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Improvements to Predictions of the Estimated Critical Blade Positions Due to Control Blade Depletion Corrections at MURR

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ABSTRACT

The University of Missouri Research Reactor (MURR®) is one of five U.S. high performance research and test reactors that are actively collaborating with the U.S. Department of Energy (DOE) to find a suitable low-enriched uranium (LEU) fuel replacement for the currently required highly-enriched uranium (HEU) fuel. Neutronic analyses performed for the conversion feasibility study included criticality studies using LEU fuel, fuel depletion, and power peaking analyses for both fresh fuel and mixed core loadings consisting of fuel elements at various stages of burnup. Although recent criticality studies on the MURR HEU core predicted k_{eff} values close to the measured values, a deficiency was noted where all of the studies unrealistically employed fresh, non-depleted BORAL® control blades. An extensive analysis was performed to estimate the depletion of control blades in-use at MURR and the effect of such depleted blades on core parameters, including power peaking, prediction of Estimated Critical Positions (ECP), etc. Results from adding depleted control blades based on actual operating histories to the previous MURR HEU criticality measurements showed a significant improvement in the predicted k_{eff} values. The deviations (% $\Delta k/k$) of the calculated core k_{eff} values at measured critical control blade positions were reduced from an average of -1.1%, when the blades are modeled as fresh, to -0.41%, when the depleted blade model is included.

1. Introduction

The University of Missouri Research Reactor (MURR®) is a 10 MW research and training reactor that is owned and operated by the University of Missouri-Columbia. The reactor is designed as a compact-type, pressurized, cylindrical core consisting of eight fuel elements surrounding a central flux trap. The core is primarily moderated by light water and has a primary beryllium reflector inside a secondary graphite reflector ring. Controlling excess reactivity for reactor operation comes from the movement of four axially-banked BORAL® shim control blades. The blades travel within an annular water channel between the outer surface of the outer reactor pressure vessel and the inner wall of the beryllium reflector. Figure 1 below shows a horizontal cross-sectional view of the MURR core. The poison zone of each blade spans an arc of 72 degrees, has a length of 34 inches and a thickness of 0.1 inch. The travel distance for the active region of each blade is constrained to the length of the fuel meat at 26 inches. A fifth control blade, constructed of stainless steel and located in the same water channel, is used for only very minor adjustments to excess reactivity during steady-state full power operation.

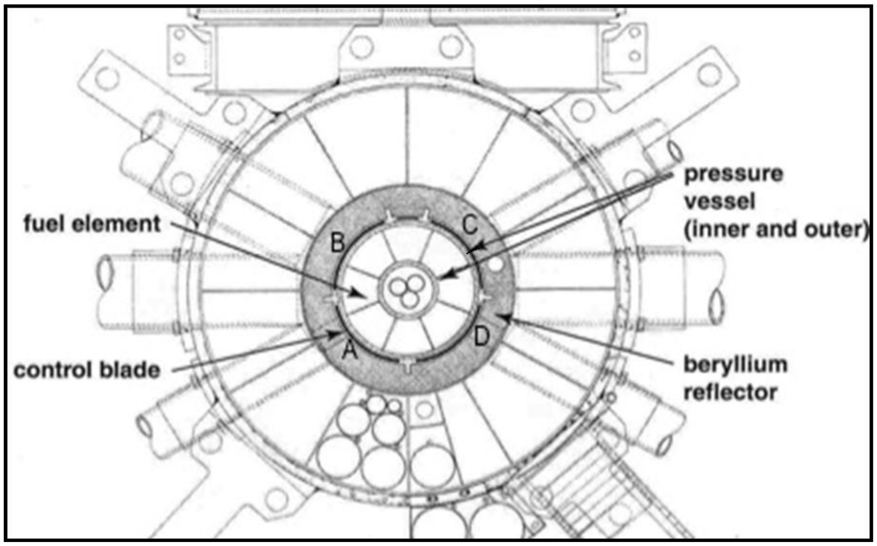


Figure 1. Cross-sectional view of the MURR core.

In collaboration with the Global Threat Reduction Initiative (GTRI) program at Argonne National Laboratory (ANL), MURR took part in a feasibility study [1] for the use of a low-enriched uranium (LEU) molybdenum alloy (U-10Mo) as a new monolithic fuel in the reactor core. The neutronic analyses performed for the feasibility study included a criticality study using LEU fuel, a fuel depletion analysis, as well as a power peaking analysis for an all-fresh core and for mixed cores consisting of fuel elements at various stages of burnup. In order to benchmark the feasibility neutronic analyses, which were performed using the 3-dimensional radiation transport code MCNP [2] and ANL's transport and depletion modules DIF3D [3] and REBUS [3], several criticality analyses were performed for the current MURR highly-enriched uranium (HEU) core. Although the criticality benchmarks predicted k_{eff} values relatively close to the measured values, a deficiency was noted where all of the studies employed fresh (non-depleted) control blades. This tended to bias the predicted k_{eff} values.

The use of control blades in the MURR core is very complex since several "active" shim control blades are cycled in and out of the core multiple times during their useable lifetime and, at any given time, blades in each of the four possible control blade locations are at different stages of burnup. Currently, there are 19 active control blades in use at the MURR. These active control blades have an independent operational cycling scheme where each blade has about a two-year irradiation (or core residence) time in one of four positions – "A", "B", "C" or "D" – of the MURR core (see Fig. 1) and a potential maximum lifespan of about 10 years – providing the blade is usable after each two-year irradiation cycle. Since a given replacement blade is selected with minimal consideration given to its burnup status, for a set of in-cycle blades, the "effective" lengths and atom density of boron-10 (B^{10}) in the poison zone for each blade may vary significantly. This disproportion in the effective lengths of the poison regions between the blades is expected to affect the power peaking factors on each fuel element differently. Although the MURR HEU fuel cycle and predictions of the LEU fuel cycle were studied in detail using the ANL-MURR MCNP models in the LEU feasibility study [1], until now no similar study for the control blades was available.

The importance of using a full depletion model of the control blades for the reactor safety analysis is clear. In this work [4], a methodology was developed to individually model the B^{10} depletion history for each active control blade that went through the MURR control blade operational cycle. Verification of this methodology was done by benchmarking the calculated k_{eff}, using control blade depletion models against actual critical rod height measurements.

2. Computational Methodology

2.1 MCNP Model

Highly discretized control blade models representing each of four possible positions "A", "B", "C" and "D" of the MURR core configuration were incorporated into the ANL-MURR MCNP model. Each control blade model was divided into 292 independent zones (cells), which include:

i. 4 azimuthal sections (over the entire length)
ii. 9 radial sections over each 1/4 inch sections of the first axial (bottom) inch for each azimuthal section
iii. 9 radial sections over each of the next three incremental one-inch sections for each azimuthal section
iv. 2 radial sections over each of the next five incremental six-inch sections for each azimuthal section.

This discretization scheme was chosen to properly account for the B^{10} atom density burnout profile in the most active regions of each control blade. Figure 2 shows the increased discretization towards the bottom tip of the control blade model. Because the bottom portion of any control blade is constrained to be within (or near) the length of the fuel meat zone whether at startup, at equilibrium xenon build-up, or at the almost fully withdrawn state, it is expected to have the fastest rate of B^{10} depletion.

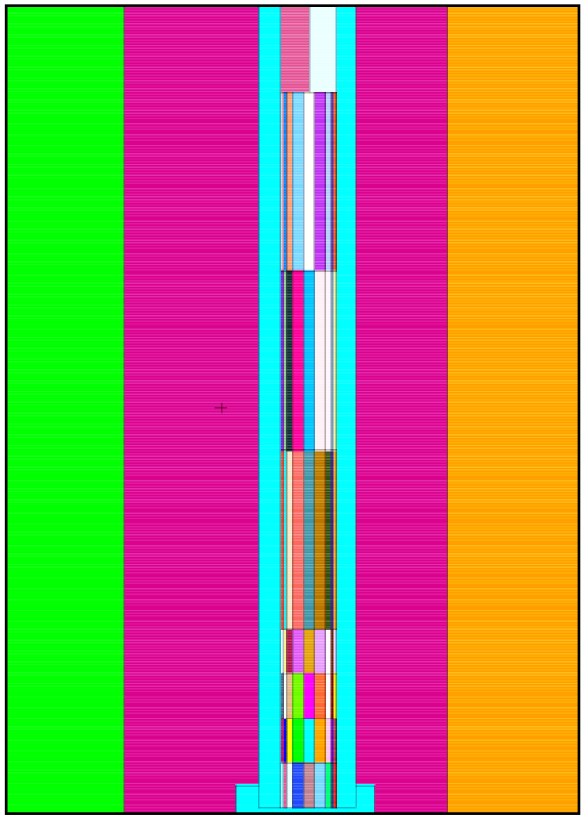


Figure 2. Details showing axial and radial discretization in the bottom four inches of the MURR MCNP control blade model.

2.2 Depletion Methodology

The B^{10} depletion calculations were done using the actual run-time histories for each of the 19 active control blades, shuffling them through their life-cycle positions "A", "B", "C" or "D" as appropriate. Each control blade initially begins its potential ten-year cycle with the atom densities for fresh BORAL® in each depletion zone. To include control blade travel during the 150-hour weekly operating cycle, the fuel definitions for two state points of the typical HEU mixed core cycle were used for improved accuracy; i.e., fuel definitions for the control blade (CB) at 17 inches and CB at 23 inches. Here it was approximated that the reactor configuration at the first state point (i.e., CB height at 17 inches) accounts for the first 36 hours of the typical MURR one week-long operating cycle (where the xenon is building up in the core and the blades are moving out). The second state point (i.e., CB height at 23 inches) accounts for the remaining 114 hours of the weekly operating cycle (where equilibrium xenon levels are established and the shim control blades are mostly out of the peak flux region of the core).

The B^{10} (n, α) reaction rates in each zone and for each state point were tallied in MCNP. Next, the reaction rates were used in a macro-modified EXCEL© worksheet where the actual B^{10} atom density depletion in each zone was calculated. For the control blade burnup simulation, a time-step of six months was used and each control blade was irradiated for a minimum of two years before being set aside for decay and potential reuse.

3. Results

3.1 Effects of Core Configuration on Control Blades Depletion

To study the effects of different reactor configurations on the B^{10} (n, α) reaction rate profiles in each control blade position, the B^{10} (n, α) reaction rate in each zone of each blade position was tallied and compared for fresh blades in eight different reactor configurations. Various reactor configurations were simulated using the ANL-MURR MCNP models to reflect the major changes in the graphite reflector region over a 30-year period. The 1971 reflector was nearly a single sleeve of graphite surrounding the core while the 2008 graphite region possesses much less graphite due to the addition of numerous experimental irradiation channels. The material definitions for the fuel assemblies in the weekly start-up core were chosen from two burnup states; either all-fresh fuel or a typical cycle consisting of both fresh and partially depleted fuel assemblies derived from an ANL REBUS-DIF3D [3, 5] simulation of the MURR HEU fuel cycle. The control blade positions for each weekly operational cycle were either approximate critical blade height at startup or approximate height at equilibrium xenon levels. The different reactor configurations used are as follows:

i. all fresh fuel, 1971 graphite reflector; critical (CB at 17 inches)
ii. all fresh fuel, 1971 graphite reflector; equilibrium Xe (CB at 23 inches)
iii. all fresh fuel, 2008 graphite reflector; critical (CB at 17 inches)
iv. all fresh fuel, 2008 graphite reflector; equilibrium Xe (CB at 23 inches)
v. mixed fuel, 1971 graphite reflector; critical (CB at 17 inches)
vi. mixed fuel, 1971 graphite reflector; equilibrium Xe (CB at 23 inches)
vii. mixed fuel, 2008 graphite reflector; critical (CB at 17 inches)
viii. mixed fuel, 2008 graphite reflector; equilibrium Xe (CB at 23 inches)

Plots of the B^{10} (n, α) reaction rates vs. the axial and radial dimensions for each control blade depletion zone were examined and showed that each reactor configuration has a unique impact on the B^{10} (n, α) reaction rate profiles in each blade position. However, the effects were observed to be small and are therefore not very significant. The results also showed that each blade position has a unique profile and that the most active regions of the blade are within the bottom four inches of the blade. Figures 3a and 3b show examples of the combined axial and radial B^{10} (n, α) reaction rate profiles over the blade's bottom four inches, for reactor configurations v and vii – MURR's current typical configuration. It also shows that the highest reaction rates occur at the surfaces of the control blade.

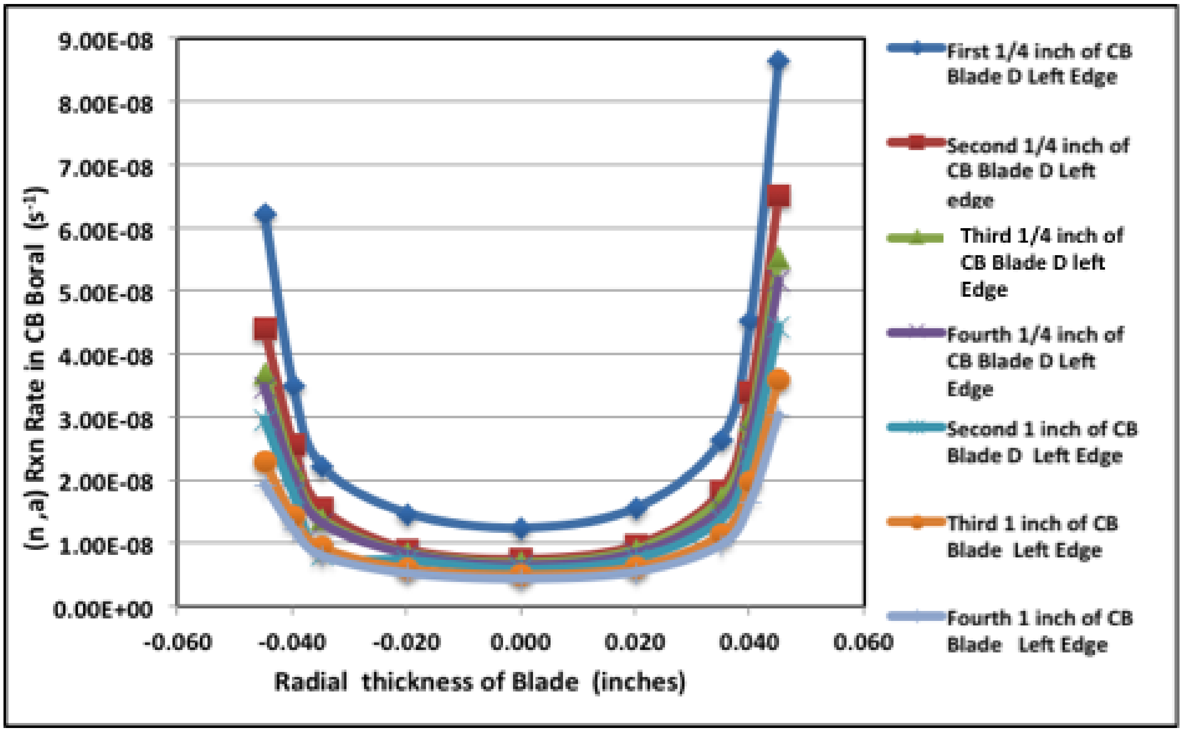


Figure 3a. Control blade B^{10} reaction rates for; mixed fuel core; 1971 graphite reflector; critical (CB at 17 inches).

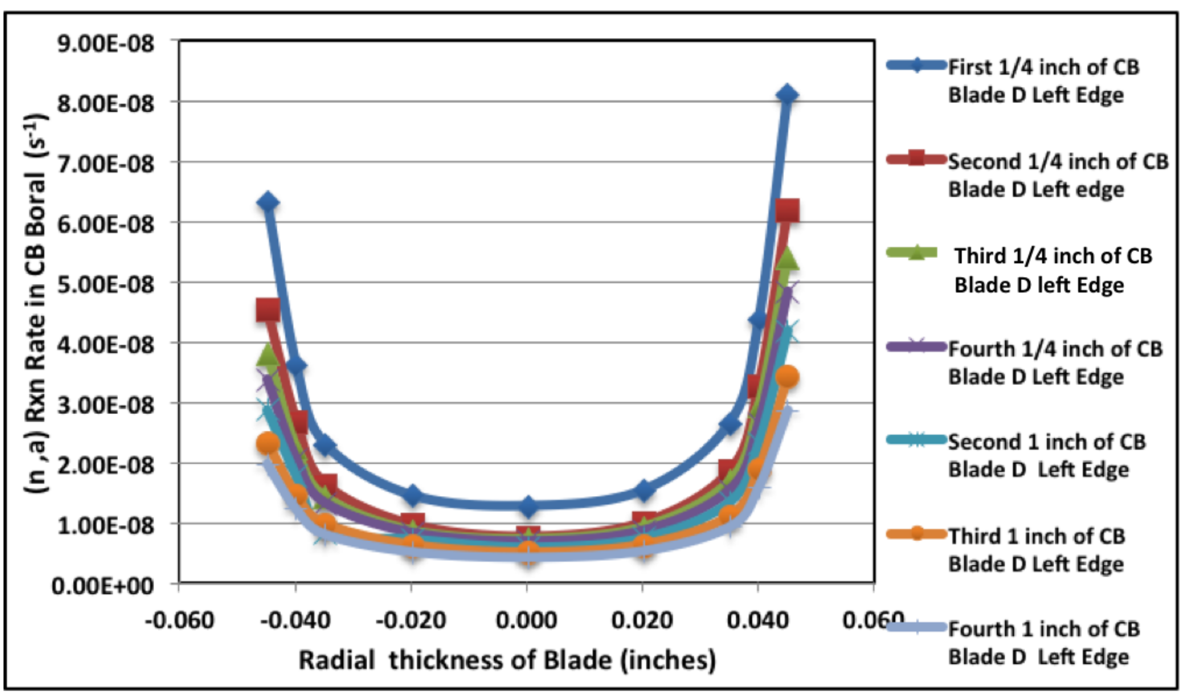


Figure 3b. Control blade B^{10} reaction rates for; mixed fuel core; 2008 graphite reflector; critical (CB at 17 inches).

3.2 Benchmarking: Comparison of Calculated K_{eff} Values

The data presented in Table 3.8 of Reference 1 (LEU feasibility study) showed the deviation of calculated core k_{eff} values for the measured critical control blade positions for various blade histories. For that study, the partially burned fuel assemblies for each criticality measurement was modeled using fuel compositions generated by a REBUS-DIF3D [3, 5] simulation of a two-year HEU fuel cycle shuffling scheme done for MURR in previous work [1, 3, 5]. The average burnup of the cores was 620 Megawatt-days and all of the control blades were modeled as fresh (non-depleted). The flux trap content was modeled as the typically loaded configuration and the graphite reflector was modeled as the "2008" configuration. Several cores from that previous study were selected and the core k_{eff} values were recalculated with depleted control blade models during the present study.

Table 3.1 shows the deviation in % Δk/k from critical state when there is no control blade burnup effect included (as in Reference 1) and when there is blade burnup effect included for each in-use control blade (from this work). When all-fresh control blades were used in the MCNP simulation (the column labeled "No CB Burnup" in Table 3.1), cores with the combination of blades that have the greatest total burnup, and correspondingly the lowest measured critical blade heights, had the greatest deviation from critical at measured critical rod heights. However, when the blades are modeled with the depleted blade compositions (the column labeled "With CB Burnup" in Table 3.1), the deviation from critical is always smaller and for the case with the maximum control blade history the deviation is reduced from 1.735% to 0.422%.

Table 3.1. Deviations for the Estimated K_{eff} Values from Critical for the Case with Fresh Control Blades (from feasibility study) and with Depleted Blades (from this work).

CB History (In-cycle Days)	CB Bank Height (inches)	No CB Burnup (% Δk/k)	With CB Burnup (% Δk/k)
287	17.63	-0.260	-0.232%
308	18.06	-0.144	-0.139%
1040	17.22	-1.301%	-0.730%
1192	16.72	-1.307%	-0.532%
1709	16.64	-1.743%	-0.390%
1835	16.00	-1.735%	-0.422%

Figure 4 shows plots of the deviation of the calculated k_{eff} values from critical at the measured critical control blade height when the blades are modeled as fresh as well as with their burnup history. As seen from the plot, the result of adding the depleted control blades to the existing HEU MURR core model shows a significant improvement; the average deviation from critical is -0.41% Δk/k when the blade depletion is modeled, compared with -1.1% Δk/k if the blades are modeled as fresh. It can also be seen from the plot that for those cases with small total control blade burnup history, the two deviations are practically the same – indicating the effect is more pronounced for the cases involving control blades with large total burnup.

However, there is still a small negative bias in the predicted k_{eff} values even when the control blade depletion effect is incorporated in the present HEU MURR model. The bias is seen as the slight negative slope in the trend line fitting the solid red squares in Figure 4 and could be due to under-depletion of the B^{10} in some of the larger axial zones above the blade tip where smaller divisions could have been more appropriate. Another contributor to this negative bias could be the MCNP MURR model itself or the bias in the partially burned fuel assemblies incorporated in the weekly start-up cores.

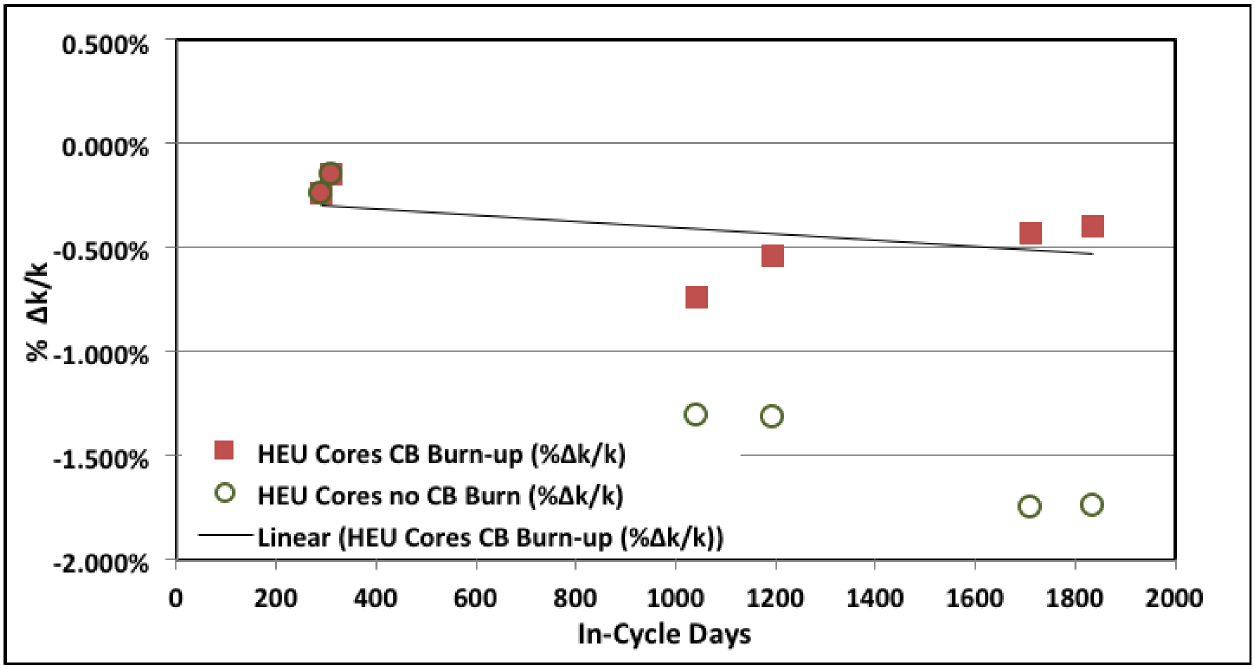
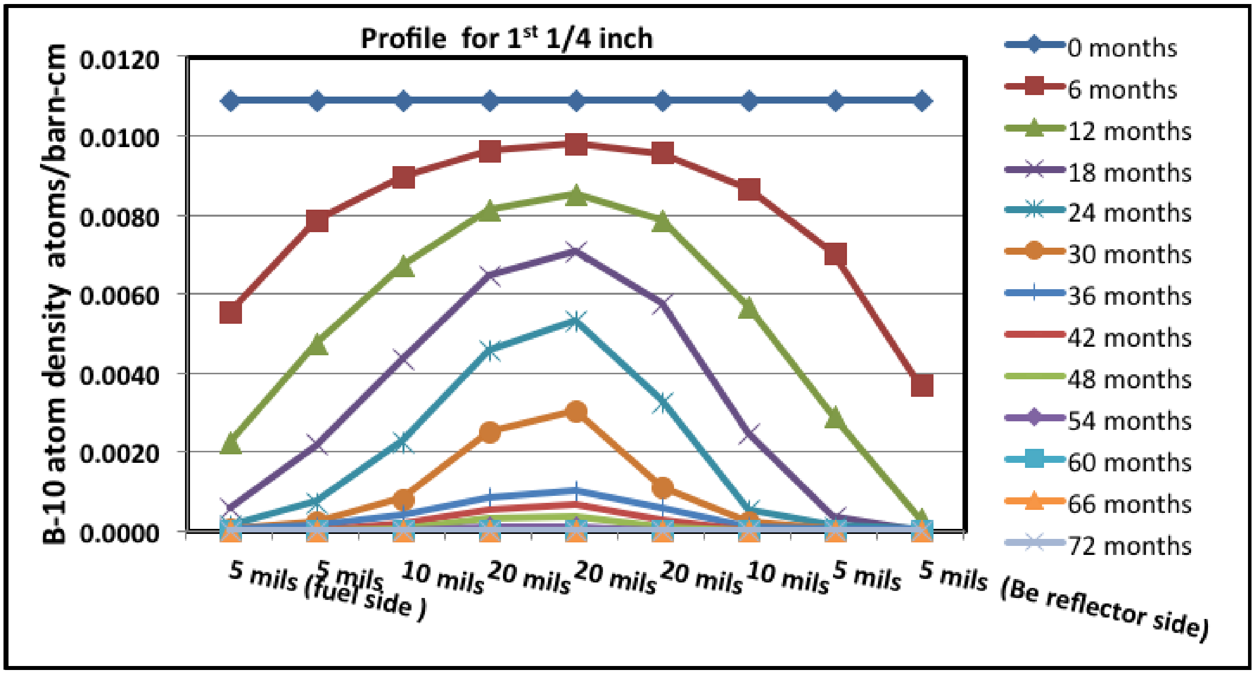


Figure 4. k_{eff} Deviations from critical vs. control blade burnup history for fresh control blades and those blades with depletion history modeled.

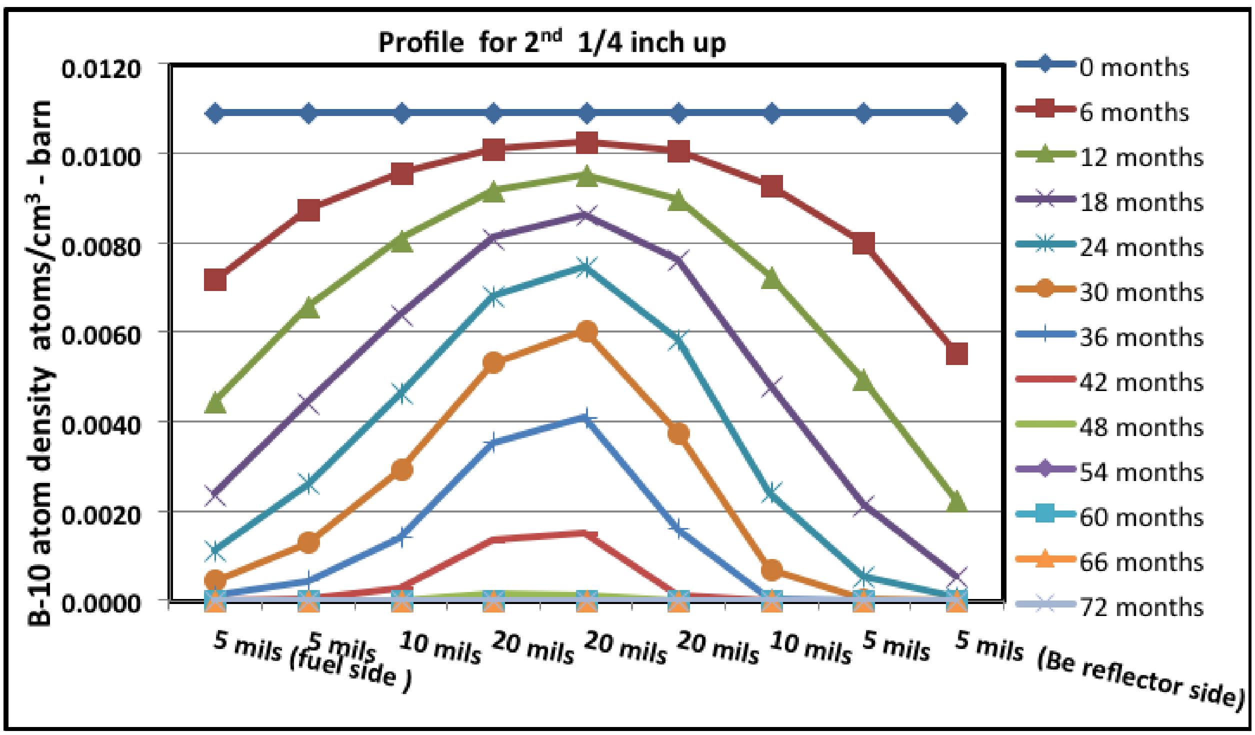
3.3 Blade Burnout Profiles

The B^{10} depletion results for control blade ID 5-08, which began operation in position "C" for its first cycle and remained in the same position for two more consecutive cycles, are shown in Figures 5a – 5c. In Figures 5a and 5b, the azimuthally-averaged radial B^{10} atom densities are shown for the bottom ½-inch of the control blade at each time step. This shows that the overall control blade B^{10} depletions are predominantly a surface driven effect with an asymmetry in the depletion rate on the surface towards the beryllium reflector. This is due to an enhancement in the thermal neutron density on the beryllium side of the blade.

Figure 5a and 5b. Bottom half-inch radial depletion profiles for control blade ID 5-08.



(a)



(b)

Figure 5c shows the axial profile of the B^{10} atom density averaged over radial and azimuthal zones for control blade ID 5-08 at residence times of 0.5, 4.0 and 8.0 years. At 8 years, the B^{10} atom density is essentially zero in the bottom four inches of the blade.

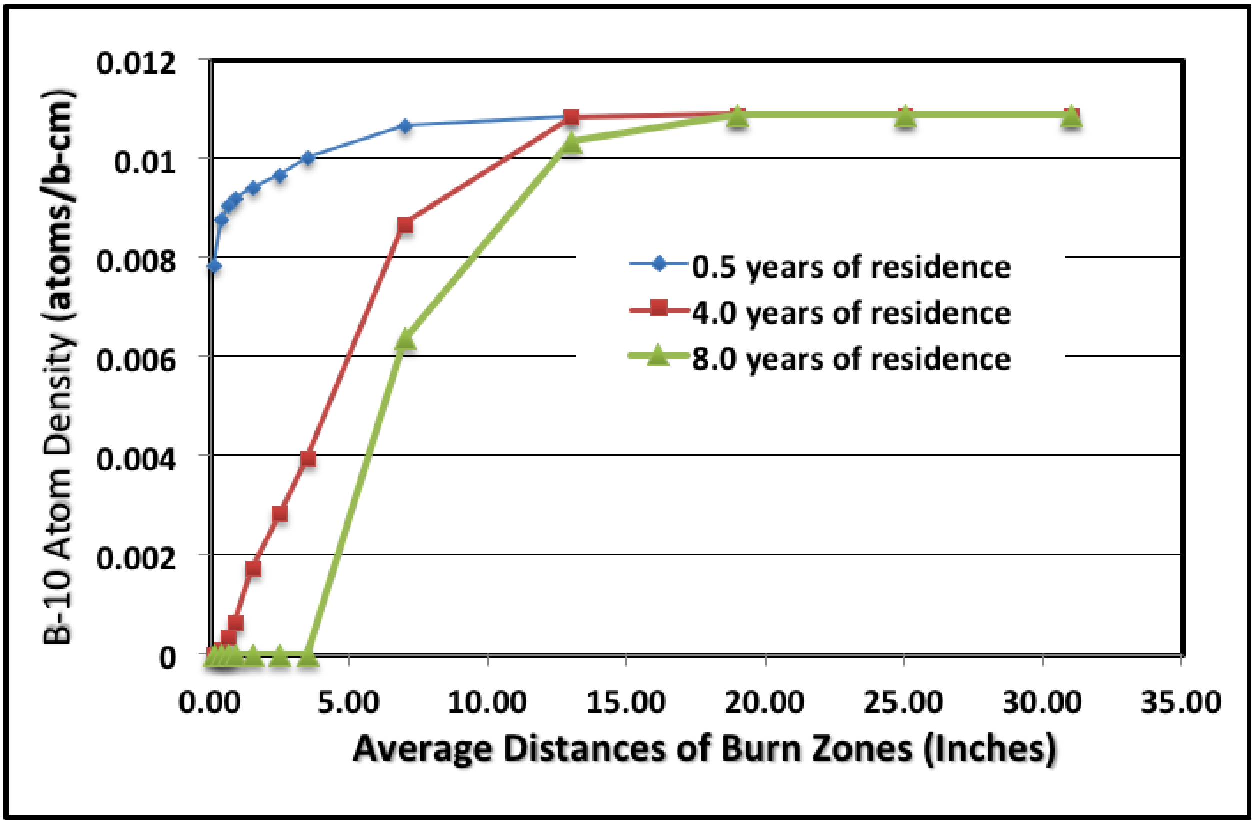


Figure 5c. Axial B^{10} atom density profiles for different residence times for control blade ID 5-08.

4. Conclusion

A comprehensive study was performed first to estimate the MURR control blade depletion profile and then to incorporate the depleted control blade models into the existing HEU MURR MCNP core model. Using a typical MURR core configuration in two fully modeled state-points, the full control blade depletion cycle was simulated, which yielded the full burnup history for 19 individual control blades. The initial part of the study focused on understanding the impact of different core configurations on the B^{10} reaction rate profiles for each blade position. The effect of core configuration was found to have little impact on the B^{10} depletion. The overall B^{10} depletion is predominantly a surface driven effect in the bottom four inches of the control blade with an asymmetry in the depletion rate on the surface towards the beryllium reflector. Combining the depleted blade models with that of partially burned fuel elements for weekly start-up cores significantly improved agreement of the calculated core k_{eff} compared to critical measurements. The deviation (% $\Delta k/k$) of the calculated core k_{eff} values from critical was reduced from an average of -1.1%, when the blades are modeled as fresh, to -0.41% when the depleted blade model is included. There remains a small negative bias in the results, which can be attributed to either the need for finer discretization of the blade depletion model or a bias in the MURR MCNP model developed for the feasibility study.

References

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[2] X-5 Monte Carlo Team, "MCNP-A General Monte Carlo N-Particle Transport Code, Version 5 Volume I, II and III," LA-UR-03-1987/LA-CP-03-0245/LA-CP-03-0284, Los Alamos National Laboratory (2003).

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[5] Deen, J. R., et al., "WIMS-ANL User Manual, Rev. 5," ANL/TD/TM99-07, Argonne National Laboratory, 2003.