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A Parametric Design Study on Fuel Assemblies using LEU+ Fuel Rods and HIGA Burnable Absorber

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1. Introduction

In recent years, global interest in Small Modular Reactors (SMRs) has been increased significantly due to their inherent safety, economic feasibility, and flexibility [1]. However, compared to conventional large-scale reactors, SMRs using PWR technology face the challenges related to shorter fuel cycle lengths and lower burnup, which can impact their overall fuel efficiency and economic competitiveness. Also, the low burnups of the discharged fuels mean a large amount of spent fuel.

To address these limitations, the adoption of Low Enrichment Uranium Plus (LEU+) fuel has been proposed as a viable solution. LEU+ fuel, enriched to 5~10 wt% uranium, allows for extended fuel cycles and improved burnup performance, mitigating some of the drawbacks associated with SMRs. In particular, the extended burnup resulted from the use of LEU+ fuels can reduce the generation of spent fuels. Also, the use of the LEU+ fuels can increase the economy of the commercial PWRs.

Furthermore, Accident-Tolerant Fuel (ATF) has emerged as a promising innovation to enhance fuel integrity under high-burnup and prolonged operational conditions. Among various ATF design enhancements, the application of micro-scale chromium coating has been introduced to improve oxidation resistance [2].

In this study, prior to designing a core loaded with LEU+ fuel, a preliminary parametric design study on the lattice parameters was performed for the fuel assembly using the Highly Intensive and Discrete Gadolinia/Alumina Burnable Absorber (HIGA). The specific objective of this study is to find a feasible fuel assembly design that has extended cycle length (and burnup) with an reduced initial uranium inventory, and negative temperature coefficients.

2. Methodologies

2.1 Computation Code

The calculation for fuel assembly depletion was performed by the 2D MOC (Method of Characteristics) code DeCART2D which was developed by Korea Atomic Energy Research Institute (KAERI) [3]. During the transport calculations, a ray spacing of 0.01cm was used with 8 azimuthal angle and 4 polar angle per octant. The multi-group cross-section data of 47 group neutron and 18 group gamma produced based on ENDF/B-VII.1 was used in DeCART2D code.

2.2 Fuel Assembly Design Model and Parameters

Fig. 1 shows the configuration of HIGA (Highly Intensive and Discrete Gadolinia / Alumina Burnable Absorber) burnable absorber rod [4]. HIGA is a discrete type of burnable absorber (BA) rod composed of a mixture of Gd_2O_3 and Al_2O_3. This discrete type of BA allows for higher gadolinium loading, which in turn enhances the self-shielding effect.

Also, **Fig. 2** shows the configuration of 2D FA consisting of a 17×17 lattice arrangement with 24 guide tubes, one instrumentation tube, and 12 HIGA rods. **Table I** summarizes the corresponding reference design parameters for the fuel assembly. The assembly linear power is 0.02432 MW_{th}/cm. The uranium enrichment in the LEU+ fuel pellet is considered to be 6.95 wt%, while 4.95 wt% uranium enrichment is also considered for comparison. To achieve high burnup levels (e.g., 60 MWd/kgHM) with LEU+ fuel while preserving fuel rod integrity, the fuel rod is coated with a 30 μm layer of chromium as a part of an accident-tolerant fuel (ATF) concept. In this study, we use the fuel pellet radius and the pitch between rods as the main design parameters, while we fixed the thicknesses of the cladding and Cr coating for considering integrity of the fuel rods.

The main objective of this parametric study is to determine the improved lattice parameters from a viewpoint of the negative moderator temperature coefficient (MTC) and extended cycle length in terms of burnup, and the amount of TRU generation per energy, compared to the reference fuel assembly lattice parameters using LEU+ fuel. In this work, the cycle length was defined as the time interval over which k_{inf} is kept to be higher than 1.01.

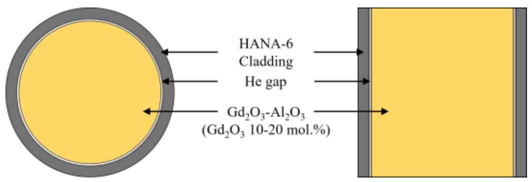

Fig. 1. Radial and axial configurations of HIGA burnable absorber rod.

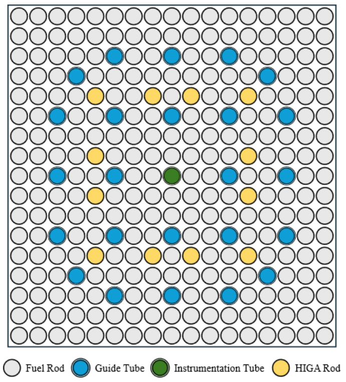

Fig. 2. Reference 17x17 fuel assembly configuration with 12 HIGA burnable absorber rods

Table I. Reference 17x17 FA design parameters

Parameters	Values
Rod array	17 x 17
Number of fuel pins without BA	264
Number of guide tubes / instrument tubes	24 / 1
Fuel assembly / pin pitch (cm)	21.5 / 1.26
Uranium enrichment (wt%)	4.95 / 6.95
UO_2 Fuel pellet radius (cm)	0.4096
HANA-6 cladding inner radius (cm)	0.4178
HANA-6 cladding outer radius (cm)	0.4750
Cr coating thickness (μm)	30
Guide / instrument tube inner radius (cm)	0.5620
Guide / instrument tube outer radius (cm)	0.6020

3. Design Analysis and Results

Fig. 3 presents a comparison of the k_{inf} evolutions for various pellet radii having different P/D ratios at a fixed boron concentration of 800 ppm. Actually, the P/D ratio was increased for a reduced pellet radius case to keep the pitch between rods. When the fuel pellet radius decreases, the cycle length tends to shorten relative to the Case 5. Nevertheless, the cases having reduced pellet radius still have extended cycle lengths by 16~37% compared to the Case 1. **Table II** shows cycle lengths with respect to various pellet radii having different P/D ratios. Notably, the Case 3 exhibits a 26.93 % increase in cycle length compared to the Case 1, while showing a 14.11 wt% decrease relative to the Case 5. But it should be noted that the cycle lengths in burnup for these variant cases having reduced pellet radii are almost the same as the Case 5.

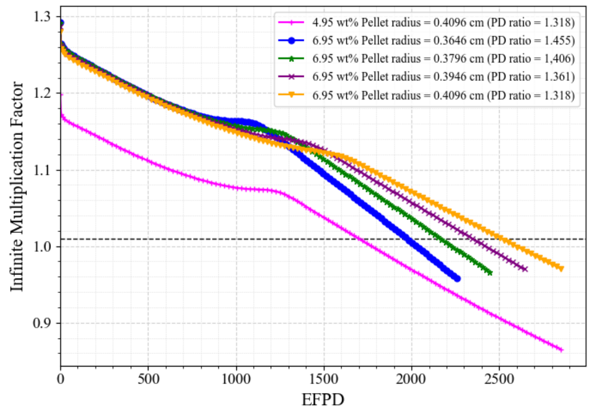

Fig. 3. Infinite muliplication factors for various P/D ratios at 800ppm over EFPD.

Table II. Cycle lengths of various pin radii at 800ppm

Case	Fuel Enrichment (wt%)	P/D ratio	Pin radius (cm)	Cycle Length (EFPD / MWd/kgHM)
1	4.95	1.318*	0.4096	1,695 / 34.5
2	6.95	1.455	0.3646	1,965 / 50.5
3	6.95	1.406	0.3796	2,152 / 51
4	6.95	1.361	0.3946	2,325 / 51
5	6.95	1.318*	0.4096	2,505 / 51

* Reference cases

Fig. 4 compares the normalized neutron spectra for the various cases at 0 MWd/kgHM. As shown in **Fig. 4**, the Case 5 has harder neutron spectra than that of the case 1. However, an increase of the P/D ratio for the reduced pellet size cases leads to more neutron scattering and thermalization, which softens the spectra and mitigates the hardening effect. Eventually, the Cases 2 and 3 are soften as well as Case 1.

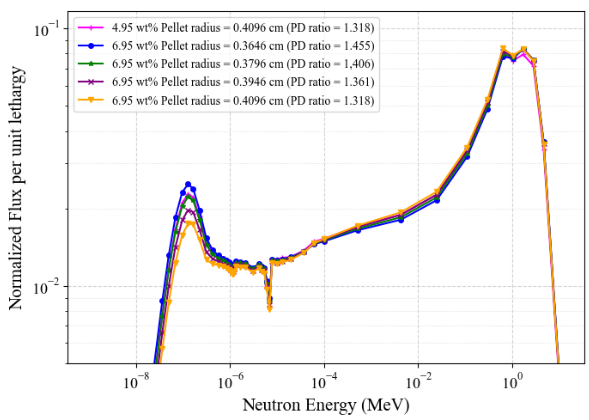

Fig. 4. Normalized neutron spectra for various pin radii at 0 MWd/kgHM

Table III compares the MTC values at BOC for the considered various cases for different boron concentrations up to 1500 ppm. **Table III** shows that all the cases give negative MTC values except for Case 3 having 1500 ppm boron concentration. **Table IV** compares initial uranium loading, TRU inventories at EOC and TRU production at EOC per energy production. The cases having reduced pellet radii show reduced initial uranium loadings by 7~21 % and TRU inventories at EOC by 14~37 % than Case 5.

Figs. 5 and **6** compare the evolutions of the TRU and Pu inventories as burnup. These figures show that the cases having reduced pellet radii generate less amount of TRU and Pu.

Table III. Comparison of MTC (pcm/°C) for various boron concentrations and cases

Case	Boron concentration (ppm)				
	0	500	800	1000	1500
2	-26.4	-16.8	-11.2	-7.42	1.83
3	**-29.1**	**-20.4**	**-15.3**	**-11.9**	**-3.58**
4	-31.7	-23.9	-19.2	-16.2	-8.61
5	-34.2	-27.1	-22.9	-20.2	-13.3

Table IV. Comparison of the initial uranium inventories and TRU inventories at EOC

Case	Initial Uranium Inventory (kgU)	TRU Inventory (kg)	TRU at EOC per Energy (kg/MWd)
1	239.02	2430.18	0.2947
2	189.34	1905.48	0.1993
3	**205.24**	**2225.00**	**0.2126**
4	221.78	2585.55	0.2286
5	238.96	3006.17	0.2467

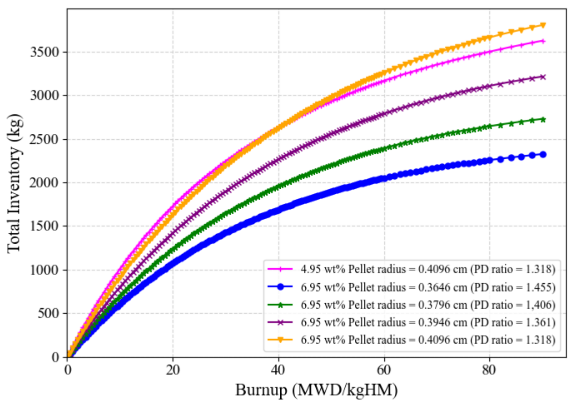

Fig. 5. Total inventories of TRU isotopes for various P/D ratios over burnup

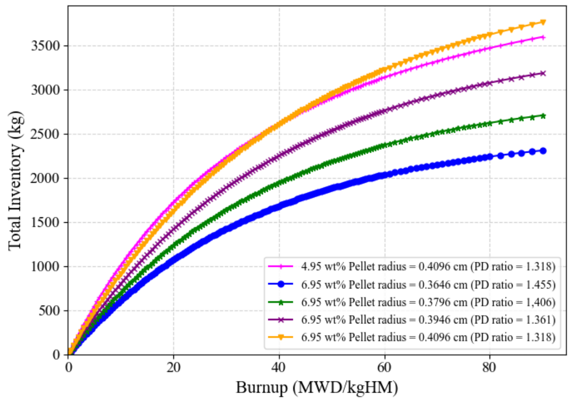

Fig. 6. Total inventories of Pu isotopes for various P/D ratios over burnup

4. Conclusion

In this work, a parametric fuel assembly design study was conducted using LEU+ fuel of 6.95wt% uranium enrichment to find a feasible design which can substantially increase cycle length with reduced initial uranium inventory leading to lower TRU production. For this purpose, the reduced pellet radii with the increased P/D ratios were considered. From the analysis of the designed fuel assemblies, it was found that the considered fuel assemblies having reduced pellet radii has substantial increase in cycle length compared to the reference fuel assembly design of 4.95 wt% uranium enrichment and almost the same cycle length in burnup than the reference fuel assembly design of 6.95 wt% uranium enrichment. In particular, it was confirmed that the new fuel assembly designs having reduced pellet radii have lower TRU production at EOC per energy production than the reference fuel assembly design of 6.95 wt% uranium enrichment. For example, the new fuel assembly having 0.3796 cm fuel pellet radius (1.406 P/D ratio) was shown to be a good feasible design from viewpoint of negative MTC (at 1500 ppm), low TRU production, initial uranium loading, and cycle length (in burnup).

Future work will focus on designing the core using these new fuel assemblies.

Acknowledgement

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