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Breeding Potential Assessment of Reduced Moderation Pressurized Water Reactor Fuel Assembly

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1. Introduction

Current thermal nuclear reactors mostly utilize uranium (^{235}U) as the fuel to allow for fission chain reaction and to eventually produce power. This decreases the amount of uranium in earth overtime. The search for the substitute fuel material is a rising research topic recently. Some considered Thorium (^{232}Th) due to its major advantage in low void coefficient [1, 2]. ^{232}Th also has the potential to breed into ^{233}U, which is a fissile fuel. Th is reported to be three to four times more abundant in nature than U, based on its average concentration in the earth's crust [3].

Implementation of Th as the fertile fuel is studied in Reduced Moderation Pressurized Water Reactor (RMPWR). Th is incorporated with other materials in the fuel, which include transuranic (TRU) materials that come from the current power plant spent fuels [4]. The reduced moderation allows for harder neutron spectrum to burn the transuranic and are expected to breed ^{233}U from the ^{232}Th. The breeding potential of RMPWR is expected to extend the fuel cycle length to a certain time. Cycle length is the operational duration before a reactor need refueling. This study assesses the breeding potential of 3-dimensional (3-D) RMPWR fuel assembly (FA) for various fissile enrichments and pitch lengths.

2. Methods

The assessment is conducted using SERPENT 2 code. It is a continuous energy Monte Carlo (MC) neutron transport code developed at VTT Technical Research Centre of Finland, Ltd.[5] RMPWR FA is similar in geometry to the normal Westinghouse PWR. The main difference is the pin diameter, which is enlarged from 9.5 mm to 11 mm and the fuel material composition.

The first procedure is to construct the geometry of the RMPWR FA using a 17x17 square lattice as shown in Figure 1. It is cut in the middle to show the radial configuration of the FA. The 3-D FA's total height is 406.3 which comprise 366 cm of active fuel as well as bottom and top part of support structures. Reflective boundary condition is defined for x and y axis, while for z axis it is set as black. In the RMPWR core, there are 193 FAs. Since a full RMPWR core designed to operate at thermal power of 3411 MW, therefore a single FA has a thermal power of 17.67 MW.

The design employs two types of fuel pin. The blanket pin consist of ^{232}Th and TRU, while the seed pin consist of ^{232}Th and U as presented in Table I. There are 144 blanket pins in the periphery and 120 seed pins in the center of the FA. The rests are occupied by the guide tubes. Therefore the configuration is divided radially, with the seed and blanket pins located in separate positions. Axially, the fuel is uniformly distributed in each pin type and 49 meshes are employed to give a finer results.

The breeding potential, or more often quantified as conversion ratio (CR) of the RMPWR FA is assessed using the burnup facility in SERPENT 2. CR is defined as the average number of fissile atoms produced per fissile atom consumed either by fission or absorption.[6] The assessment utilizes the nuclear data library based on the evaluated file ENDF/B-VII.1. The burnup simulation solves the Bateman depletion equation using the default method in SERPENT 2, that is, the matrix exponential method based on the Chebysev Rational Approximation Method (CRAM) [5]. For this purpose, the FA is burned to 40 MWd/kg and divided into several steps, ranging from 0.1 to 2.5 MWd/kg.

The burnup calculation is performed for various fissile enrichments and pitch lengths to obtain the best design and to evaluate the reference design which employs 6.41% of fissile enrichment and 1.26 cm pitch length [1]. There are 5 fissile enrichment variations for 1.26 cm pitch length: 5.41%, 5.91%, 6.41%, 6.91% and 7.41%. These enrichment values correspond to the total weight fraction of the fissile isotopes in the FA. The fissile enrichment is a contribution of ^{239}Pu and ^{241}Pu in the blanket pin, and also ^{233}U and ^{235}U in the seed pins. Then, the total enrichment is calculated using Equation 1 which accommodates for the total number of each type of pin in the FA.

$$wt,fissile = \frac{144 * (wt_{Pu-239} + wt_{Pu-241})}{264} + \frac{120 * (wt_{U-233} + wt_{U-235})}{264} \quad (1)$$

where $wt, fissile$ = total average fissile enrichments for one variation; wt_{Pu-239}, wt_{Pu-241}, wt_{U-233}, wt_{U-235} = mass fraction of ^{239}Pu, ^{241}Pu, ^{233}U, ^{235}U.

Table I. Beginning-of-cycle (BOC) material compositions of Th-TRU (blanket) and Th-U3 (seed) fuel

Isotope	Th-TRU, at%	Th-U3, at%
^{241}Am	2.37	-
^{242m}Am	0.06	
^{243}Am	1.36	
^{244}Cm	0.99	
^{245}Cm	0.40	
^{246}Cm	0.37	
^{247}Cm	0.07	
^{248}Cm	0.04	
^{237}Np	1.08	
^{238}Pu	4.11	
^{239}Pu	6.69	
^{240}Pu	9.39	
^{241}Pu	2.09	
^{242}Pu	4.91	
^{232}Th	66.08	90.50
^{233}U	-	4.30
^{234}U		3.26
^{235}U		0.97
^{236}U		0.97

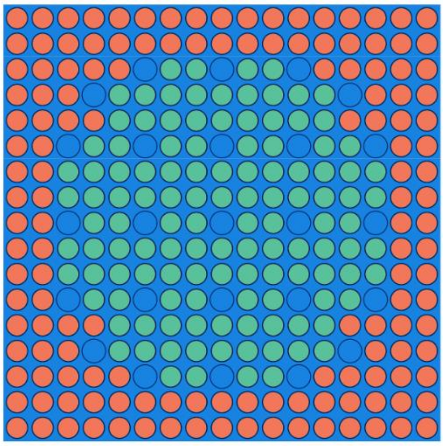

Figure 1. Radial view of RMPWR FA showing blanket pins in the periphery (red) and seed pins in the center (light green).

In practice, this could be achieved by managing the material weight fraction other than the fissile isotopes so that no extra fissile material needs to be procured. Whereas there are 5 pitch length variations for 6.41% fissile enrichment: 1.25 cm, 1.26 cm. 1.28 cm, 1.31 cm and 1.35 cm. The change of pitch length automatically change the total FA length, the pitch to diameter ratio and the moderator-to-fuel ratio. For a more reasonable comparison, the various pitch lengths are presented in terms of moderator-to-fuel ratio. Each pitch length correspond to moderator-to-fuel ratio of 0.644, 0.670, 0.723, 0.805, 0.917, respectively.

Each simulation implements 50 inactive cycles, 1000 active cycles and 20000 histories. The calculation result gives directly the value of CR for each variation. Then, the time or effective full power day (EFPD) is plotted against k_{eff} and CR for each variation to conclude for the RMPWR FA breeding potential. The best design is determined for the one that able to maintain longest cycle length, that is, the value when k_{eff} reach exactly 1.0 and highest conversion ratio. The cycle length is also compared with PWR so that a final recommendation can be made.

3. Results and Discussion

More fissile enrichment result in less CR as shown in Figure 2. This is due to the fact that there are more fissile isotopes to be burned in the fuel compared to the production of new fissile isotopes. In contrast, the cycle length of the RMPWR FA is longer for higher fissile enrichment, as more fissile isotopes are available in the fuel to sustain the fission reaction. The opposite trend is observed for the CR which increases overtime as more ^{233}U is produced from the burning of ^{232}Th. The various moderator-to-fuel ratios does not significantly affect the criticality of the FA. However a slight difference can still be observed, with the biggest moderator-to-fuel ratio results in highest k_{eff} and the smallest results in the lowest k_{eff} as presented in Figure 3. The value of k_{eff} is proportional to the cycle length. Each simulation result, both for k_{eff} and CR have the statistical error in order of 10^{-4}. It is not given in the figure due to the far smaller value compared to the nominal value being calculated.

The summary of cycle length, CR and breeding duration is given in Table II and Table III. As have been mentioned in the previous chapter, the best design is chosen based on the one that can give longest cycle length and highest CR. The longest cycle length is given by the design that implements 7.41% fissile enrichment with cycle length of 1351 days, or ~3.7 years. The design with moderator-to-fuel ratio of 0.917 gives the longest cycle of 938 days, or ~2.57 years. The highest average CR is given by the design with 5.41% fissile enrichment (1.005), although it is severely limited by the short cycle length of only 346 days. In case of moderator-to-fuel ratio variations, the highest average CR is obtained by the design with moderator-to-fuel ratio of 0.644 (0.877). However, the CR difference for various moderator-to-fuel ratios is not significant. In this study, the longer cycle length is preferred than higher CR, since a longer cycle length can save the reactor's operator a lot of efforts by performing the refueling less often.

The reference design with 6.41% fissile enrichment and 1.26 cm pitch length has a cycle length of 899 days. It can have a CR equal to 1.0 at 855 days, and therefore act as a fully breeder for 44 days, the longest compared to all the other designs. If a longer cycle length is pursued, the implementation of higher fissile enrichment can be done, although a significantly higher cost in procuring the fissile isotopes is an incriminating consequence.

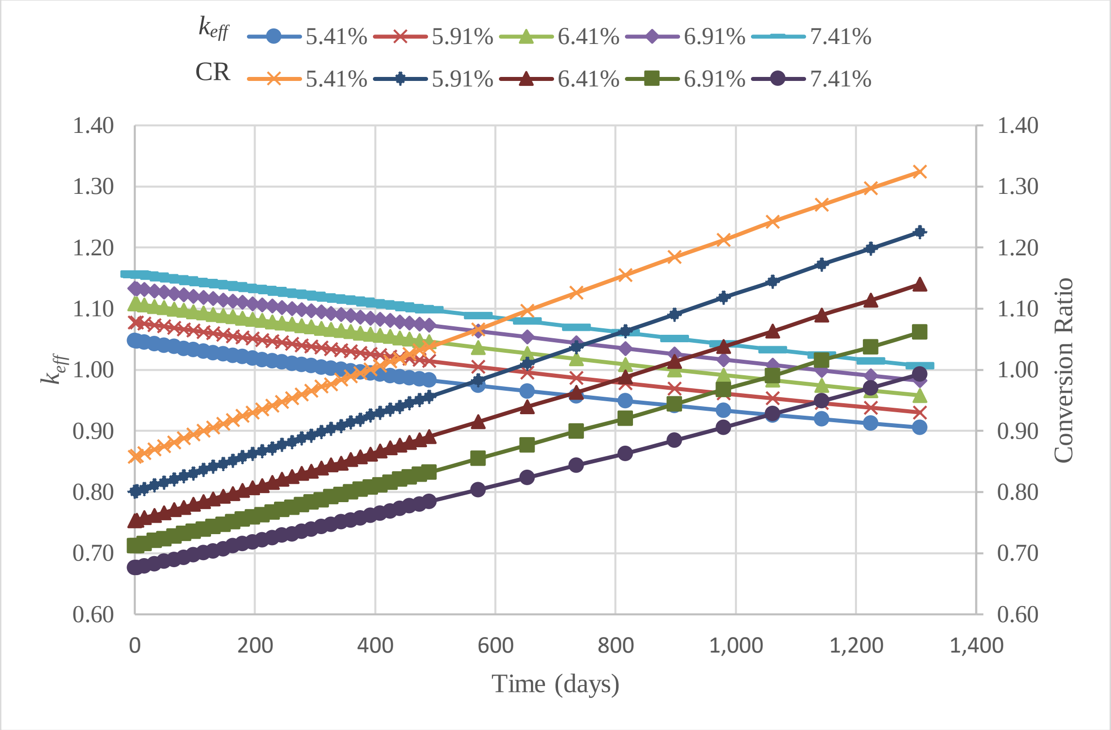

Figure 2. Burnup Results for Various Fissile enrichments

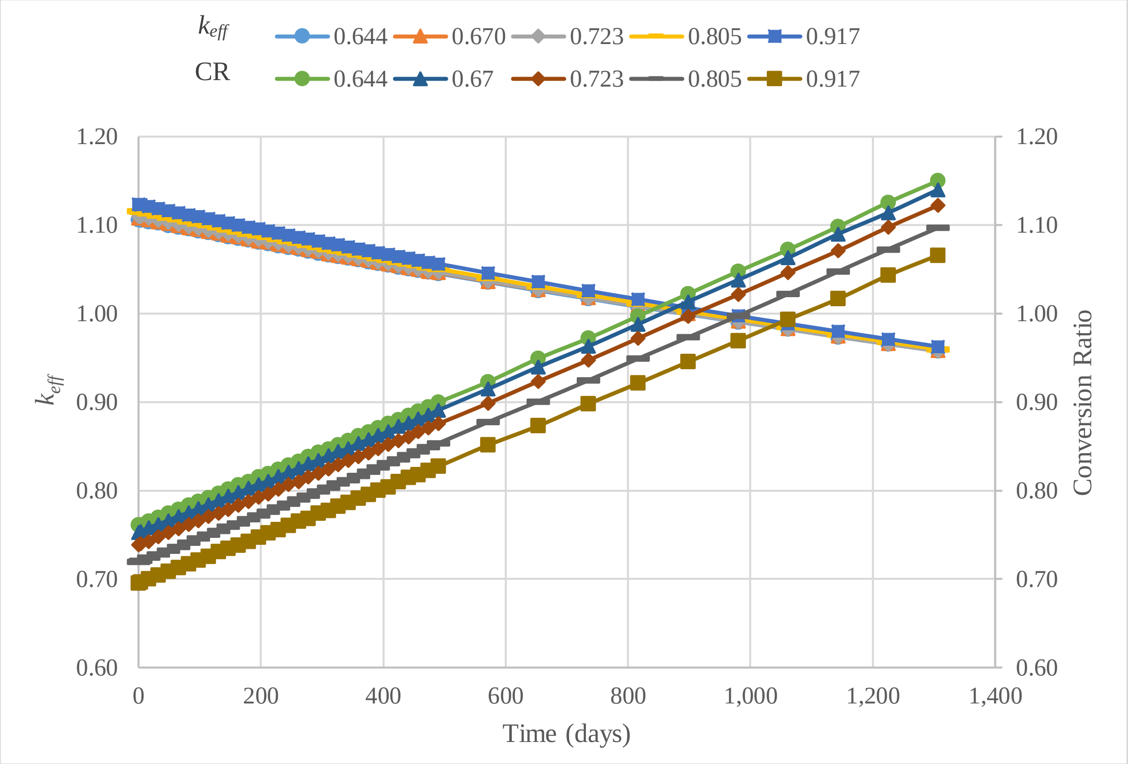

Figure 3. Burnup Results for Various Moderator-to-fuel Ratio

Table II. Summary of Burnup for Various Fissile Enrichments

Fissile Enrichment (%)	Cycle Length (days)	Time at CR = 1 (days)	Optimum Breeding Duration (days)	Average CR
5.41	346	391	-	1.005
5.91	615	623	-	0.930
6.41	899	855	44	0.868
6.91	1115	1093	22	0.814
7.41	1351	1332	19	0.768

Table III. Summary of Burnup for Various Moderator-to-fuel Ratios

Moderator -to-fuel Ratio	Cycle Length (days)	Time at CR =1 (days)	Optimum Breeding Duration (days)	Average CR
0.644	850	826	24	0.877
0.670	899	855	44	0.868
0.723	876	907	-	0.853
0.805	901	988	-	0.832
0.917	938	1085	-	0.806

The reference design with 1.26 cm pitch length also gives the advantage of possibility in retro-fitting the FA into the current PWR core considering the similar geometry. This retro-fitting process is investigated and requires less cost compared to building a completely new reactor. [2]

The lowest CR for all of the variations is around 0.7. This is higher than the current commercial PWR with average CR of 0.6. This is made possible by the use of high concentration of fertile ^{232}Th in the fuel: there are 66.08% in the blanket pins and 90.50% in the seed pins. The reduced moderation shifts the neutron spectrum to higher energy range which is favorable to for the neutron capture cross section of ^{232}Th to increase [1]. Moreover, the higher CR leads to longer cycle length of RMPWR, which for the reference design could last to ~2.5 years.

PWR usually performs refueling every 1 to 2 years, and RMPWR is superior in term of longer cycle length, although a full core assessment is required for a more complete information.

4. Conclusion

A single 3-dimensional reduced moderation pressurized water reactor (RMPWR) fuel assembly (FA) model has been developed using SERPENT 2. The model is implemented to assess the breeding potential of RMPWR FA by performing burnup simulation for various fissile enrichments and pitch lengths which are presented as moderator-to-fuel ratios.

Overall, the minimum conversion ratio (CR) for all designs of RMPWR FA is ~0.7. This is higher than the average CR of PWR (0.6). This is due to the employment of high concentration of ^{232}Th in the fuel. Highest average CR of 1.005 is observed for the design with 5.41% fissile enrichment, but it is limited by the very short cycle length of 346 days. The longest cycle length of 1351 days is achieved by implementing design with 7.41% of fissile enrichment and pitch length of 1.35 cm, or moderator-to-fuel ratio of 0.917. Drawbacks in term of cost in procuring more fissile isotopes for high fissile enrichment and building new RMPWR core design with 1.35 cm of pitch length are noted.

The reference design which implements fissile enrichment of 6.41% and pitch length of 1.26 cm possess several interesting advantages. First, it can be retro-fitted into the current PWR as the geometry is similar. This process can reduce the capital cost compared to building a completely new reactor. Second, its cycle length of ~2.5 years is longer than the current PWR (1 to 2 years). Lastly, the optimum breeding duration is 44 days, which is the longest compared to all other designs.

A full core RMPWR assessment is recommended to give a more comprehensive result and a more relevant comparison with full core PWR.

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