A DETAILED NEUTRONICS COMPARISION OF THE UNIVERSITY OF FLORIDA TRAINING REACTOR (UFTR) CURRENT HEU AND PROPOSED LEU CORES

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ABSTRACT

For over 35 years, the UFTR highly-enriched core has been safely operated. As part of the Reduced Enrichment for Research and Test Reactors Program, the core is currently being converted to low-enriched uranium fuel. The analyses presented in this paper were performed to verify that, from a neutronic perspective, a proposed low-enriched core can be operated as safely and as effectively as the highly-enriched core. Detailed Monte Carlo criticality calculations are performed to determine: i) Excess reactivity for different core configurations, ii) Individual integral blade worth and shutdown margin, iii) Reactivity coefficients and kinetic parameters, and iv) Flux profiles and core six-factor formula parameters.

KEYWORDS: Research reactor, core physics, HEU, LEU, conversion, Monte Carlo

1. Introduction

For over 35 years, the University of Florida Training Reactor (UFTR) highly-enriched (HEU) core has been safely operated according to the Final Safety Analysis Report (FSAR) [1], which describes the UFTR safety and operational limits. The objective of the work presented in this paper is to verify that a proposed low-enriched (LEU) core can be operated as safely and effectively as the current HEU core.

More specifically, this paper presents the core physics analyses performed, as part of the conversion of the UFTR for HEU to LEU uranium fuel, by the University of Florida Nuclear and Radiological Engineering (NRE) Department with the support of Argonne National Laboratory (ANL). Detailed Monte Carlo criticality calculations are performed to determine: i) Excess reactivity for different core configurations, ii) Individual integral blade worth and shutdown margin, iii) Reactivity coefficients and kinetic parameters, and iv) Flux profiles and core six-factor formula parameters.

The remainder of the paper is organized in six sections. Section 2 presents a brief description of the UFTR core. Section 3 describes the characteristics (geometry and composition) of the current HEU fuel and the LEU fuel. Section 4 presents a comparison between the calculated and measured values for the control blade worths, excess reactivity, and shutdown margin of the HEU core. These analyses are performed in order to benchmark the computational models.

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Section 5 presents the neutronic analyses of the current HEU and the proposed LEU core. Finally, Section 6 summarizes the results and conclusions of all these studies.

2. UFTR General Description

The UFTR core, as shown in Figure 1, can physically accommodate up to 24 bundles (fuel, dummy, or partial fuel) of MTR-type fuel element. These bundles are arranged in 2x2 arrays within six aluminum cans referred to as fuel boxes. The fuel boxes are surrounded by a stack of graphite stringers, which act as both a moderator and a reflector. Note that the cooling water flowing in the boxes during operation provides additional moderation and reflection.

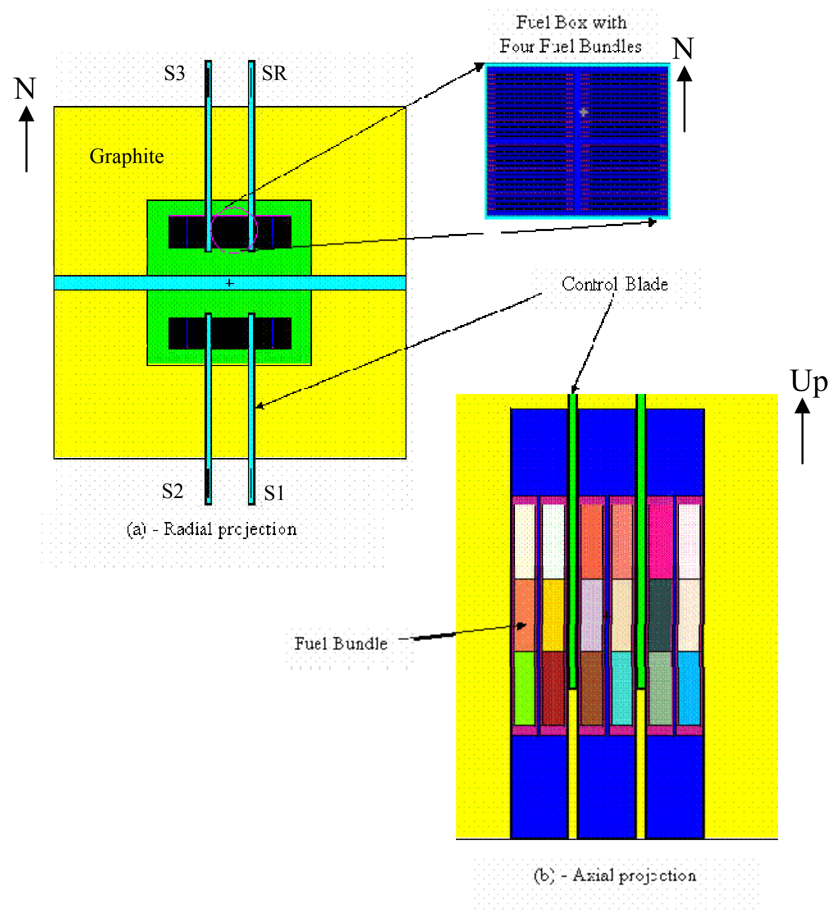


Figure 1 UFTR Core Schematic

Figure 1 also shows the control and shutdown mechanism comprising three safety blades labeled S1, S2 and S3, and one regulating blade labeled SR. These blades, of the swing-arm type, are mounted on the side of the core and swing on an arc downward through the core between the fuel boxes.

Figure 2 shows the fully inserted and fully withdrawn position of a control blade with respect to its shroud and the centerline of the core.

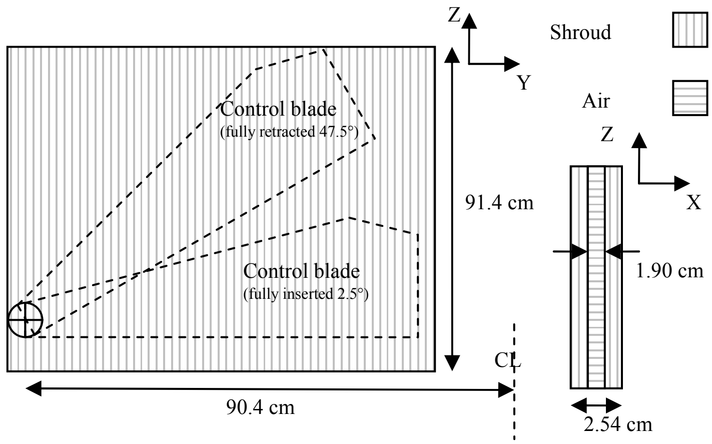


Figure 2 UFTR Control Blade and Magnesium Shroud

3. HEU and LEU Fuel Description

The HEU and LEU fuel elements are both of plate-type elements composed of a "sandwich" of fuel "meat" and cladding (often referred to as "MTR fuel"). The HEU fuel meat consists of uranium-aluminum alloy with 93 wt% enriched uranium, while the LEU fuel meat consists of U_3Si_2-aluminum dispersion fuel [2] with 19.75 wt% enriched uranium. The cladding of the HEU fuel is made of 1100 aluminum alloy, while the LEU fuel cladding is made of 6061 aluminum alloy.

There are four major differences between the HEU and LEU fuel bundle designs: i) The LEU fuel meat is half the thickness of the HEU fuel meat, ii) The LEU bundle has more fuel plates (14 plates instead of 11 plates) due to lower enrichment, iii) The LEU bundle has a smaller coolant channel, and iv) As shown in Figure 3, the LEU bundle is slightly smaller than the HEU bundle.

Figure 3 Drawings Comparing the LEU and HEU Bundles

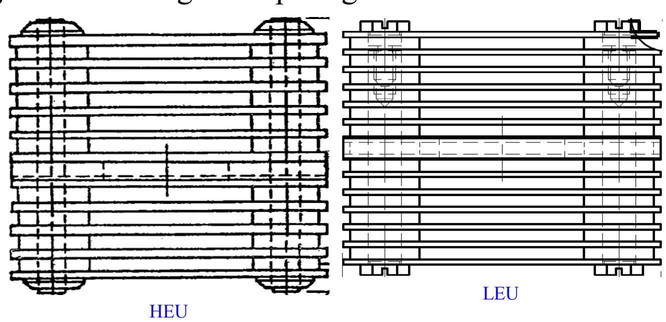


Table 1 summarizes the major differences between the current HEU fuel and the new LEU fuel.

Table 1 Differences Between the HEU and LEU Fuel Bundle

	HEU	**LEU**
Fuel Type	U-Al alloy	U_3Si_2-Al dispersion
Cladding	1100 Al	6061 Al
Fuel meat, Thickness (cm)	0.102	0.051
Fuel plate, Thickness (cm)	0.178	0.127
Number of Plates/Bundle	11	14
Coolant Channel Thickness (cm)	0.348	0.282

4. Benchmarking of Computational Models

To determine the critical LEU core configuration and verify that the new core meets necessary operational and safety limits, detailed computational neutronics models were developed for performing criticality calculations using MCNP5 [3]. The SAS2 sequence of the SCALE5 package [4] was used to perform the fuel depletion calculations in order to determine the isotopic composition of the current HEU fuel.

A model of the current HEU core was developed and benchmarked against experimental measurements of the individual integral blade worth, excess reactivity, and shutdown margin. Table 2 gives a comparison between calculated and measured values of these parameters.

Table 2 Calculated and Measured Reactivity Worth for the Current HEU Core

		Calculated	Measured
Control Blade Worth[2],	SR (%Δk/k)	0.87	0.82
	S1 (%Δk/k)	1.35	1.21
	S2 (%Δk/k)	1.63	1.36
	S3 (%Δk/k)	2.06	1.88
Excess Reactivity[3] (%Δk/k)		0.47	0.38
Shutdown Margin[4](%Δk/k)		3.11	3.01

The calculation values exhibit small positive biases (about 0.1%Δk/k) but they are consistent and in overall in good agreement with the measured values. These differences can mainly be attributed to: i) Experimental uncertainty, ii) Inconsistency between the procedures to experimentally measure the blade worth and the computational procedure, and iii) Uncertainties in material impurity concentrations.

The HEU core model is further benchmarked by comparing measured and calculated reaction rates in uncovered and cadmium-covered gold foils in the center vertical port (CVP) and the rabbit system. Table 3 compares measured and calculated reaction rates at different axial locations within the CVP and in the rabbit system.

Table 3 Measured and Calculated Foil Reaction Rates in the CVP and Rabbit System

Foil Type	Position of Foil Center	Measured	Calculated	Ratio
Cd-covered Au	3.8 cm [5]	6.77E+09	6.78E+09 (7.47%)	1.00
Au	11.4 cm	2.39E+10	2.43E+10 (3.79%)	0.98
Cd-covered Au	19.1 cm	6.91E+09	5.80E+09 (8.25%)	1.19
Au	26.7 cm	2.23E+10	1.82E+10 (4.70%)	1.23
Cd-covered Au	Rabbit system	5.96E+09	6.05E+09 (6.10%)	0.99
Au	Rabbit system	2.17E+10	2.29E+10 (3.22%)	1.06

The good agreement between the measured and calculated reaction rates provides strong additional confidence in the models and methodologies. Therefore, a similar model was developed for the LEU core by appropriately modifying the HEU model.

[2] Calculated by comparing the case of a given blade fully inserted and the excess reactivity.
[3] Calculated by rotating the control blades to their fully withdrawn positions
[4] Calculated assuming that the most reactive blade (S3 for the HEU core) is stuck out.
[5] Distance measured from the bottom of the CVP.

Due to the uncertainties in the concentrations of certain impurities, it was necessary to perform a small sensitivity study. Table 4 presents changes in k_{eff} obtained for different changes in the concentrations boron-equivalent impurities for the HEU core.

Table 4 Impact of Impurities on the Excess Reactivity of the HEU Core

Case (ppm of natural boron-equivalent)	**Δk/k (%)** [1]
-1 ppm in graphite	0.303
+1 ppm in graphite	-0.133
-10 ppm in cladding	0.254
+10 ppm in cladding	-0.177
-10 ppm in Al structure	0.146
+10 ppm in Al structure	-0.015
Graphite/cladding/structure impurities at minimum	0.546
Graphite/cladding/structure impurities at maximum	-0.472
+5.72ppm [2] in fuel aluminum alloy	-0.107

[1] The 1σ relative errors for these values is below 0.00025

[2] This value is taken from ANL intra-laboratory memo of June 30th, 2005

Table 4 shows that using a concentration of 5.72ppm of natural boron-equivalent impurity in the fuel greatly reduces the positive bias observed in Table 2. Note that the calculated k_{eff} of the depleted HEU core with the control blades at their measured critical positions is 0.99993 (+/- 0.00013).

5. Steady-State Core Physics Analyses

In order to determine a proposed LEU core and compare it to the current HEU core, different criticality calculations were performed to determine the following:

- i) Excess reactivity for different core configurations,
- ii) Individual blade worths, and shutdown margin,
- iii) Kinetic parameters and reactivity coefficients,
- iv) Flux profiles
- v) Six-factor formula parameters

5.1 Proposed LEU Core Configuration and Excess Reactivity

The neutronics models discussed previously were used to study various new LEU core in order to obtain a core loading with close to 1%Δk/k of excess reactivity. Figure 4 shows the fuel bundle numbering scheme used throughout this paper.

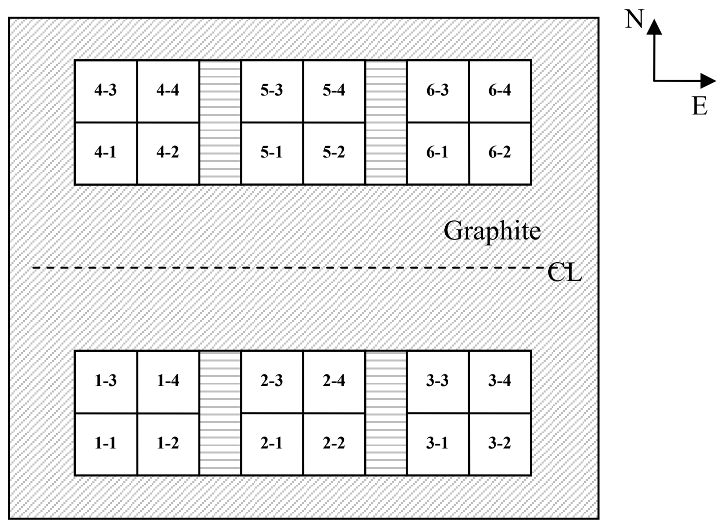


Figure 4 Numbering of the Fuel Bundle Locations

As indicated in above figure, starting from the SW corner, the fuel boxes are numbered from 1 to 6, and within each box, the bundles are similarly numbered from 1 to 4.

Table 5 presents the excess reactivity for five LEU core configurations in which the number of bundles is varied between 22 and 24 with different number of partial/dummy bundles.

Table 5 Excess Reactivity for Various LEU Core Configuration

Configuration	**Description**	**Excess Reactivity** (%Δk/k)
1	24 full fuel bundles	2.51[6]
2	23 full fuel bundles one dummy bundle at location 3-2	1.31
3	22 full fuel bundles two dummy bundles at locations 3-2 and 6-4	0.00
4	22 full fuel bundles 5 fuel plates at location 6-4 one dummy bundle at location 3-2	0.65
5	22 full fuel bundles one dummy bundle at location 6-4 10 fuel plates for bundle at location 3-2	0.93

Based on the above results and targetting the excess reactivity to ~1%Δk/k, the reference LEU core is composed of 22 full fuel bundles, one partial fuel bundle (10 fuel plates and 3 dummy plates), and one full dummy bundle. Table 6 compares the positions of the control blades for the current HEU and this proposed LEU critical cores.

Table 6 Control Blade Positions for the HEU and LEU Critical Cores

Control Blade	**Position (degrees)**	
	HEU	**LEU**
Safety 1, 2 and 3	38.5	26.3
Regulating	18.7	16.9

[6] The 1-σ relative error on excess reactivity is about 0.03%.

From Table 6, it can be concluded that the safety control blades for the LEU core could be moved sufficiently to compensate for negative reactivity insertion from experiment and buildup of fission products while keeping the regulating blade in region where it is most effective.

5.2 LEU Core Blade Worth and Shutdown Margin

We evaluated the integral reactivity worth of the control blades. To evaluate the worth of each control blade, %Δk/k was calculated between the case where all the blades are fully withdrawn and the case where a given blade is fully inserted. Table 7 presents the worth of control blades for the fresh and depleted LEU core.

Table 7 Control Blades Integral Reactivity Worth for the HEU and LEU Cores

Control Blade	LEU-fresh (%Δk/k)	LEU-depleted (%Δk/k)
Regulating	0.63%	0.66%
Safety 1	1.62%	1.65%
Safety 2	1.77%	1.76%
Safety 3	1.42%	1.46%

By comparing results in Table 2 and Table 7, it can be observed that the two control blades on the south part of the reference LEU core (safety 1 and 2) have higher relative worths as compared to the HEU core, while the two control blades on the north part of the LEU core (safety 3 and regulating) have lower relative worths than in the HEU core. This is expected because, in the LEU core, more fuel is added to the south part of the core. It can also be observed in Table 7 that control blade worths do not change significantly during the lifetime of the core.

We also studied the shutdown margin by fully inserting two of the safety blades and the regulating blade, and withdrawing the safety blade with the highest worth (most reactive blade stuck out of the core). Table 8 compares the shutdown margins of the HEU and LEU cores.

Table 8 Shutdown Margins for the Current HEU Core and the Reference LEU Core

	Depleted HEU Core (calculated)	HEU Core (measured)	Reference LEU Core
Shutdown Margin (Δk/k %)	3.11	3.01	3.17

Table 8 shows that shutdown margin for the proposed LEU core meets the requirement of being at least 2 %Δk/k with the most reactive blade stuck out.

5.3 Kinetic Parameters and Reactivity Coefficients

Reactivity coefficients provide a measure of the core reactivity response to changes in the water properties or fuel temperature changes under both off-nominal (e.g., changes to inlet coolant conditions) and accident conditions (e.g., inadvertent reactivity insertion accidents).

The reactivity coefficients calculated using MCNP5 assumed that the reactivity effects resulting from simultaneous changes in multiple state properties are separable. The coefficients C_x are calculated from core eigenvalue calculations with independent perturbations to the state properties. Consequently,

$$C_x = \frac{\Delta\rho}{\Delta_x} = \frac{k_1 - k_o}{k_1 k_o} \cdot \frac{1}{(x_1 - x_o)} . \qquad (1)$$

Table 9 gives the reactivity coefficients for the reference LEU core with ranges on coolant voiding and temperature selected to cover any perturbations that may occur during normal operations and accident conditions.

Table 9 Comparison of the Kinetic Parameters and Reactivity Coefficients of the HEU and LEU Cores

Parameter		Current HEU			LEU (Depleted)		
β_{eff}		0.00792	±	1%	0.00756	±	2%
l (μs)		187.4	±	3%	195.1	±	6%
C_{void} (Δρ/%void)	*(0 to 5% void)*	-1.48E-03	±	1%	-1.46E-03	±	2%
C_{water} (Δρ/°C)	*(21 to 127°C)*	-5.91E-05	±	1%	-5.26E-05	±	3%
C_{fuel} (Δρ/°C)	*(21 to 227°C)*	-2.91E-06	±	12%	-1.49E-05	±	4%

As expected, because of the Doppler effect, the LEU fuel has a much larger fuel temperature coefficient compare to the HEU fuel. It is important to note that all the coefficients are negative which is essential for the safe operation of the reactor.

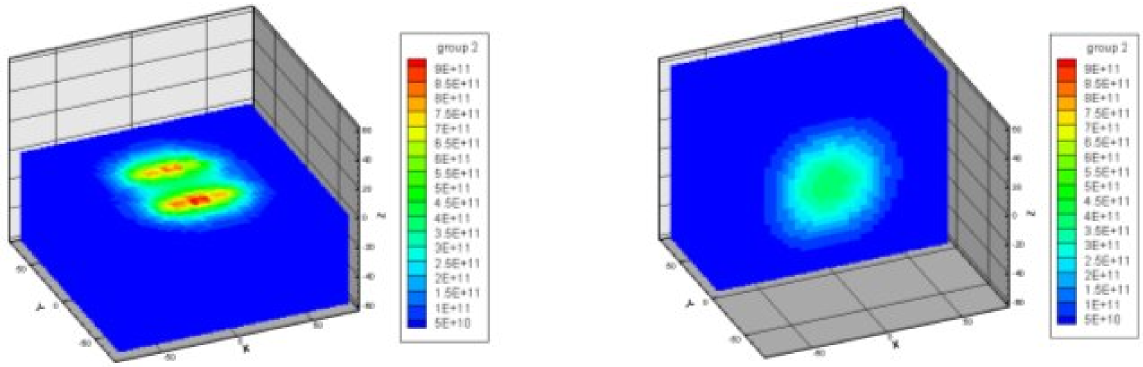
5.4 Flux Profiles

Table 10 presents a seven group structure used to tally the flux profiles using the mesh tally option in MCNP5.

Table 10 Energy Group Structure for UFTR

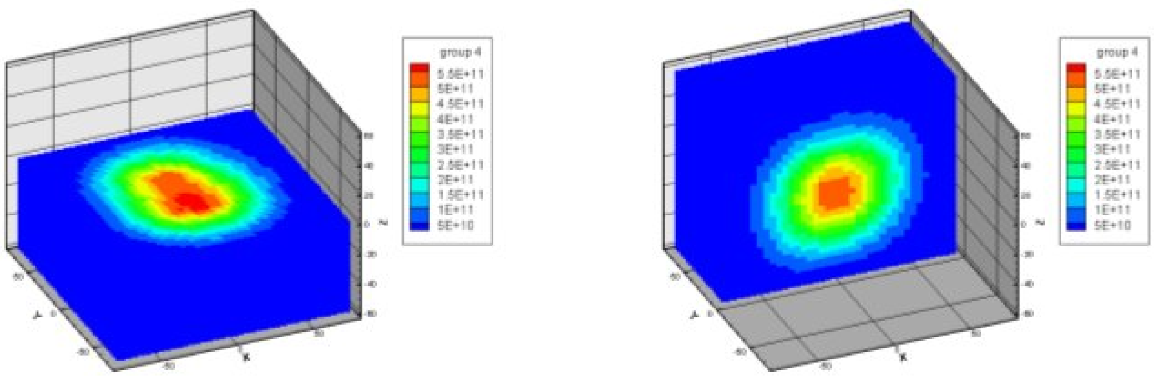
Spectrum Region	Group Number	Upper Energy (MeV)
Fast	1	2.00e1
	2	1.00e0
Epithermal	3	1.00e-1
	4	1.00e-2
	5	1.00e-4
Thermal	6	1.00e-6

Figures 4 to 6 show axial and radial cuts of the 3D flux profiles for a fast, epithermal and thermal group.



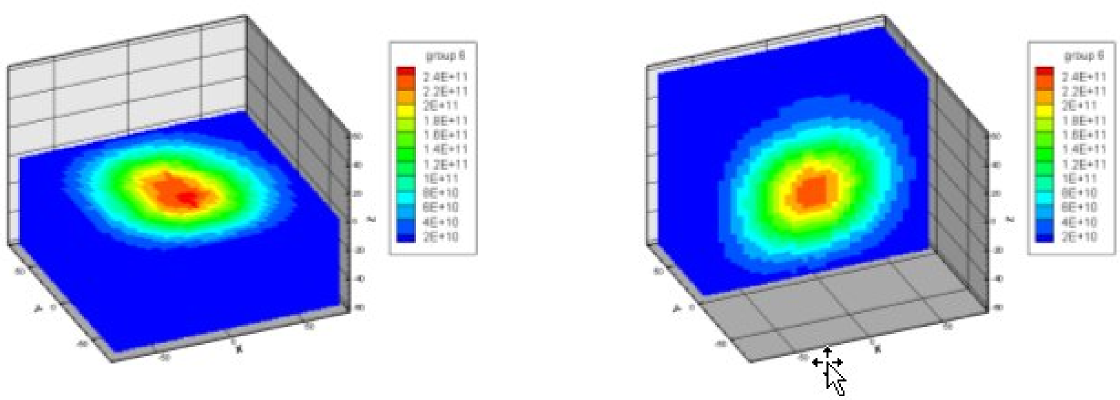
(a) x-y projection¶ (b) x-z projection¶

Figure 4 Flux distribution for energy group 2 (0.10 – 1.0 MeV)



(a) x-y projection¶ (b) x-z projection¶

Figure 5 Flux distribution for energy group 4 (1.0 E-4 - .01 MeV)



(a) x-y projection¶ (b) x-z projection¶

Figure 6 Flux distribution for energy group 6 (1.0E-7 – 1.0E-6 MeV)

In Figure 4, it possible to clearly identify the two rows of individual fuel boxes. Moreover, the location of the dummy bundle can also be easily seen in that figure. In Figures 5 and 6, it can be observed that the flux have the expected profiles.

5.5 Six-Factor Formula Parameters

The six-factor parameters provide an alternative way to characterize a reactor and provide insight into different physical processes occurring in the reactor core. Each factor represents a step in the "life cycle" of a neutron, and is defined by specific parameters of the system, i.e. by compositions, cross sections and other nuclear properties. The six-factor formula is given by

$$k = \eta f \varepsilon p P_{FNL} P_{TNL} \tag{2}$$

The first of factor (η) is the number of fission neutrons produced per absorption in the fuel. The second factor is the *thermal utilization* (*f*); it represents the effectiveness of the fuel in competing with other materials in the reactor for the absorption of the thermal neutrons. Then to account for the process of slowing down, two other factors are introduced. The third factor, the *fast fission factor* (ε), take into account that some of the fissions are produce by fast neutrons. The fourth factor, the *resonance escape probability* (*p*), represents the fraction of neutrons that managed to slow-down to the thermal energies without being absorbed. The last two factors are related to the probability of non-leakage and can be broken down into P_{FNL} (*fast non-leakage*) and P_{TNL} (*thermal non-leakage*). Table 11 compares the calculated parameters of the six-factor formula for the HEU and LEU cores.

Table 11 Six Factors for the depleted HEU core and the reference LEU Core

Factor	**HEU**	**LEU**	**Relative Diff. (%)**
η	1.987	1.889	-4.932%
Thermal utilization f	0.613	0.640	4.405%
Fast fission factor ε	1.057	1.067	2.156%
Resonance escape probability p	0.945	0.937	-0.847%
Probability of non-leakage P_{NL} [1]	0.822	0.828	-0.730%

[1] Note that the fast and thermal non-leakage have been combined in one probability of non-leakage

A lower η value and a higher ε value are expected for the LEU core because of the low enrichment of U-235.

6. Conclusions

This paper presented a detailed and systematic comparison of the neutronics characteristics of a proposed LEU and the current HEU cores. These analyses were performed as part of the conversion of the UFTR for HEU to LEU uranium fuel.

First, the models and methodologies were verified by benchmarking results obtained for the HEU core against experimental measurements. The good agreement between the calculated and measured quantities provided confidence in our approach.

After determining a reference LEU core configuration with close to 1 %Δk/k of excess reactivity, criticality calculations were performed to evaluate the control blade worths, shutdown margin, kinetics parameters, and reactivity coefficients for both the LEU and HEU cores. These results enable us to conclude that, from a neutronics perspective, the proposed LEU core can be operated as safely as the HEU core.

Further characterization of the proposed LEU core was accomplished via analysis of flux profiles modeling results and relative changes in the six-factor formula parameters.

Based on this study and related thermal hydraulics and accident analyses, a Safety Analysis Report (SAR) has been prepared for UFTR. The methodologies and results of this SAR will be published in relevant journals and conference proceedings.

References

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