Proceedings of the Korean Nuclear Society Autumn Meeting
Seoul, Korea, October 1998

Initial and Transition Cycle Development for KALIMER Uranium Fueled Core

Sang-Ji Kim, Young-In Kim, Young-Jin Kim, and Chang-Kue Park

Korea Atomic Energy Research Institute
150 Dukjin-dong, Yusong-gu, Taejon, Korea 305-353

Abstract

An economic and safe equilibrium Uranium metallic fuelled core having been established, strategic loading schemes for initial and transition cycles to early reach target equilibrium cycles are suggested for U-U and U-Pu transition cycles. An iterative method to find initial core enrichment splits is developed. With non-uniform feed enrichments at the initial core adopted, this iterative method shows KALIMER can reach Uranium equilibrium cycles just after 4 reloads, keeping feed enrichment unchanged from cycle 2. Recycling of self-generated Pu is not sufficient to make KALIMER a pure Pu equilibrium core even after 56 reloads.

1. Introduction

Equilibrium cycle searches for the KALIMER U metallic fueled core[1] had been performed in pursuit of economic and safe operation. Since these analyses assumed the scattered reloading, they provided only some approximate numbers for use in the safety analysis. In order to account for a realistic loading of fresh fuel assemblies, an explicit cycle analysis needs to be done even for the equilibrium cycle core. Such an explicit cycle analysis could provide bounding physics data over the reactor lifetime in either the initial core or transition cycles. There arises the necessity to develop fuel loading strategies from the very beginning of the reactor lifetime up to the equilibrium cycle cores. Although KALIMER is supposed to use uranium metallic fuel for its driver fuel assembly, this analysis deals with U-Pu transition cycles as well as U-U transition cycles up to respective equilibrium cycles.

As results of these works, this paper presents a number of cycles to reach equilibrium cycle and evolutions of heavy metal mass balances, power distributions, breeding ratios for projected KALIMER U initial core, transition cycles and equilibrium cycle.

2. Target Equilibrium Cycle

The fuel management studies performed in Ref. [1], has shown that the fat fuel usage is recommended to result in a reasonable enrichment split of 5w/o between the inner and outer core fuel subassemblies. In those analyses, a focus has been given to the enrichment split and resulting power distributions. In addition, those studies investigated possible benefits due to changes in the core designs such as core height, core configuration, and pellet dimension.

Once the configuration was fixed, fuel management studies further proceeded by changing fuel management schemes to improve fuel cycle economics as well as achieving a flatter power distribution. This effort[2] has shown that I4O4B4 is the maximum achievable batches for inner core, outer core and radial blanket in the equilibrium cycle mode run of REBUS-3[3]. One of drawbacks of an equilibrium cycle analysis by REBUS, is the fact that it models a scattered reloading in which explicit subassembly positions are occupied by an artificial mixture of subassemblies in a few stage. In a real world, this type of reloading cannot be realized, since an explicit cycle analysis places fresh fuel assemblies in distinctive subassembly positions. If the positioning of fresh fuels in the outer most ring of the outer core region can be avoided, there are some rooms that the core wide maximum power density still resides in the outer core. This possibility was taken into account in a detailed analysis of the next section for the transition cycle analysis, and proved that even I5O5.5B7 operation is allowed.

3. Transition Cycle Development

Burnup calculation and fresh fuel subassembly loading were carried out in 3-dimensional hexagonal-z geometry using REBUS-3[3] with the KAFAX[4] 80 g library. Moreover, the depletions were performed with all control rods withdrawn to the top of the active core. This approach is not quite right, but would be accurate enough to give rough estimates of global performance parameters.

In search of transition cycles to the equilibrium cycle, there can be a few different scenarios of achieving equilibrium cycles. One may allow the cycle length as a free variable, and feed the same enrichment once the equilibrium feed enrichment is already known. Another may fix the cycle length, allowing the feed enrichment to change. The latter is known to usually take up more cycles to reach the equilibrium cycle. The former option is usually prohibited by the utility, because the cycle energy requirement comes from the utility company. Therefore, the cycle length has been fixed with the feed enrichment being left as a free variable in this analysis.

The outer core enrichment was decided to directly start from the maximum allowed 20w/o in order to decrease the degree of freedom during the search process. Instead of a fixed outer core fuel enrichment, one can also assume the fixed enrichment split between the inner and outer core fuels. This approach will lead to complicated figures to be understood and dealing with a small enrichment change in a cycle by cycle. In addition, it is already known that the equilibrium core will require an outer core feed enrichment of 20 w/o. Therefore, only the inner core fuel enrichment is allowed to change to meet a cycle energy extraction of 310 EFPD, satisfying the EOC eigenvalue of 1.002.

When the explicit cycle by cycle analysis is being done, there can be two modes of reloading which may involve shuffling or not. When the shuffling is not exercised, transition cycles will show cyclic feed enrichment variations depending on where fresh feed assemblies are positioned. This cyclic behavior of feed enrichment variations even after a number of cycles, can be avoided by assuming the fuel shuffling and thereby keeping fuel management paths invariant for every cycle.

Taking into account the fact that the outer core consists of 66 assemblies, a fuel management strategy for the outer core region can be given by either 5 or 6 batches. Therefore, an explicit cycle analysis was decided to be done in 5/5.5/7 batches for inner/outer/blanket assemblies. The batch increase in the outer core region tends to move the core wide maximum pin power peaking toward the inner region of the core. Although the equilibrium mode run of REBUS indicates the maximum pin power peaking in the inner region, this can be avoided as soon as the judicious subassembly shuffling is assumed. When the outer core fresh feeds are not located in the outer most ring of the outer core region, the peak will tend to occur in the outer core fresh feed assembly.

When the shuffling of inner/outer/blanket are assumed, there arises the necessity of developing the fuel shuffling scheme. Several non-equilibrium REBUS's calculations were run, using different reloading schemes. From exploratory searches, a shuffling pattern with the minimum peak in one of its non-equilibrium cycles was decided to be the equilibrium cycle shuffling pattern. The shuffling pattern determined in this manner is shown in Figure 1 which implies I5O5.5B7 operations.

3.1 U-U Transition Cycles from Initial Core with Uniform Inner Core Fuel Enrichment

This is the case when the outer core feed enrichment is fixed as 20w/o and a single inner core fuel feed enrichment for each cycle is sought to meet the cycle energy extraction requirement.

Feed enrichments for transition cycles up to cycle 20 are given in Figure 2(a), where a whole inner core average enrichment and a cycle specific inner core feed enrichment are also shown. The initial core starts with uniform inner core feed enrichment of 13.45 w/o. Even after 19 reloads, a stabilized feed enrichment is not yet achieved. Accordingly, inner core powers also did not settle down, as shown in Figure 3(a). The projected equilibrium cycle inner core feed enrichment is estimated to be 15.39 w/o. The feed enrichment variations show a cyclic mode behavior, although the fixed fuel shuffling pattern is assumed. The source of this cyclic mode behavior was found to be the uniform feed enrichment for the initial core inner fuel assemblies. It is obvious from the fact the feed enrichment for cycle 2 is 16.4 w/o, which means that discharged fuel assemblies at the end of cycle 1 were too valuable to be thrown away.

3.2 U-U Transition Cycles from Initial Core with Inner Core Enrichment Split

In order to reach the equilibrium cycle quickly, the inner core enrichment has been decided to have appropriate enrichment splits. Having known the equilibrium cycle feed enrichment, a linear equation was set up to evaluate the optimum initial cycle feed enrichment by iterative calculations of transition cycles. The initial guess for the enrichment split between feed subassemblies of near enrichment was decided to be 0.9 w/o, since this amount of enrichment split is approximately equal to the reactivity loss per cycle.

Following fundamental assumptions were made for the iterative optimum feed enrichment search:

¨ ç EOC eigenvalues are strictly determined through the feed enrichment and weight for the inner core fuel.

¨ è Power distributions do not change during the depletion.

¨ é Geometric effects on weights of fuel assemblies fed in the initial core, are indifferent from those on the corresponding assemblies newly loaded in subsequent cycles.

¨ ê Fresh feeds from the 2nd equilibrium cycle, have the same weights and enrichment.

The quality of all these assumptions depends on how much the power distribution does change over cycles and burnups. If the power distribution keeps almost constant, these assumptions will remain valid to provide good estimates for the initial core feed enrichment.

With these assumptions, it was possible to set up a following matrix equation:

$$\begin{pmatrix} \varepsilon_{1s} & \varepsilon_{2s} & \varepsilon_{3s} & \varepsilon_{4s} & \varepsilon_{5s} \\ \varepsilon_{1s} & \varepsilon_{2s} & \varepsilon_{3s} & \varepsilon_{4s} & 0 \\ \varepsilon_{1s} & \varepsilon_{2s} & \varepsilon_{3s} & 0 & 0 \\ \varepsilon_{1s} & \varepsilon_{2s} & 0 & 0 & 0 \\ \varepsilon_{1s} & 0 & 0 & 0 & 0 \end{pmatrix}^{(n)} \begin{pmatrix} \varpi_{1s} \\ \varpi_{2s} \\ \varpi_{3s} \\ \varpi_{4s} \\ \varpi_{5s} \end{pmatrix}^{(n+1)} = \begin{pmatrix} \lambda_{c1} \\ \lambda_{c2} \\ \lambda_{c3} \\ \lambda_{c4} \\ \lambda_{c5} \end{pmatrix}^{(n)} - \frac{\lambda_{c6}^{(n)}}{5} \begin{pmatrix} 0 \\ 1 \\ 2 \\ 3 \\ 4 \end{pmatrix} \qquad (1)$$

where ε is an enrichment in weight percent for subscripted burnup stage,

λ is a calculated EOC eigenvalue for subscripted cycle, and

ϖ is a weight for subscripted burnup stage.

From the 1st trial run with an initial guess of feed enrichments, elements in the matrix equation can be determined. By inverting Eq. (1), the 1st estimates of weights are obtained. To get new estimates for enrichment splits for a predetermined EOC target eigenvalue per each cycle, Eq. (1) is rearranged into Eq. (2):

$$\begin{pmatrix} \varpi_{1s} & \varpi_{2s} & \varpi_{3s} & \varpi_{4s} & \varpi_{5s} \\ \varpi_{1s} & \varpi_{2s} & \varpi_{3s} & \varpi_{4s} & 0 \\ \varpi_{1s} & \varpi_{2s} & \varpi_{3s} & 0 & 0 \\ \varpi_{1s} & \varpi_{2s} & 0 & 0 & 0 \\ \varpi_{1s} & 0 & 0 & 0 & 0 \end{pmatrix}^{(n+1)} \begin{pmatrix} \varepsilon_{1s} \\ \varepsilon_{2s} \\ \varepsilon_{3s} \\ \varepsilon_{4s} \\ \varepsilon_{5s} \end{pmatrix}^{(n+1)'} = \begin{pmatrix} \lambda_{target} \\ \lambda_{target} \\ \lambda_{target} \\ \lambda_{target} \\ \lambda_{target} \end{pmatrix} - \frac{\lambda_{c6}^{(n)}}{5} \begin{pmatrix} 0 \\ 1 \\ 2 \\ 3 \\ 4 \end{pmatrix} \qquad (2)$$

By inverting Eq. (2), one gets a new vector consisting of interim feed enrichments. The equations (1) and (2) are repeatedly solved for a first few iterations. After the convergence to the desired initial core feed enrichments is obtained, new enrichment splits are obtained by an extrapolation using the following Eq. (3):

$$\begin{pmatrix} \varepsilon_{1s} \\ \varepsilon_{2s} \\ \varepsilon_{3s} \\ \varepsilon_{4s} \\ \varepsilon_{5s} \end{pmatrix}^{(n+1)} = q \begin{pmatrix} \varepsilon_{1s} \\ \varepsilon_{2s} \\ \varepsilon_{3s} \\ \varepsilon_{4s} \\ \varepsilon_{5s} \end{pmatrix}^{(n+1)'} + (q-1) \begin{pmatrix} \varepsilon_{1s} \\ \varepsilon_{2s} \\ \varepsilon_{3s} \\ \varepsilon_{4s} \\ \varepsilon_{5s} \end{pmatrix}^{(n)} \qquad (3)$$

In this search, an extrapolation parameter was set to be 1.5, and the extrapolation began to apply after 3 iterations.

After 13 iterations with updated enrichment splits, converged enrichment splits were obtained. The final results have shown that the initial core feed enrichments are 12.471 / 12.490 / 13.468 / 13.890 / 15.125 w/o for 5/4/3/2/1th burnup stage fuels in the initial core, respectively. Accounting for the manufacturing tolerance, these enrichments were rounded off to a single decimal digit such as 12.5/12.5/13.5/13.9/15.1. Finally, starting from the initial core loaded with assemblies of these enrichments, the REBUS explicit transition cycle calculations proceeded up to cycle 20 with the feed enrichment for cycle 2 and for subsequent cycles being set to 15.4 w/o. The cycle by cycle feed information is available in Figure 2(b). Figure 3(b) shows the inner core assembly power evolutions as cycles proceed. From cycle 5, the power distributions do not change for the initial core with enrichment splits, while those for the initial core with a uniform inner core enrichment fluctuates even after 20 cycles. The reason why the inner core power rises up to cycle 5, comes from the fact that the outer core fuels are supplied with 20 w/o from the initial core. Once the outer core fuels are converted into the non-uniform enrichments, one would be able to get an essentially constant power distribution from the initial core throughout the reactor lifetime.

A significant benefit originating from the iterative search process of initial core fuel enrichment splits comes from the fact that right after the initial core the feed enrichment does not change from the projected equilibrium feed enrichment of 15.4 w/o. Accordingly, the core average enrichment does not change after cycle 5 and thereafter the power distribution does not change, either. In this manner, the number of transition cycles can be minimized. This feature will, then, allow to make reload licensing concerns easily manageable, since the equilibrium cycle is achieved after only a few cycles.

The average discharge burnups for inner and outer core fuel amount to 65.8 and 59.5 MWD/KgU, respectively. This is a remarkable improvement from the previous ones (52.5 and 44.2 MWD/KgU) obtained in the FAT I4O4 design[2]. These values are higher than the achievements in BN-350 and BN-600[5] and highlights, since these burnups are achieved even with the maximum enrichment limit of 20 w/o.

3.3 Transition Cycles for Pu Recycled Equilibrium Core from Initial Core with Inner Core Enrichment Split

This is the case when self-generated(bred) plutonium is recycled into reload cores with the U initial core for the fast transition to the U equilibrium core. The transition cycle analysis assumed one cycle cooling and one cycle fabrication.

The first 3 cycles assumed the U-U transition cycles given in Section 3.2. The discharged fuel subassemblies from cycle 1 are cooled in cycle 2, reprocessed in cycle 3, and are fed into the 4th cycle reload core.

The evolution of U_{235}, U_{236} , U_{238} and Pu isotopes are shown in Figure 4. Even after 57 cycles of operation, KALIMER is expected to be unable to achieve the pure Pu equilibrium core, in which U_{235} is neither fed from the reprocessing nor from the external supply. The reactor breeding ratios are plotted in Figure 5(a). The reactor breeding ratio at cycle 57 is 0.97, while that of its Pu equilibrium counterpart is 1.03. The reactor breeding ratio increments per cycle are shown in Figure 5(b). It suggests that KALIMER will require about 100 cycles to reach a Pu equilibrium core. This is because the Pu production is almost equal to the depletion, as the Pu enrichments approaches around 12 w/o, and this is true for the KALIMER core which has 11.3 w/o fissile Pu after 56 reloads. In order for the core to overcome increased Pu burnout, a massive production of Pu by blankets is required.

As can be seen in Figure 4, a slight increase in the breeding ratio can be achieved by operating radial blanket in 3.5 batches instead of 7 batches(i.e., B7 to B3.5). It is obvious that the KALIMER cycle 57 core is still far away from the Pu equilibrium cycle. A drastic change in its configuration to achieve Pu equilibrium core would have to be pursued for the fast transition to the fissile self-sufficient Pu equilibrium core.

4. Conclusion

Although the shortcomings of equilibrium cycle search modes of REBUS-3 led to the FAT I4O4 core refueling scheme, even further extended burnups for the discharged fuel subassemblies have been achieved for the KALIMER U metallic fueled core by employing the appropriate fuel shuffling, i.e., FAT I5O5.5B7 scheme. Expected average discharge burnups with KALIMER are higher than what have been achieved in any U fueled LMR's. With an iterative enrichment split search process applied, KALIMER core exhibits equilibrium power distribution after just 4 reloads, and requires a constant feed enrichment from cycle 2. Early reach of an equilibrium cycle would eliminate many licensing concerns which can arise in the transition cycles.

The transition cycle analysis with a self-generated Pu recycled, exhibited that KALIMER core will need about 100 cycles to attain a Pu equilibrium core. In the sense that the natural resource utilization should be maximized to overcome the limited God's gift, KALIMER needs to suffer drastic design changes.

Acknowledgments

This work was supported by Nuclear R&D Long-Term Development Program, the Ministry of Science and Technology, R.O.K.

5. References

1. ±èÁö ±èµÀÎ¿Ü "KALIMER ¿¶ó½¼Ó¬âÈĂÇÆÕÁÖâ¼ªÀÂÚº¯æ¿±¸" ÇÑ¿ÀÚÇÐ¸'98Ãá¿Ð¼ÇÈ¸³ìÁý1998³ â5¿ù

2. S. J. Kim, "KALIMER U Core Equilibrium Cycle Searches and Transition Cycle Analyses up to Equilibrium Cycles," KALIMER/CD110-AR-02/1998, August 1998.

3. B. J. Toppel, "A User's Guide for the REBUS-3 Fuel Cycle Analysis Capability," ANL-83-2, March 1983.

4. ±Áþµµ±Ãæ¸· "KAFAX-F22:JEF-2.2¸ ¦ÀÌçÑº¼ÓÎë´ÙºÜÀû¶ÀÌê¯®»ýê¹×°Ãõ" KAERI/TR-842/97, 1997³ â2¿ù

5. "Fast Reactor Database," IAEA-TECDOC-866, IAEA, 1996.

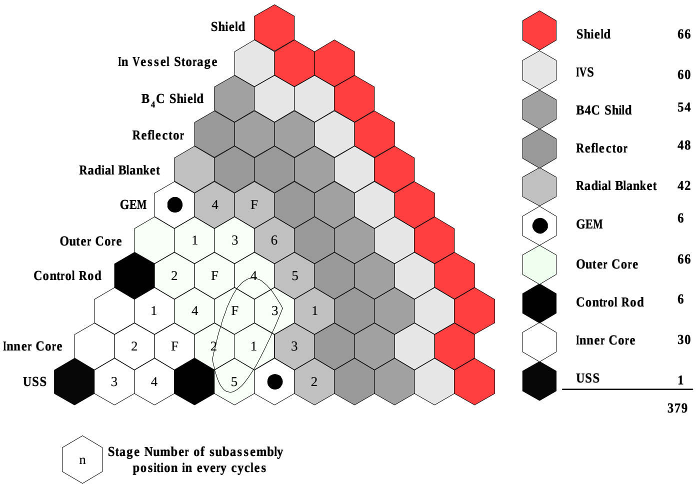
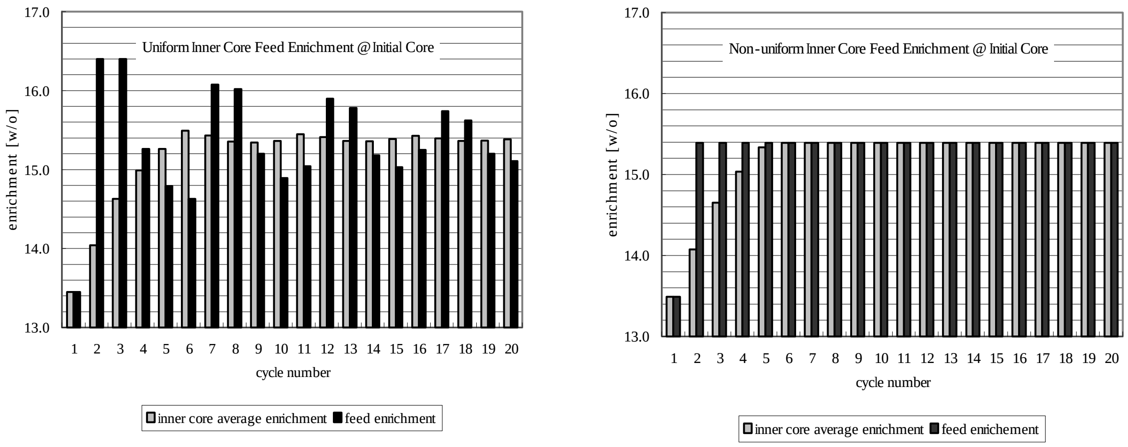
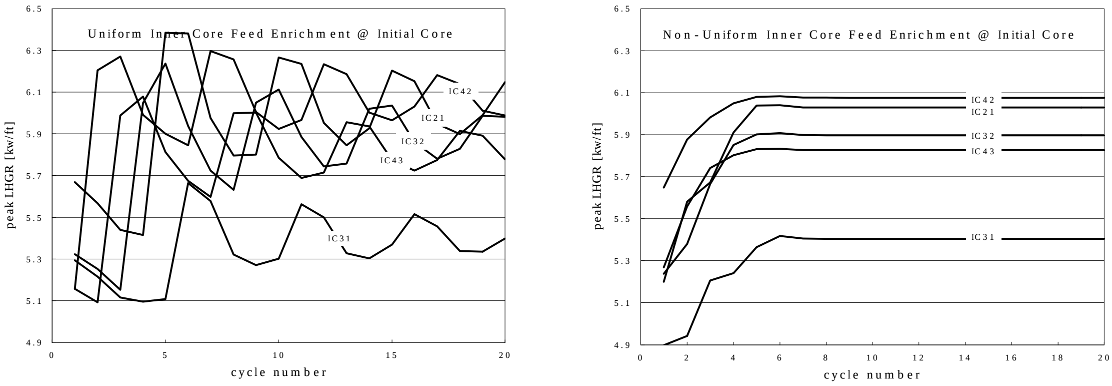


Figure 1. Batch Refueling Scheme for Transition Cycle Analysis (I5O5.5B7)



(a) (b)

Figure 2. Evolution of Feed Enrichment for KALIMER U-U Transition Cycles



(a) (b)

Figure 3. Evolution of Inner Core Assembly Peaks for KALIMER U-U Transition Cycles

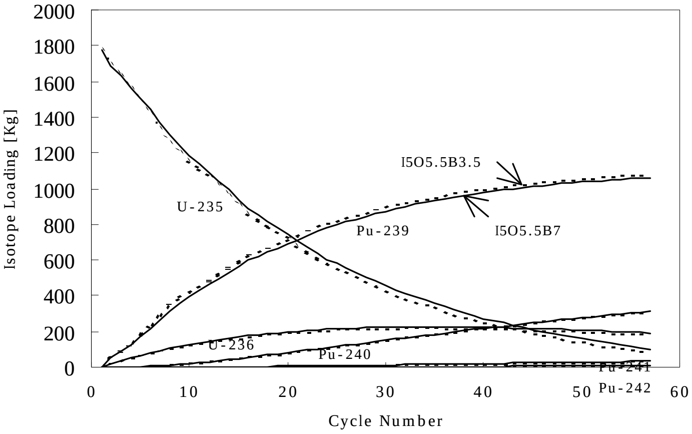
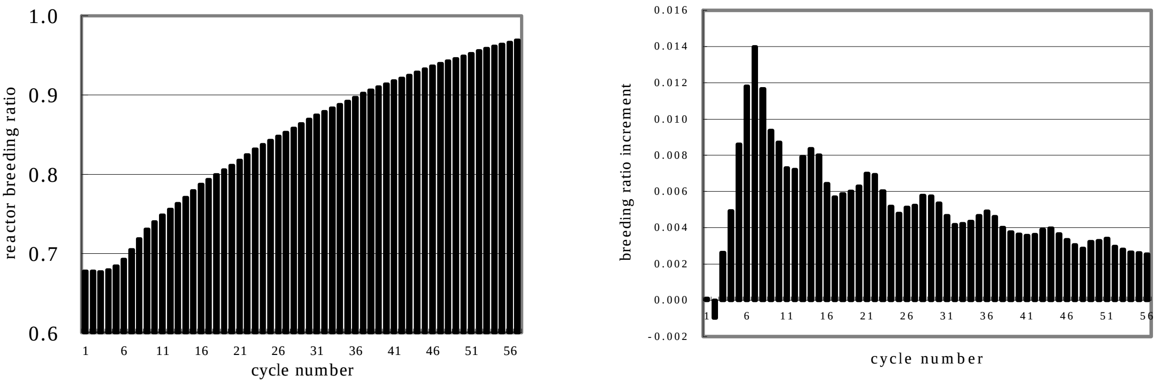


Figure 4. Isotope Loading Changes for Recycled U-Pu Transition Cores



(a) (b)

Figure 5. Reactor Breeding Ratio and Its Increment per Cycle for Recycled U-Pu Transition Cycles (I5O5.5B7)