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ISBN

9784888982566

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Publication Date

2017

DOI

10.115/ICONE25-68001

Peer reviewed

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Proceedings of the 2017 25th International Conference on Nuclear Engineering
ICONE25
May 14-18, 2017, Shanghai, China

UNCERTAINTY ANALYSIS OF THE TRU-BURNING THORIUM-FUELED RBWR USING GENERALIZED PERTURBATION THEORY

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ABSTRACT

The RBWR-TR is a thorium-based reduced moderation BWR (RBWR) with a high transuranic (TRU) consumption rate. It is charged with LWR TRU and thorium, and it recycles all actinides an unlimited number of times while discharging only fission products and trace amounts of actinides through reprocessing losses. This design is a variant of the Hitachi RBWR-TB2, which arranges its fuel in a hexagonal lattice, axially segregates seed and blanket regions, and fits within an ABWR pressure vessel. The RBWR-TR eliminates the internal axial blanket, eliminates absorbers from the upper reflector, and uses thorium rather than depleted uranium as the fertile makeup fuel. This design has been previously shown to perform comparably to the RBWR-TB2 in terms of TRU consumption rate and burnup while providing significantly more margin against critical heat flux.

This study examines the uncertainty in key neutronics parameters due to nuclear data uncertainty. As most of the fissions are induced by epithermal neutrons and since the reactor uses higher actinides as well as thorium and ^{233}U, the cross sections have significantly more uncertainty than in typical LWRs. The sensitivity of the multiplication factor to the cross sections of many actinides is quantified using a modified version of Serpent 2.1.19. Serpent is a Monte Carlo code which uses delta tracking to speed up the simulation of reactors; in this modified version, cross sections are artificially inflated to sample more collision, and collisions are rejected to preserve a "fair game." The impact of these rejected collisions is then propagated to the multiplication factor using generalized perturbation theory. Covariance matrices are retrieved for the ENDF/B-VII.1 library, and used to collapse the sensitivity vectors to an uncertainty on the multiplication factor. The simulation is repeated for several reactor configurations (for example, with a reduced flow rate, and with control rods inserted), and the difference in keff sensitivity is used to assess the uncertainty associated with the change (the uncertainty in the void feedback and the control rod worth). The uncertainty in the RBWR-TR is found to be dominated by the epithermal fissions in ^{233}U in reference conditions, although when the spectrum hardens, the uncertainty in fast captures of ^{232}Th become dominant.

INTRODUCTION

The RBWR-TR core design is based off of the Hitachi RBWR-TB2 (1), a reduced-moderation BWR that employs axial seed and blanket segregation for continuous burning of LWR transuranic waste (TRU). The discharge fuel from the RBWR-TR is recycled, and a mixture of natural thorium and reprocessed LWR TRU is added to maintain the fuel inventory. The RBWR-TR differs from the RBWR-TB2 in that it uses thorium rather than depleted uranium as the fertile component of the makeup fuel, and it eliminates the internal blanket while elongating the seed region and the outer blankets.

Reduced-moderation BWR core concepts, referred to by Hitachi as the Resource-renewable BWR (RBWR), were initially pursued by Hitachi (1) in an attempt to design hard spectrum BWRs to provide missions traditionally assigned to liquid metal cooled reactors – fuel sustainability (RBWR-AC) or TRU transmutation with unlimited recycling (RBWR-TB2) (2,3). As the RBWR-TB2 and RBWR-TR use water coolant, although of low density, their spectrum is softer than that of a TRU-burning SFR (4) but harder than of a typical BWR, as

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shown in Figure 1. Figure 2 shows the spectra of neutrons inducing fission; more than half of the fissions in the RBWR-TR are induced by neutrons between 1 eV and 0.1 MeV.

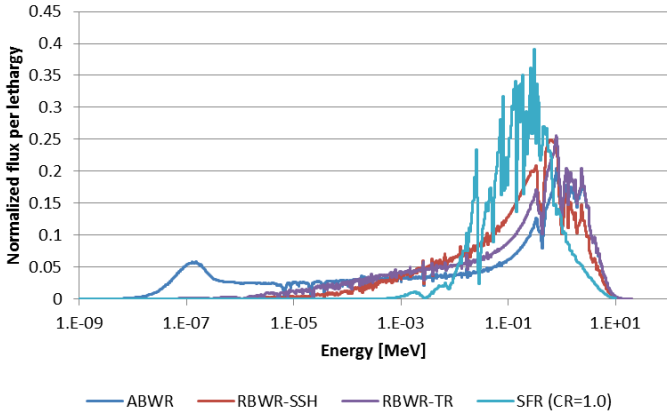

Figure 1. Flux spectra of the RBWRs against an ABWR and an SFR.

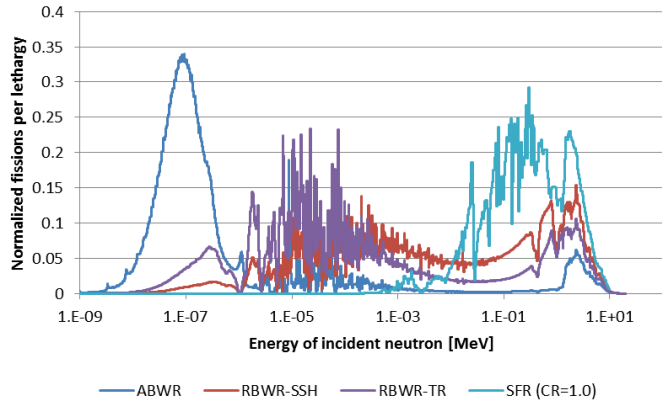

Figure 2. Spectra of neutrons inducing fission of the RBWRs and other reactors.

There were several concerns regarding the RBWR-TB2 core that provided incentive to examine a thorium-based counterpart: uncertainty in the void reactivity feedback, possibly too small margin against critical heat flux, weak neutronic coupling between the two axial seed segments, and insufficient margin for fuel survivability (5). The very strong axial heterogeneity of the RBWR-TB2 core was dictated by the need to maximize the negative leakage component of fuel voiding reactivity effect so as to overcome its large positive spectrum hardening reactivity component. In addition, since depleted uranium was used as the blanket material and as the makeup fuel, the transmutation rate was reduced by breeding extra ^{239}Pu from the fertile ^{238}U.

As shown in Figure 3, ^{233}U has a much flatter fuel reproduction factor with energy than ^{239}Pu. Also, the ^{232}Th fast fission cross section has a higher threshold and lower value than that of ^{238}U. Therefore, the spectral component of void reactivity in a Th-^{233}U fueled RBWR core is inherently less positive and there is no need to design the core to have enhanced leakage probability from the seed. This enables use of a single relatively long seed region thereby avoiding many of the concerns about the U-Pu core design.

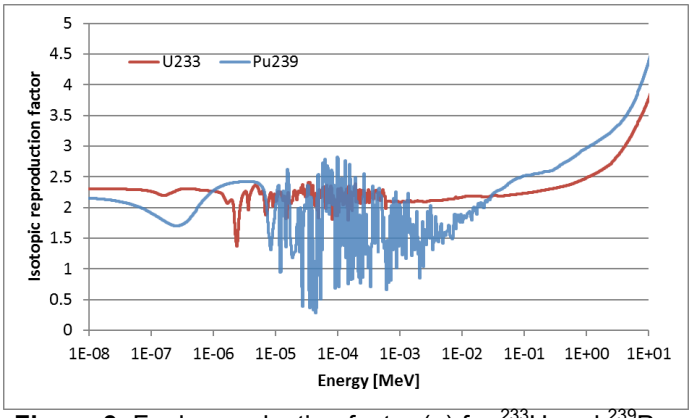

Figure 3. Fuel reproduction factor (η) for ^{233}U and ^{239}Pu.

The RBWR-TR has been previously shown to achieve similar transmutation rates and discharge burnups to the RBWR-TB2 while maintaining much higher margin against critical heat flux, although it is questionable whether it can maintain sufficient shutdown margin while having a negative void coefficient of reactivity (VCR) (8). This study focuses on using generalized perturbation theory (GPT) to assess the sensitivity of the multiplication factor of the RBWR-TR to the nuclear data. The sensitivity is then used with the covariance of the cross sections in order to quantify the uncertainty in the multiplication factor.

NOMENCLATURE

α	Void fraction
η	Neutron reproduction factor
σ	Uncertainty or cross section, depending on context
ρ	Coolant density
BOL	Beginning of life; fresh fuel
EOL	End of life; discharged fuel
GPT	Generalized perturbation theory
RBWR	Resource-renewable boiling water reactor
VCR	Void coefficient of reactivity

METHODOLOGY

Serpent 2.1.19 was modified to use GPT to assess the sensitivity of the multiplication factor to the cross sections of specified isotopes, as documented in Reference (6). To summarize, each of the cross sections were artificially inflated. In order to preserve the "fairness" of the Monte Carlo simulation, the collisions were rejected according to the bias. These rejected collisions were still recorded, and their effects were propagated to the multiplication factor using GPT. This methodology has been benchmarked against deterministic codes in Reference (6).

An assembly unit cell of the RBWR-TR was made in Serpent and used for this simulation. The seed is 100 cm long,

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with 15 cm thorium blankets on the top and bottom. The sensitivity was assessed for fresh fuel and discharge fuel; the fuel was burned using average flow conditions up to an average burnup of 50 GWd/t. The seed was divided into 20 5-cm burnup zones, while each blanket was divided into 5 3-cm burnup zones. A cross-sectional cutaway of the unit cell model is shown in Figure 4.

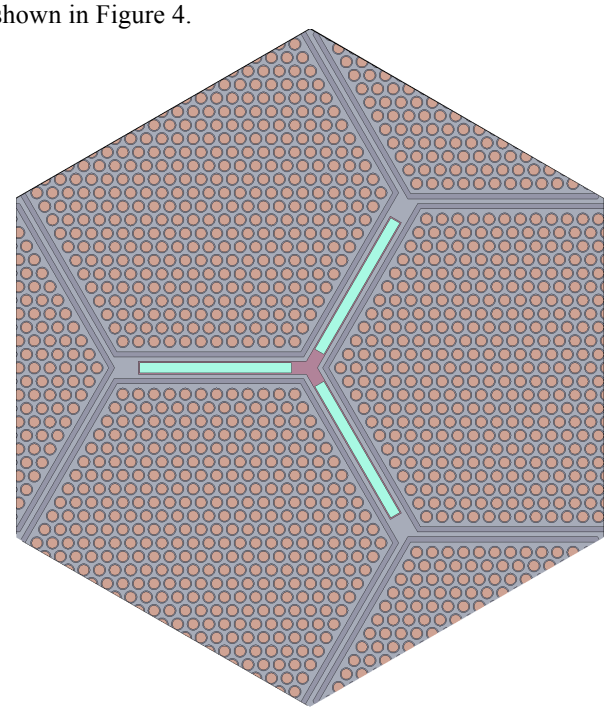

Figure 4. Cross-sectional view of the RBWR-TR unit cell, as modeled in Serpent.

The sensitivities of the multiplication factor to each reaction were divided into 175 energy groups. The sensitivity coefficients were calculated using 15 latent generations as documented in Reference (6). ENDF/B-VII.1 cross sections were used. The covariance in the reaction cross sections were retrieved from the JANIS (7).

The variance of the multiplication factor was calculated as

$$\sigma_i^2 = \sum_{r_1} \sum_{r_2} \underline{S}_{r_2,i} \times \underline{\underline{C}}_{r_1,r_2,i} \times \underline{S}^T_{r_1,i}$$

where i designates the isotope, r_1 and r_2 denote reactions, $\underline{S}$ is the vector of sensitivity coefficients, and $\underline{\underline{C}}$ is the relative covariance matrix. The uncertainty due to the change in conditions (such as moving from the reference water densities to flooded conditions) was calculated similarly, except that the change in sensitivity coefficients between the two cases was used. The uncertainty due to flooding the reactor (i.e. using 1 g/cc water in the entire unit cell), voiding the reactor (i.e. using 0.001 g/cc water in the entire unit cell), and inserting the control rods was assessed. In addition, the coolant void coefficient of reactivity (VCR) and its uncertainty was calculated by setting the coolant flow rate to 85% of the nominal value, and dividing the change in reactivity and the its uncertainty by the change in void fraction. In equation form,

$$\mathrm{VCR} = \frac{\frac{1}{k_{100\%\,\mathrm{flow}}} - \frac{1}{k_{85\%\,\mathrm{flow}}}}{\alpha_{85\%\,\mathrm{flow}} - \alpha_{100\%\,\mathrm{flow}}}$$

The sensitivity due to every isotope that was present in the fuel at BOL was calculated; in addition, the sensitivity due to hydrogen was calculated due to the importance of moderation on the results. It was also desired to assess the importance of fission products, but it was not considered feasible to calculate the uncertainty from each one. Additionally, the covariance matrices for most unstable fission products were not available, including ^{135}Xe. In order to assess the impact of fission products, ^{149}Sm and ^{151}Sm were used since they are stable and have very large capture cross sections. The considered reactions were radiative capture, fission, elastic scattering, inelastic scattering, and (n,2n) reactions.

RESULTS

The k_∞ at BOL was calculated to be 1.09561 ± 823 pcm, while at EOL, it was calculated to be 0.99296 ± 907 pcm. Effectively all of the quoted uncertainty is due to the uncertainty from the nuclear data, as the statistical uncertainty from the Monte Carlo simulation contributed less than 1 pcm towards the final uncertainty. The decomposition due to reaction type and isotope is shown in Table 1 and Table 2 at BOL and EOL, respectively, while the uncertainty as a function of energy is shown in Figure 5 and Figure 6.

At both BOL and EOL, by far the largest contribution to uncertainty is fissions in ^{233}U, followed by capture in ^{232}Th. The uncertainty due to fission undergoes a step change around 0.8 keV, since the uncertainty in the ^{233}U fission cross section also undergoes a step change at the same energy. The capture in ^{232}Th undergoes a similar increase in uncertainty around 2 keV and 0.1 MeV. (n, 2n) reactions contributed negligible amounts of uncertainty, so they were omitted from Table 1 and Table 2. The uncertainty from the fission products ^{149}Sm and ^{151}Sm were very small compared to the uncertainty from the actinides; considering that these isotopes are among the most absorbing fission products (aside from ^{135}Xe), it is unlikely that other fission products contribute a non-negligible amount of uncertainty.

Table 1. Uncertainty from each isotope and reaction at BOL in pcm. The ten largest values are highlighted.

Isotope	(n,γ)	Elastic	Fission	Inelastic	Cross-terms	Total
Am-241	116	2	6	2	11	117
Am-242m	15	0	32	0	n/a	35
Am-243	94	2	29	2	n/a	98
Cm-243	2	0	1	0	0	2
Cm-244	102	4	16	1	5	104
Cm-245	72	0	90	1	9	115

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Isotope	(n,γ)	Elastic	Fission	Inelastic	Cross-terms	Total
Cm-246	18	0	5	0	1	19
Cm-247	11	0	11	0	3	16
Cm-248	1	0	1	0	1	2
H-1	5	40	n/a	n/a	n/a	40
Np-237	100	1	10	1	n/a	101
O-16	155	23	n/a	4	2	157
Pu-238	155	1	12	1	4	156
Pu-239	53	1	74	7	26	95
Pu-240	79	2	21	14	5	83
Pu-241	138	2	105	2	n/a	173
Pu-242	153	4	17	4	n/a	154
Th-232	329	39	17	n/a	21	333
U-232	4	0	10	0	3	11
U-233	66	2	588	6	40	594
U-234	77	6	166	6	n/a	183
U-235	29	0	7	1	6	31
U-236	20	0	23	2	n/a	31
Total	518	61	634	19	55	823

Table 2. Uncertainty from each isotope and reaction at EOL in pcm. The ten largest values are highlighted.

Isotope	(n,γ)	Elastic	Fission	Inelastic	Cross-terms	Total
Am-241	87	2	5	2	3	87
Am-242m	10	0	28	0	n/a	29
Am-243	91	1	31	2	n/a	96
Cm-243	2	0	2	0	0	3
Cm-244	111	4	21	1	6	113
Cm-245	75	0	109	1	10	133
Cm-246	18	0	6	0	1	19
Cm-247	12	0	13	0	4	18
Cm-248	1	0	1	0	1	2
H-1	9	44	n/a	n/a	n/a	45
Np-237	72	0	8	1	n/a	73
O-16	155	28	n/a	4	2	158
Pu-238	155	2	13	1	10	156
Pu-239	35	1	57	5	15	68
Pu-240	72	2	21	15	7	76
Pu-241	126	2	119	2	n/a	173
Pu-242	151	5	18	4	n/a	152
Sm-149	21	0	n/a	0	n/a	21
Sm-151	13	0	n/a	0	n/a	13
Th-232	337	40	20	n/a	18	341
U-232	4	0	12	0	2	13
U-233	67	4	695	7	66	701
U-234	76	5	194	6	n/a	208
U-235	30	0	9	1	6	32
U-236	18	0	27	3	n/a	33
Total	508	67	745	19	73	907

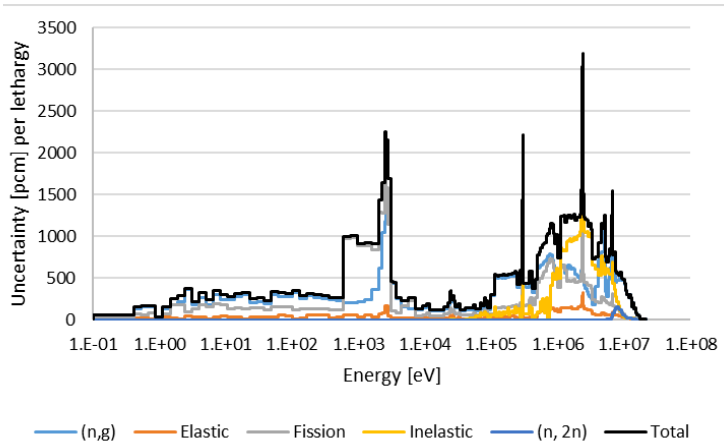

Figure 5. Uncertainty per lethargy for each reaction at BOL.

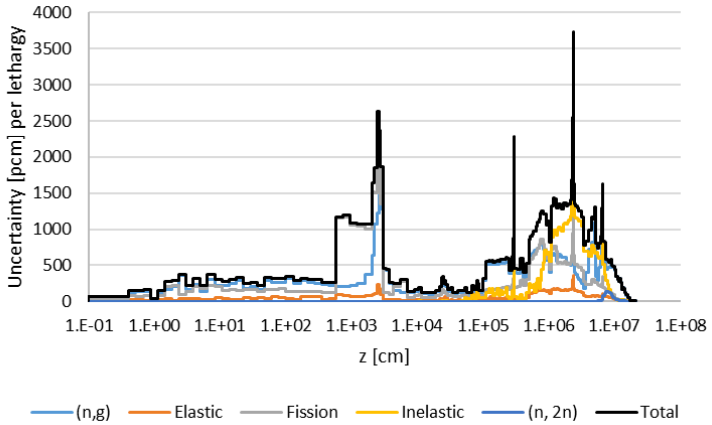

Figure 6. Uncertainty per lethargy for each reaction at EOL.

The summary of the uncertainties in parameters calculated by changing the reactor state is shown in Table 3. The largest difference in uncertainty occurred when voiding and flooding the reactor, due to the large spectral shift; therefore, the uncertainty in the flooded and voided states are compared against the reference conditions in Table 4 through Table 7. Table 8 through Table 11 show the uncertainty associated with the change in each of the states.

As shown in Table 4 and Table 6, both flooding and voiding the reactor significantly reduce the uncertainty from ^{233}U, since fewer neutrons are in the epithermal range with a high uncertainty in the fission cross section; however, the ^{232}Th capture uncertainty dramatically increases when the reactor is voided. It has been observed that the radial leakage in the full core model softens the spectrum slightly; it is expected that this will reduce the uncertainty somewhat, although it will very likely be higher than the uncertainty in the flooded conditions.

The uncertainty in the VCR is roughly 10 pcm/% void at both BOL and EOL; although the VCR indicated in Table 3 is positive, the added radial leakage in the full core model reduces it significantly. The uncertainty in the control rod worth is nearly negligible; however, this may be due to the fact that ^{10}B (n,α) reactions were omitted from this analysis.

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Table 3. Uncertainty in performance metrics derived from the multiplication factor in different states.

Parameter	BOL	EOL
VCR [pcm/% void]	4.3 ± 9.1	23.1 ± 10.1
Reactivity insertion from flooding the reactor [pcm]	1495 ± 362	198 ± 422
Reactivity insertion from voiding the reactor [pcm]	5328 ± 843	6873 ± 854
Control rod worth [pcm]	-10356 ± 59	-12311 ± 61

Table 4. Uncertainty from each isotope at BOL in the reference, flooded, and voided conditions. All uncertainties are in pcm.

Isotope	Ref. Cond.	Flooded	Voided
Am-241	117	189	31
Am-242m	35	58	50
Am-243	98	97	67
Cm-243	2	2	2
Cm-244	104	97	108
Cm-245	115	139	92
Cm-246	19	15	20
Cm-247	16	15	8
Cm-248	2	2	2
H-1	40	37	2
Np-237	101	91	73
O-16	157	157	209
Pu-238	156	219	101
Pu-239	95	122	105
Pu-240	83	108	114
Pu-241	173	178	118
Pu-242	154	167	45
Th-232	333	195	814
U-232	11	9	9
U-233	594	334	399
U-234	183	117	381
U-235	31	17	93
U-236	31	26	35
Total	823	640	1052

Table 5. Uncertainty from each reaction at BOL in the reference, flooded, and voided conditions. All uncertainties are in pcm.

Reaction	Ref. Cond.	Flooded	Voided
(n,γ)	518	493	881
Elastic	61	51	144
Fission	634	398	544
Inelastic	19	8	100
(n, 2n)	2	2	1
Cross-terms	55	80	54
Total	823	640	1052

Table 6. Uncertainty from each isotope at EOL in the reference, flooded, and voided conditions. All uncertainties are in pcm.

Isotope	Ref. Cond.	Flooded	Voided
Am-241	87	147	23
Am-242m	29	53	43
Am-243	96	94	70
Cm-243	3	3	3
Cm-244	113	103	130
Cm-245	133	174	107
Cm-246	19	15	21
Cm-247	18	17	9
Cm-248	2	2	2
H-1	45	45	2
Np-237	73	66	57
O-16	158	157	216
Pu-238	156	209	107
Pu-239	68	99	71
Pu-240	76	99	101
Pu-241	173	185	113
Pu-242	152	163	46
Sm-149	21	88	4
Sm-151	13	18	8
Th-232	341	193	817
U-232	13	10	11
U-233	701	382	504
U-234	208	127	436
U-235	32	17	101
U-236	33	25	41
Total	907	603	1102

Table 7. Uncertainty from each reaction at EOL in the reference, flooded, and voided conditions. All uncertainties are in pcm.

Reaction	Ref. Cond.	Flooded	Voided
(n,γ)	508	420	870
Elastic	67	55	154
Fission	745	426	650
Inelastic	19	9	84
(n, 2n)	1	1	1
Cross-terms	73	54	64
Total	907	603	1102

Table 8. Uncertainty from each isotope associated with each change in reactor state at BOL. All uncertainties are in pcm, except for the VCR which is in pcm/% void.

Isotope	VCR [pcm / % void]	Flooding	Voiding	CR Worth
Am-241	1.7	75	117	9
Am-242m	0.5	34	47	2
Am-243	0.5	12	94	8
Cm-243	0.0	1	1	0
Cm-244	0.8	23	109	8
Cm-245	1.4	64	96	7
Cm-246	0.2	5	17	2
Cm-247	0.1	6	13	1

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Isotope	VCR [pcm / % void]	Flooding	Voiding	CR Worth
Cm-248	0.1	1	2	0
H-1	0.2	16	38	5
Np-237	0.9	35	84	8
O-16	0.2	9	121	12
Pu-238	1.3	75	156	12
Pu-239	1.1	64	110	5
Pu-240	0.9	39	102	7
Pu-241	1.0	31	186	10
Pu-242	0.8	16	145	11
Th-232	3.9	144	579	23
U-232	0.1	4	8	1
U-233	7.2	281	385	35
U-234	2.0	73	225	27
U-235	0.4	15	64	2
U-236	0.2	8	25	4
Total	9.1	362	843	59

Table 9. Uncertainty from each reaction associated with each change in reactor state at BOL. All uncertainties are in pcm, except for the VCR which is in pcm/% void.

Reaction	VCR [pcm / % void]	Flooding	Voiding	CR Worth
(n,γ)	4.9	198	690	35
Elastic	0.9	19	131	15
Fission	7.4	297	456	45
Inelastic	0.6	11	86	5
(n, 2n)	0.0	0	0	0
Cross-terms	1.8	54	43	7
Total	9.1	362	843	59

Table 10. Uncertainty from each isotope associated with each change in reactor state at EOL. All uncertainties are in pcm, except for the VCR which is in pcm/% void.

Isotope	VCR [pcm / % void]	Flooding	Voiding	CR Worth
Am-241	1.8	63	87	7
Am-242m	0.4	33	40	2
Am-243	0.5	12	91	7
Cm-243	0.0	2	2	0
Cm-244	0.9	27	123	7
Cm-245	1.5	84	115	7
Cm-246	0.2	6	17	1
Cm-247	0.2	7	15	1
Cm-248	0.0	1	2	0
H-1	0.2	15	43	6
Np-237	0.6	27	61	6
O-16	0.9	11	126	10
Pu-238	1.4	65	157	9
Pu-239	0.8	54	78	3
Pu-240	0.8	36	91	5
Pu-241	1.0	37	183	7
Pu-242	0.9	15	142	10
Sm-149	0.6	68	21	3
Sm-151	0.1	10	13	1
Th-232	3.9	155	572	28
U-232	0.1	5	10	1
U-233	8.3	343	415	35
U-234	2.2	86	251	32
U-235	0.5	16	71	2
U-236	0.1	9	25	4
Total	10.1	422	854	61

Table 11. Uncertainty from each reaction associated with each change in reactor state at BOL. All uncertainties are in pcm, except for the VCR which is in pcm/% void.

Reaction	VCR [pcm / % void]	Flooding	Voiding	CR Worth
(n,γ)	4.8	208	675	35
Elastic	1.6	18	137	14
Fission	8.6	362	497	46
Inelastic	0.4	11	71	2
(n, 2n)	0.0	0	0	0
Cross-terms	1.5	60	51	14
Total	10.1	422	854	61

CONCLUSIONS

The uncertainty of the RBWR-TR multiplication factor due to uncertainty in the nuclear data was assessed, and found to vary between about 800 pcm and 900 pcm over the lifetime of the fuel. In addition, the uncertainty in the change between reactor states was also assessed. It was found that the uncertainty in the void coefficient of reactivity is roughly 10 pcm/% void for both fresh fuel and discharge fuel; the uncertainty associated with flooding the reactor and voiding the reactor was approximately 400 pcm and 850 pcm, respectively; and the control rod worth had a negligible amount of uncertainty compared to the value of the control rod worth. However, the sensitivity to ^{10}B (n,α) reactions was not assessed, so the uncertainty in the control rod worth may be underestimated. The uncertainty in the VCR is on the same order of the full core VCR.

Softening the spectrum tended to reduce the uncertainty, while hardening it tended to increase the uncertainty. Since these calculations were performed on a unit cell model, it is expected that the increased leakage of a full core model will soften the spectrum slightly; therefore, the uncertainty of the full core model may be slightly lower. Using the uncertainty of the flooded reactor as a lower bound, it is not expected that the uncertainty of the full core multiplication factor would be less than 600 pcm.

ACKNOWLEDGMENTS

The authors would like to acknowledge Hitachi, University of Michigan, and MIT for their ongoing collaboration. This research used the Savio computational cluster resource provided by the Berkeley Research Computing program at the University of California, Berkeley (supported by the UC

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Berkeley Chancellor, Vice Chancellor for Research, and Chief Information Officer).

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