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Parametric Studies of the Internally and Externally Cooled Annular Fuel Concept

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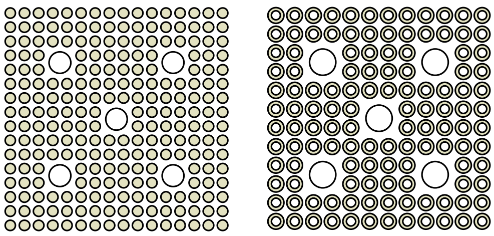
1. Introduction

Annular fuel concept, which is internally and externally cooled, was proposed for a high power density application in a conventional PWR fuel by decreasing the maximum fuel centerline temperature.[1] The feasibility of the annular fuel concept has been studied for the Westinghouse fuel by MIT under the NERI program since 2001.[2] From last year, the annular fuel concept has been studied in KAERI in order to apply it to the OPR-1000 fuel assembly and the conceptual assembly design of 12x12 fuel arrays was suggested.[3,4] In this paper, parametric studies have been performed for the proposed 12x12 annular fuel assembly design in order to optimize the design parameters.

2. Methods and Results

2.1 Annular Fuel Assembly Design

One of the characteristic features of the annular fuel concept compared to a solid fuel is that it has an internal and external coolant flow path with in a fuel channel. The energy generated in the fuel region is transferred to the coolant through the internal and external fuel surface. A both sides cooling has a benefit for a maximum fuel centerline temperature.



a) OPR-1000 Fuel Assembly b) 12X12 Annular Fuel Assembly

Figure 1. Cross-sectional View of Assemblies.

Figure 1 shows the layout of the OPR-1000 fuel assembly and the proposed annular fuel assembly. The possible number of fuel pin arrays when annular fuel rods are loaded in the OPR-1000 fuel assembly is restricted because the control rod system of the OPR-1000 will be used in the annular fuel core design without any change. In the proposed annular fuel assembly design, maximum pin power generation near the guide tube is much higher than that of the OPR-1000 fuel assembly because of the enlarged coolant area near the guide tube. However, the radial pin power distributions in the proposed annular fuel assembly can be controlled either by using a low enriched fuel near the guide tube or using a thick guide tube.

2.2 Parametric Studies

In order to optimize the proposed annular fuel assembly design, parametric studies are being performed by using the HELIOS code with the 190 neutron group library. When considering the neutronic characteristics of the annular fuel concept, the effects of an annular fuel geometry, low fuel temperature, and double cladding layers are analyzed. Since the proposed annular fuel geometry has a larger fuel surface area than that of the OPR-1000 fuel assembly, resonance absorption is increased in the annular fuel geometry. When the geometry is changed from a solid to an annular fuel shape, the fuel surface area is higher than that of the OPR-1000 fuel assembly by 32%. Generally, the fuel surface area depends on the annular fuel thickness, and therefore the sensitivity of the fuel thickness to the k-infinite is also analyzed. The average fuel temperature in the annular fuel geometry is expected to be 600K, which will have a positive effect on the k-infinite. Double claddings at the internal and external fuel surface will increase the parasite neutron absorptions and have a negative effect on the k-infinite. In these cases, all the material composition data is preserved as the same except for the geometry data. Calculation results are analyzed base on the four factors form of an eigenvalue. In order to optimize the annular fuel assembly design parameters, nuclear physics calculations as well as Departure from Nucleate Boiling Ratio(DNBR) analysis have been performed. DNBR calculation was performed for the single fuel rod by the MATRA code with assumed conditions for a relative comparison between OPR-1000 fuel and the proposed annular fuel.

2.3 Results Analysis

The results of the nuclear physics calculations are shown in Table 1. The difference of the k-infinite for the geometry change from the solid to the annular fuel shape is -1.78% as shown in Annular 1 case due to an increase of the resonance absorption. Lower fuel temperature of 600K in the Annular 2 case increases the k-infinite by 1.3% due to the doppler effect. When the cladding mass is double, it is shown that the k-infinite value is decreased by 1.8% in the Annular 3 case. The dominant factor of the k-infinite reduction in the annular fuel design is the resonance escape probability as shown in Table 1. The fuel loading mass reduction of the proposed annular fuel design is 15% while the moderator to fuel volume ratio is increased by 15% due

Table 1. Neutronic parameters of study cases

Case / Factor	OPR-1000 Solid Fuel	Annular 1	%Δ	Annular 2	%Δ	Annular 3	%Δ	Reference Design	%Δ
η	1.9001	1.9001	-	1.9003	0.02	1.9003	-	1.9011	0.05
f	0.9495	0.9436	-0.62	0.9437	0.01	0.9398	-0.41	0.9357	-1.46
p	0.5951	0.5874	**-1.29**	0.5939	**1.10**	0.5905	**-0.58**	0.6227	**4.64**
ε	1.3257	1.3345	0.66	1.3319	-0.19	1.3282	-0.28	1.2834	-3.19
k-infinite	1.42339	1.40555	-1.78	1.41852	1.30	1.40057	-1.80	1.42170	-0.17

Annular 1 : Geometry effect from solid to annular shape. All material data are same those of OPR-1000 fuel assembly.
Annular 2 : Fuel temperature effect from 960K to 600K. Other data are same those of Annular 1.
Annular 3 : Cladding mass is double and other material data are same those of Annular 2 except gap.

to the double cladding layers. The penalty for k-infinite of the proposed annular fuel is 170 pcm at a zero burnup and 450 pcm at a 35GWd/tHM burnup point.

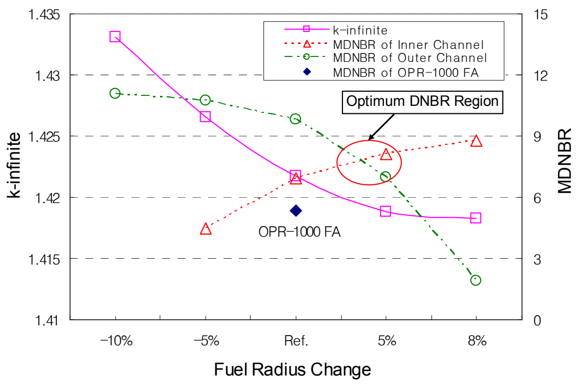


Figure 2. Minimum DNBR of Inner & Outer Channel and k-infinite vs. Various Rod Sizes.

The results of the thermal hydraulic studies for the hot fuel pin are shown in Figure 2. Since the coolant channel has been divided into two regions within the sub-channel, calculation results indicate that the coolant area ratio between the inner and outer channel is very important. The current reference annular design has a DNBR margin of 30% when compared with the OPR-1000 fuel rod. The optimum DNBR region is the point of balanced MDNBR in both channels of the annular fuel. It is located at the larger fuel rod size than the reference one and the maximum DNBR margin is about 50%. However the large fuel rod size, in turn, a thin annular fuel thickness decreases the k-infinite value by increasing the fuel surface area as shown in Figure 2. Even though a 10% reduction of the fuel rod size can extend the fuel cycle length to the same as that of the OPR-1000 fuel assembly, there is large DNB difference between inner and outer coolant channels.

Figure 3 shows the k-infinite value of various moderator to fuel volume ratios at a 35 GWd/tHM burnup point in order to compare the fuel cycle length. The reference design has a larger moderator to fuel volume ratio than that of the OPR-1000 fuel assembly due to a fuel loading mass reduction. For the same neutronic performance of the annular fuel design, the fuel enrichment is increased, but it is very small. To have the same fuel cycle length, only 4.57w/o and 4.6w/o of a fuel enrichment are needed for the reference annular design and the optimum design while 4.5w/o is needed for the OPR-1000 fuel assembly.

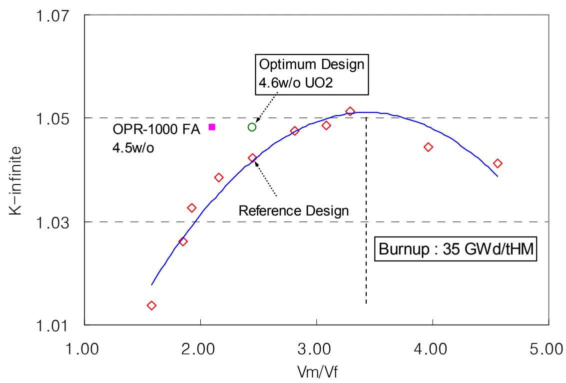


Figure 3. k-infinite vs. Vm/Vf ratios.

3. Conclusion

Parametric studies have been performed for the reference annular fuel design to optimize the design parameters from the view point of the neutronics and thermal hydraulics. In order to maximize the DNBR margin of the proposed annular fuel design, the rod size is to be increased by 5% from the reference one and have a 50% DNBR margin while it is more than that of the OPR-1000 fuel rod. To have the same fuel cycle length as the OPR-1000 fuel assembly, the increase of the fuel enrichment in the optimum design is only 0.1w% while the reduction of the fuel loading mass is 15%, which will contribute to the fuel economics.

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[4] D.S.Oh, et al., “Feasibility Study of Double-Cooled Annular Fuel With KSNP(II),” Proceeding of the Korean Nuclear Society Autumn Meeting, Busan, Korea 2005.