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A Study on LEU+ APR1400 Using ATF Clad and CSBA

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1. Introduction

The extension of the nuclear fuel cycle Burnup (BU) is becoming increasingly important due to the growing demand for energy and the need to improve the efficiency of the nuclear fuel cycle [1]. To achieve this goal, researchers are proposing the use of nuclear fuel with a higher enrichment level than that currently used in Pressurized Water Reactors (PWRs). Currently, PWRs are operated with an enrichment level less than 5 w/o, referred to as Low Enriched Uranium (LEU), while fuel with enrichment higher than 5 w/o and less than 10 w/o is called LEU+ [2]. In this study, a core design for the Advanced Power Reactor (APR1400) using LEU+ fuel is presented to extend the fuel cycle length and improve the average assembly discharge Burnup (BU) [3].

Additionally, a two-batch fuel management scheme is being adopted for a 24-month cycle, instead of the current 18-month three-batch scheme used in APR1400. The shift from three-batch to two-batch is aimed at reducing the number of refueling outages, thereby improving the availability of the nuclear power plant over its full lifetime [4]. The extension of the fuel cycle length requires an increase in fuel enrichment, as well as an increase in the assembly BU, particularly the peak BU. However, the peak assembly BU must not exceed certain limits set by the regulatory body, such as 62 GWD/MTU in the USA and 60 GWD/MTU in Korea [5]. To increase this limit, the fuel assembly clad must be enhanced.

Accident Tolerant Fuel (ATF) is another important modification being introduced in this study [6,7]. Following the Fukushima accident, there has been a growing interest in improving the clad performance, as zirconium oxidation at high temperatures can lead to significant hydrogen production and potentially cause a massive hydrogen explosion [8]. Researchers are exploring the use of alternative oxidation-resistant materials or enclosing the conventional zircaloy with another material. In this study, an ATF clad using swaging technology is suggested to prevent zircaloy oxidation and allow for a higher BU resulting from the extension of the nuclear fuel cycle [9,10].

Finally, a Centrally Shielded Burnable Absorber (CSBA) is being adopted as a means of controlling reactor core excess reactivity [11]. The BA material is sintered into a cylindrical shape to enhance self-shielding, and Gadolinia (Gd_2O_3) is used in the CSBA design, placed at the center of the fuel pellet. The analysis was performed using the in-house diffusion-based code KAIST Advanced Nodal Tachygraphy (KANT), with data generated using the two-step method and the SERPENT continuous energy Monte Carlo code with the ENDF/B-VII.1 data library [12].

2. Accident Tolerant Fuel Clad Design

In this paper, an innovative technique has been utilized to design and manufacture the ATF clad, the swaging technique was introduced to manufacture the new clad. In this concept, the ATF clad is forged by cold work in which three layers of clad tubes are rolled together resulting in the formation of a single cluster. Typically, an inner SS316 tube, zircalloy clad, and another outer SS316 tube are placed in the swaging machine as demonstrated in Figure 1. Using proper die and plug configuration the final dimension of the combined cladding layer can be obtained, a very important parameter to be measured and monitored in this process is the gap between the layers, which shall be minimized to prevent thermal conductivity degradation.

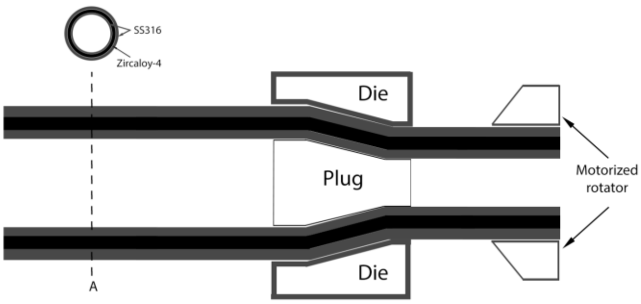

Figure 1 A schematic representation of the swaging process of two tubes.

The SS316 has a slightly higher thermal conductivity compared to zircaloy-4 within the normal operating range. However, the thermal conductivity of the zircaloy is much higher at a higher temperature, but this effect shall be minimum since the SS tube layers considered are very thin.

Another important parameter to look at is the reactivity penalty due to the introduction of the additional SS tubes, as illustrated in Figure 2, since SS has a much higher capture cross section compared to zircaloy, the thicker the SS layer is the higher the reactivity penalty. In this study, an inner SS316 tube of 10 μm thickness and another outer SS316 with 30 μm thickness will be utilized, and the reactivity penalty for these additional layers is ranging between 600 to 700 pcm, which shall be an acceptable penalty for an improved clad design that would allow enhancing the fuel BU.

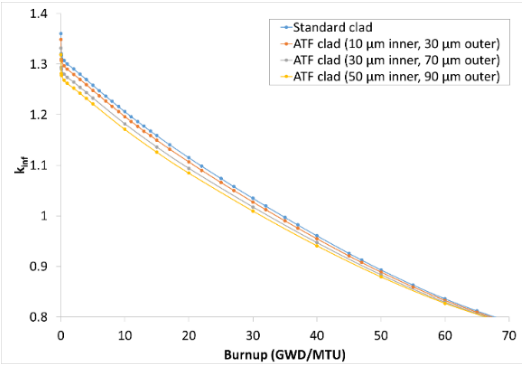

Figure 2 k_{inf} comparison for single fuel assembly depletion between the standard clad and different ATF clad layer thicknesses.

3. LEU+ Core Design

Table 1 represents the important design parameters used in the LEU+ APR1400 core, the major core parameters are similar to the standard APR1400 such as the reactor core power, dimensions, and thermal-hydraulic parameters. To achieve the targeted cycle length of 24 months the core enrichment was increased from 4.0/4.5 w/o used in the standard APR1400 equilibrium cycle to 5.9/5.2 w/o for the LEU+ APR1400 reactor core. Figure 3 illustrates the core loading pattern and the shuffling scheme. Where the green color fuel assemblies represent the fresh fuel assemblies to be loaded in the core each cycle and the white color fuel assemblies represent once burned position. In this scheme, 121 fuel assemblies including the central fuel assembly are discharged in each cycle to achieve a single equilibrium cycle. It also emphasizes placing the fresh fuel assemblies at the peripheral region to help in flattening the radial power profile and achieving an acceptable assembly power peaking.

Table 1 Important design parameters for LEU+ APR1400.

Parameter	**Value**
Reactor power (MWth)	3983
Lattice design	16X16
Fuel cycle length (months)	24
Number of discharged FAs	121
Active core height (cm)	381
Burnable absorber cutback thickness (cm)	15
Equilibrium cycle fuel enrichment (w/o)	5.9/5.2
Burnable absorber	CSBA (Gd_2O_3)/UO_2 +Er_2O_3
Soluble neutron absorber	Boron
Cladding material	SS316/Zr-alloy

To control the higher reactivity of the raw LEU+ material, Er_2O_3 with 0.13 w/o is admixed with the UO_2 fuel to lower the reactivity to the levels of LEU so that the currently available fuel fabrication facilities especially in Korea would be able to handle the higher enrichment without modifying the systems or apply for license renewal. However, controlling the core excess reactivity requires another advanced type of BA, where CSBA is loaded to the core.

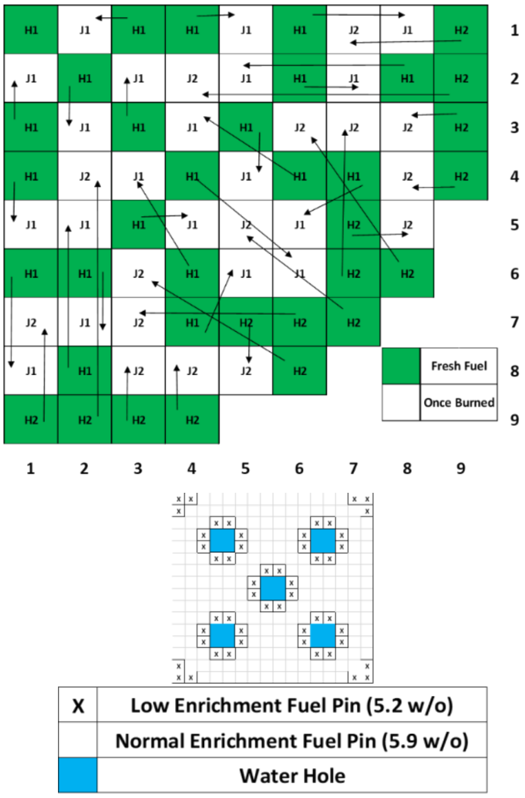

Figure 3 APR1400 core loading pattern and fuel shuffling scheme.

Figure 4 gives a schematic representation of CSBA loaded fuel pellet, where a cylindrical shape gadolinia CSBA is loaded at the centerline of the fuel pellet. This type of BA design would allow controlling the depletion rate of the BA material within the cylinder, which can be accomplished by adjusting the height/diameter ratio, since the smaller the ratio is the larger the surface area of the CSBA is. That way the rate of gadolinia depletion can be controlled.

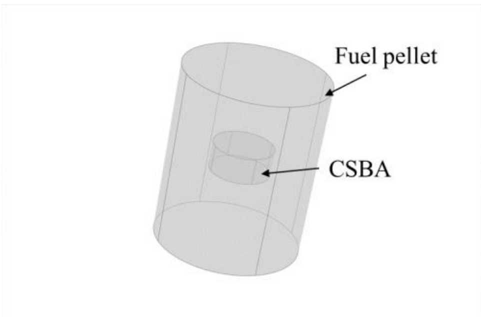

Figure 4 A cartoon for a cylindrical CSBA-loaded fuel pellet

Controlling the radial power profile could also be achieved by adjusting the CSBA volume in the fuel assemblies, Table 2 shows the CSBA dimensions used in the LEU+ APR1400 core design. Where fuel assemblies H1/J1 are loaded with larger volume CSBA, and fuel assemblies H1/J2 contain a smaller amount of BA with a fixed H/D ratio.

Table 2 CSBA design for LEU+ APR1400.

FA	Height (cm)	Radius (cm)
H1/J1	0.108	0.2
H2/J2	0.098	0.18

4. Results and Discussion

Figure 5 provides the Critical Boron Concentration (CBC) letdown curve, as represented in the cartoon, the CBC at the Beginning of Cycle (BOC) of the equilibrium cycle after the Xenon equilibrium is around 960 ppm. While the cycle BU is 26.1 GWD/MTU, which is equivalent to 678 Effective Full Power Days (EFPD), this low CBC from the BOC is very important in reducing the boron concentration to guarantee a negative Moderator Temperature Coefficient (MTC) and reducing the negative effects of boron to the clad.

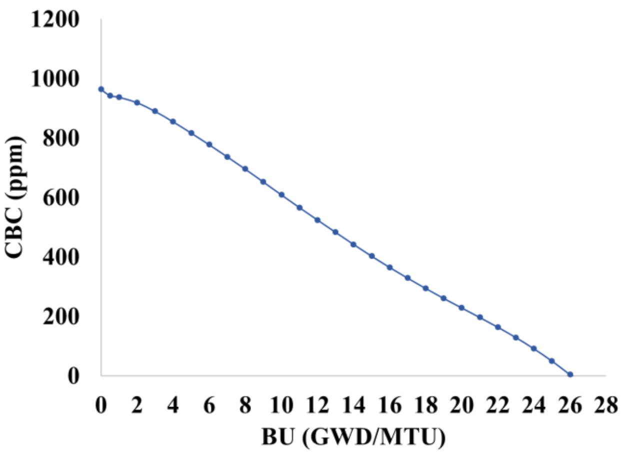

Figure 5 LEU+ APR1400 core equilibrium cycle CBC letdown curve.

For the same equilibrium cycle, Figure 6 provides the radial power distribution at BOC, Mid of Cycle (MOC), and End of Cycle (EOC) conditions, the analysis shows that the maximum assembly power peaking for the three BU points was 1.39, 1.3, and 1.3 respectively, which is a very realistic value and close to the standard APR1400 assembly power peaking. Similarly, Figure 7 shows the axial power distribution for the same three BU points, where a maximum power peaking of 1.2 was observed at the BOC, and as cycle BU increases, the saddle shape starts to appear with low power peaking values.
Another important parameter that was investigated is the average discharge BU, Figure 8 depicts the BU distribution at the EOC of the equilibrium cycle, where the average discharge BU was 52.2 GWD/MTU which is higher than the average discharge BU of the standard APR1400 by more than 16%. Also, the maximum assembly discharge BU is around 62 GWD/MTU. However, the local peak BU could exceed that value by around 16% if the local pin peaking is considered. Fortunately, with the utilization of ATF clad, increasing the maximum fuel assembly BU would be possible.

When comparing the energy generation of the standard APR1400 with a two-batch 24-months LEU+ loaded core for a 60-year lifetime, it was found that the latter resulted in a ~6% increase in total energy generation. However, the total volume of radioactive waste increased by ~5% due to an increase in the number of discharged fuel assemblies throughout the power plant's lifespan with the two-batch fuel management scheme.

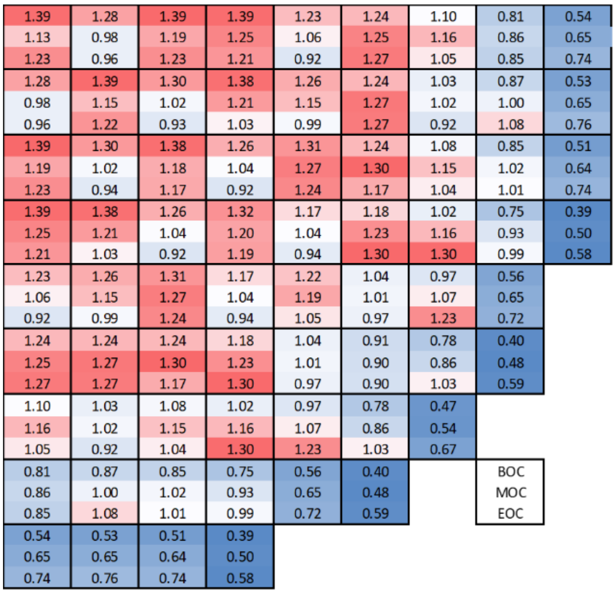

Figure 6 Radial power distribution for the LEU+ APR1400 equilibrium core at the BOC, MOC, and EOC BU.

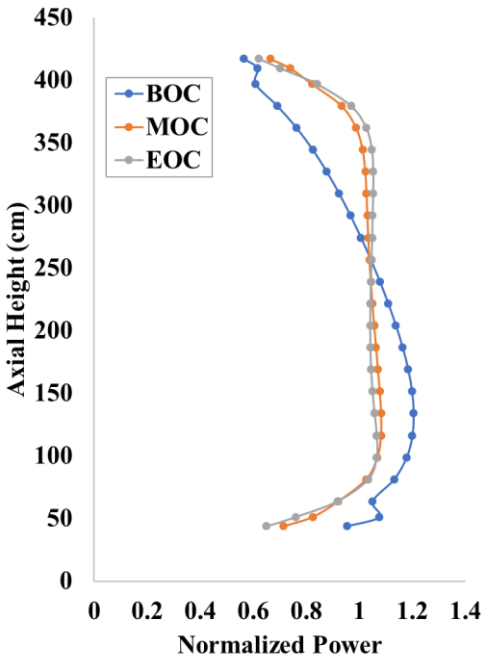

Figure 7 Axial power distribution for the LEU+ APR1400 equilibrium core at the BOC, MOC, and EOC BU.

	A	B	C	D	E	F	G	H	I
1	31.60	59.93	32.69	33.56	61.72	33.10	46.21	55.17	16.71
2	59.96	31.90	59.98	48.70	55.88	33.39	59.56	25.71	16.89
3	32.72	59.82	32.13	60.29	33.43	45.76	51.97	42.08	16.51
4	33.58	48.71	60.30	32.09	60.88	32.48	30.42	36.52	12.83
5	61.74	55.89	33.44	60.89	44.84	56.77	28.29	45.22	
6	33.10	33.39	45.77	32.48	56.77	55.61	22.89	12.70	
7	46.21	59.56	51.97	30.42	28.29	22.89	14.31		
8	55.17	25.71	42.08	36.52	45.22	12.70			
9	16.71	16.89	16.51	12.82					

Figure 8 BU distribution at the end of the equilibrium cycle for LEU+ APR1400.

5. Conclusions and Future Work

In this paper, the utilization of LEU+ fuel in the APR1400 reactor to achieve a 24-month two-batch fuel management scheme has been investigated, in this core design, Accident Tolerant Fuel (ATF) clad based on the swaging technology was introduced to enhance the clad performance against postulating design-based accidents and to enhance the clad performance for a higher fuel assembly Burnup (BU). the Centrally-Shielded Burnable Absorber (CSBA) was adopted to control the excess reactivity, while the Erbia (Er_2O_3) admixed with UO_2 is loaded in all fuel pins so that the reactivity of the raw LEU+ fuel material is small enough to be handled in the currently existing front-end fuel facilities. The equilibrium cycle was designed with a low Critical Boron Concentration (CBC) from the BOC around 960 pcm, and cycle BU 26.1 GWD/MTU, with this the targeted cycle length with over 94% availability factor is achieved. The results show a reasonably low power peaking factor in radial and axial directions.

For future work, additional analysis will be performed to evaluate the important safety parameters such as Moderator Temperature Coefficient (MTC) and the Fuel temperature Coefficient (FTC). Also, the applicability of performing the load-follow operation of the LEU+ loaded APR1400 core will be investigated to enhance the economy of the nuclear power plant [13].

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