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# Planning the HEU to LEU Transition for the NBSR

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**ABSTRACT**

A study has been carried out to understand how the NIST research reactor (NBSR) might be converted from using high-enriched uranium (HEU) to using low-enriched uranium (LEU) fuel. An LEU fuel design had previously been determined which provides an equilibrium core with the desirable fuel cycle length—a very important parameter for maintaining the experimental, scientific program supported by the NBSR. In the present study two options for getting to the equilibrium state are considered. One option starts with the loading of an entire core of fresh fuel. This was determined to be unacceptable. The other option makes use of the current fuel management scheme wherein four fresh fuel elements are loaded at the beginning of each cycle. However, it is shown that without some alterations to the fuel cycle, none of the transition cores containing both HEU and LEU fuel have sufficient excess reactivity to enable reactor operation for the required amount of time. It was determined that operating the first mixed cycle for a sufficiently reduced length of time provides the excess reactivity which enables subsequent transition cycles to be run for the desired number of days.

## 1. Introduction

Planning is underway to convert the NIST research reactor (NBSR) from using high-enriched uranium (HEU) fuel to low-enriched uranium (LEU) fuel. Analysis has been carried out to determine the core neutronic parameters for the equilibrium LEU core but the question remains as to how to transition from the current equilibrium HEU core to the new equilibrium core. This must be done with minimum impact on the mission of the reactor (providing neutrons for experimentalists) and on the safety envelope. The object of this study is to consider the different possibilities and the difficulties which might need to be overcome.

## 2. Loading a Complete Core of Fresh LEU Fuel

One obvious way to switch the fuel in the core is to load an entire core of 30 fresh LEU fuel elements and then use the current fuel management scheme in succeeding cores until equilibrium is achieved. However, analysis shows that this approach is unacceptable because the excess reactivity would be too high.

NBSR Technical Specification 3.1.2, Reactivity Limitations, states that the core cannot be loaded such that the excess reactivity will exceed 15% $\Delta k/k$ and it also states that the NBSR shall not be operated if it cannot be kept shutdown with the most reactive shim arm fully retracted. Calculations of a full LEU core give an excess reactivity of 15.6% $\Delta k/k$ which is greater than the 15% $\Delta k/k$ allowed by the Technical Specification and calculations also show that the reactor could not be kept subcritical with one of the shim arms withdrawn while the others were inserted.

The analysis also shows that a fresh LEU core will have local power densities that are much higher than the current HEU or a future LEU equilibrium core. The maximum half-fuel element power generation would be 524 kW if the core would be loaded with 30 fresh LEU fuel elements. This is in contrast to the 427 KW for the current HEU core and 450 kW for the equilibrium LEU core. A complete thermal hydraulic analysis of the situation does not need to be completed because the core is already disqualified because excess reactivity and shutdown margin exceed the Technical Specifications. Nevertheless, it is plausible that an almost 25% increase in half-element power would also lead to unacceptable thermal conditions.

## 3. The Present HEU Fuel Management Scheme

Another plan to transition to an equilibrium core filled with 30 LEU fuel elements is to follow the fuel management scheme that has been used for the HEU fuel. In this scheme, four fresh fuel elements are placed at the perimeter of the core each cycle and then moved to other locations in succeeding cycles. They are placed at the edge in order to maximize the flux in neutron beam tubes which extract neutrons for use in research. A gradual transition from HEU to LEU fuel like this will require more than one year to complete; eight cycles to replace all HEU fuel plus additional cycles to reach equilibrium. An important constraint--essential to the scientific program supported by the NBSR--on this and any scheme is to maintain an operational cycle length of 38.5 days.

The current fuel management scheme is illustrated in Figures 1 and 2. Figure 1 shows the fuel element position designation for the 30 fuel elements. There are four rows numbered 1 through 7 and 14 columns labeled A through M. The positions denoted in the figures with <> are the locations of the 3.5-inch in-core irradiation thimbles and the position denoted with <RR> is the regulating rod.

Figure 2 shows the core labeled with three characters. The third character is either E or W for east or west half of the core. The first character is a 7 or 8 indicating the fuel elements that will be in the core for either 7 or 8 cycles. The second character is a number 1 through 8 indicating the cycle in which the fuel is presently residing. At startup, the 7-1 and 8-1 fuel elements are fresh, unirradiated fuel elements. The 7-7 and 8-8 are fuel elements in their final cycle. At the end of each 38.5-day cycle, the four fuel elements labeled 7-7E, 7-7W, 8-8E and 8-8W are removed from the core. The remaining 26 fuel elements are moved to new locations: the 7-6E fuel element is moved into the 7-7E position; the 8-7W fuel element is moved into the 8-8W position, and so forth with the fuel elements always staying in either the east or west half of the core. All the fuel elements are relocated in this manner, until the four 7-1 and 8-1 positions are vacant. Fresh fuel elements are then loaded into those positions.

| | A | B | C | D | E | F | G | H | I | J | K | L | M |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | COLD SOURCE | | | | | | | | | |
| 1 | | | | D1 | | F1 | | H1 | | J1 | | | |
| 2 | | | C2 | | E2 | | <> | | I2 | | K2 | | |
| 3 | | B3 | | <> | | F3 | | H3 | | <> | | L3 | |
| 4 | A4 | | C4 | | E4 | | <> | | I4 | | K4 | | M4 |
| 5 | | B5 | | <> | | F5 | | H5 | | <> | | L5 | |
| 6 | | | C6 | | E6 | | <RR> | | I6 | | K6 | | |
| 7 | | | | D7 | | F7 | | H7 | | J7 | | | |

**Figure 1. Fuel Element Position Designation**

| | A | B | C | D | E | F | G | H | I | J | K | L | M |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | COLD SOURCE | | | | | | | | | |
| 1 | | | | 8-1W | | 7-2W | | 7-2E | | 8-1E | | | |
| 2 | | | 8-3W | | 7-5W | | <> | | 7-5E | | 8-3E | | |
| 3 | | 7-3W | | <> | | 8-7W | | 8-7E | | <> | | 7-3E | |
| 4 | 7-1W | | 8-6W | | 7-7W | | <> | | 7-7E | | 8-6E | | 7-1E |
| 5 | | 8-4W | | <> | | 8-8W | | 8-8E | | <> | | 8-4E | |
| 6 | | | 7-4W | | 7-6W | | <RR> | | 7-6E | | 7-4E | | |
| 7 | | | | 8-2W | | 8-5W | | 8-5E | | 8-2E | | | |

**Figure 2. Fuel Management Scheme**

## 4. Methodology

The analysis carried out for a transition using the current fuel management scheme is done with MCNP.v5, [1] and MCNPX.v6 [2], invoking the BURN option. ENDF/B-VII libraries were used. This BURN option allows for the extraction of inventories as has been described in [3]. The flow chart for the logic is shown in Figure 3. SU (startup) refers to the core without xenon and other short lived isotopes, and with fresh fuel loaded. BOC (beginning-of-cycle) is the core one and a half day into the cycle, with the xenon burned in. MID is a point between BOC and EOC and EOC is end-of-cycle when the shim arms are completely removed and the reactor must be refueled. The methodology described in [3] is used, however, the development of the models with cores that contain both LEU and HEU is more laborious than that with only one type of fuel.

## 5. The NBSR Transition Problem and Solution

Unfortunately, there is a problem with using the current fuel management scheme. Even though there is enough $^{235}U$ in each fresh fuel element to have the proper excess reactivity to maintain a 38.5-day cycle when the core is all HEU or all LEU, the distribution of $^{235}U$ in the mixed core is insufficient to provide an acceptable amount of excess reactivity. The excess reactivity with the equilibrium HEU core required to maintain a 38.5 day cycle is calculated to be 6.7% Δk/k. For the LEU equilibrium core it is calculated to be 6.3% Δk/k. When the first four LEU fuel elements are loaded into the core the excess reactivity immediately drops to 6.1% Δk/k and there is insufficient reactivity to maintain the 38.5-day cycle.

The drop in excess reactivity is related to a redistribution of power within the core as LEU is introduced. One way to understand this is to consider the power distributions for the equilibrium cores. The cooling system for the NBSR has two plena, the inner plenum cools the inner six fuel elements, (E4, F3, F5, H3, H5, and I4), and the outer plenum cools the other 24 fuel elements. Changes in the power levels for each plenum need to be calculated in case the flow in each plenum needs to be adjusted. At startup the total power generated in the six central fuel elements changes from 4.00 MW for the HEU core to 4.34 MW for the LEU core, an 8.5% increase. At EOC the innermost six fuel elements generate 3.82 MW with the HEU core and 4.24 MW with the LEU core, an 11% increase. This is further demonstrated in Figures 4 and 5.

Figures 4 and 5 show the total power generated for the equilibrium HEU and LEU fueled cores at startup in the two 7-cycle (Figure 4) fuel element pairs (E+W) and two 8-cycle (Figure 5) fuel element pairs (E+W) as a function of the cycle in which they reside. The 7-1(E+W) and 8-1(E+W) fuel elements in Cycle 1 are the freshest fuel elements and are located on the perimeter of the core, as shown in Figure 2. The 7-2(E+W) and 8-2(E+W) fuel elements in Cycle 2 have completed one cycle and are also located on the perimeter of the core. The fuel elements in cycles 3 and 4 are also located on the perimeter of the core. Cycle 5 has the 8-5(E+W) fuel elements on the perimeter of the core and the 7-5(E+W) fuel elements on the interior of the core. The fuel elements in Cycles 6, 7, and 8 are all in the interior of the core. The six fuel elements serviced by the inner plenum are the 8-7(E+W), 7-7(E+W), and the 8-8(E+W) fuel elements. These figures demonstrate that the power generated on the perimeter of the core is higher for the HEU core than it is for the LEU core and the power generated in the interior of the core is higher for the LEU core than it is for the HEU core when both are at equilibrium. This is problematic because the NBSR is more efficient in providing neutrons to experimentalists when the power is peaked at the periphery of the core.

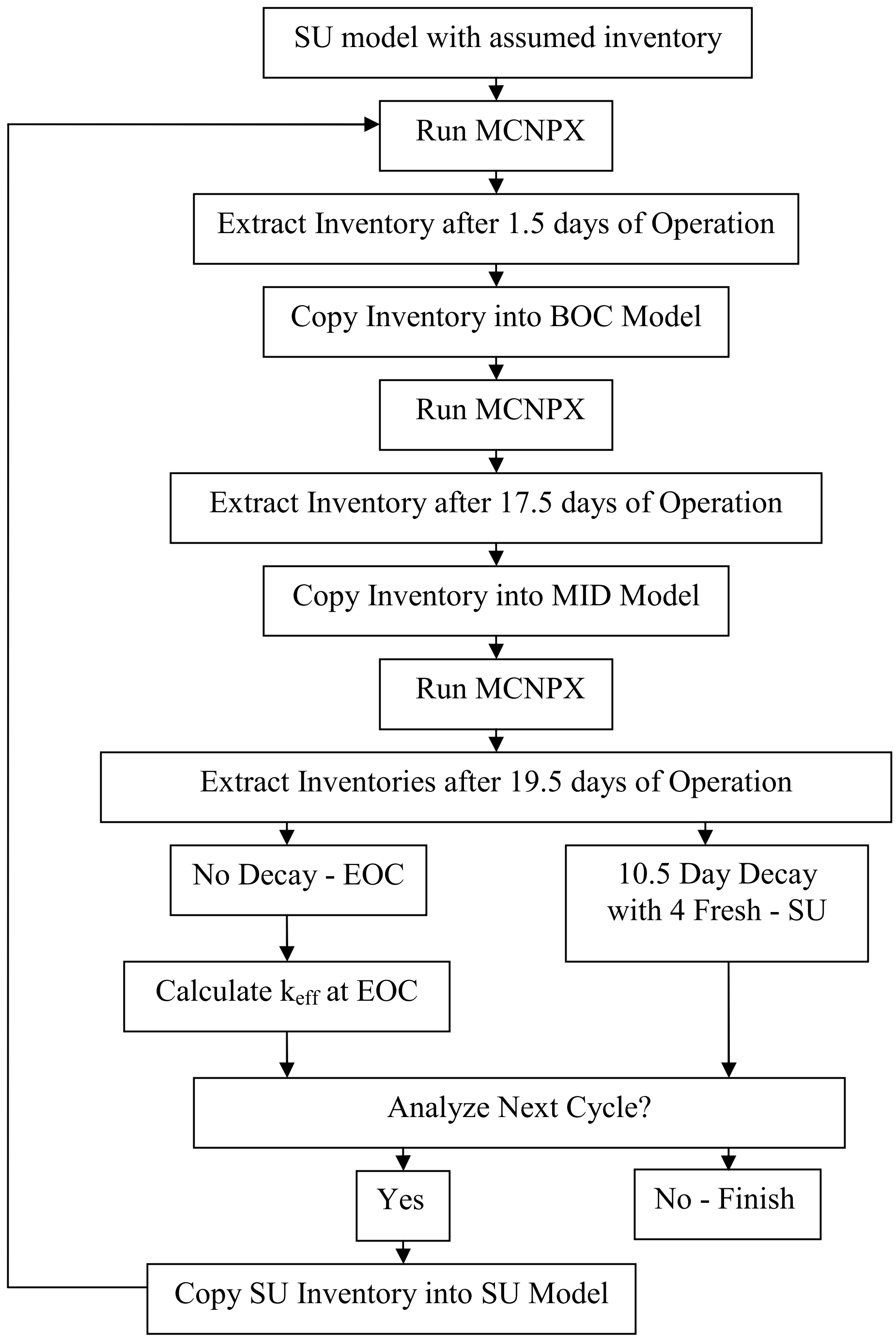


**Figure 3. Flow Chart for the Methodology for Generating Inventories with MCNPX**

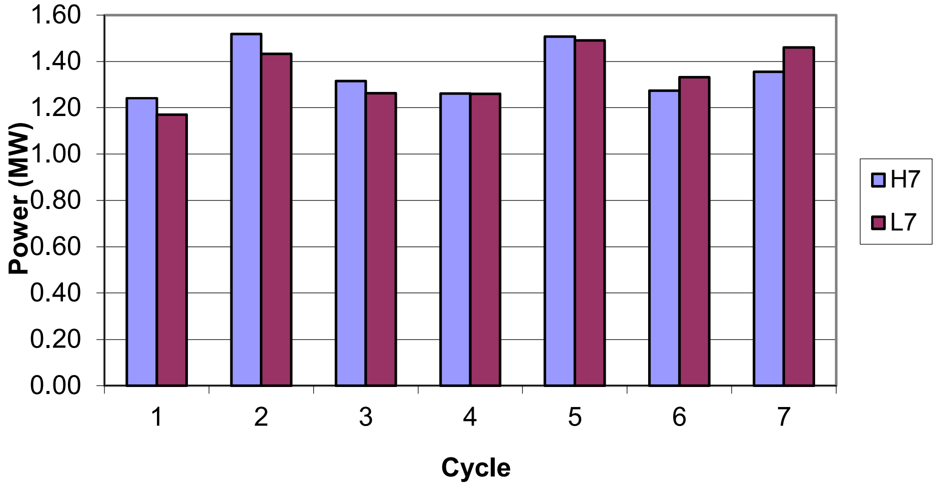


**Figure 4. Power generated in each fuel element pair (E+W) for 7-cycle fuel elements for HEU (H7) and LEU (L7) fuels at SU.**

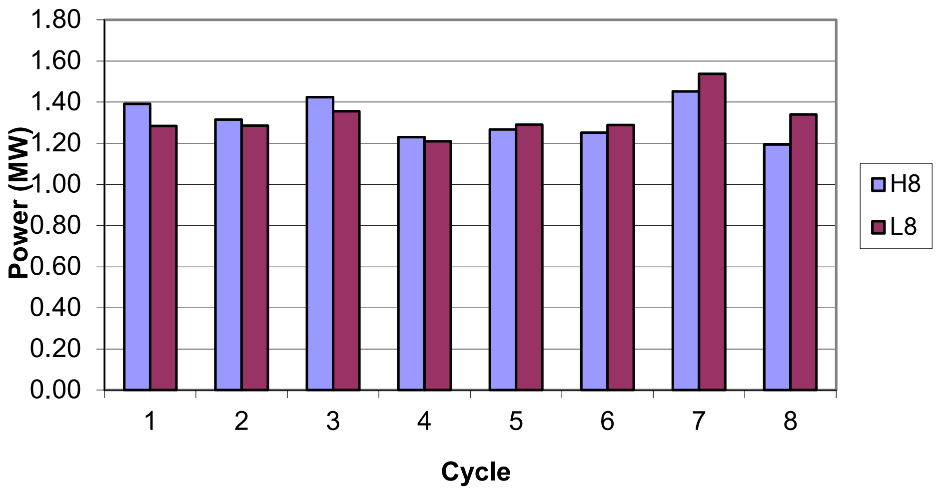


**Figure 5. Power generated in each fuel element pair (E+W) for 8-cycle fuel elements for HEU (H8) and LEU (L8) fuels at SU.**

Two ways to proceed with the transition are the following:

1. Continue with the present fuel management scheme and operate the reactor in each transition cycle until it cannot continue to run. This will mean there will be no 38.5-day cycles until all of the HEU fuel has been removed from the core, which is eight cycles or approximately one year.

2. Shorten the first mixed cycle to provide subsequent cores enough needed excess reactivity to operate the NBSR for 38.5 days after the initial shortened cycle.

Success is determined if all of the cycles will have a calculated $k_{eff}$ equal to, or greater than, 1.00616, the calculated value of $k_{eff}$ at the end of a cycle for the HEU fuel (i.e. the bias in the MCNPX calculation). Figure 6 shows the value of $k_{eff}$ at the end of each cycle assuming a 22-day and 24-day first cycle (as opposed to the normal 38.5 day cycle). Also plotted is the value of $k_{eff}$ if no cycle were shortened and if one could keep the reactor running for 38.5 days. From this analysis shortening the first transition cycle to 22 days should allow for the consecutive cycles to be operated for 38.5 days.

NBSR Technical Specification 3.1.2, Reactivity Limitations, states that the core cannot be loaded such that the excess reactivity will exceed 15% Δk/k and it also states that the NBSR shall not be operated if it cannot be kept shutdown with the most reactive shim arm fully retracted. Figure 7 shows the calculated values for the excess reactivity for eight transition cores with the 22-day (22 D) shortened first cycle and if there were no shortened cycle (38.5). The figure also shows the excess reactivity for the equilibrium HEU and LEU cores.

Table 1 shows the values for the shutdown reactivity (all shims in) along with the shutdown margin (SDM) for each shim arm withdrawn for the HEU and LEU equilibrium cores along with the smallest shutdown reactivity and shutdown margin for the transition cores, assuming the first cycle is shortened to 22 days.

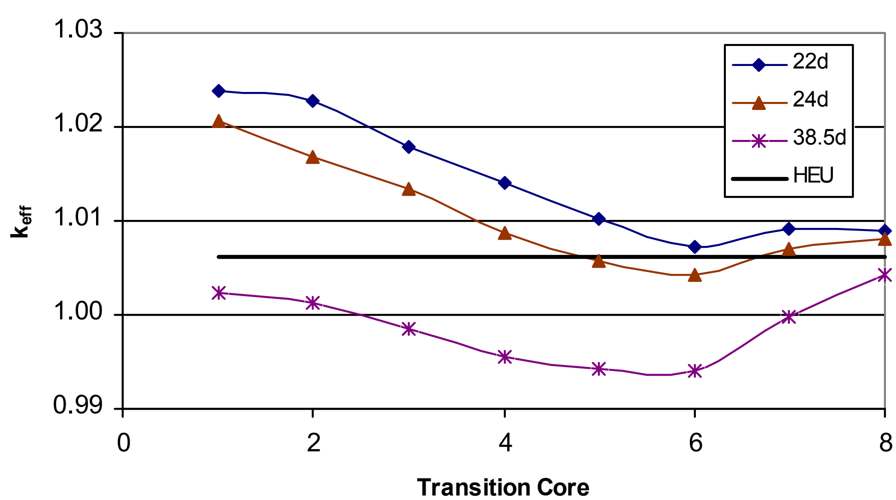


**Figure 6. $k_{eff}$ at EOC for three scenarios for the transition core: 22-day first cycle, 24-day first cycle, and no shortened first cycle (38.5 d), and $k_{eff}$ at EOC for the current HEU core.**

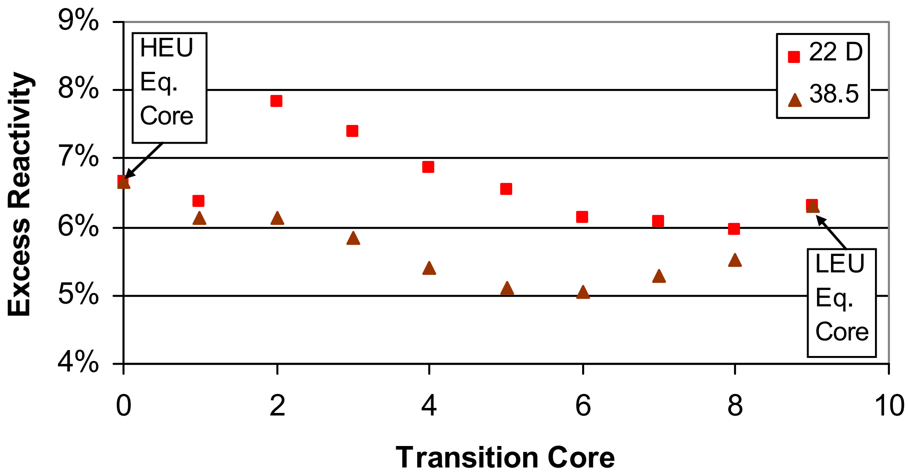


**Figure 7. Excess reactivity for different transition cores with the HEU and LEU equilibrium cores identified**

**Table 1. Shutdown Margins for the HEU, LEU, and 22-day cases.**

| | | | HEU | LEU | 22-day |
|---|---|---|---|---|---|
| Shutdown reactivity (all shim arms in) | | | -18.2% | -18.3% | -16.8% |
| SDM | Shim 1 out | | -12.1% | -12.2% | -10.7% |
| SDM | Shim 2 out | | -11.1% | -11.2% | -9.5% |
| SDM | Shim 3 out | | -10.1% | -10.8% | -9.0% |
| SDM | Shim 4 out | | -11.6% | -11.9% | -10.3% |
| Excess reactivity (all shim arms out) | | | 6.7% | 6.3% | 7.8% |

The additional excess reactivity needed to help minimize the impact of the transition cores on the scientific program is achieved with the loss of only one full cycle where operation will be limited to 22 days. The reduction in the shutdown reactivity and shutdown margin are shown in Table 1. However, the reduction in these quantities is within Technical Specification 3.2.1, assuming fresh shim arms. Since the shim arms degrade over time, the shim arm condition needs to be considered in planning the transition.

## 6. Returning to an Equilibrium Core

After the transition is completed to the extent that no HEU fuel is left in the core, there will be a significant amount of time before the core will approach true equilibrium operations with LEU fuel. This is in part because of the excess reactivity that was needed to be introduced into the system in order to maintain the 38.5-day cycles after the first cycle during the transition. Even if one did not introduce some excess reactivity with the first cycle in the transition, i.e. if the reactor operated with eight reduced-length cycles, there would still be extra excess   Figure 8 shows a plot of $k_{eff}$ as a function of cycle after the transition is completed, with Cycle 8 being the final step in the transition to all LEU fuel.  This figure shows that the value of $k_{eff}$ is higher than the equilibrium value of 1.00616. It will take several cycles of operation before true equilibrium is achieved.  One could consider some extra hours of operation for the NBSR after the transition is completed in order to help reduce the extra excess reactivity.

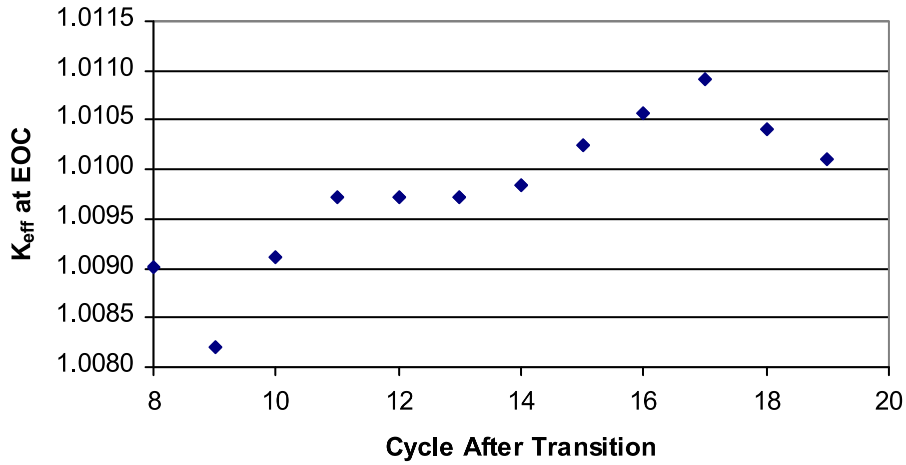


**Figure 8.  The value of $k_{eff}$ as a function of cycle after the transition is completed, with cycle 8 being the last transition core.**

## 7. Conclusions

The conversion of the NBSR from HEU fuel to LEU fuel cannot occur with a single loading of fresh fuel; the fuel must be introduced in a gradual manner.  One promising option for loading the LEU fuel is to use the current fuel management scheme which replaces four fuel elements at a time.  However, if the transition occurs without planning, none of the eight cycles needed to switch out all 30 HEU fuel elements will have enough excess reactivity to operate for a normal 38.5-day period.  This will be a penalty on the experimental program that is unacceptable.  Hence, an alternative plan has been devised with only the first transition cycle having a reduced length.  It has been found that a 22-day first cycle will work, allowing for all the remaining cycles to be the standard 38.5-day length.  This approach would result in a transition that would not be in violation of Technical Specifications on excess reactivity and shutdown margin.  Further calculations are planned to see if the transition cores meet other requirements.

## 8. References


1. "MCNP – A General Monte Carlo N-Particle Transport Code, Version 5", LA-UR-03-1987, Los Alamos National Laboratory, April 24, 2003.

2. D.B. Pelowitz, Ed., MCNPX User's Manual version 2.6.0, LANL report, LA-CP-07-1473, Los Alamos National Laboratory, April 2008.

3. A.L. Hanson and D.J. Diamond, "Calculation of Inventories, Power Distributions and Neutronic Parameters for the NBSR Using MCNPX," Presented at the TRTR_IGORR Joint Meeting, Knoxville, TN, September 19-23, 2010.