Proceedings of the Korean Nuclear Society Spring Meeting
Kwangju, Korea, May 2002

Analysis of Uranium Isotopic Variation Effect of RUFIC Fuel on Burnup and Power Distribution in CANDU-6 Reactor

Soon Young Kim and Ho Chun Suk

Korea Atomic Energy Research Institute
150 Dukjin, Yusong, Daejeon, Korea 305-353

Abstract

The impact of uranium isotopes variations in recovered uranium fuel in CANDU (RUFIC) have been investigated on the average exit burnup and power distributions. In this work, variations in U-235 content in the range of 0.92±0.02 *w/o* were considered, and, for U-234 and U-236 isotopic variations, the ranges from 0.010 to 0.018 *w/o* and from 0.22 to 0.40 *w/o* were considered, respectively. 0.92 *w/o* U-235, 0.016 *w/o* U-234, and 0.34 *w/o* U-236 were used as the nominal specifications of the isotopic contents in the reference recovered uranium fuel. It is confirmed that a coefficient of 1.933 *MWh/kgU/mk* was obtained as the burnup gain/loss per *mk* of core reactivity in RUFIC-fuelled core with 4-BS scheme. The impact on channel and bundle powers was assessed by fuelling simulations for 1 full power day, and compiling the statistics on power variations, based on the instantaneous snapshot calculation. As a result, it is shown that the effects of U-234 and U-236 are so small that the effects can be disregarded. For U-235 isotope, it is found that, for a ±0.02 *w/o* variation in U-235 content, the expected maximum variations (EMV) in channel and bundle powers were up to 1.38 % and 3.2 %, respectively, and, for a ±0.01 *w/o* variation in U-235 content, the EMVs up to 0.6 % and 1.5 %, respectively.

1. Introduction

The CANDU reactor design has the flexibility to use alternative fuel cycles other than natural uranium (NU). These alternative fuel cycles utilize a variety of fissile materials, including slightly enriched uranium (SEU) from enrichment facilities, and recovered uranium (RU) or plutonium obtained from the reprocessing of the spent fuel of light water reactors (LWR). The choice depends on economics, resource conservation, as well as political considerations.

Considering Korea having both LWR and CANDU reactors, RU fuel is a very attractive alternative to the use of NU in CANDU reactors, since the fuel from its LWR can be used in CANDU reactors without re-enrichment. The recovered uranium fuel in CANDU reactor is called as RUFIC. The RUFIC program has been initiated to assess the use of RU with 0.92 *w/o* U-235, in a CANFLEX (CANdu FLEXible fuelling) bundle carrier, to be implemented in Wolsong reactors. The program covers all aspects of design and operation with the RUFIC bundles and minimal modifications to the basic core design.

In this work, the effects of RUFIC fuel enrichment on bundle and channel powers, and burnup were investigated in a CANDU-6 core. Time-average flux/power calculations and snapshot core simulations had been firstly performed in order to investigate the power variations due to fuelling and achievable exit burnup.

The computer codes used for this study are:

- WIMS-AECL version 2-5d[1] with the nuclear libraries ENDF/B-VI for the lattice cell calculation;
- RFSP version IST-REL_3-00-05HP[2] for the fuelling simulation and the core flux/power calculation

2. Time-Average Study

Time-average calculations for 0.92 *w/o* RUFIC fuel in CANDU-6 had been previously performed to study the core characteristics with 4 bundle-shift (BS), 3 bundle-shift, and 2 bundle-shift fuelling schemes [3]. The general trend indicates that all these fuelling schemes can be used to control the channel power distribution to a target shape, which is taken as the power shape of the current operating 37-element NU core. As expected, fuelling rate increases when a smaller number of new bundles are inserted per visit; however, the fuelling ripples are lower.

Time-average calculation with 4 BS refuelling scheme was carried out using RFSP code, and the major results are presented in Table 1. The core was divided into 5 irradiation zones, over which the average fuel discharge irradiation is constant. These average exit irradiations in the five zones were chosen to make the reactor critical, and to provide an appropriate degree of flattening of the radial channel power distribution and match as closely as possible of a current operating CANDU-6 reactor such as Wolsong 1 unit with 37-element natural uranium fuel. The water level in the zone control compartments was fixed at 50 % full. In this time-average calculation, the maximum channel power and maximum bundle power were calculated as 6521 and 755.6 *kW*, respectively.

The incremental cross sections had been previously generated [3] for the RUFIC fuel at mid-burnup as the background lattice, using DRAGON version 3.04[4] with the ENDF/B-V library. The original adjuster rod designs in terms of the absorption strength and axial grading have not been modified. It is noted that, in the RUFIC core, the adjuster rod worth is about 13 *mk*, compared to 16 *mk* in the 37-element NU core with 8 BS. The reduced worth is due to the difference in flux shape and in the relative neutron absorption in the adjusters and in the fuel.

In order to estimate fuelling ripples without having to simulate fuelling operations over an extended period of time, instantaneous power distributions were generated based on the time-average result and “patterned random channel age distribution”. A 7x7 channel age array was created, ranging from age 0 for just refuelled to 1 for just about to be refuelled. A channel in the array was specified as the “starting” channel or the most matured channel to be refuelled first, and a sequence of fuelling of the 49 channels was created and the corresponding channel ages were assigned. The 7x7 channel age pattern was then repeated to cover the entire 22x22 channel array. In the current study, three instantaneous snapshot calculations were carried out with different age maps corresponding to the choice of three different “starting” elements in the 7x7 array. The variations of core parameters from the three snapshot calculations are presented in Table 2. It should also be noted that the instantaneous power distributions created with the “patterned random age” method is a reasonable approximation, and often snapshots could exhibit local hot spots and higher than realistic instantaneous powers. It is also noted that the spatial control function of the liquid control system (which was not active in the simulations) would also tend to reduce the peak powers.

The results indicate that, with the 4 BS scheme applied to all channels, the maximum instantaneous channel power is around 6800 to 7200 *kW*, and fuelling ripple is around 1.09 to 1.13. More accurate ripple estimates from refuelling simulations are available from Reference 3.

3. Tolerances to RU Isotopic Variations

The RU has a nominal specification of the isotopic contents as follows: U-235 0.92 *w/o*, U-234 0.016 *w/o*, and U-236 0.34 *w/o*. Certain variations from these nominal specifications are expected. These variations, especially in U-235 content, will have an impact on fuel burnup and on peak powers. In order to establish the tolerance to such variations from the viewpoint of uncertainties in peak channel and bundle powers, sensitivities to RU isotopic contents have been investigated. Variations in U-235 content in the range of 0.92±0.02 *w/o* were considered. For U-234 and U-236 isotopic variations, the ranges from 0.010 to 0.018 *w/o* and from 0.22 to 0.40 *w/o* were considered, respectively.

3.1 Generation of Fuel Tables

The lattice k-infinity calculations for five RUFIC fuels with U-235 content of 0.92, 0.92±0.01 and 0.92±0.02 *w/o* (with the U-234 and U-236 at their nominal isotopic concentrations) were performed using WIMS-AECL with ENDF/B-VI library in order to estimate the reactivity differences between the nominal 0.92 *w/o* RUFIC and other RUFIC fuels, and the results are shown in Figure 1 as a function of bundle-averaged fuel burnup. It is found that the average difference in k-infinity corresponding to the variation of 0.01 *w/o* in U-235 enrichment is 4.31 *mk* at zero fuel burnup (with saturating fission products).

In order to investigate the effects of variations of U-234 and U-236 contents in RUFIC fuel, four depletion calculations were performed with various U-234 and U-236 contents and fixed U-235 enrichment at 0.92 *w/o*, and the results are shown in Figures 2 and 3. The U-234 and U-236 contents were varied from 0.010 to 0.018 *w/o* and from 0.22 to 0.40 *w/o*, respectively, and not varied simultaneously. That is, when assessing the effect of U-234 content, U-236 contents were kept as its nominal value, and for U-236 content, vice versa. From these two sets of lattice calculation results, the effects of the variations of the two isotopes within their respective specified ranges on lattice parameters and on fuel depletion are negligible.

In Figure 4, the highest and the lowest k-infinity values are shown from the depletion calculations of another two RUFIC fuels that were conservatively constructed with the combination of U-234, U-236, and U-235 contents to have the highest or lowest reactivity within their ranges considered. The contents of U-234, U-235, and U-236 in one RUFIC fuel that has the highest k-infinity were 0.010 *w/o*, 0.94 *w/o*, and 0.22 *w/o*, respectively, and in case of the other RUFIC fuel that has the lowest reactivity, 0.018 *w/o*, 0.90 *w/o*, and 0.40 *w/o* respectively. Since the effects of U-234 and U-236 are negligible, it can be seen that Figure 4 is very similar to Figure 1.

3.2 Impact of Enrichment on Fuel Burnup

To assess the impact of U-235 content variation on fuel burnup, two time-average calculations were carried out using the RFSP code. First, a time-average calculation for the reference RUFIC-fuelled core with a 4 BS scheme was performed with the k-effective value set to unity. Secondly, another time-average calculation for the same core was performed with the k-effective set to 0.9990, in order to calculate the changes in the core average burnup that result from varying the reactivity by 1 *mk*.

The two calculation results are summarized in Table 3. The channel power distributions in the two calculations were adjusted to be as close as possible. A coefficient of 1.933 *MWh/kgU/mk* was obtained as the burnup gain/loss per *mk* of core reactivity in a RUFIC-fuelled core with a 4 BS scheme.

To establish the burnup effect if all the RUFIC bundles in the core have a U-235 content at 0.91 *w/o* (or 0.93 *w/o*), the previous time-average calculation was repeated with fuel properties for the 0.91 *w/o* bundle and keeping the previous bundle irradiations fixed. The time-average calculation would show a subcritical k-eff value, with an estimated average exit burnup. The exit burnup was then adjusted for the difference in k-eff values using the coefficient of 1.933 *MWh/kgU/mk*. The results are presented in Table 4. It was found, if all the bundles in the core have a U-235 content of 0.01 *w/o* higher or lower than the nominal value of 0.92 *w/o*, then the gain or loss in average exit burnup is estimated to be 5.67 *MWh/kgU*.

3.3 Impact of Isotopic Content Variations on Channel and Bundle Powers

It is possible that a batch of new fuel bundles could have different isotopic contents than the nominal values, and these bundles are being introduced when channels are fuelled. The impact on channel and bundle powers was assessed by fuelling simulations, and by compiling the statistics on power variations. Two snapshot calculations discussed in Section 2 were selected as starting points for the analysis of channel and bundle power on fuel enrichment. The two instantaneous snapshots were based on the "patterned random channel age distribution" with Channel 25 and Channel 13 in array of 7x7 as the "starting element", which showed the lowest channel power ripple and the highest one, respectively.

For the two snapshot cores (labelled as Cases 1 and 2), the average exit burnup for all channels are shown in Figures 5 and 6. Ten mature channels in each snapshot were represented in bold in the Figures and selected for refuelling to estimate the effects of U-235 enrichment variation on channel and bundle power. For Case 1, G-10, F-12, H-15, J-08, L-17, M-16, N-11, O-17, Q-11, and Q-15 were chosen, and for Case 2, F-10, K-07, K-13, L-11, M-09, N-17, O-10, O-15, P-07, and Q-12 were chosen.

For each of the selected mature channels, refuelling simulations with 4 BS were performed. The maximum channel and bundle powers after fuelling using the nominal 0.92 *w/o* fuel and irradiation for 1 full-power day were calculated and set as reference powers. The maximum channel and bundle powers were also calculated when other four RUFIC fuels having 0.90, 0.91, 0.93, and 0.94 *w/o* U-235 contents were fuelled and irradiated for 1 full-power day, respectively. The differences of maximum channel and bundle powers to the reference powers were tabulated in Tables 5 and 6 for Case 1 and 2, respectively. The differences were averaged over the ten channels, and the standard deviation (σ) was also calculated. In order to estimate the deviation from the reference powers, expected maximum variation (EMV) was, in this study, defined as the ratio of the averaged difference plus 2σ due to the variation of U-235 content to averaged maximum channel or bundle power of reference calculation. It is found that, for a ±0.02 *w/o* variation in U-235 content, the EMV in channel and bundle powers were up to 1.38 % and 3.2 %, respectively.

The effects of U-234 and U-236 content variations on channel and bundle powers were also evaluated just as the same way except the number of channels considered. Reference enrichment of 0.92 *w/o* was used for U-235 content, and the maximum and minimum contents of U-234 and U-236 that can be varied in RU fuel were considered in the calculations. Since the effects of U-234 and U-236 are expected to be negligible, only 2 and 4 channels were selected, in which power variations were relatively large compared to other channels based upon the previous results of U-235 enrichment effect. As expected, it is shown that the effects of U-234 and U-236 are so small that the effects can be disregarded compared to the enrichment variation of U-235.

For the extreme combinations of isotopic variations, EMVs in channel and bundle powers for the two RUFIC fuels having the highest reactivity and the lowest reactivity that RUFIC fuels can have, as stated in Section 3.1 above, were also calculated and are presented in Tables 7 and 8 for Case 1 and 2 respectively. The RUFIC fuel of the highest reactivity has the lowest U-234 and U-236 contents, and the highest U-235 enrichment; whereas the RUFIC fuel of the lowest one has the highest U-234 and U-236 contents, and the lowest U-235 enrichment within the range of uranium isotope contents in RU fuel. As shown in the Tables, EMVs in channel and bundle powers for the two severe cases were similar to the EMV results in Tables 5 and 6.

4. Summary and Conclusions

The performance characteristics of the RUFIC-fuelled CANDU-6 core have been studied in order to investigate the tolerances to RU isotopic variations. Time average calculations have been done to determine the essential performance indicators such as exit burnup, time-average and instantaneous power distributions, channel visit rate and reactivity decay rate. Instantaneous core snapshots were also generated based on the time average calculation with a 4 BS fuelling scheme and artificially created channel age maps. These snapshots provided estimates of peak powers and fuelling ripple factors. Based on the time average and snapshot calculation results, it is concluded as the follows about the sensitivities of average exit burnup and peak powers and the tolerances to RU isotopic variations:

- An average exit burnup and core reactivity relationship for RUFIC-fuelled CANDU-6 core with a 4 BS has been established. The coefficient is 1.93 *MWh/kgU/mk*.
- If all the RUFIC bundles in the core have U-235 content that differs by ±0.01 *w/o* from the nominal value of 0.92 *w/o*, then the variation in burnup is estimated to be ±5.7 *MWh/kgU*.
- The variations of U-234 and U-236 isotopic contents within the specified allowable ranges have negligible impact on power distribution and exit burnup.
- In the scenario that all the RUFIC bundles in the core have the nominal U-235 content, and when a channel is refuelled (4 BS) with a new batch of fuel with U-235 content deviating from the nominal value by ±0.01 *w/o*, the variation in channel power is estimated to be up to ±0.6 %, and the variation in bundle power is estimated to be up to ±1.5 %.
- For a situation that each RUFIC bundle in the core can have a U-235 content that varies in a totally random fashion by ±0.01 *w/o* from the nominal value, it is expected that there will be minimal effect on power distribution and burnup. This situation has not been considered in this study.
- For a scenario that describes a localized region of the core, all the RUFIC bundles in a group of channels have a U-235 content at 0.93 *w/o*, there will possibly be a local hot spot. However, given the conventional fuelling practices and fuelling schedule in a CANDU reactor, such a scenario is highly unlikely.
- Pin-to-pin variations of U-235 contents or pellet-to-pellet variations have not been considered. Such random variations would have minimal impact on bundle and channel powers.

Acknowledgement

This work is supported by the Ministry of Science and Technology through the Mid- and Long-term Nuclear R&D Program.

References

[1] J. Griffiths, “WIMS-AECL User's Manual,” RC-1176/COG-94-52 Rev. 3, February 1999.

[2] B. Arsenault, D. A. Jenkins and A. U. Rehman, “RFSP-IST User's Manual,” COG-98-272 Rev. 0, June 1999.

[3] S. Y. Kim, “1200 FPD Refuelling Simulation of RUFIC Fuel in a CANDU 6 Reactor,” KAERI/TR-1891/2001, July 2001.

[4] G. Marleau, A. Hebert and R. Roy, “A User Guide for DRAGON, Version DRAGON 000331 Release 3.04,” IGE-174 Rev. 5, April 2000.

Table 1. Time-Average CANDU-6 Core Models and RFSP Calculation Results for RUFIC Fuel

Model	0.92 w/o RUFIC, 4-BS* Wolsong Unit I Core
Total Reactor Power, MW	2061.4
Average Zone Level, %	50
Moderator Temperature, °C	69.0
Moderator Purity, a/o	99.85
Coolant Purity, a/o	99.1
Bundle Mass, kg-U	18.45
k-effective	0.999985
Maximum Channel Power, kW	6520.5 (M-18)
Maximum Bundle Power, kW	755.57 (M-19/5)
Average Exit Burnup, MWh/kgU (MWD/tU)	343.84 (14326.7)
Average Fuelling Rate, Channels/day (Bundles/day)	2.04 (8.15)
Adjuster Rod Worth, mk	12.9
Reactivity Decay Rate, mk/FPD	-0.530
Channel Dwell Time, FPD	186.4

- BS : Bundle Shift

Table 2. Four Bundle-Shift Instantaneous CANDU-6 Core Parameters Variations

Parameter	Channel 1 as “Starting Element” in 7x7Array	Channel 13 as “Starting Element” in 7x7Array	Channel 25 as “Starting Element” in 7x7 Array
AZL (%)	50	50	50
Max. CP (kW)	7004.7 (F-15)	7172.3 (H-15)	6836.7 (N-17)
Max. BP (kW)	826.1 (G-14/4)	843.6 (H-15/4)	805.9 (N-07/9)
CP Ripple (CPPF Region)	1.101 (G-13)	1.131 (H-15)	1.090 (G-16)
CP Ripple (Whole Core)	1.103 (N-22)	1.131 (H-15)	1.101 (J-21)
Max. Bundle Overpower	1.156 (N-22)	1.168 (G-20)	1.153 (J-21)
Average Exit Discharge Burnup (% of Time-average)	84.6	84.7	84.4
Zone 4/11 Overpower (% of Time-average)	101.4	102.2	100.1

Table 3. Calculation of Burnup Gain/Loss Coefficient in RUFIC-Fuelled CANDU-6 Core with 4-BS

Parameter	Time-Average Calculation I	Time-Average Calculation II
k-eff	0.999985	0.998985
Burnup, MWh/kgU	343.987	345.921
Max. Channel Power, kW	6520.49	6526.85
Difference in k-eff, mk	1	
Difference in Burnup, MWh/kgU	1.9332	
Burnup Gain/Loss Coefficient, MWh/kgU/mk	**1.9332**	

Table 4. Effects of U-235 Enrichment on Burnup in RUFIC-Fuelled CANDU-6 Core with 4-BS

Parameter	Reference (0.92 w/o RUFIC)	0.93 w/o RUFIC	0.91 w/o RUFIC
k-eff	0.999985	1.001837	0.998112
Burnup, MWh/kgU	343.987	346.040	341.911
Delta k-eff, mk	-	1.849	1.877
Burnup Gain/Loss Coefficient, MWh/kgU/mk	1.933		
Delta Burnup, MWh/kgU (Delta k-eff × Burnup Gain Coefficient)	-	3.573	3.627
Effects of U-235 Enrichment on Burnup, MWh/kgU/0.01 w/o U-235	-	**5.626**	**5.704**

Table 5. Effects of U-235 Enrichment on Maximum Channel and Bundle Power in RUFIC-Fuelled CANDU-6 Core with 4-BS for Case 1

	G10	F12	H15	J08	L17	M16	N11	O17	Q11	Q15	Average	1 σ	2 σ	Average + 2 σ	EMV
0.92 w/o U-235															
MCP	7141.7	6971.7	7219.0	7237.3	7040.0	7071.2	6905.6	7092.0	6961.1	7442.6	7108.2	-	-	-	-
MBP	829.8	813.5	851.2	831.7	813.5	829.3	820.3	837.0	813.5	841.2	828.1				
0.90 w/o U-235															
MCP	7095.9	6929.1	7169.9	7195.5	6989.4	7025.5	6904.4	7057.9	6922.8	7381.8	7067.2				
Diff.	-45.8	-42.6	-49.1	-41.8	-50.6	-45.7	-1.2	-34.1	-38.3	**-60.8**	-41.0	15.8	31.5	-72.5	**-1.02%**
MBP	830.3	813.5	835.3	821.1	813.6	823.1	820.1	837.1	813.6	838.8	824.7				
Diff.	0.5	0.3	**-15.9**	-10.6	0.1	-6.2	-0.2	0.1	0.1	-2.4	-3.4	5.7	11.4	-14.8	**-1.79%**
0.91 w/o U-235															
MCP	7117.9	6950.0	7195.8	7217.6	7009.8	7049.8	6905.3	7076.4	6938.6	7407.1	7086.8				
Diff.	-23.8	-21.7	-23.2	-19.7	-30.2	-21.4	-0.3	-15.6	-22.5	**-35.5**	-21.4	9.2	18.5	-39.9	**-0.56%**
MBP	830.0	812.6	843.4	825.0	814.2	824.0	820.2	837.1	813.8	839.1	825.9				
Diff.	0.2	-0.9	**-7.8**	-6.7	0.7	-5.3	-0.1	0.1	0.3	-2.1	-2.2	3.2	6.4	-8.6	**-1.04%**
0.93 w/o U-235															
MCP	7164.6	6996.6	7243.0	7274.4	7051.6	7103.5	6905.5	7109.5	6972.6	7466.8	7128.8				
Diff.	22.9	24.9	24.0	**37.1**	11.6	32.3	-0.1	17.5	11.5	24.2	20.6	10.8	21.7	42.3	**0.59%**
MBP	837.4	813.2	859.0	841.2	814.4	837.8	820.3	836.9	813.8	848.7	832.3				
Diff.	7.6	-0.3	7.8	**9.5**	0.9	8.5	0.0	-0.1	0.3	7.5	4.2	4.3	8.5	12.7	**1.54%**
0.94 w/o U-235															
MCP	7182.4	7013.4	7267.5	7289.0	7075.0	7168.9	6908	7124.5	6987.3	7491.1	7150.7				
Diff.	40.7	41.7	48.5	51.7	35.0	**97.7**	2.4	32.5	26.2	48.5	42.5	24.1	48.2	90.7	**1.28%**
MBP	843.9	813.5	866.9	847.6	814.3	852.1	820.7	836.7	813.8	856.5	836.6				
Diff.	14.1	0.0	15.7	15.9	0.8	**22.8**	0.4	-0.3	0.3	15.3	8.5	9.0	18.0	26.5	**3.20%**

Table 6. Effects of U-235 Enrichment on Maximum Channel and Bundle Power in RUFIC-Fuelled CANDU-6 Core with 4-BS for Case 2

	F10	K07	K13	L11	M09	N17	O10	O15	P07	Q12		Average	1 σ	2 σ	Average + 2 σ	EMV
0.92 w/o U-235																
MCP	7124.2	7225.8	7139.6	7164.6	7230.5	7272.5	7298.9	7522.1	7638.9	7166.9		7278.4	-	-	-	-
MBP	851.8	852	853.5	855.8	863	853.1	869.3	888.3	885.3	853.6		862.6				
0.90 w/o U-235																
MCP	7119.2	7159.9	7142.9	7163.8	7226.8	7232.7	7296.4	7472	7627.6	7166.7		7260.8				
Diff.	-5.0	**-65.9**	3.3	-0.8	-3.7	-39.8	-2.5	-50.1	-11.3	-0.2		-17.6	24.8	49.5	-67.1	**-0.92%**
MBP	850.9	852.1	854	855.8	862.3	852.7	869.6	876.7	888.8	853.5		861.6				
Diff.	-0.9	0.1	0.5	0.0	-0.7	-0.4	0.3	**-11.6**	3.5	-0.1		-0.9	3.9	7.9	-8.8	**-1.02%**
0.91 w/o U-235																
MCP	7123.3	7211.3	7138.8	7164.5	7228.5	7254.4	7298.8	7497.5	7617.3	7166.3		7270.1				
Diff.	-0.9	-14.5	-0.8	-0.1	-2.0	-18.1	-0.1	**-24.6**	-21.6	-0.6		-8.3	10.1	20.2	-28.6	**-0.39%**
MBP	851.6	852.2	853.4	855.8	862.6	852.7	869.6	880.5	885.3	853.8		861.8				
Diff.	-0.2	0.2	-0.1	0.0	-0.4	-0.4	0.3	**-7.8**	0.0	0.2		-0.8	2.5	4.9	-5.7	**-0.67%**
0.93 w/o U-235																
MCP	7124.5	7247.2	7140.1	7163	7231.9	7295.8	7304	7546.3	7658	7167.5		7287.8				
Diff.	0.3	21.4	0.5	-1.6	1.4	23.3	5.1	**24.2**	19.1	0.6		9.4	11.0	22.0	31.5	**0.43%**
MBP	851.8	852.2	853.6	855.5	863.3	852.8	869.7	896	885	853.6		863.4				
Diff.	0.0	0.2	0.1	-0.3	0.3	-0.3	0.4	**7.7**	-0.3	0.0		0.8	2.4	4.9	5.7	**0.66%**
0.94 w/o U-235																
MCP	7120	7271.8	7141.5	7165.2	7234.3	7340.8	7305.6	7573.4	7680	7167.5		7300.0				
Diff.	-4.2	46.0	1.9	0.6	3.8	**68.3**	6.7	51.3	41.1	0.6		21.6	26.9	53.8	75.4	**1.04%**
MBP	850.9	852.3	853.8	855.8	863.6	850.7	869.5	904.2	885	853.6		863.9				
Diff.	-0.9	0.3	0.3	0.0	0.6	-2.4	0.2	**15.9**	-0.3	0.0		1.4	5.2	10.4	11.7	**1.36%**

Table 7. Effects of the Two RUFIC Fuels Having the Highest and the Lowest Reactivity on Maximum Channel and Bundle Powers

	G10	F12	H15	J08	L17	M16	N11	O17	Q11	Q15		Average	1 σ	2 σ	Average + 2 σ	EMV
Reference																
MCP	7141.7	6971.7	7219.0	7237.3	7040.0	7071.2	6905.6	7092.0	6961.1	7442.6		7108.2	-	-	-	-
MBP	829.8	813.5	851.2	831.7	813.5	829.3	820.3	837.0	813.5	841.2		828.1				
The Highest Reactivity RUFIC Fuel (0.94 w/o U-235, 0.22 w/o U-236, and 0.010 w/o U-234)																
MCP	7195.1	7004.3	7275.3	7290.0	7080.6	7122.6	6908.4	7125.1	6999.4	7498.4		7149.9				
Diff.	53.4	32.6	56.3	52.7	40.6	51.4	2.8	33.1	38.3	**55.8**		41.7	16.5	33.0	74.7	**1.05%**
MBP	847.0	815.2	869.0	848.4	814.3	845.4	820.8	836.4	813.5	858.4		836.8				
Diff.	17.2	1.7	**17.8**	16.7	0.8	16.1	0.5	-0.6	0.0	17.2		8.7	8.7	17.5	26.2	**3.17%**
The Lowest Reactivity RUFIC Fuel (0.90 w/o U-235, 0.40 w/o U-236, and 0.018 w/o U-234)																
MCP	7088.9	6928.6	7165.9	7193.4	6983.6	7026.4	6903.8	7053.6	6917.8	7388.9		7065.1				
Diff.	-52.8	-43.1	-53.1	-43.9	-56.4	-44.8	-1.8	-38.4	-43.3	**-53.7**		-43.1	15.7	31.4	-11.8	**-0.17%**
MBP	829.7	813.3	834.4	821.2	814.5	823.4	820.0	836.8	813.9	840.4		824.8				
Diff.	-0.1	-0.2	**-16.8**	-10.5	1.0	-5.9	-0.3	-0.2	0.4	-0.8		-3.3	5.9	11.9	8.5	**1.03%**

Table 8. Effects of the Two RUFIC Fuels Having the Highest and the Lowest Reactivity on Maximum Channel and Bundle Powers

	F10	K07	K13	L11	M09	N17	O10	O15	P07	Q12		Average	1 σ	2 σ	Average + 2 σ	EMV
Reference																
MCP	7124.2	7225.8	7139.6	7164.6	7230.5	7272.5	7298.9	7522.1	7638.9	7166.9		7278.4	-	-	-	-
MBP	851.8	852	853.5	855.8	863	853.1	869.3	888.3	885.3	853.6		862.6				
The Highest Reactivity RUFIC Fuel (0.94 w/o U-235, 0.22 w/o U-236, and 0.010 w/o U-234)																
MCP	7123	7278	7139.3	7166.1	7233.1	7320.7	7305.6	7577	7687.2	7173.1		7300.3				
Diff.	-1.2	**52.2**	-0.3	1.5	2.6	48.2	6.7	54.9	48.3	6.2		21.9	25.1	50.3	72.2	**0.99%**
MBP	851.5	852.2	853.5	855.8	863.5	852.7	869.4	905.6	885.3	853.4		864.3				
Diff.	-0.3	0.2	0.0	0.0	0.5	-0.4	0.1	**17.3**	0.0	-0.2		1.7	5.5	11.0	12.7	**1.47%**
The Lowest Reactivity RUFIC Fuel (0.90 w/o U-235, 0.40 w/o U-236, and 0.018 w/o U-234)																
MCP	7126.3	7172.3	7142.6	7164.3	7225.5	7231.1	7295.9	7469.5	7591.5	7168.7		7258.8				
Diff.	2.1	-53.5	3.0	-0.3	-5.0	-41.4	-3.0	**-52.6**	-47.4	1.8		-19.6	25.4	50.7	31.1	**0.43%**
MBP	852.1	852.1	853.9	855.8	862.1	852.7	869.7	876.6	885.1	853.4		861.4				
Diff.	0.3	0.1	0.4	0.0	-0.9	-0.4	0.4	**-11.7**	-0.2	-0.2		-1.2	3.7	7.4	6.2	**0.72%**

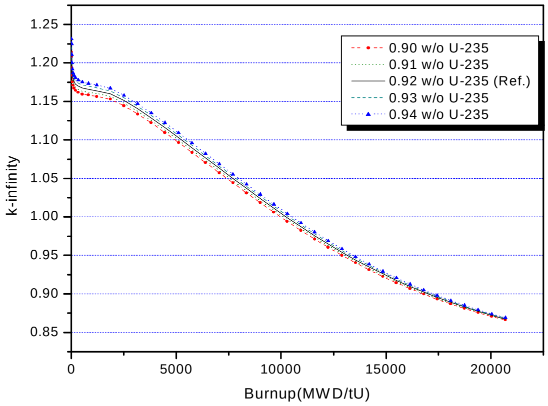

Figure 1. k-infinity of 0.90, 0.91, 0.92, 0.93 and 0.94 w/o RUFIC Fuels

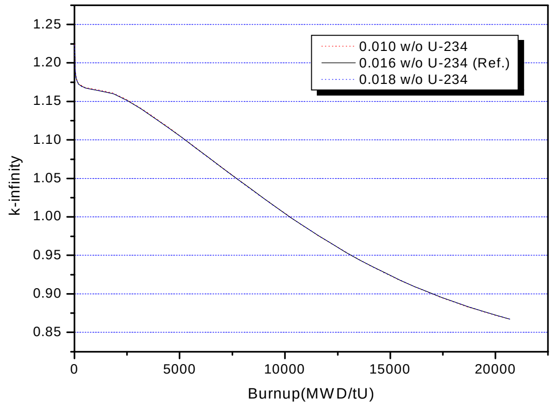

Figure 2. k-infinity of Three RUFIC Fuels Having Different U-234 Contents

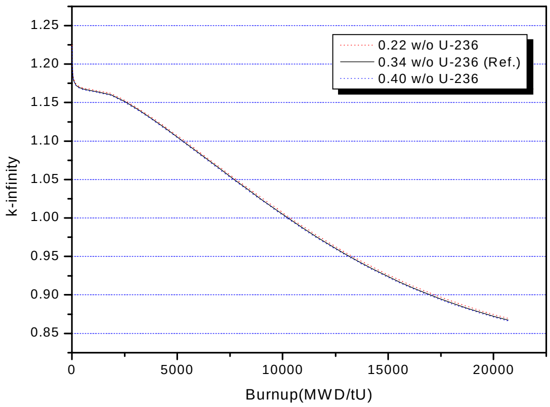

Figure 3. k-infinity of Three RUFIC Fuels Having Different U-236 Contents

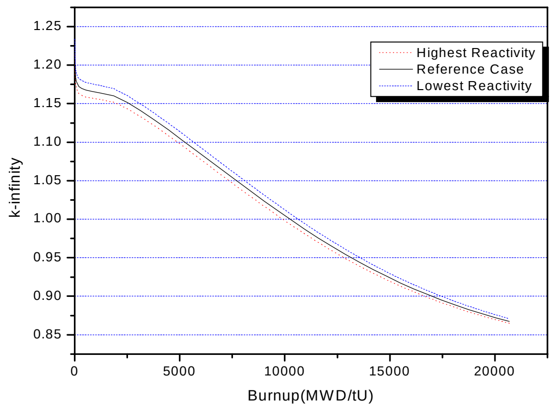

Figure 4. The Highest and Lowest Reactivity that RUFIC Fuel Can Have

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
A									297	261	256	275	284	273								
B						269	248	280	271	248	300	298	250	238	297	271	248					
C					279	240	302	252	240	262	285	256	265	290	258	248	262	305				
D				278	294	259	288	266	291	304	274	286	307	276	251	300	285	274	296			
E			260	286	281	298	267	279	306	273	294	279	257	302	270	297	253	286	280	300		
F			266	307	260	250	292	238	277	250	271	**319**	261	252	280	244	265	307	262	252		
G		242	291	277	303	240	271	305	255	**322**	306	281	311	266	284	250	289	277	303	244	257	
H		296	259	252	272	282	285	331	293	261	278	297	249	304	**331**	316	257	251	273	283	269	
J	281	271	246	300	297	263	245	**315**	283	242	309	327	273	252	293	285	260	300	297	249	236	294
K	255	241	261	284	251	280	308	268	249	271	325	289	243	321	260	245	277	283	253	265	288	259
L	269	292	304	273	284	329	291	258	320	299	287	313	265	305	277	309	**326**	271	285	307	275	252
M	283	306	275	294	277	273	324	285	316	261	302	294	318	278	296	**327**	291	293	279	260	300	272
N	246	264	240	256	298	261	249	298	253	275	**329**	270	255	310	248	275	250	253	298	249	241	281
O	289	247	302	288	266	313	267	282	240	307	291	323	246	264	304	256	**323**	288	267	293	254	270
P		280	253	267	281	241	305	331	315	268	259	286	298	282	331	295	251	266	281	244	286	
Q		273	241	292	306	262	260	295	285	252	**320**	317	256	244	**316**	288	238	292	306	265	249	
R			264	305	276	242	301	248	248	275	302	268	279	309	255	241	262	304	277	244		
S			287	274	295	257	288	264	290	304	273	285	307	275	248	300	284	276	295	262		
T				288	280	299	267	281	306	275	294	280	260	303	272	297	256	286	283			
U					257	242	284	235	255	233	251	290	242	235	273	242	257	298				
V						214	221	249	212	261	250	232	254	220	234	205	252					
W									242	219	232	244	211	249								

Figure 5. Average Exit Burnup from INSTANTAN Calculation for Snapshot 1 (*MWh/kgU*)

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
A									260	275	261	289	267	295								
B						280	260	283	288	245	298	303	250	277	257	289	305					
C					292	309	248	249	304	246	267	273	240	307	273	245	247	282				
D				301	268	285	270	296	260	278	300	294	260	285	257	297	268	300	273			
E			276	294	292	250	282	298	253	289	266	291	261	278	286	303	272	295	292	257		
F			243	262	263	306	267	238	291	**331**	302	264	327	248	261	244	240	260	265	306		
G		279	307	286	280	237	267	322	270	252	285	299	282	263	312	295	307	286	280	241	254	
H		257	274	258	287	264	312	245	296	257	315	318	249	322	245	267	273	257	287	265	291	
J	284	289	243	297	303	263	293	263	305	325	272	264	288	267	297	307	256	297	303	249	275	257
K	252	304	246	265	270	252	**329**	287	245	251	292	307	**331**	249	256	325	259	264	272	240	305	273
L	296	262	278	300	293	274	302	265	316	276	**320**	279	299	282	314	273	295	299	294	260	283	258
M	299	256	290	266	290	277	295	303	**323**	284	313	309	257	297	318	265	309	264	291	263	278	286
N	246	276	309	283	247	327	245	275	253	243	270	274	327	280	248	290	**331**	282	249	306	238	264
O	302	259	245	270	282	286	263	311	290	**329**	302	294	242	260	**322**	271	258	269	282	269	251	292
P		283	250	296	298	241	**322**	245	263	287	267	304	276	311	244	299	248	296	299	244	299	
Q		290	305	262	257	275	274	298	306	249	317	**324**	256	292	266	308	304	263	257	276	260	
R			249	279	290	309	241	245	326	257	281	289	250	329	271	238	247	279	291	309		
S			271	300	270	284	270	295	259	276	300	294	258	284	255	297	266	301	269	287		
T				296	291	254	282	298	254	290	268	291	263	279	287	303	274	294	293			
U					260	296	262	235	267	299	276	245	296	232	256	242	233	257				
V						212	218	261	223	213	235	245	233	218	254	239	266					
W									244	216	256	259	211	261								

Figure 6. Average Exit Burnup from INSTANTAN Calculation for Snapshot 2 (*MWh/kgU*)