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LEU CORE DESIGN FOR THE CONVERSION OF UNIVERSITY OF WISCONSIN NUCLEAR REACTOR

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ABSTRACT

In September 2009 the University of Wisconsin Nuclear Reactor, a TRIGA 1MW MTR conversion reactor, was converted from HEU fuel (70 percent enriched TRIGA-FLIP) to LEU fuel (20 percent enriched TRIGA LEU 30/20). The HEU core was used to validate models in preparing the conversion safety analysis report, but limited data was available to establish reactivity bias. Core design indicated a reduction in fuel pins was necessary. Initial core startup testing revealed a reactivity deficit largely attributed to the inability to define the MCNP model reactivity bias of the HEU core. Part of the reactivity bias was due to modeling of new reflector assemblies installed during the fuel conversion. A future fuel shuffle is planned in order to increase core excess reactivity and core lifetime to be consistent with the original conversion safety analysis report. Extra fuel pins were ordered but are not expected to be used at this time.

1. Introduction

In August 2007 the University of Wisconsin Nuclear Reactor (UWNR) was notified that funding would be available to complete the conversion of the reactor fuel from Highly Enriched Uranium (HEU) to Low Enriched Uranium (LEU). The conversion safety analysis report was prepared by the university with technical assistance provided by Argonne National Laboratory. The analysis used an existing MCNP model of the HEU core[1] to make predictions for the LEU core, and was submitted to the NRC after one year in August 2008[2]. A spent fuel shipment was made in May 2009 to make room in the fuel storage pit for the new LEU fuel. In June 2009 the NRC approved the conversion safety analysis report and issued the order to convert, after which all operations on the HEU core ceased. New LEU fuel was received in July 2009 followed by inspection and assembly into four-pin clusters and off-loading of all HEU fuel. The new LEU core achieved initial criticality in September 2009[3]. After performing core startup testing it was discovered that the new LEU core had a 0.5 %Δk/k reactivity deficit when compared to predictions. Finally in July 2010 a spent fuel shipment was made to remove HEU fuel from the facility.

2. Benchmarking the HEU MCNP Model

A MCNP model of the HEU core recently developed in 2005[1] was used in performing the safety analysis of the HEU core to provide comparisons to the LEU core analysis. Unfortunately there were limited records available for benchmarking the HEU model, largely due to a previous file storage purge of non-essential records which included details of core startup testing and recorded control element configurations. Even if these records had been available, the mixed core history of the HEU fuel would made comparisons to the fresh fuel MCNP model inappropriate. The HEU fuel was phased into use in three stages of mixed cores with significant burnup in each mixed core. In order to make suitable comparisons to the HEU mixed core startup testing measurements, the burnup of the old TRIGA LEU fuel would need to be modeled in addition to the burnup of the mixed cores with HEU. This extensive modeling of the TRIGA core history was beyond the scope of the original MCNP model development, and there was insufficient time in the conversion project schedule to include this in the LEU conversion safety analysis. Therefore efforts continued in refining the HEU MCNP model for calculating baseline values to be used for comparison to the LEU core design. Because of the limited availability of detailed core startup testing records, as well as the complex mixed core history of the HEU fuel, it was not possible to estimate the MCNP model reactivity bias with any reasonable certainty.

3. LEU Core Design

Because no reactivity bias could be established in the HEU MCNP model, the LEU core design proceeded with the assumption that there was no reactivity bias in the LEU MCNP model. Since the LEU 30/20 fuel was designed to be a like-for-like replacement of HEU FLIP fuel, the initial LEU core design was identical to the HEU core with 23 fuel bundles (91 fuel pins) and 10 reflector assemblies. However, this core was found to be too reactive and could not be shutdown even with all control elements fully inserted. In hindsight, it should not have been a surprise that the LEU 30/20 fuel was predicted to be more reactive. Erbium, a burnable neutron poison, is loaded to 1.48% in the HEU fuel but only 0.90% in the LEU fuel. Furthermore, the U-235 content is only 124g HEU compared to 149g LEU. Less neutron poison and more U-235 make the LEU 30/20 fuel more reactive than HEU FLIP.

In order to meet shutdown margin requirements, the LEU core was designed with 2 fewer fuel bundles for a total of 21 fuel bundles (83 fuel pins). Additional reflector assemblies were added, for a total of 14, in order to boost reactivity to compensate for the loss of so much fuel. Figure 1 shows the core maps of the HEU and LEU cores. The burnup curves shown in Figure 3 show that the predicted LEU core life was significantly reduced compared to the HEU core due to having fewer fuel pins. Because of the shorter lifetime, and the uncertainty in the model reactivity bias, the purchase of LEU fuel pins included enough extra fuel to allow adding 2 fuel bundles at a later time if needed.

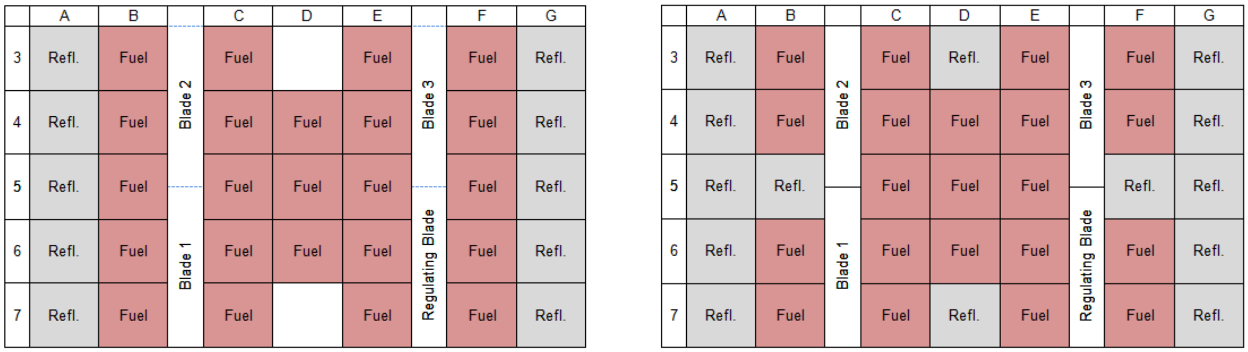


Figure 1, Core Map: HEU on Left, LEU on Right

4. LEU Core Startup Testing

After struggling with limited or incomplete data on the HEU core startup testing, the LEU core startup plan was written to include extensive measurements on the new core for possible future academic work at the university. After achieving initial criticality with 18 fuel bundles, critical bank height and rod-drop shutdown margin measurements were made with each fuel bundle addition until reaching the full complement of 21 fuel bundles. Control elements were calibrated and the reactivity worth of individual reflector positions measured before loading the full complement of 14 reflector assemblies. Critical bank height and rod-drop shutdown margin measurements were again made with each step of reflector addition. After loading all fuel and reflectors, control elements were calibrated again and the reactivity worth of individual reflector positions measured. In addition to detailed control element calibrations, various control element configurations were attempted in order to shift the flux into specific areas of the core. This resulted in 115 unique critical control element configurations being measured on the operational core. Additional measurements on the operational core included reactivity and flux of experimental facilities, coolant void coefficient, pulsing, square-wave curves, and a complete core map of fuel temperature using the installed instrumented fuel elements.[3]

After recording critical bank heights and performing control element calibrations on the operational core, a significant reactivity deficit was observed with the new LEU core. The measured excess reactivity was approximately 0.5 %Δk/k less than predicted in the conversion safety analysis report. Therefore an investigation was begun to explain the reactivity deficit of the new core and to predict what the consequences of such a deficit could be.

5. Investigating Reactivity Deficit

The first possibility to explain the loss of reactivity is a difference between as-built fuel material compositions vs. what was assumed when performing the conversion analysis. No mass spectrometer analysis on LEU fuel had been performed for detailed impurity analysis, but data was provided on U-235 and total uranium content, erbium and carbon weight percent, and hydrogen-to-zirconium atom ratio.[4] Average values were calculated for all fuel loaded in the core and compared to values assumed in the analysis. The as-built U-235 content was identical to the assumed value, the erbium content was 0.88% instead of 0.90%, and the hydrogen-to-zirconium atom ratio was 1.59 instead of 1.60. Although the as-built hydrogen-to-zirconium atom ratio is slightly lower, which would lead to loss of reactivity, the more significant change is the reduction in erbium. Since erbium is a neutron poison, a reduction would result in a reactivity increase, not a decrease. It was concluded that the as-built fuel was not the cause of the reactivity deficit.

Other than the LEU fuel, the only change made in converting the core was the replacement of 10 old reflectors with 14 newly fabricated reflectors. During the process of loading reflector assemblies in the new core, some of the new reflector bases had to be machined down to properly fit in the grid plate. Because of this, measurements were made comparing the reactivity worth of old and new reflectors, including mixtures of both, until all new reflectors could be swapped into service and all old reflectors were removed from the core. These measurements confirmed that the reactivity of the new reflectors was identical to the old reflectors. Therefore the new as-built reflectors were not the cause of the reactivity deficit.

The remaining cause of the reactivity deficit was a reactivity bias or inaccuracy in the MCNP model. Before calculating the model bias, the LEU MCNP model was updated to be as detailed and current as possible. As-built fuel material data on a slug-by-slug basis was used to update the fuel material definitions in the model. Furthermore, the as-built drawings of the new reflector assemblies were used to update the model geometry and material composition to include the appropriate boron impurity. A few minor corrections were also made to the control element geometries.

After updating the LEU MCNP model of the core, the 115 unique critical control element configurations recorded during core startup testing were run using the MCNP model to establish the model reactivity bias. For all measured critical control element configurations, MCNP calculated a k_{eff} value of 1.01222 ± 0.00040, or approximately a $1.60 reactivity bias. The hot model, representing operation at 1MW full power, calculated a k_{eff} of 1.00971, or approximately $1.20 reactivity bias. Because operational practice precludes operation at high power with other than a banked control element configuration, there was only one measurement to use in estimating the hot model reactivity bias.

To determine if the model reactivity bias was the result of inaccurate modeling of fuel pins or reflector assemblies, the MCNP model was modified to reflect intermediate loading steps for which critical bank height information was available. The results are shown in Figure 2. The first data point is with 18 fuel bundles and no reflectors, when initial criticality was achieved, followed by 3 more fuel bundle additions. There is a positive but very small trend in reactivity bias as fuel is loaded, indicating that fuel pins are being reasonably represented in the MCNP model. The remainder of the graph shows a significant positive trend in reactivity bias as reflector assemblies are loaded. Clearly there is a discrepancy between the modeling of reflector assemblies and the physical reflectors, but despite a thorough investigation and sensitivity study on reflector graphite and clad dimensions and graphite impurities, nothing was found to explain this discrepancy. However, even accounting for the reflector contribution, there is still a remaining model reactivity bias which is unexplained. It is likely that this reactivity bias, including the reflector contribution, was pre-existing in the HEU MCNP model. But, as discussed previously, the HEU MCNP model reactivity bias could not be established due to lack of detailed records and a complicated fuel history. Therefore the MCNP model reactivity bias of 1.01222 cold and 1.00971 hot was accepted to be used in future analysis.

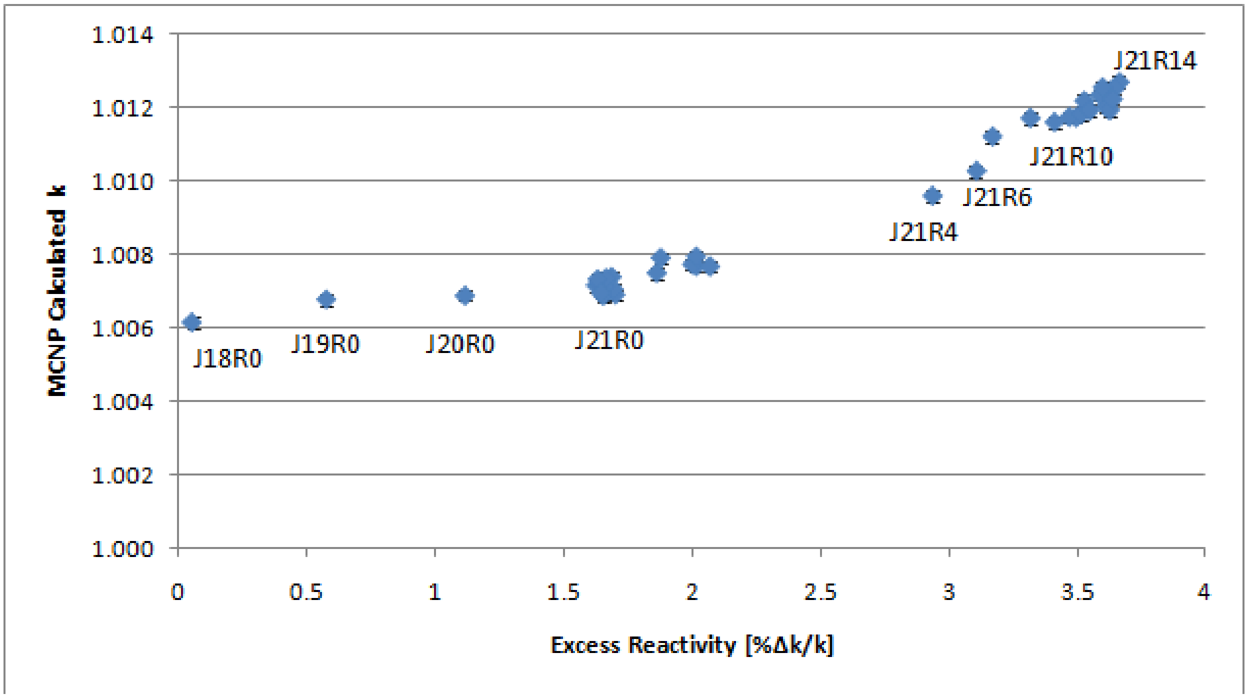


Figure 2, MCNP Reactivity Bias during Fuel and Reflector Loading

The original conversion safety analysis used REBUS-MCNP[5] to calculate core burnup. This calculation was repeated using the updated MCNP model and accounting for the established reactivity bias to see what effect it had on predicted core life. Figure 3 shows a significant reduction in core life. With an operational minimum of 0.5 %Δk/k hot excess reactivity, the revised burnup curve of the LEU core predicts reaching end of core life after only 50 MWd. With the typical operating schedule of the UWNR, this would mean reaching end of life after only 2 years. This motivated a core redesign to shuffle the fuel and possibly add new fuel within the next few years.

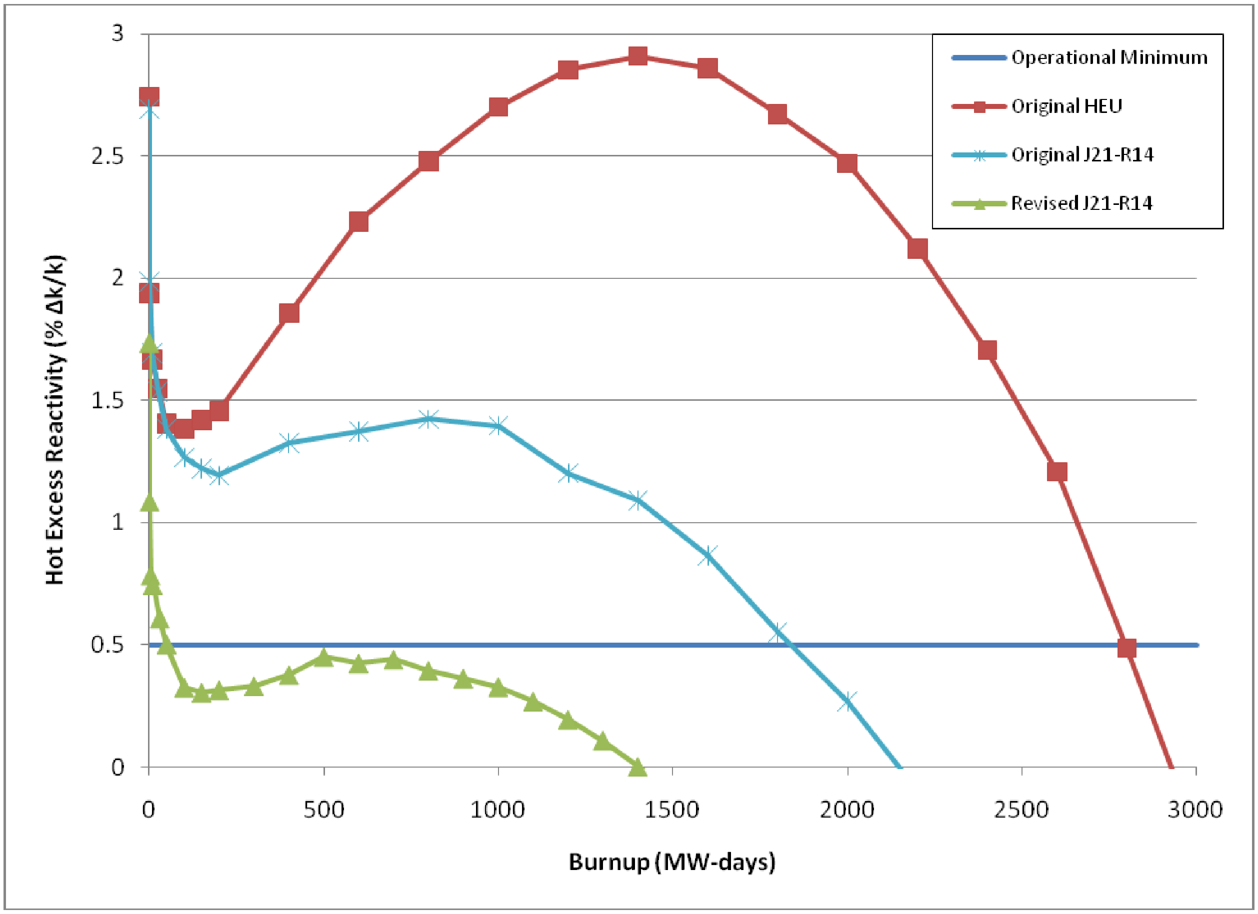
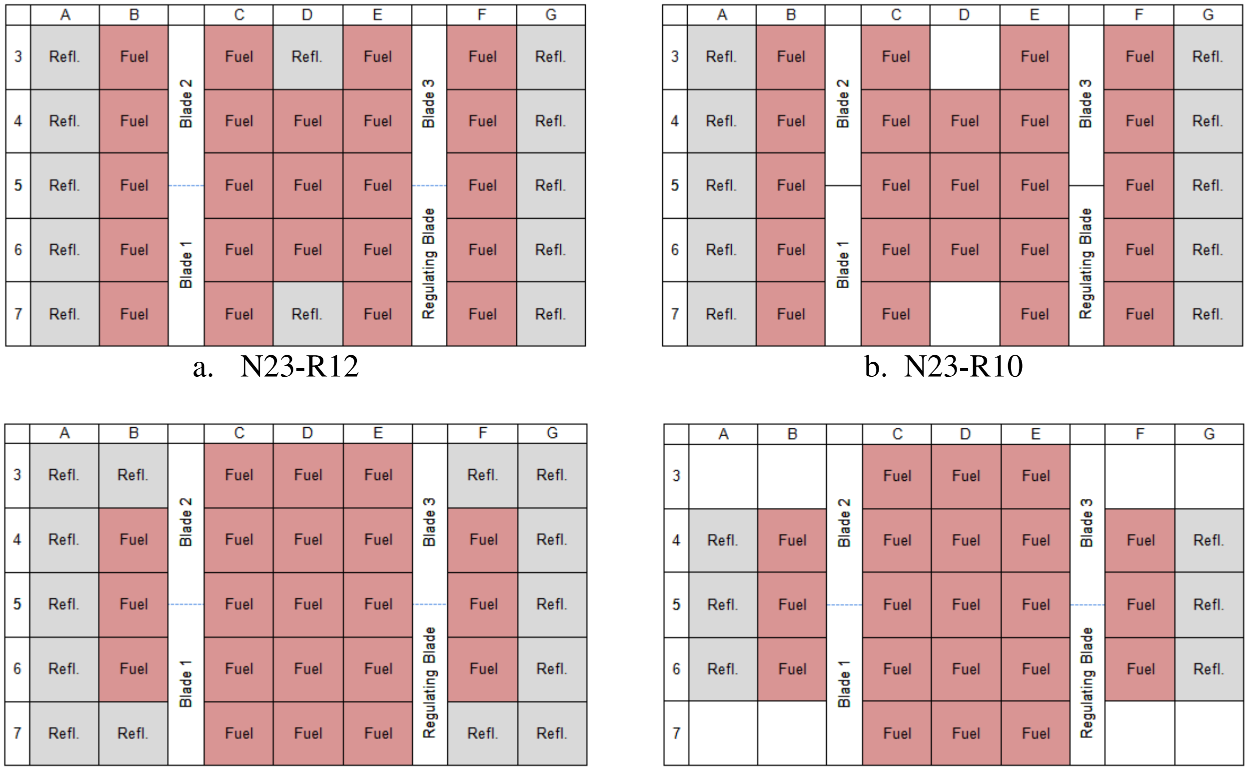


Figure 3, Revised Core Burnup Curves

6. LEU Core Shuffle Design

The initial core design considered was a return to the HEU core design, with 23 fuel bundles and 10 or 12 reflectors, shown in Figure 4 a and b. Even after accounting for the model reactivity bias, these cores could not meet shutdown margin requirements and were rejected. Rather than add additional fuel, the existing 21 fuel bundles were shuffled to a more compact design shown in Figure 4 c and d. Several reflector configurations with this compact shuffled core were investigated, with the final core shuffle design shown in Figure 4 d. This core was the only one that satisfied shutdown margin requirements. It was also desired to maintain reflectors on the sides to ensure a consistent neutron flux to the nuclear instrumentation. Possible new experimental facilities may also be installed in the corner positions where reflector assemblies have been removed.



a. N23-R12

b. N23-R10

c. N21-R14

d. N21-R6 (final design)

Figure 4, Proposed Core Shuffle Maps

The burnup curve for the new shuffled core design was calculated and shown in Figure 5. With the core shuffle, the core lifetime is extended to nearly the same value as the original conversion analysis predicted. A 50.59 analysis is currently in progress on the core shuffle design, but preliminary calculations of neutronic and thermal-hydraulic parameters predict no problems with the new core design.

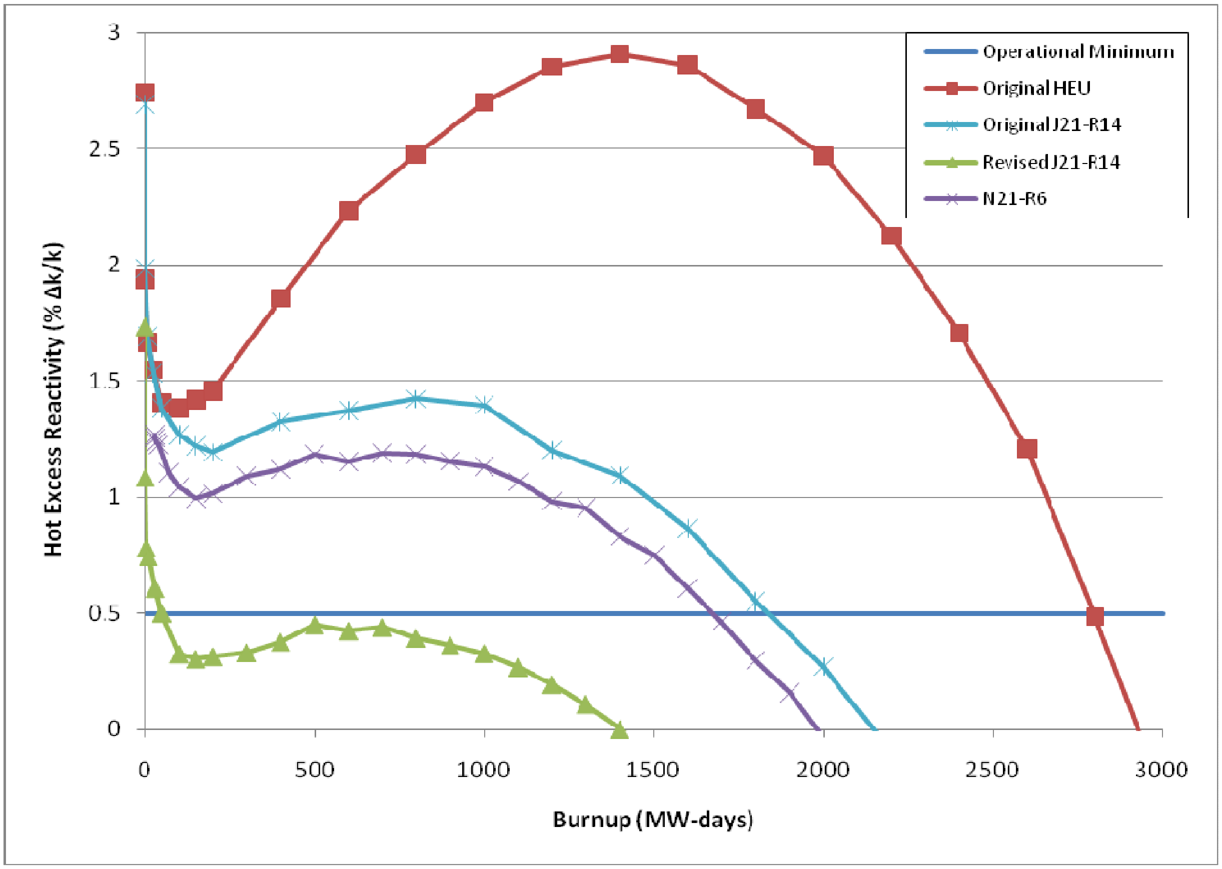


Figure 5, Core Shuffle Burnup Curve

7. Conclusions

The conversion of UWNR from HEU to LEU fuel was a positive experience overall. The only major difficulty was the observed excess reactivity deficit in the LEU core. However, this was not attributed to the manufacture of fuel pins or reflector assemblies, but rather was due to the inability to begin the initial core design with an accurate verified MCNP model with a well established reactivity bias. For other facilities still waiting to convert, efforts should be made to refine and verify the accuracy of any existing MCNP models of current HEU cores. Furthermore, after physically converting efforts should be made to establish the measured reactivity bias in order to investigate impacts on core burnup. Although the UWNR experienced a reactivity deficit on the new LEU core, there are still sufficient spare fuel pins to accommodate future core redesigns to significantly extend core life well into the foreseeable future.

[1] Paul W. Humrickhouse and Paul P.H. Wilson, "Validating a Monte Carlo Model of the University of Wisconsin Nuclear Reactor with Operational Data," *Nuclear Technology* (September 2005).

[2] University of Wisconsin Nuclear Reactor, "Safety Analysis Report for the Conversion of the University of Wisconsin-Madison TRIGA Reactor from HEU to LEU Fuel," August 2008.

[3] University of Wisconsin Nuclear Reactor, "Reactor Start-up Report," June 2010.

[4] AREVA & TRIGA International, "Documentation for Wisconsin Fuel Elements," CI 8782.

[5] J.G. Stevens, "The REBUS-MCNP Linkage," April 2008, Argonne National Laboratory Document Number ANL/RERTR/TM-08-04.