ANALYSIS OF CONTROL ROD MOVEMENT ON REACTIVITY OF THE RSG-GAS FIRST CORE USING CITATION

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ABSTRACT

The availability of control rod as a safety tool in a nuclear reactor and as an absorber of its generating neutron is a mandatory. Core reactivity can be analyzed as a function of control rod movement in the reactor core. In this research work, the core reactivity and effective multiplication factor \( (k_{\text{eff}}) \) were successfully simulated as a function of control rod movement in the reactor core. To analyze all mention earlier, WIMSD4 and CITATION codes respectively to estimate diffusion parameters and \( k_{\text{eff}}/\text{core reactivity} \) have been utilized. The results showed that all S-curves achieved are in a good agreement. The combination of those two codes was also applied to estimate core reactivity at the first criticality condition. Those results are also in a good agreement with those achieved using BATAN-3DIFF.

Key Words: Control Rod, Movement, CITATION.

INTRODUCTION

Reactor Serba Guna G.A. Siwabessy (RSG-GAS) has five transition cores (smaller cores) prior to achieving the typical working core containing 40 standard and 8 control elements. This typical working core (TWC) was achieved at the sixth transition core. As already known, the first transition core (the first core) had mainly 12 standard fuel and 6 control elements/rods \([1]\). While the RSG-GAS standard fuel element has 21 fuel plates, each control element contains 15 fuel plates, allowing 3 fuel plates in each side of the fuel filled with absorbers made of Ag, In and Cd.

As everybody aware of, the availability of absorber in a nuclear reactor core is mainly to control the neutron production in the core. Each control element has a reactivity worth, indicating the strength of the control element to absorb the neutron \([2]\). The balance of excess reactivity worth of the reactor core and reactivity worths of the control elements should be estimated in such a way that the reactor will then be able to be operated safely.

As mentioned in paragraph 1, RSG-GAS had six transition cores, so that commissioning of each transition core had been carried out. The commissioning of the first core was carried out in July 1987. In the RSG-GAS first core as shown Figure 1, there were 12 standard fresh fuel elements and 6 fresh control elements. Since elements of the first core had been all fresh, it was predicted that calculations of reactivity worths of RSG-GAS control rods would be accurate enough.
This paper describes the calculations of reactivity worths of all six control elements/rods in the first core as well as first criticality computation of RSG-GAS core. The introduction of the paper will be presented in the first Section of the paper. The second Section describes methodology/calculation method of reactivity worth. The third section presents calculation results and discussion. Finally, the conclusion of the paper can be clearly seen in the final section of the paper.

THEORETICAL CALCULATION

Design Calculation and Diffusion Approximation

The scheme of overall calculation of reactivity worth of a reactor core can be seen in Figure 2. The general step of the calculation flow is to start with small system such as pin cell (B1) and to proceed via intermediate systems such as fuel assembly (B2) to the whole core calculation (C). The calculation procedures start from a detailed to a crude representation of the energy and space variables. The flux obtained in each phase is used to produce cross section for the next phase, after condensation and homogenization. Furthermore, to compute the cell averaged thermal group constants for a few region cell, it is important to perform a thermal spectrum calculation for an infinite medium with the number densities of fuel and moderator being uniformly distributed over the cell. The second step is to determine the disadvantage factors characterizing the cell.

Although in principle it is possible to perform transport calculation for many groups (i.e. 69 groups for WIMS), in practice 3 or 4 neutron groups are often sufficient and even in more accurate computations it is recommended not to used more than 20 groups.

The energy and spatial condensation is used mainly to reduce computational problems in fuel pin/assembly calculation. The principle of both condensation is to preserve reaction rates and reactivity. The pin cell interaction in an assembly is sufficiently strong to warrant combination of parts B1 and B2 in a simple program.

In the resonance region, from about 100 keV down to about 1 eV, the cross section of the resonance isotopes can vary by several orders of magnitude in the library groups. This offers problems not only with the generation of resonance integral tables, but also with their use in design calculations. Regarding this problem, WIMS/D4 code provides better treatment for resonance integral in cell calculation.

Whole core calculation describes the interaction between the fuel assemblies and reflectors. Because the calculation has to be performed in two or three dimensions and because of the complexity of the reactor core, the calculation is performed in 2 to 4 groups only. The slow variation of the
global flux allows the use of the diffusion equation. The numerical solution is normally solved with coarse or fine mesh, say 1 to 3 cm.

To estimate reactivity worth of RSG-GAS reactor core, the integral differential transport equation called the transport or Boltzmann equation is originally the neutron transport equation from which a multi-group diffusion equation seen below was applied [1].

\[
\frac{1}{v} \frac{\delta \Phi(r, \Omega, E)}{\delta t} = -\nabla \cdot \Phi(r, \Omega, E) - \sum_i (E) \Phi(r, \Omega, E) + \int_{\Omega} \left( \sum_i (\Omega \rightarrow \Omega', E' \rightarrow E) \Phi(r, \Omega', E') d\Omega' \right) + S(r, \Omega, E)
\]

(1)

Initial Condition : at \( t=0 \), \( \Phi(r, E, \Omega) = \Phi_0(r, E, \Omega) \)

Boundary Condition : \( \Phi(r_s, E, \Omega) = 0 \), if \( \Omega \cdot e_s < 0 \), all \( r_s \) on \( S \).

where,

\[ \Phi(r, \Omega, E) = \text{number of neutrons at the point } r \text{ with the energies } E \text{ and flight direction around } \Omega \text{ and } \Omega \text{ is a vector} \]

First term of RHS = leakage out the volume element

Second Term of RHS = loss due to absorption and scattering into other directions

Third term of RHS = gain due to in-scattering of neutrons from other directions and energy intervals

Fourth term of RHS = productions of neutrons by sources of volume element

By applying scientific approximation, such as, the neutron field rotationally symmetric around a distribution axis and independent to \( r \) and \( E \); plane symmetry and the distribution axis be the \( x \)-axis; the scattering cross sections, \( \Sigma_s(\Omega \rightarrow \Omega') \) developed into a series of Legendre polynomials of \( \cos \theta = \Omega \cdot \Omega' \); integration once over \( d\Omega \) and once over \( \cos \theta \ d\Omega \) and the Fick’s Law of diffusion, the elementary diffusion equation can be yielded as seen below.

\[
D \frac{d^2 \Phi}{dx^2} - \sum_a \Phi(x) + S(x) = 0
\]

(2)

The calculation of power distribution, effective multiplication factor and others mentioned earlier is accomplished by solving the few-group diffusion equation which is a simplification to the neutron transport equation [1]. Equation (2) can be expanded to the more comprehensive diffusion equation given below.
- \nabla D^g(r) \nabla \phi^g(r) + \sum_{g'}^{G} \Sigma_{s}^{g'}(r) \phi^{g'}(r) = \sum_{g=1}^{G} \Sigma_{r}^{g}(r) \phi^g(r) + \frac{Z_g}{k_{eff}} \sum_{g'=1}^{G} \Sigma_{f}^{g'}(r) \phi^{g'}(r), \quad (3)

g = 1, 2, \ldots, G,

where,
\begin{align*}
G &= \text{number of energy groups} \\
r &= \text{position} \\
D^g &= \text{diffusion constant for group } g \left( = \frac{1}{3} \Sigma_{u}^{g} \right) \\
u \Sigma_{f}^{g} &= \text{fission source cross section from group } g \\
\Sigma_{a}^{g} &= \text{absorption cross section for group } g \\
\chi^{g} &= \text{fission source fraction in group } g \\
g &= \text{energy group index} \\
\phi^{g} &= \text{neutron flux in group } g \\
\Sigma_{t}^{g} &= \text{transport cross section from group } g \\
\Sigma_{s}^{g} &= \text{total cross section for group } g \\
\Sigma_{s}^{g'} &= \text{scattering cross section from } g' \text{ to group } g \\
k_{eff} &= \text{effective multiplication constant}
\end{align*}

These equations are solved by using finite difference methods to discretize the spatial variable and then, following the usual inner-outer iteration strategy, solving for criticality eigen value \( k_{eff} \) and the corresponding multi-group flux \( \phi^g(r) \) is applied \[1\].

**Method of Calculation**

To estimate reactivity worth of each control rod of the RSG-GAS first core, the following steps were applied:

a. The RSG-GAS first reactor core was divided into meshes in x, y and z direction. Division of meshes in x, y and z direction are respectively divided into 101, 135 and 88 meshes,
b. To estimate diffusion parameters, computer code WIMSD4 was applied \[4\],
c. To calculate reactivity worth of the RSG-GAS first core, computer code CITATION-3D was utilized \[5\],
d. To make a curve of S-shape between \( k_{eff} \) and reactivity worth and control rod withdrawal, the following steps were applied:
   1. All five control rods were entrenched in fully-up condition in the core and an interested control rod was established in fully-down condition core \( \rho_{suIn} \)
2. The interested rod was then moved up commencing from 0 cm to 60 cm (fully-up), \( \rho_{\text{up}} \)
3. The reactivity worth or \( k_{\text{eff}} \) of the reactor core can be each computed

e. Reactivity worth of each control rod can be computed from the following simple formula

\[
(\rho_{\text{wcr}}) = (\rho_{\text{Sutn}}) - (\rho_{\text{up}})
\]  

(4)

RESULTS AND DISCUSSION

Verification of CITATION Code

To verify of CITATION code, reactivity worth calculation of the IAEA Benchmark Research Reactor with the power of 10 MW thermal has been carried out. The reactor has a very similar control absorber compared to that of the RSG-GAS reactor. Again, the intention of the calculation is to validate computer code CITATION by comparing the calculation results carried out with those achieved by using ANL’s and BATAN-3-DIFF codes.

The IAEA benchmark reactor is a typical 10 MWth Material Testing Reactor (MTR) with LEU core defined somewhere in IAEA-TECDOC-233\(^6\) as the benchmark core. Generally, the IAEA benchmark reactor core consists of core and reflectors made of graphite or water. The end boxes on the top and bottom of each fuel element were represented using a homogenized mixture of 25 v/o aluminum and 75 v/o H\(_2\)O extending 15 cm above the fuel. Furthermore, the reactor core has four control elements, meaning fuel elements with absorber plates. It is required to know that the control rod geometry of the benchmark core is fork-type with blades fitting into guides described in IAEA-TECDOC-233 benchmark problem \(^7\). In short, the geometry of the control rod is 600 mm long, 66 mm wide and 3.18 mm thick. The absorber is 3.1 mm thick with a 0.04 mm layer of nickel on each surface of Ag-In-Cd. The absorber materials are 80.5 w/o Ag, 14.6 w/o In and 4.9 w/o Cd \(^8\).

Only ANL accomplished this benchmark problem and ANL used its own computer code to investigate partially-inserted control rods. For partially-inserted problems, the following parameters for BOC core using LEU fuel were applied \(^8\).

a. Effective multiplication factor versus rod position for 8 withdrawn positions, 0%, 10%, 20%, 33%, 50%, 67%, 85% and 100%.

b. Reactivity values versus rod position for 8 withdrawn positions, 0%, 10%, 20%, 33%, 50%, 67%, 85% and 100%.

c. Peak power densities in CFE-1 (control fuel element-1) for withdrawn positions, 50% and 100%.
For this analysis, 58 meshes, 54 meshes and 64 meshes were modeled in X, Y and Z directions respectively. Moreover, the IAEA benchmark core were modeled in 37 materials and the material cross-section were calculated using WIMS/D-4 code available in BATAN main frame.

The structure of the five energy groups is 10 to 0.821 MeV, 0.821 MeV to 5.53 keV, 5.53 keV to 1.855 eV, 1.855 eV to 0.625 eV and 0.625 eV to 0 eV. To estimate effective multiplication factor (k_{eff}) or reactivity of the benchmark core, the CITATION-3D code was applied. To verify the calculation results, these results have been compared to those achieved by both using BATAN-3DIFF and ANL’s codes and the calculation results can be clearly seen in Table 1.

For all positions as seen in Ref. 8, the S-shaped curves for both codes show the same shape and give agreement for the rod worth within 7.4% in the both code ratio. For calculation of k_{eff}, the maximum difference between ANL’s code and CITATION-3D is 0.20%. Moreover, for the peak power densities in CFE-1 (control fuel element) with 50% and 100% withdrawn, the maximum difference between those two codes is around 6%. These peak power densities are retrieved at the edge of the mesh interval with highest power. It, is therefore, CITATION code is very feasible to calculate reactivity worth of control rods in a reactor core as well as the RSG-GAS reactor core.

Reactivity Worths of Each Control Rods of the RSG-GAS First Core

To estimate reactivity worth of each control rod, the reactor were set in two condition respectively, five rods in fully up and an interested rod in fully down. For every step condition, effective multiplication factor (k_{eff}) as well as core reactivity will be obtained. By applying Eq. 4, every reactivity worth of each control rod can be estimated. Table 2 shows reactivity worth of each control rod in the RSG-GAS first core.

To develop S-shape curve between control rod withdrawal with effective multiplication factor (k_{eff}) and that with core reactivity worth, while five other control rod are in fully down, an interested control rod moves up from 0 cm (fully down) to 60 cm (fully up). Those calculation results are respectively summarized in Tables 3 and 4.

While Figure 3 shows S-curves of core reactivity for rods E9, F5 and F8, Figure 4 displays those for rods C8, C5 and D4. In Figure 3, the S-curve for rods E9 and F8 are very close one to another. This is due to the very close arrangement between those two rods. The similar curve is also shown in Figure 4, especially for rods C5 and D4. Since the configuration of those two rods, reactivity worth of each of those two control rods is not significantly different.

As Figure 5 shows the K-effective S-curve for rods C5, C8 and D4, Figure 6 displays K-effective S-curves for rods E9, F5 and F8. In Figure 5, the S-curve for rods C5 and D4 is very close one to another. This is due to the very close arrangement between those two rods. The similar curve is also
shown in Figure 6, especially for rods E9 and F8. The difference of reactivity worth for each of those two control rods is not significant.

Other than results previously mentioned, Table 5 shows comparison of CITATION-3D calculation results with experiment data for the RSG-GAS first core. For first criticality of the RSG-GAS first core, the C/E values using BATAN-3DIFF and CITATION-3D are 0.998 and 0.992, respectively. For the excess reactivity of the full core, the C/E (calculation/experiment) values using BATAN-3DIFF and CITATION-3D are 0.993 and 0.990, respectively. It is, therefore, there is no doubt to apply the combination of WIMSD4 and CITATION to estimate reactivity worth of the reactor core as well as that of control rods.

CONCLUDING REMARKS

The code CITATION-3D combined with WIMSD4 generating diffusion parameters have been conducted on the RSG-GAS first core for the calculation of reactivity worth of its control rod. It is very clear that the S-curves for K-effective and core reactivity versus control rod withdrawal for each rod showed very good. The calculation result of individual control rod worth is different compared to that achieved by experiment and the maximum differences between those two’s are very significant and this is due to a very big shadowing/anti-shadowing effect in the RSG-GAS first core.

For first criticality of the RSG-GAS first core, the C/E values using BATAN-3D and CITATION-3D codes are 0.988 and 0.992, respectively. For the excess reactivity of the full core, the C/E values using BATAN-3D and CITATION-3D codes are 0.993 and 0.990, respectively. It is, therefore, there is no doubt to apply the combination of WIMSD4 and CITATION to estimate reactivity worth of the reactor core as well as that of control rods.

ACKNOWLEDGEMENT

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REFERENCES


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Table 1. Reactivity Values versus Rod Position for LEU IAEA Benchmark Reactor Core [9].

<table>
<thead>
<tr>
<th>Rod Position, % Withdrawal</th>
<th>Height of Rod Tip, cm</th>
<th>ANL’s Code</th>
<th>Batan-3DIFF</th>
<th>CITATION</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.0</td>
<td>-11.45</td>
<td>-11.45</td>
<td>-11.43</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(1.000)*</td>
<td>(0.998)*</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>6.0</td>
<td>-10.89</td>
<td>-10.89</td>
<td>-10.86</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(1.000)</td>
<td>(0.998)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>(1.001)</td>
<td>(0.996)</td>
<td></td>
</tr>
<tr>
<td>33</td>
<td>19.8</td>
<td>-6.76</td>
<td>-6.88</td>
<td>-6.77</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(1.017)</td>
<td>(1.001)</td>
<td></td>
</tr>
<tr>
<td>50</td>
<td>30.0</td>
<td>-3.03</td>
<td>-3.03</td>
<td>-3.02</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(1.000)</td>
<td>(0.997)</td>
<td></td>
</tr>
<tr>
<td>67</td>
<td>40.2</td>
<td>-0.17</td>
<td>-0.18</td>
<td>-0.16</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(1.034)</td>
<td>(0.942)</td>
<td></td>
</tr>
<tr>
<td>85</td>
<td>51.0</td>
<td>1.74</td>
<td>1.64</td>
<td>1.67</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(0.942)</td>
<td>(0.960)</td>
<td></td>
</tr>
<tr>
<td>100</td>
<td>60.0</td>
<td>2.29</td>
<td>2.46</td>
<td>2.46</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(1.074)</td>
<td>(1.074)</td>
<td></td>
</tr>
</tbody>
</table>

Note: a) values in parenthesis show each CITATION and BATAN’s codes to ANL’s code.

Table 2. Reactivity Worth of Each Control Element for the RSG-GAS First Core.

<table>
<thead>
<tr>
<th>Condition</th>
<th>( k_{\text{eff}} )</th>
<th>Core Reactivity, ( \rho_c ) (%)</th>
<th>Reactivity Worth of Each Control Rod, ( \rho_{cr} ) (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Five rods fully-up, <strong>C5</strong> rod fully-down</td>
<td>1.064409</td>
<td>6.051</td>
<td>-1.509</td>
</tr>
<tr>
<td>Five rods fully-up, <strong>C8</strong> rod fully-down</td>
<td>1.063416</td>
<td>5.963</td>
<td>-1.597</td>
</tr>
<tr>
<td>Five rods fully-up, <strong>D4</strong> rod fully-down</td>
<td>1.065899</td>
<td>6.182</td>
<td>-1.378</td>
</tr>
<tr>
<td>Five rods fully-up, <strong>E9</strong> rod fully-down</td>
<td>1.063679</td>
<td>5.987</td>
<td>-1.573</td>
</tr>
<tr>
<td>Five rods fully-up, <strong>F5</strong> rod fully-down</td>
<td>1.066566</td>
<td>6.241</td>
<td>-1.319</td>
</tr>
<tr>
<td>Five rods fully-up, <strong>F8</strong> rod fully-down</td>
<td>1.063745</td>
<td>5.993</td>
<td>-1.570</td>
</tr>
</tbody>
</table>

Note: \( \rho_{cr} = \rho_c - \rho_{up} \); a) – ratio between calculation and experimental results.
Table 3. K-effective versus Rod Withdrawal for the RSG-GAS First Core a).

<table>
<thead>
<tr>
<th>Rod Withdrawal (cm)</th>
<th>(k_{\text{eff}}) (C8 Rod)</th>
<th>(k_{\text{eff}}) (C5 Rod)</th>
<th>(k_{\text{eff}}) (D4 Rod)</th>
<th>(k_{\text{eff}}) (E9 Rod)</th>
<th>(k_{\text{eff}}) (F5 Rod)</th>
<th>(k_{\text{eff}}) (F8 Rod)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1.064316</td>
<td>1.064409</td>
<td>1.065899</td>
<td>1.063679</td>
<td>1.066566</td>
<td>1.063745</td>
</tr>
<tr>
<td>10</td>
<td>1.064426</td>
<td>1.065332</td>
<td>1.06741</td>
<td>1.064696</td>
<td>1.067335</td>
<td>1.064731</td>
</tr>
<tr>
<td>20</td>
<td>1.067375</td>
<td>1.068069</td>
<td>1.069289</td>
<td>1.067646</td>
<td>1.069737</td>
<td>1.067628</td>
</tr>
<tr>
<td>30</td>
<td>1.071966</td>
<td>1.072471</td>
<td>1.072415</td>
<td>1.072177</td>
<td>1.073596</td>
<td>1.072178</td>
</tr>
<tr>
<td>40</td>
<td>1.076730</td>
<td>1.077037</td>
<td>1.076523</td>
<td>1.076546</td>
<td>1.077639</td>
<td>1.076896</td>
</tr>
<tr>
<td>50</td>
<td>1.080206</td>
<td>1.080347</td>
<td>1.080234</td>
<td>1.079567</td>
<td>1.080554</td>
<td>1.080026</td>
</tr>
<tr>
<td>60</td>
<td>1.081787</td>
<td>1.081787</td>
<td>1.081787</td>
<td>1.081787</td>
<td>1.081787</td>
<td>1.081787</td>
</tr>
</tbody>
</table>

a) Note : While an interested control rod moves up, the other five rods are fully-up.

Table 4. Core Reactivity versus Rod Withdrawal for the RSG-GAS First Core a).

<table>
<thead>
<tr>
<th>Rod Withdrawal (cm)</th>
<th>(\Delta k/k%) (C8 Rod)</th>
<th>(\Delta k/k%) (C5 Rod)</th>
<th>(\Delta k/k%) (D4 Rod)</th>
<th>(\Delta k/k%) (E9 Rod)</th>
<th>(\Delta k/k%) (F5 Rod)</th>
<th>(\Delta k/k%) (F8 Rod)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>5.963424</td>
<td>6.051151</td>
<td>6.182481</td>
<td>5.986675</td>
<td>6.241152</td>
<td>5.992508</td>
</tr>
<tr>
<td>40</td>
<td>7.126206</td>
<td>7.152679</td>
<td>7.108348</td>
<td>7.110332</td>
<td>7.204546</td>
<td>7.140522</td>
</tr>
<tr>
<td>50</td>
<td>7.425065</td>
<td>7.437148</td>
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<td>7.370270</td>
<td>7.454880</td>
<td>7.409636</td>
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<tr>
<td>60</td>
<td>7.560361</td>
<td>7.560361</td>
<td>7.560361</td>
<td>7.560361</td>
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</tr>
</tbody>
</table>

a) Note : While an interested control rod moves up, the other five rods are fully-up.

Table 5. Comparison of CITATION-3D Calculation Results with Experiment Data for First Criticality and Excess Reactivity of RSG-GAS First Core.

<table>
<thead>
<tr>
<th>Core Configuration</th>
<th>Experiment Data</th>
<th>3-D Diffusion Calculations</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Batan-3Diff and WIMSD4 Library</td>
<td>Citation-3D and WIMSD4 Library</td>
</tr>
<tr>
<td>Full Core (9 Fes, 6 CEs, CRs all down)</td>
<td>(K_{\text{eff}})</td>
<td>1.009242 (^a)</td>
</tr>
<tr>
<td></td>
<td>C/E</td>
<td>C/E</td>
</tr>
</tbody>
</table>

a) \(\beta = 0.00765\)

b) n.c. = not conducted

c) Shim rod bank compensation method, measured by reactivity meter, summation of single control rod worth

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Figure 1. Configuration of the RSG-GAS First Reactor Core.
Figure 2. Scheme of Reactor Physics Design.
Figure 3. Core React. vs. Rod Withdr. for the First Core.

Figure 4. Core React. vs. Rod Withdrawal for the First Core.
Figure 5. K-effective vs. Rod Withdrawal for the First Core.

Figure 6. K-effective vs. Rod Withdrawal for the First Core.