INL/CON-11-23258
PREPRINT

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RRFM-IGORR 2012

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March 2012

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ABSTRACT

The Advanced Test Reactor (ATR), currently operating in the United States, is used for material testing at very high neutron fluxes. Powered with highly enriched uranium (HEU), the ATR has a maximum thermal power rating of 250 MWth. Because of the large test volumes located in high flux areas, the ATR is an ideal candidate for assessing the feasibility of converting HEU driven reactor cores to low-enriched uranium (LEU) cores. The burnable absorber – ^{10}B, was added in the inner and outer plates to reduce the initial excess reactivity, and to improve the peak ratio of the inner/outer heat flux. The present work investigates the LEU Monolithic foil-type fuel with ^{10}B Integral Cladding Burnable Absorber (ICBA) design and evaluates the subsequent neutronics operating effects of this proposed fuel designs. The proposed LEU fuel specification in this work is directly related to both the RERTR LEU Development Program and the Advanced Test Reactor (ATR) LEU Conversion Project at Idaho National Laboratory (INL).

1. Introduction

The Advanced Test Reactor (ATR) at the Idaho National Laboratory (INL) is a high power density and high neutron flux research reactor operating in the United States. Powered with highly enriched uranium (HEU), the ATR has a maximum thermal power rating of 250 MW_{th} with a maximum unperturbed thermal neutron flux rating of 1.0×10^{15} n/cm^2–s. The conversion of nuclear test reactors currently fueled with HEU to operate with low-enriched uranium (LEU) is being addressed by the reduced enrichment for research and test reactors (RERTR) program.

The scope of this work is to assess the feasibility of converting the ATR HEU fuel to LEU fuel while retaining all key functional and safety characteristics of the reactor. Using the current HEU ^{235}U enrichment of 93.0 % as a baseline, this study will evaluate the LEU uranium density required in the fuel meat to yield an equivalent K-eff between the ATR HEU core and an LEU core after 150 effective full power days (EFPD) of operation with a total core power of 115 MW. A lobe power of 23 MW is assumed for each of the five lobes. Then, the LEU ^{235}U loading that yields an equivalent K-eff as the HEU ^{235}U loading will be used to predict radial, axial, and azimuthal power distributions. ^{10}B loading for LEU case studies will have 0.635 g in the LEU fuel meat at the inner 2 fuel plates (1-2) and outer 2 fuel plates (18-19), which can achieve peak to average ratios similar to those for the ATR reference HEU case study. The investigation of this paper shows the optimized LEU Monolithic (U-10Mo) Foil-type with Integral Cladding

Burnable Absorber (ICBA) (MF-ICBA) case can meet the LEU conversion objectives. The heat rate distributions will also be evaluated for this core and used to predict the core performance as it relates to the current Upgraded Final Safety Analysis Report (UFSAR) and the associated Technical Safety Requirements (TSRs).

2. ATR Full Core Model and MCWO – Fuel Burnup Analysis Tool

The ATR CIC-1994 (NT-3 of Cycle 103A-2) core configuration was chosen to build the ATR MCNP full core model in this work. For the detailed Cycle 103A-2 core configuration data refers to Table 1 in Reference 1. The detailed validation of the full core plate-by-plate MCNP model is in Reference 2. This model is used to optimize the ^{235}U and minimize ^{10}B loading in the LEU core by minimizing the K-eff differences with respect to the HEU core after 150 EFPD of operation with a total core power of 115 MW (23 MW per lobe).

The fuel burnup analysis tool used in this study consists of a BASH (Bourne Again Shell) script file that links together the two FORTRAN data processing programs, m2o.f and o2m.f. [3] This burnup methodology couples the Monte Carlo transport code MCNP [4,5] with the radioactive decay and burnup code ORIGEN2. [6] The methodology is known as Monte Carlo with ORIGEN2, or MCWO. [7] The MCWO fuel burnup analysis tool uses MCNP-calculated one-group microscopic cross sections and fluxes as input to a series of ORIGEN2 burnup calculations. ORIGEN2 depletes/activates materials and generates isotopic compositions for subsequent MCNP calculations.

3. ATR HEU Reference Case and LEU MF-ICBA Models Description

The typical ATR 7F fuel element (FE) was chosen in the HEU reference case model. The detailed 19 plate FE model with burnable absorbers is described in Section 3.1. Then, the proposed LEU Monolithic Foil-type and Integral Cladding Burnable Absorber (MF-ICBA) detailed FE model is described in Section 3.2.

3.1 Detailed ATR 7F Fuel Element Model

The ATR 7F FE was chosen as the reference HEU Case-A in this study. Table 4 in Ref. 2 shows the nominal ^{235}U and ^{10}B loadings for each fuel plate of the 7F FE. In the 7F fuel element, all 19 fuel plates are loaded with 93% enriched uranium in an aluminum matrix to a total of 1075 g U-235. The eight outer plates (plate-1 to plate-4 and plate-16 to plate-19) contain boron as a burnable poison for a total of 0.66 g ^{10}B.

The detailed, full core MCNP ATR model was used to perform the evaluation of the ATR reference HEU case with burnable absorber ^{10}B at the beginning of cycle (BOC) condition. Then, MCWO was used to evaluate the fuel cycle performance versus the EFPD using the following assumptions:

- Each nominal operating cycle was 50 EFPD, followed immediately by a seven day outage.
- Each 50 EFPD cycle was subdivided into 5 EFPD time step intervals.

- The OSCC positions were set to 105°.
- The resultant MCNP-calculated tallies were normalized to a core source power of 115 MW.

3.2 LEU Monolithic Foil-type and Integral Cladding Burnable Absorber Detailed FE model

A LEU monolithic fuel design with varied fuel meat thickness in the four inner plates (plate-1 to plate-4) and four outer plates (plate-16 to plate-19) was recommended in Ref. [2]. However, those LEU fuel designs did not include the 10B loading minimization. Because the 10B (n,α) reaction will produce Helium-4 (He-4), which can degrade the LEU foil fuel (U10Mo) type fuel performance. An alternative burnable absorber loading option – Integral Cladding Burnable Absorber (ICBA) is proposed in this study. In monolithic plates the fuel-cladding interface is protected with Zr diffusion barrier. Therefore an addition of layer of burnable absorber (5 mil) in ICBA was proposed, where the burnable absorber ^{10}B can be totally separated from not only the LEU foil-type fuel meat, but also from the fuel-cladding Zr diffusion barrier.

The optimization was achieved by reducing the fuel meat thickness as well as loading the two inner/outer plates with 0.635 g of ^{10}B in LEU ICBA Case. The isotopic concentration of ^{10}B in the boron of the burnable absorber is 20 wt%. The ^{10}B loading specification of ICBA in plates-1, -2, -18, and -19 are tabulated Table 1. The optimized LEU fuel plate specifications for the ICBA Case are given in Table 2. Table 2 shows that the nominal fuel meat thickness is 0.0330 cm (13 mil). The varied four inner plates (plate-1 to plate-4) fuel meat thicknesses are 0.0203 cm (8 mil), 0.0203 cm (8 mil), 0.0354 cm (10 mil), and 0.0305 cm (12 mil), respectively. While the varied 4 outer plates (plate-16 to plate-19) fuel meat thicknesses are 0.0305 cm (12 mil), 0.0354 cm (10 mil), 0.0203 cm (8 mil), and 0.0203 cm (8 mil), respectively. The detailed FE-18 model of LEU monolithic foil type ICBA Case is shown in Figure 1. The detailed MF-ICBA FE-18 with 4 fuel plates with 10B (Plates-1 to -2 and -18 to -19) are plotted in Figure 2.

Table 1. Integral Cladding Burnable Absorber (ICBA) with Boron-10 Specification.

ICBA	Boron-10	Thickness	ICBA	Boron-10
ICBA ID	g/cc	mil.	Vol. (cc)	Mass (g)
ICBA-01	0.008	5	6.888	0.058
ICBA-02	0.020	5	7.332	0.149
ICBA-18	0.008	5	13.663	0.111
ICBA-19	0.022	5	14.138	0.317
Total			42.021	0.635

Table 2. LEU Monolithic (U10Mo) Foil-type with ICBA (Boron-10) Specification.

LEU Plate ID	Fuel Meat Total U g/cc	Thickness mil.	Fuel meat Vol. (cc)	U-235 Mass (g)	Boron_10 Mass (g)	U-235 Density (g/cc)
Plate-1	15.21	8	10.947	32.876	0.058	3.00
Plate-2	15.21	10	11.660	35.016	0.149	3.00
Plate-3	15.21	10	15.367	46.150	0	3.00
Plate-4	15.21	11	16.153	48.512	0	3.00
Plate-5	15.21	13	22.030	66.162	0	3.00
Plate-6	15.21	13	23.057	69.247	0	3.00
Plate-7	15.21	13	24.087	72.339	0	3.00
Plate-8	15.21	13	25.123	75.450	0	3.00
Plate-9	15.21	13	26.150	78.536	0	3.00
Plate-10	15.21	13	27.178	81.623	0	3.00
Plate-11	15.21	13	28.205	84.707	0	3.00
Plate-12	15.21	13	29.237	87.805	0	3.00
Plate-13	15.21	13	30.257	90.869	0	3.00
Plate-14	15.21	13	31.293	93.981	0	3.00
Plate-15	15.21	13	32.315	97.049	0	3.00
Plate-16	15.21	10	25.655	77.049	0	3.00
Plate-17	15.21	10	26.444	79.417	0	3.00
Plate-18	15.21	9	21.789	65.439	0.111	3.00
Plate-19	15.21	8	22.544	67.704	0.317	3.00
Total			449.490	1349.931	0.636	

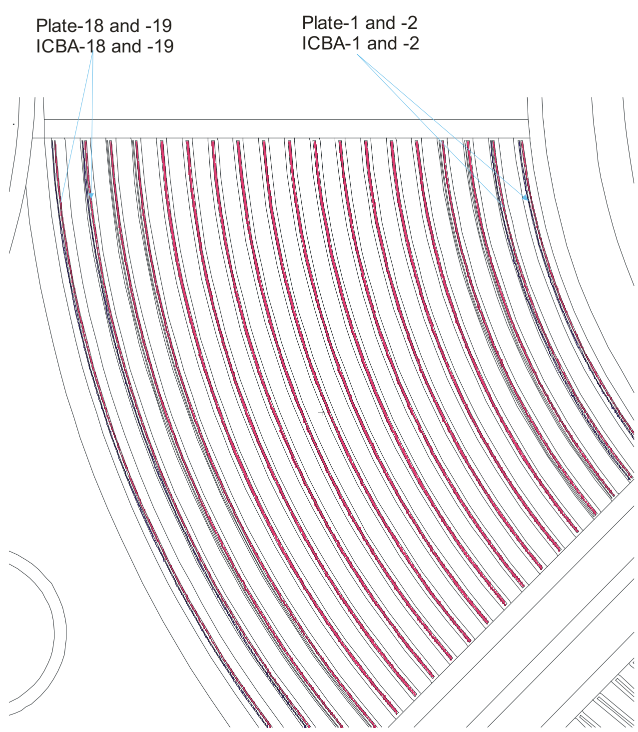

Figure 1. Monolithic foil-type with ICBA fuel element detailed configuration.

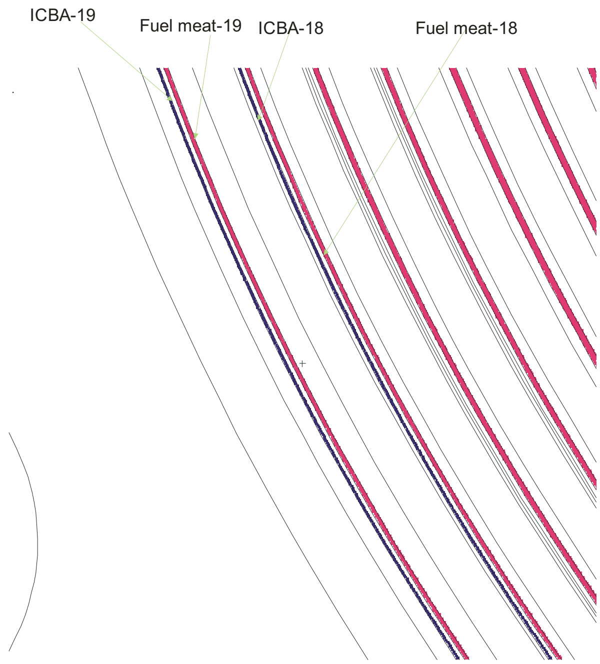

Figure 2. LEU ICBA and Fuel meat plates-18 and -19 detailed configuration.

4. HEU Reference Case and LEU Monolithic foil-type with ICBA Fuel Neutronics Performance Evaluation

Based upon the comparison between Case-A and Case-B relative heat flux L2AR profiles, the ^{235}U contents and fuel meat thickness of the inner/outer plates were evaluated and optimized in order to reduce the difference of K-eff profiles versus EFPD and LEU fuel peak heat flux L2AR. The LEU fuel loading was optimized such that the L2AR at the four inner/outer plates closely matches the ATR reference HEU Case-A.

The optimization was based upon a comparison of the MCWO-calculated K-eff versus EFPD and the radial power L2AR profile for various LEU fuel and ^{10}B loading schemes. In order to reduce the ^{10}B depletion impact on the fuel plate performance, ^{10}B was modeled in the two inner plates (plate-1 and plate-2) and two outer plates (plate-18 and plate-19). The LEU fuel (^{235}U enrichment 19.7wt%) loading schemes included varying parameters such as fuel meat thickness within the monolithic U10-Mo LEU fuel type as Case-B.

4.1 HEU Reference Case and LEU MF-ICBA Radial Fission Power Profiles Versus Burnup

The above tables, Table 1 and Table 2, summarize the fuel and ^{10}B minimization loading parameter variations that resulted in the flattest radial fission heat profile while still maintaining sufficient reactivity within the LEU core. Not surprisingly, the optimal LEU fuel loading is similar to the HEU reference case. The optimal LEU fuel loading has thinner plates at the inner/outer plate positions. For the purposes of determining the feasibility of HEU to LEU conversion, the present study demonstrates a satisfactory loading scheme to achieve acceptable reactivity for three nominal 50 EFPD fuel cycles as well as maintain the radial heat flux L2AR profile.

The MCWO fuel burnup analysis code was used to calculate the relative radial plate fission power heat flux for the HEU Case-A and LEU Case-B at the beginning of the first cycle (BOC), 1st End of Cycle (EOC), 2nd , and 3rd EOC. For Fe-18 at BOC, the respective peak heat fluxes L2AR for Case-A and Case-B were determined to be 1.25 and 1.20, respectively, as shown in Figure 3. Figure 3 also indicates that HEU Case-A and LEU Case-B have a very similar fission power density profiles.

Results for Case-A and Case-B at the 1st, 2nd, and 3rd EOC are plotted in Figures 4, 5, and 6. These plot demonstrates that Case-A and Case-B yield very similar radial L2AR profiles versus burnup. Figures also indicate that the fission power density profiles are flattened toward the discharged burnup. These studies indicate that the LEU radial L2AR profiles can achieve flattened profiles bounded by HEU reference Case-A by varying fuel meat thickness of the inner/outer 2 plates. However, the fission power density (W/cm^3) L2AR profiles for the LEU cases with varied fuel meat thickness produced larger peaks within the inner/outer plates. This power density peaking will not result in a large, undesirable heat flux profile.

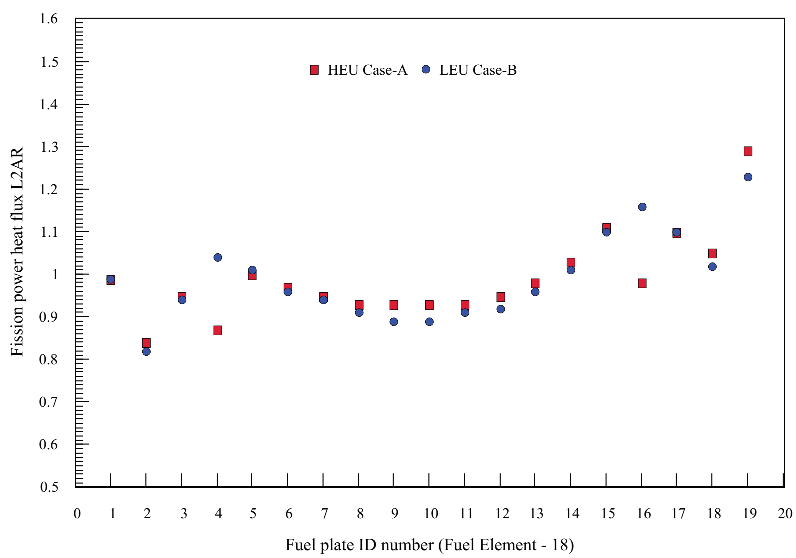

Figure 3. Fission power heat flux L2AR radial profiles for HEU Case-A and optimized LEU Case-B at BOC.

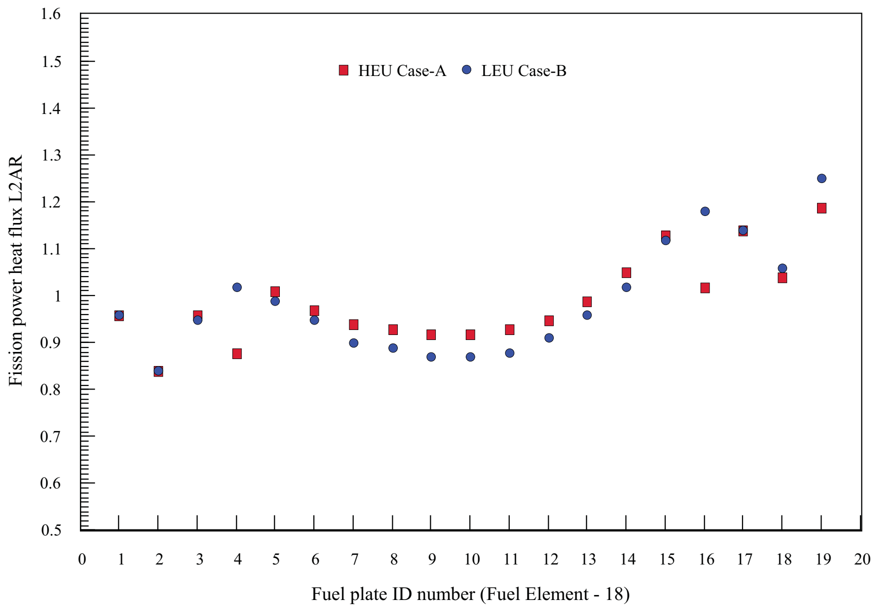

Figure 4. Fission power heat flux L2AR radial profiles for HEU Case-A and optimized LEU Case-B at 1st EOC.

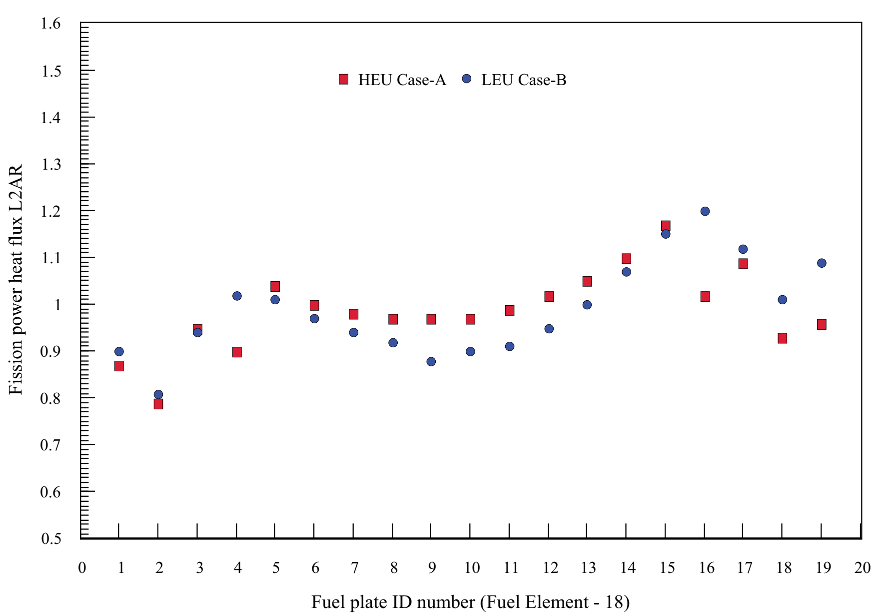

Figure 5. Fission power heat flux L2AR radial profiles for HEU Case-A and optimized LEU Case-B at 2nd EOC.

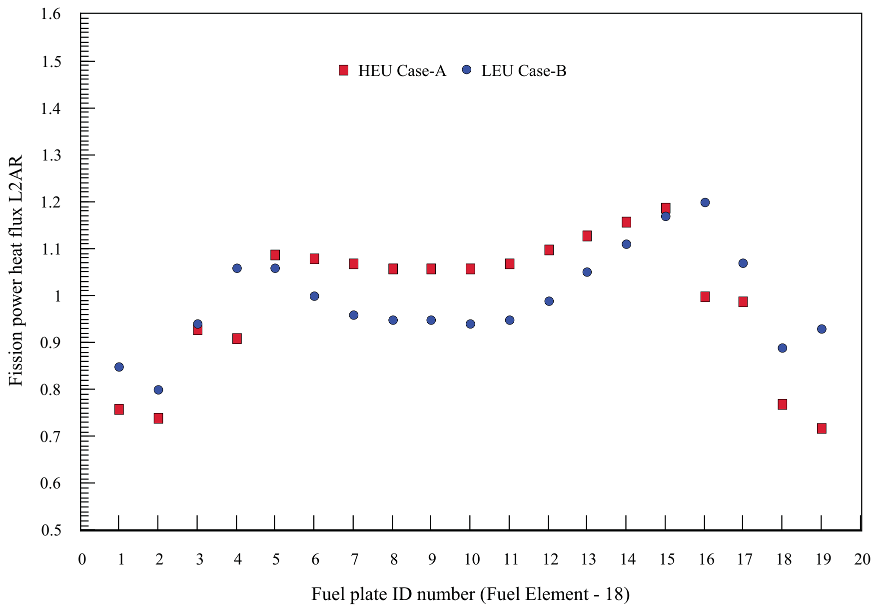

Figure 6. Fission power heat flux L2AR radial profiles for HEU Case-A and optimized LEU Case-B at 3rd EOC.

4.2 HEU Reference Case and Optimized LEU Case K-eff versus EFPD

Using the optimized LEU fuel loading, the MCWO-calculated K-eff for LEU Case-B as a function of EFPD as compared to the ATR reference HEU Case-A is shown in Figure 7. Note that the LEU fuels contain 80.25 wt% U-238, which can be transmuted to Pu-239. Although the LEU cases have a lower K-eff at the BOC when compared with HEU Case-A, the LEU cases sustain operation for the same EFPD as HEU Case-A (150 EFPD). The K-eff of HEU Case-A with and without ^{10}B at BOC are 1.1025 and 1.1969, respectively, which represents a hold-down reactivity of $9.94. While, the K-eff of LEU Case-B with and without ^{10}B at BOC are 1.0625 and 1.1389, respectively, which represents a hold-down reactivity of $8.77. The Figure 9 indicates that Case-A and Case-B has a small K-eff difference toward the end of three cycles EFPDs.

For a typical ATR new core fuel loading consists of about 1/3 fresh, 1/3 once-burnt at 1st EOC, and 1/3 twice-burnt at 2nd EOC fuel elements. Although the K-eff of all 40 fuel elements approaching the discharged burnup is about 0.988, which is less than 1. We believe (In phase-II, the LEU fuel cycle performance analysis will validate it in detailed analysis.) that the typical new core fuel loading can provide an adequate K-eff for the complete cycle operation.

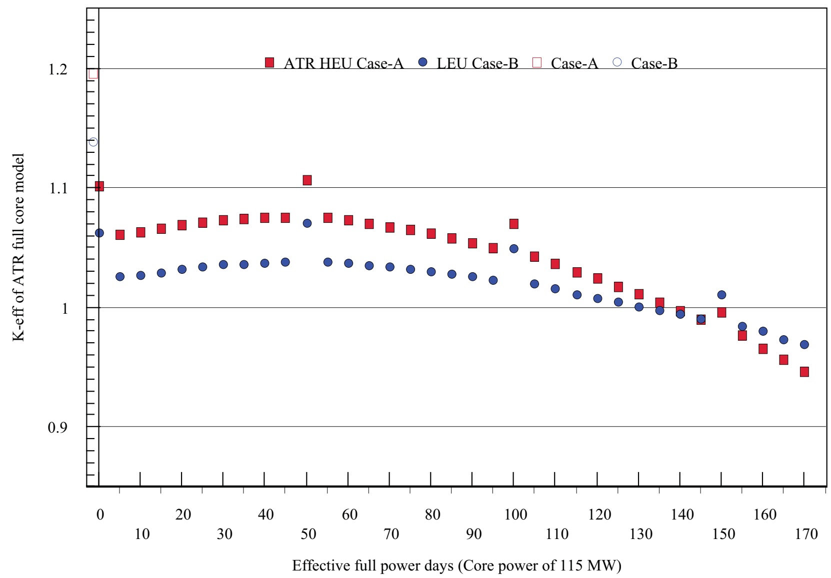

Figure 7. MCWO-calculated K-eff versus EFPD for ATR reference HEU Case-A and optimized LEU Case-B.

5. Conclusion and Recommendations

The detailed plate-by-plate MCNP ATR full core model used in this study handles complex spectral transitions at the boundaries between the plates in a straight forward manner. The MCWO-calculated K-eff versus EFPD results indicate that LEU Case-B provide adequate excess reactivity versus burnup while providing fission heat profiles similar to the ATR reference HEU Case-A. The LEU core conversion designer will be able to optimize the ^{235}U fuel loading so that the K-eff and relative radial fission heat flux profile are similar to Case-A. To achieve the flattened heat flux profile, the LEU monolithic core designer can fix the ^{235}U enrichment of 19.75wt% and vary the thickness of the four inner/outer plates, as well as adjust the amount of burnable absorber in the two inner/outer plates. The investigation of this paper shows the optimized LEU Monolithic (U-10Mo) case can all meet the LEU conversion objectives. As a result, it has been concluded that LEU core conversion for the ATR is feasible.

For the reference HEU 7F and LEU MF-ICBA cases, the BA is used not only to hold-down the initial excess reactivity , but also flatten the radial heat flux profile. Because the ^{10}B (n,α) reaction generates ^{4}He gas, which can potentially degrades the fuel plate performance. An alternative complex LEU MF fuel design with Integral Side-plate Burnable Absorber (ISBA), Cadmium (Cd), is currently undergoing a more in depth evaluation. As we know, if we put BA in side-plates, it only hold-down the initial excess reactivity. Then, using the fuel meat thickness variation approach in outer and inner four plates to flatten the radial plates profile to meet the LEU conversion project requirements. This ISBA design locates the BA in the side-plates, which physically separates the BA from both the fuel meat and the cladding, and takes advantage of the fact that the Cd (n,γ) reaction does not produce ^{4}He gas. A preliminary proposed complex MF-

ISBA can achieve a flattened fuel plate radial power profile by reducing the thickness of the fuel meat of the inner/outer plates. The complex LEU MF-ISBA fuel design can be shown to meet all the ATR LEU conversion operational and safety requirements in the LEU complex fuel design Phase-II.

The proposed LEU fuel specification in this work is directly related to both the RERTR LEU Development Program and the ATR LEU Conversion Project at INL. The LEU core designer can use the detailed plate-by-plate MCNP ATR full core model to optimize the ^{235}U loading by either minimizing K-eff differences with respect to the HEU core during the 150 EFPD of operation at a total core power of 115 MW (23 MW per lobe), or by reducing the higher L2AR of heat flux at the inner/outer plates. However, to demonstrate that the LEU core fuel cycle performance can meet the UFSAR safety requirement, a further study will be necessary in order to investigate the detailed radial, axial, and azimuthal heat flux profile variations versus EFPD. In addition, the safety parameters such as void reactivity and Doppler coefficients, control components worth (outer shim control cylinders, safety rods and regulating rod), and shutdown margins between the LEU cores need to be evaluated in depth.

6. References

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