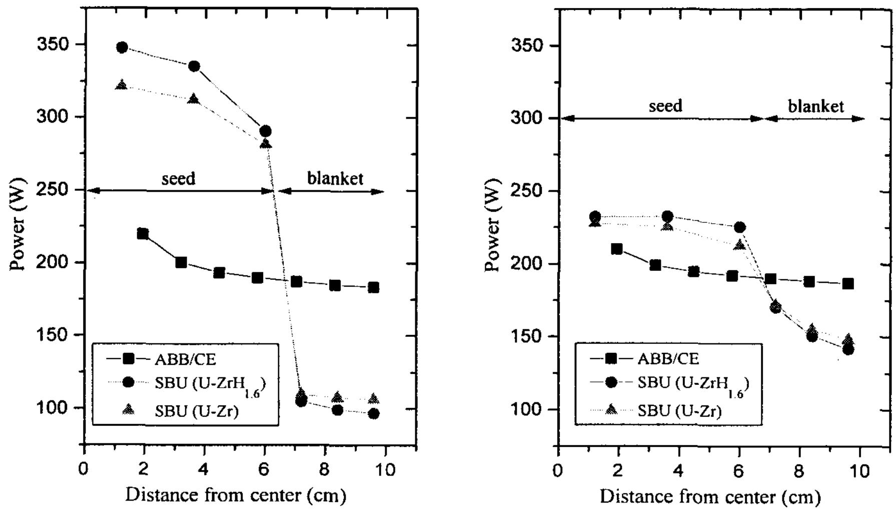
Table 2. Reactivity Coefficients

	ABB/CE		SBU (U-ZrH$_{1.6}$)		SBU (U-Zr)	
	BOC	EOC	BOC	EOC	BOC	EOC
MTC (pcm/ °C)	-19.9606	-37.4599	-21.5684	-25.6616	-32.428	-39.7755
FTC (pcm/ °C)	-1.9727	-2.8309	-3.1653	-3.6083	-2.5612	-3.5656
Boron worth (pcm/ppm)	-7.7415	-8.5010	-7.1540	-12.6096	-7.3692	-11.7403
β_{eff}	7.5238E-03	5.4442E-03	7.0200E-03	5.2877E-03	7.0534E-03	5.2803E-03

Table 3. Pin Power Peak and Maximum Fuel Centerline Temperature at BOC

	ABB/CE	SBU (U-ZrH$_{1.6}$)	
		Seed	Blanket
Average power density	352 W/cm^3	592 W/cm^3	180 W/cm^3
Maximum power density	430 W/cm^3	838 W/cm^3	195 W/cm^3
Pin power peak	1.2216	1.4155	1.0833
Limit power density	1241 W/cm^3	5291 W/cm^3	1241 W/cm^3
T_c at maximum power density[a]	1179 °K	834 °K	866 °K
Fuel melting temperature	2487 °K	1600 °K	2487 °K

[a] fuel centerline temperature



(a) at BOC

(b) at EOC

Fig. 2. Pin-wise power distribution along a symmetry axis.

2. Results of Core Calculation

Average fuel requirement for 10 fuel cycles is given in Table 4. Requirement of U^{235} is similar to others, but requirement of U^{238} is reduced by a factor of 7 in RTR-type reactors. Thus the RTR-type reactor is more efficient in the effective utilization of natural uranium resource. The two RTR-type reactors have very similar results.

Discharged fuel compositions for uranium and plutonium are given in Tables 5 and 6. The amount of uranium and plutonium contained in the RTR-type spent fuel is much smaller and the total mass of plutonium of RTR-type spent fuel is reduced by a factor of 4. The discharged plutonium contains a plutonium composition, which is quite different from the ABB/CE discharged plutonium. The fissile isotopic composition of the RTR-type discharged fuel is reduced by about 10% and indicates enhanced proliferation resistance. The total weight percents of fissile plutonium for ABB/CE, RTR (U-ZrH$_{1.6}$), and RTR (U-Zr) are 57.78%, 60.16%, and 67.27%, respectively. Due to the high discharge burnup of the blanket and the high thermal flux of the seed at EOC, weight percent of Pu^{238}, a spontaneous fission source, which is generated by beta decay of Np^{238} and by alpha decay of Cm^{242}, is much greater in RTR than in ABB/CE type reactor. From the tables, we also find that RTR (U-ZrH$_{1.6}$) has less fissile enrichment in both uranium and plutonium composition. This result indicates enhanced proliferation resistance of RTR (U-ZrH$_{1.6}$). In both cases of RTR-type reactors, the total mass of plutonium is almost the same.

Table 4. Average Fuel Requirement

	RTR (U-ZrH$_{1.6}$)			RTR (U-Zr)			ABB/CE
	seed	blanket	total	seed	blanket	total	
Th^{232}	-	7379[a]	7379	-	7275	7275	-
U^{235}	1074	182	1256	1059	180	1239	1246
U^{238}	4634	730	5364	4569	719	5288	39034
Total heavy metal mass	13999			13802			40280

[a] average mass (kg/yr)

Table 5. Discharged Uranium Composition

	RTR (U-ZrH$_{1.6}$)			RTR (U-Zr)			ABB/CE
	seed	blanket	total	seed	blanket	total	
U^{233}	-	123 [16.33][b]	123	-	125 [17.05]	125	-
U^{235}	158 [4.08]	14 [1.86]	172	175 [4.54]	15 [2.05]	190	213 [0.68]
U^{238}	3710[a]	616	4326	3673	593	4266	30985
Total mass of U	4621			4581			31198

[a] average mass (kg/yr)

[b] enrichment of uranium (wt%)

Table 6. Discharged Plutonium Composition

	RTR ($U\text{-}ZrH_{1.6}$)			RTR (U-Zr)			ABB/CE
	seed	blanket	total	seed	blanket	total	
Pu^{238}	2.40[a]	2.91	5.31	2.27	3.32	5.59	4.92
Pu^{239}	22.42	9.53	31.95	22.96	10.16	33.12	173.35
Pu^{240}	13.56	3.81	17.31	11.77	3.83	15.60	81.97
Pu^{241}	7.42	3.63	11.05	7.08	3.91	10.99	45.03
Pu^{242}	5.15	3.65	8.80	4.16	3.86	8.02	19.34
Fissile enrichment	58.56[b]	55.92	57.78	62.27	56.10	60.16	67.27
Total mass of Pu	74.42			73.32			324.43

[a] average mass (kg/yr)

[b] weight percent

Ⅳ. Conclusions

From the assessment of overall performance for an RTR-type thorium fueled reactor, we could ascertain its advantages in proliferation resistance, fuel cycle economics, and back-end fuel cycle. However, there are some remaining problems such as the extensive use of burnable absorbers for power share control and soluble boron free reactivity control, and other thermomechanical problems.

More importantly, we found that some technical problems of the standard RTR-type reactor could be solved by the use of $U\text{-}ZrH_{1.6}$ fuel in the seed region. Using $U\text{-}ZrH_{1.6}$, we obtained safer operating conditions, enhanced proliferation resistance, and flexibility in the seed fuel design.

Finally, we conclude that, with the problems above resolved, RTR-type thorium reactors have a potential for reducing the two major problems of the existing LWR technology, which are possible proliferation danger and the storage and disposal of the spent fuel. More enhanced performance of the RTR-type reactor may be achieved by using the $U\text{-}ZrH_x$ metal alloy fuel in the seed region.

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