Flattening of UCFR Power Distribution with Fuel Zoning

Taewoo Tak [a] and Deokjung Lee [a*]
[a] *Ulsan National Institute of Science and Technology, UNIST-gil 50, Ulsan, 689-798, Korea*
[*] *Corresponding author: deokjung@unist.ac.kr*

1. Introduction

The Ultra-long Cycle Fast Reactor (UCFR) has been developed for the purpose of 60-year operation and has a power rating of 2600 MW (thermal). UCFR utilizes a breed-and-burn strategy to achieve such a long cycle by using low enrichment uranium (LEU) as an igniter and natural uranium (NU) as a blanket material [1]. Only the feasibility of the core from the neutronics point of view had been reported, so the optimization of UCFR was performed to consider thermal hydraulic feedback analysis and mitigate the power peaking issue. Also the study on using spent fuel for the blanket material has been performed [2]. It was noticed that the high reactor power rating combined with high peaking could cause a very large amount of local power and consequently violate the limits of temperature or fast neutron fluence in the fuel and clad regions [3]. Thorium fuel had been utilized as a blanket material to flatten the radial power distribution of UCFR-1000 and the result shows the radial peaking factor at the center decreases at the middle of cycle (MOC), which confirmed that thorium loading has an effect on the power flattening [4]. In this paper, several designs of UCFR-1000 have been developed to flatten the power distribution not only at MOC but also throughout the whole cycle. They have an inner fuel region whose radius is 35% of the whole fuel region in contrast to the previous UCFR-1000 with an inner fuel region of only 1/4 the radius of the whole fuel region. In addition, LEU zoning has been performed to flatten the radial power distribution at beginning of cycle (BOC).

2. Core design

In this section, 5 design cases that have inner core region and LEU zoning are introduced along with their geometry and fuel compositions.

2.1 Core Design Parameters

Fuel zoning has been performed from the reference core with only one fuel form of U-10Zr. It has been performed only for the blanket region in case 1, and for the LEU region as well as the blanket region in case 2 and the others. Table I shows the core design parameters that the cores should have in common: the power rating, the cycle length, and the geometry that are the design requirements of UCFR-1000. Fuel variation is followed by the change of heavy metal loading, but it is not noticeable. The fuel form and LEU enrichment have been decided to satisfy the criticality through the cycle length.

Table I: Core Design Parameters

Parameters	Value
Thermal power [MWth / MWe]	2600 / 1000
Cycle Length (effective full power years)	60 (Once through)
Equivalent Core Diameter [m]	5.9
Fuel pin overall length [cm]	340
Active core height [cm]	240
Average Linear Power [W/cm]	158.7
Core Volume [kL]	42.4
Average Volumetric power density [W/cc]	61.3

2.2 Core Layout

Figure 1 shows the core layout of UCFR-1000 in an x-y cross section, which is a top view. The equivalent core diameter is 5.9 m and that of the outer and inner cores are 5.0 m and 1.8 m respectively. There are a total of 19 control assemblies: 13 primary and 6 secondary. The primary system uses natural boron as an absorber material, and the secondary system uses 90 % enriched boron. The reflector, cladding, and structure material is HT-9, and sodium is used for the coolant material.

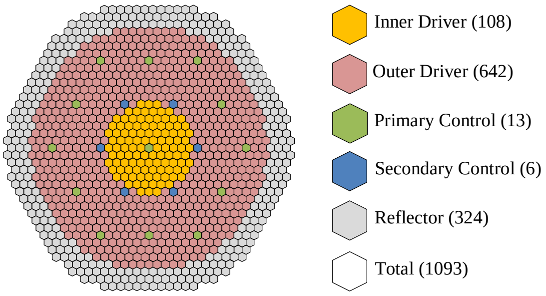
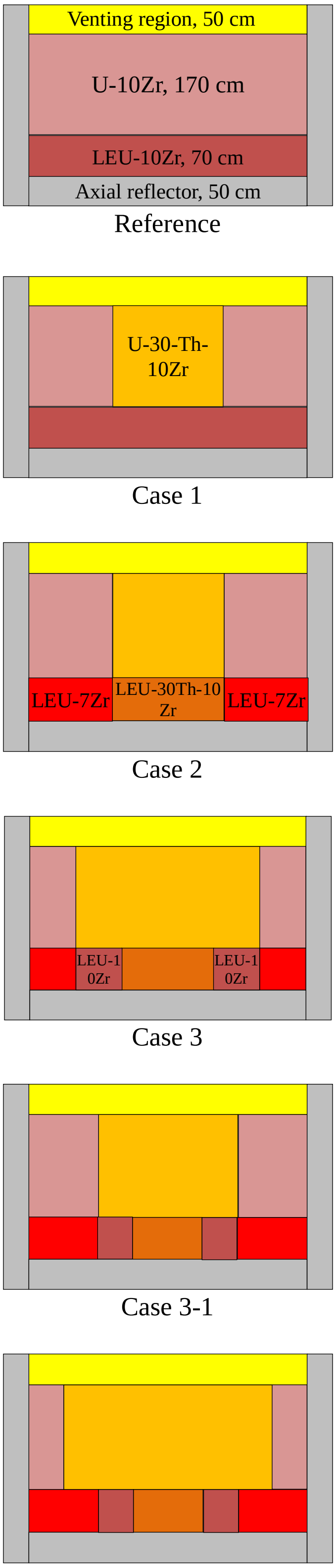


Fig. 1. Core Layout of UCFR-1000 in x-y plane

The Case 1 core has only one fuel form of U-10Zr in the bottom driver region, while Case 2 has various forms of fuel for power flattening even at BOC. Figure 2 shows the core layout in an x-z cross section, which shows the fuel zoning of each case.



Reference

Case 1

Case 2

Case 3

Case 3-1

Case 4

Fig. 2. Core Layouts of UCFR-1000 in x-z plane

3. Performance evaluation

The computations for the UCFR core design and performance evaluation were done using the McCARD code, which solves a continuous energy neutron transport equation based on the Monte Carlo method.

3.1 Depletion Performance

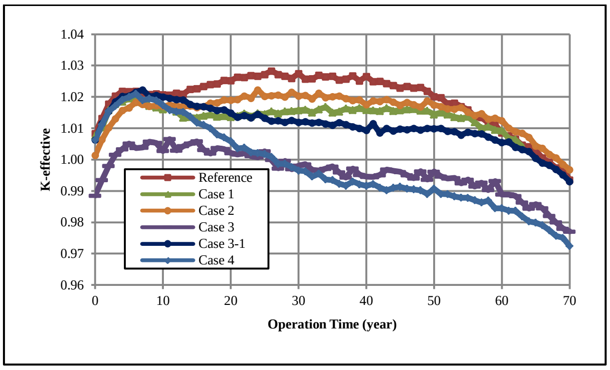


Fig. 3. K-effective vs. operation time

Figure 3 shows the multiplication factors behavior of each core model. The reference case has a 60-year lifetime and the factors are less than 1.03. The initial k-effective values of thorium-loaded cores are less than those of the reference core, which is caused by the thorium fuel loading. Case 3 and Case 4 have many points that do not achieve criticality in their operation time, which is due to the fact that they have a relatively large central thorium fuel region that is not enough to make criticality. In the other cases, it can also be found that larger inner core regions have lower multiplication factors.

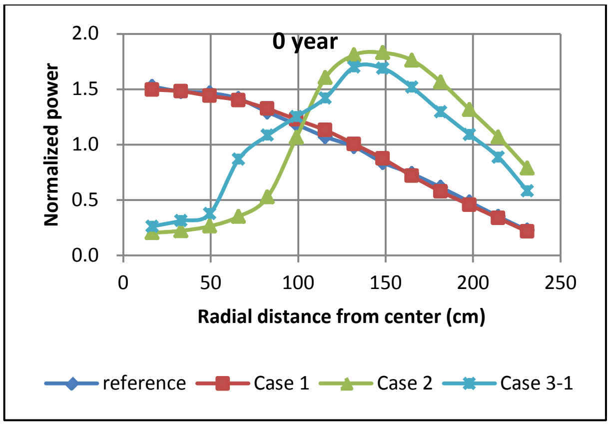
3.2 Power Flattening Performance

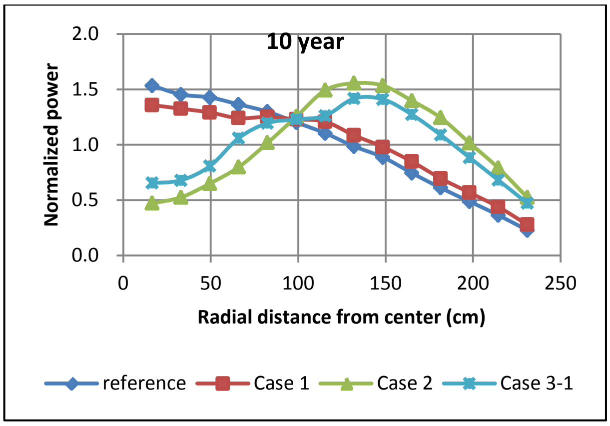
The power flattening effect has been analyzed. Figure 4 shows the normalized radial power distribution every 10 years. The values are normalized with the axially integrated power density of each assembly. There are control assemblies not only in the center, but also 99 cm and 198 cm from the center, so the center spot in each graph is extrapolated and the two other spots in each graph are interpolated by averaging the two values of both sides.

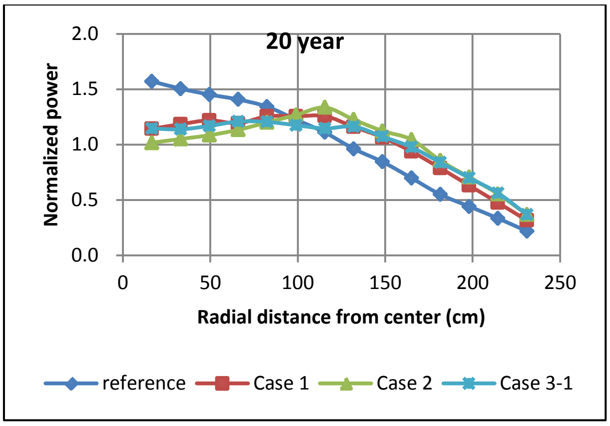
The figures show that the cores achieve radial power flattening in comparison with the reference core. The peak of the reference core appears in the center fuel region at BOC, and moves to the peripheral region as time goes on. The peak of the Case 1 core also moves from the center to the peripheral region, but the peak factor at the center has decreased, especially at year 20, from 1.57 to 1.14 by the effect of thorium fuel in the inner core region.

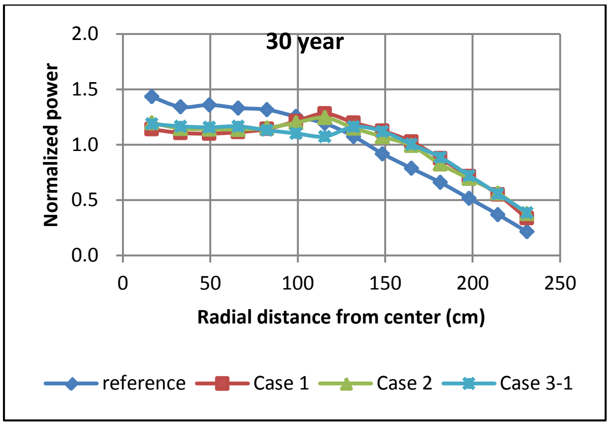
On the other hand, the peaks of the Case 2 and Case 3-1 cores appear in the peripheral region at BOC due to the LEU zoning, and then move to center. These two cases show more flattened radial power distribution than Case 1 throughout the operation time excepting the initial state. At the end of the cycle, at year 60, it is noticeable that Case 2 and Case 3-1 have a more flattened shape while reference and Case 1 have a peripheral peak.

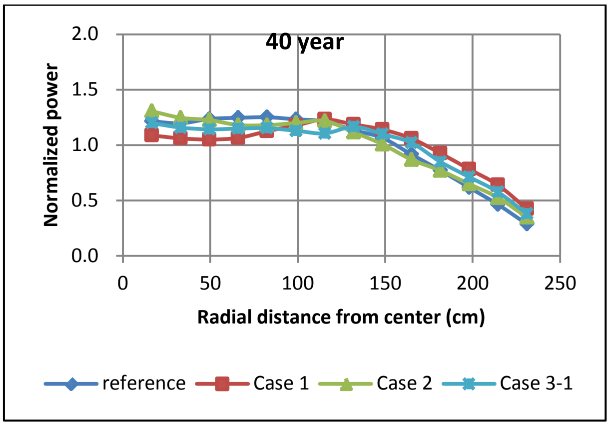
There is a difference between Case 2 and Case 3-1, which causes a difference in the radial power distribution especially at year 0 and year 60. Case 3-1 has one more zone in its LEU region while Case 2 has only two zones. It can be visible in the radial power distribution figure for year 0. The peripheral peak of Case 3-1 is lower than that of Case 2 and the distribution of Case 3-1 at year 0 and year 60 is more flattened than Case 2. For year 60, Case 3-1 has a maximum peak of 1.15 while the reference case has a peripheral peak of 1.34.

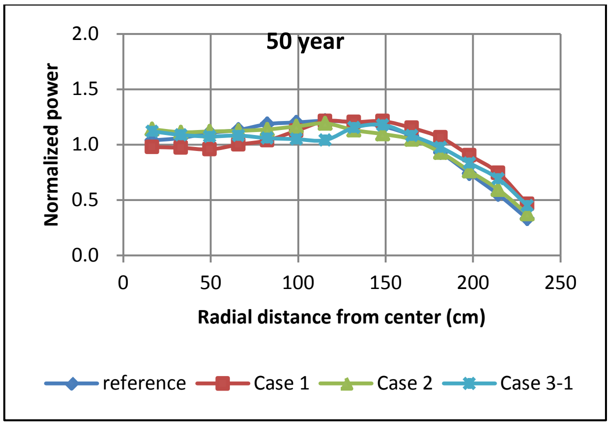












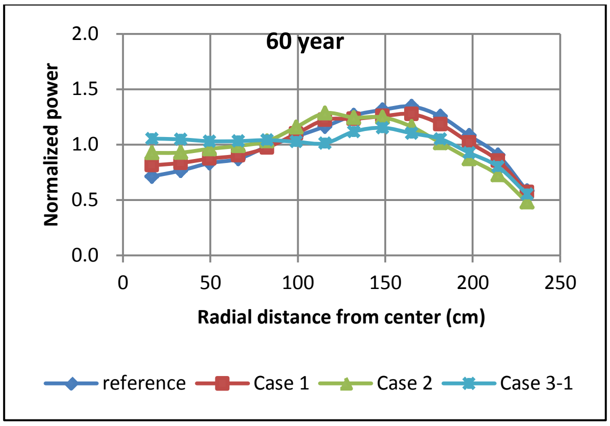


Fig. 4. Normalized radial power distribution

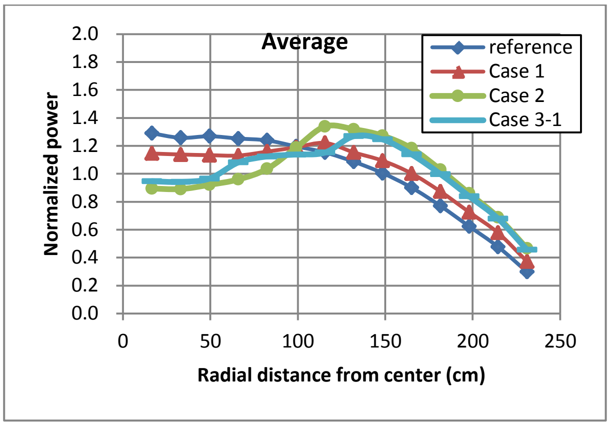


Fig. 5. Average normalized radial power distribution

Figure 5 shows the average value distribution of the normalized radial power distribution every 10 years of figure 4. The standard deviation of each case is 0.30, 0.24, 0.23, and 0.21 for reference, Case 1, Case 2, and Case 3-1, respectively, which shows that Case 3-1 has the most flattened shape for radial power distribution throughout the operation time.

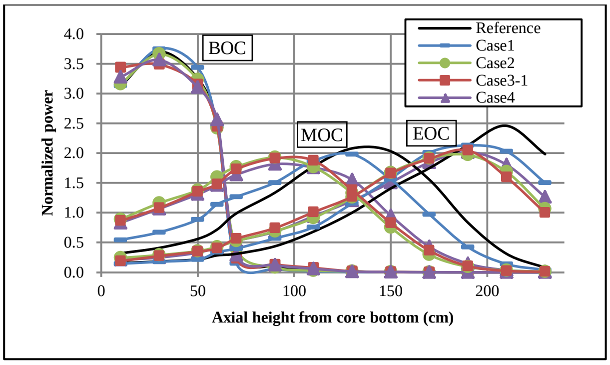


Fig. 6. Normalized axial power distribution

Figure 6 shows the normalized axial power distribution of the center fuel assembly at BOC, MOC, and EOC, which tells the active core movement. At BOC, the active core of each case stays within 70 cm of the bottom of the core where the peaking factor is greatest and the peak linear power is 555 W/cm, which needs to be lowered. The active core moves to the top of the core as the core burns and breeds. The speed of active core movement is fastest for the reference case, and the speed is slower for Case 1 due to the thorium blanket loading. Case 2, Case 3-1, and Case 4 have slower movement of the active core than Case 1 because they have an enrichment zoning region which makes the speed of the active core at the center slow.

4. Conclusion

The flattening of the radial power distribution for UCFR-1000 has been performed and compared by loading the thorium fuel only in the inner blanket for the Case 1 core, and in both the blanket and LEU region for the case 2 and the other cores. It has been confirmed that fuel zoning can achieve radial power flattening, which decreases the maximum power peak. The Case 1 core has a center peak at BOC like the reference core, but the peaking factor has decreased due to the thorium fuel in the inner fuel region, which is shown by the fact that at year 20 it has decreased from 1.57 to 1.14. In contrast to the reference and Case 1 cores, the peak of the Case 2 and Case 3-1 cores appears in the peripheral region at BOC, which causes a power shape more flattened at MOC and EOC than that of Case 1. At EOC, Case 3-1 has a maximum peak of 1.15 while the reference case has a maximum peak of 1.34.

ACKNOWLEDGEMENTS

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