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Additional Studies of the Criticality Safety of Failed Used Nuclear Fuel*

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ABSTRACT

Commercial used nuclear fuel (UNF) in the United States is expected to remain in storage for periods potentially greater than 40 years. Extended storage (ES) time and irradiation to high-burnup values (>45 GWd/t) may increase the potential for fuel failure during normal and accident conditions involving storage and transportation. Fuel failure, depending on the severity, could result in changes to the geometric configuration of the fuel, which has safety and regulatory implications. The likelihood and extent of fuel reconfiguration and its impact on the safety of the UNF are not well understood. The objective of this work is to assess and quantify the impact of fuel reconfiguration due to fuel failure on the criticality safety of UNF in storage and transportation casks. Criticality analyses are conducted considering representative UNF designs covering a range of enrichments and burnups in multiple cask systems.

Prior work developed a set of failed fuel configuration categories, and specific configurations were evaluated to understand trends and quantify the consequences of worst-case potential reconfiguration progressions. These results are summarized here and indicate that the potential impacts on subcriticality can be rather significant for certain configurations (e.g., >20% Δk_{eff}). However, for credible fuel failure configurations from ES or transportation following ES, the consequences are judged to be manageable (e.g., <5% Δk_{eff}).

The current work expands on the previous efforts by including part-length rods in fresh boiling water reactor fuel assemblies and studying the effect of damage in varying numbers of fuel assemblies.

INTRODUCTION

Commercial used nuclear fuel (UNF) in the United States is expected to remain in storage for periods potentially greater than 40 years. This extended storage (ES) of fuel with high-burnup (>45 GWd/MTU) may increase the potential for fuel failure and reconfiguration during normal and accident conditions of storage and transportation. Potential reconfiguration, that is, changes to the geometric configuration of the fuel, has safety and regulatory implications. While the likelihood and extent of fuel reconfiguration are not well understood, the objective of this work is to further investigate some aspects of fuel reconfiguration impacts on criticality safety documented in [1] and [2]. The effort documented in these references is summarized below. The work described here includes modifications to the modeling of boiling water reactor (BWR) fuel assemblies to include some consideration of part-length fuel and examines the effects of a

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range of assemblies experiencing reconfiguration within the storage and transportation (dual-purpose) canister.

PRIOR WORK

The work documented in [1] and [2] evaluated a set of potential end states for fuel reconfiguration and examined the potential impact on the canister criticality safety of those configurations. Both of these efforts were extensions of earlier work documented in [3]. After the configurations were defined and analyzed, they were qualitatively screened for potential credibility and applicability to safety analyses based on engineering judgment. A summary of the configurations defined and the determinations of credibility is presented in Table 1. More detailed discussion of the configurations can be found in [1] and [2].

Two fuel assembly designs were used in the previous analyses: one pressurized water reactor (PWR) type and one BWR type. The designs chosen are intended to represent a large portion of the current inventory of discharged UNF and a significant portion of the fuel in use currently. The Westinghouse 17 × 17 Optimized Fuel Assembly (OFA) is used as the basis for the PWR fuel type, and GE 10 × 10 fuel is used as the basis for the BWR fuel type. Further details on the modeling of the fuel assemblies and casks are included in [2].

The depletion conditions used in this analysis are intended to be representative of conditions that would be used in a burnup credit safety analysis. Generic data are used in the PWR depletion conditions. The BWR depletion conditions are based on the operating history of a specific assembly [4]. All UNF compositions are represented with 12 actinide and 16 fission product isotopes defined as Set 2 in [5] and shown in Table 2. Further details on the generation and application of the specific operating parameters are included in [2].

The impact on criticality safety was determined by calculating the change in k_{eff} (Δk_{eff}) associated with each of the fuel reconfiguration scenarios applied to all fuel assemblies in a dual-purpose canister. Two canister designs were considered, one containing PWR fuel and the other containing BWR fuel. The PWR canister model used is the GBC-32 calculational benchmark model defined in [6], and holds 32 fuel assemblies. A burnup credit loading curve was determined so that representative used fuel loadings were used in the calculations. The loading curve consisted of enrichments of 1.92, 3.5 and 5 w/o ^{235}U with burnups of 0, 25.5, and 44.25 GWd/MTU, respectively. The BWR canister is based on the Holtec HI-STAR 100 system [8–10], with the 68 assembly MPC-68 canister. The MPC-68 canister is designed for storing used fuel under the fresh fuel assumption; the burnup experienced by the BWR fuel is neglected in the safety analysis. In the work documented in [1] and [2], a range of burnups from 0 to 70 GWd/MTU is considered to identify any potential impacts of burnup on the k_{eff} changes experienced after fuel reconfiguration. Burned fuel was considered with post-irradiation cooling times of 5, 80, and 300 years for both BWR and PWR fuel; the selected times are determined based on the behavior of k_{eff} as a function of time after discharge as described in [5]. The complete list of enrichments, burnups, and cooling times considered for each fuel assembly type is shown in Table 3. The impact of each configuration on the criticality safety of the GBC-32 canister is shown in Table 4 and the MPC-68 in Table 5.

The SCALE code system [7] is used to perform the k_{eff} calculations and depletion calculations to generate the UNF compositions for the various burnups and cooling times considered. The KENO V.a and KENO-VI Monte Carlo codes are used for k_{eff} calculations, and the depleted fuel compositions are generated using the STARBUCS sequence.

The change in k_{eff} ranges from a decrease (safer condition) to an increase of over 20% Δk_{eff} for the GBC-32 and over 30% Δk_{eff} for MPC-68. The most extreme cases are for configurations that are deemed to be nonphysical and thus not credible. This highlights the importance of determining credible failed fuel configurations, which follows from an ability to determine the probability of UNF failure and the reconfiguration scenarios that proceed from such failures. Such determinations and modeling are beyond the scope of this effort; additional data from ongoing material testing campaigns, especially for high-burnup cladding materials, are necessary to characterize performance and quantify reconfiguration potential.

Table 1. Credibility and Relevance of Analyzed Configurations to ES Analyses [2]

Configuration	Credibility and Relevance to Storage and Transportation Analyses
Clad thinning	Potentially credible as a result of clad creep, corrosion, oxidation, or other mechanisms; relevant to storage and transportation analyses
Clad removal	Nonphysical configuration that is not considered credible; relevant as bounding case for a potentially credible condition
Single rod failure	Potentially credible as a result of cladding failure; relevant to storage and transportation analyses
Multiple rod failure	Potentially credible as a result of multiple cladding failures; relevant to storage and transportation analyses
Uniform rod pitch expansion	Potentially credible as a result of rod bowing or accident condition; relevant to storage and transportation analyses
Radial nonuniform rod pitch expansion	Potentially credible as a result of rod bowing or accident condition; relevant to storage and transportation analyses
Axial nonuniform rod pitch expansion	Potentially credible as a result of rod bowing or accident condition; relevant to storage and transportation analyses
Loss of assembly position control	Small misalignments potentially credible, larger misalignments not credible; small misalignments relevant to storage and transportation analyses, large misalignments relevant to understand potential impact
Uniform pitch pellets	Nonphysical configuration that is not considered credible; relevant as potential bound of credible condition
Homogeneous rubble outside absorber region	Nonphysical configuration that is not expected to be credible; relevant as potential bound of credible condition
Homogeneous rubble in absorber region	Potentially credible configuration as a result of gross assembly failure leading to fine debris particles; relevant to storage and transportation analyses
Missing neutron absorber segment (5 cm)	Not credible for intact dry storage and transportation system; relevant as potential bound of credible condition
Missing neutron absorber segment (10 cm)	Not credible for intact dry storage and transportation system; relevant as potential bound of credible condition
Uniform thinning of all neutron absorbers	Not credible for intact dry storage and transportation system; relevant as potential bound of credible condition

Table 2. Isotopes Included in Used Fuel Compositions

Actinides					
^{234}U	^{235}U	^{236}U	^{238}U	^{238}Pu	^{239}Pu
^{240}Pu	^{241}Pu	^{242}Pu	^{241}Am	^{243}Am	^{237}Np
Fission products					
^{95}Mo	^{99}Tc	^{101}Ru	^{103}Rh	^{109}Ag	^{133}Cs
^{143}Nd	^{145}Nd	^{147}Sm	^{149}Sm	^{150}Sm	^{151}Sm
^{152}Sm	^{151}Eu	^{153}Eu	^{155}Gd		

Table 3. Fuel Conditions Considered in GBC-32 and MPC-68 Canisters [1]

GBC-32			**MPC-68**		
Enrichment (w/o ^{235}U)	**Burnups (GWd/MTU)**	**Cooling Time (years)**	**Enrichment (w/o ^{235}U)**	**Burnups (GWd/MTU)**	**Cooling Time (years)**
1.92	0	0	5.0	0	0
5.0	44.25	5		35.0	5
		80			80
		300			300
	70.0	5		70.0	5
		80			80
		300			300

Table 4. Summary of k_{eff} Changes in the GBC-32 Canister [1]

Configuration	**Range of Max. k_{eff} Changes (% Δk_{eff})**	**Limiting condition**	
		Burnup (MWd/MTU)	**Cooling time (years)**
Single rod removal	0.04 – 0.10	44,250	300
Multiple rod removal	0.03 – 1.87	44,250	80
Cladding removal	2.81 – 3.52	44,250	80
Uniform rod pitch expansion, clad	0.78 – 2.65	44,250	5
Uniform rod pitch expansion, unclad	3.30 – 5.34	44,250	5
Missing neutron absorber segment (5 cm)	0.29 – 1.24	70,000	300
Missing neutron absorber segment (10 cm)	0.81 – 2.63	70,000	300
Missing neutron absorber panel	0.79 – 1.08	0	0
Axial displacement	10.38 – 17.38	44,250	300
Uniform pitch pellets	11.09 – 22.21	44,250	80
Homogeneous rubble	6.66 – 15.34	44,250	300

Table 5. Summary of k_{eff} Changes in the MPC-68 Canister [1]

Configuration	**Range of Max. k_{eff} Changes (% Δk_{eff})**	**Limiting condition**		
		Burnup (MWd/MTU)	**Cooling time (years)**	**Channel present**
Single rod removal	0.26 – 0.29	0	0	Yes
Multiple rod removal	2.24 – 2.42	35,000	300	Yes
Cladding removal	4.67 – 4.98	0	0	Yes
Uniform rod pitch expansion, clad	9.40 – 13.16	0	0	No
Uniform rod pitch expansion, unclad	8.51 – 15.33	0	0	No
Missing neutron absorber segment (5 cm)	0.83 – 2.90	70,000	80	Yes
Missing neutron absorber segment (10 cm)	2.68 – 6.36	70,000	300	Yes
Missing neutron absorber panel	0.54 – 0.71	0	0	Yes
Axial displacement	8.10 – 20.76	70,000	300	Yes
Uniform pitch pellets	17.21 – 35.63	70,000	300	No
Homogeneous rubble	22.90 – 30.40	70,000	300	No

MODELING PART-LENGTH RODS

One of the expansions on the previous work considered here is the incorporation of part-length rods in the BWR fuel assembly to represent the GE14 fuel product as shown in [11]. The removal of the top portion of the rods in the pattern shown in Figure 1 increases reactivity by removing rods in internal locations, thus increasing internal moderation. The impact of this feature on reconfiguration is also of interest because the results of earlier studies [1, 2] show that in many of the configurations considered the fuel is undermoderated. The additional moderator volume introduced by the removal of the top portion of some of the fuel rods may result in larger k_{eff} increases. It should be noted that tie rods are fuel rods with end fittings designed to capture the top and bottom assembly ties plates. They are modeled as standard fuel rods.

Only fresh fuel is considered with part-length rods because the burnup profiles available in [4] and [12] do not contain any part-length features. The axial power shape could therefore also be about the same or even more top-skewed than that described in Appendix E of [2] and used to generate the results presented in [1] and [2]. Given the unknown relative impact of these effects, depleted fuel is not considered in this study.

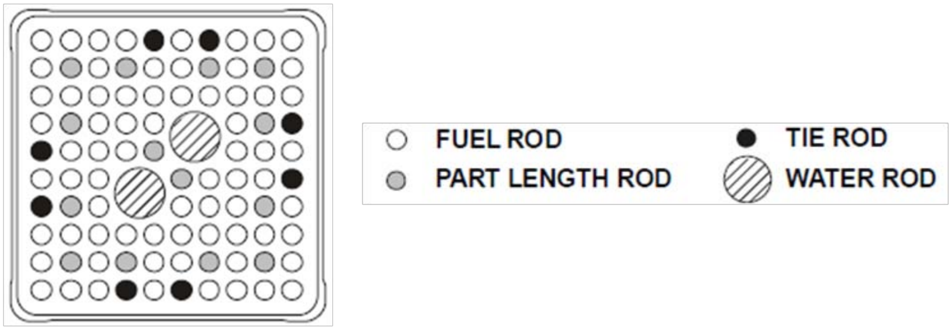

Figure 1. Location of part-length rods in GE 10 × 10 fuel assembly.

RESULTS

This section documents the new results presented in this work that are extensions of what was done in [1] and [2]. These new areas of investigation are the modeling of part-length rods in fresh BWR fuel and the effects of a range of fuel assemblies experiencing reconfiguration within a canister.

BWR Fuel with Part-Length Features

Most of the degraded fuel and neutron absorber panel configurations defined in [1] and [2] are considered for part-length fuel; however, the pellet array configuration of gross assembly failure is not considered. It is possible that some additional configurations could result from assemblies with part-length rods, but none are considered here. The results of the base cases without reconfiguration are shown in Table 6. It should be noted that the base case k_{eff} values for the fuel with part-length rods are approximately 0.7% Δk_{eff} higher than the full-length rod base case values. The additional moderation introduced in the upper portion of the assembly by the removal of the upper sections of the part-length rods is responsible for this increase in k_{eff}, and is consistent with the results of other analyses such as [10].

A summary of the k_{eff} impact of the configurations modeled with fresh fuel with part-length rods is shown in Table 7. These results are compared with fresh full-length fuel to demonstrate the relative impact of reconfiguration for assemblies with part-length rods. In general, it appears that the part-length rods reduce the impact of reconfiguration. This result can be explained because the removal of some fissile material will move the moderator-to-fuel ratio closer to optimum in the base configuration. The moderation change caused by reconfiguration thus has a smaller impact than it does in the full-length fuel case. The neutron absorber defects and limited axial misalignment cases are the only configurations that cause a larger increase in k_{eff} than the full-length assembly. The overall conclusions presented in [1] and [2] are not impacted by the inclusion of fresh BWR fuel with part-length features.

Table 6. Base Case k_{eff} Values for MPC-68 with Full-Length and Part-Length BWR Fuel

Rod length	Channel present	Burnup (GWd/MTU)	Base Case	
			k_{eff}	σ
Full	Yes	0	0.96800	0.00010
	No	0	0.96768	0.00010
Partial	Yes	0	0.97497	0.00010
	No	0	0.97391	0.00010

Table 7. Summary of k_{eff} Changes for Fresh Fuel in the MPC-68 Canister

Configuration	Change in k_{eff} Part-Length Fuel (% Δk_{eff})	Change in k_{eff} Full-Length Fuel (% Δk_{eff})
50% reduction in clad thickness	2.10	2.69
Clad removal	4.16	4.98
Single rod failure	0.18	0.29
Multiple rod failure (2 rods removed)	0.32	0.52
Uniform rod pitch expansion, cell constraint	12.28	13.16
Uniform rod pitch expansion, channel constraint	N/A	
Radial nonuniform pitch expansion	N/A	
Axial nonuniform pitch expansion	N/A	
Axial displacement (30 cm)	6.17	6.36
Axial displacement (20 cm)	0.56	0.33
Uniform pellet array	N/A	
Homogeneous rubble	21.96	22.90
Homogeneous rubble within absorber region	8.78	9.51
Missing neutron absorber (5 cm segment)*	1.01	0.83
Missing neutron absorber (10 cm segment)	2.92	2.68
50% reduction in neutron absorber panel thickness	3.49	3.67

*Limiting elevation for part-length fuel is 270 cm and for full-length fuel is 190.5 cm.

Varying Number of Reconfigured Assemblies

The results presented in [1] and [2] and the previous section on part-length BWR fuel assume that all fuel assemblies in a canister experience the same reconfiguration. In reality, it is unlikely that all fuel assemblies or absorber panels would experience the same degradation at the same time. It is of some interest to examine the effect that varying the number of damaged fuel assemblies has on the change in k_{eff} associated with fuel reconfiguration. For this reason, the homogeneous rubble configuration of gross assembly failure is considered with various combinations of failed assemblies.

A series of calculations is performed to establish the k_{eff} increase as a function of the number of reconfigured assemblies within the canister. The first fuel assembly to experience gross failure is selected in an attempt to maximize the k_{eff} increase; therefore, one near the center of the canister is selected. Additional assemblies are added in mostly symmetric groups of equal distance from the first reconfigured assembly. In the GBC-32 canister, two arrangements of reconfigured assemblies are considered for the 2 and 5 reconfigured assembly cases. Results are presented in Table 8 and Figure 2 for the GBC-32 canister and in Table 9 and Figure 3 for the MPC-68 canister.

The configuration used for this study fills the entire inside volume of the storage cell with homogeneous rubble, as described in [1] and [2]. Each axial zone of rubble is sized so that the debris bed fills the cask from the base plate to the lid and retains the axial burnup profile of the intact assembly. The PWR fuel composition is based on fuel with an initial enrichment of 5 w/o and 44.25 GWd/MTU burnup. This configuration resulted in the largest k_{eff} increase of the homogeneous rubble configurations. The BWR fuel composition corresponds to 5 w/o fuel depleted to 35 GWd/MTU and 5 years of cooling time.

An increase in k_{eff} is noted after a sufficient number of assemblies have experienced reconfiguration. For the GBC-32 canister, more than 60% of the increase in k_{eff} is caused by the first nine reconfigured assemblies and more than 70% of the total k_{eff} increase results from the reconfiguration of 13 assemblies. For the MPC-68 canister, more than 50% of the increase is caused by the first nine reconfigured assemblies and more than 80% of the total k_{eff} increase results from the reconfiguration of 21 assemblies. The results indicate that the change in k_{eff} is sensitive to the number of degraded assemblies for the first third of the assembly reconfigurations, particularly when they are in the center region of the canister. The k_{eff} increase is much less sensitive to the reconfiguration of the remaining assemblies.

Table 8. Change in k_{eff} in GBC-32, homogeneous rubble configuration of gross assembly failure (5 w/o initial enrichment, 44.25 GWd/MTU burnup, 5 year cooling)

Number of degraded assemblies	Change in k_{eff} (% Δk_{eff})
1	-0.53
2	-0.87
2	-1.07
4	1.93
5	2.91
5	1.70
9	8.59
13	10.07
21	12.94
24	13.37
32	14.30

Table 9. Change in k_{eff} in MPC-68, homogeneous rubble configuration of gross assembly failure (5 w/o initial enrichment, 35 GWd/MTU burnup, 5 year cooling)

Number of degraded assemblies	Change in k_{eff} (% Δk_{eff})
1	0.03
2	0.10
4	4.48
5	5.04
9	15.67
13	18.60
21	23.73
25	24.78
29	25.42
37	27.05
45	27.97
48	28.14
52	28.35
58	28.82
62	29.10
66	29.26
68	29.36

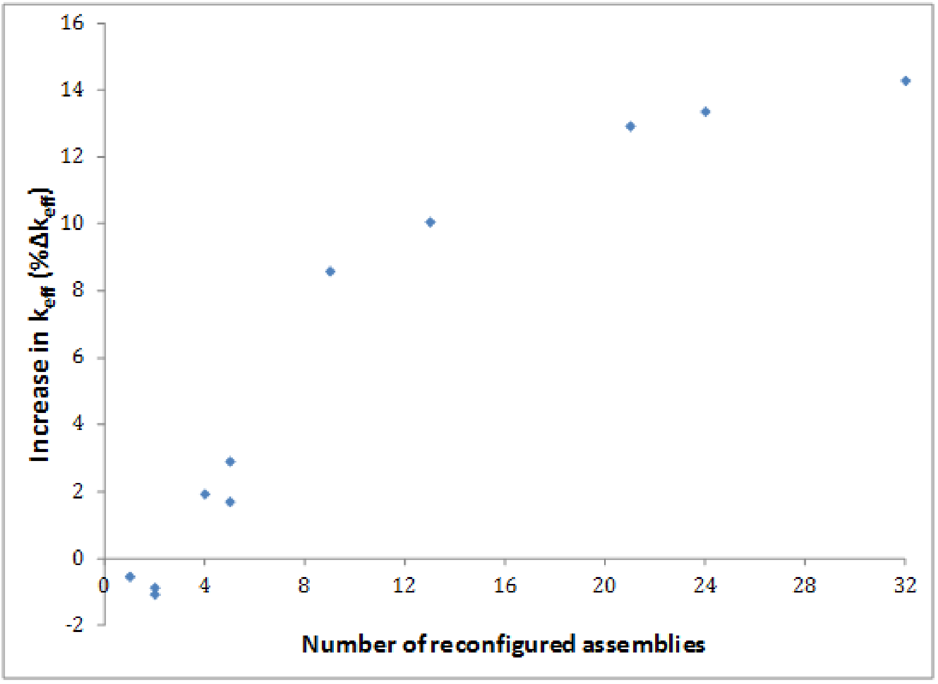

Figure 2. Change in k_{eff} in GBC-32, homogeneous rubble configuration of gross assembly failure (5 w/o initial enrichment, 44.25 GWd/MTU burnup, 5 year cooling).

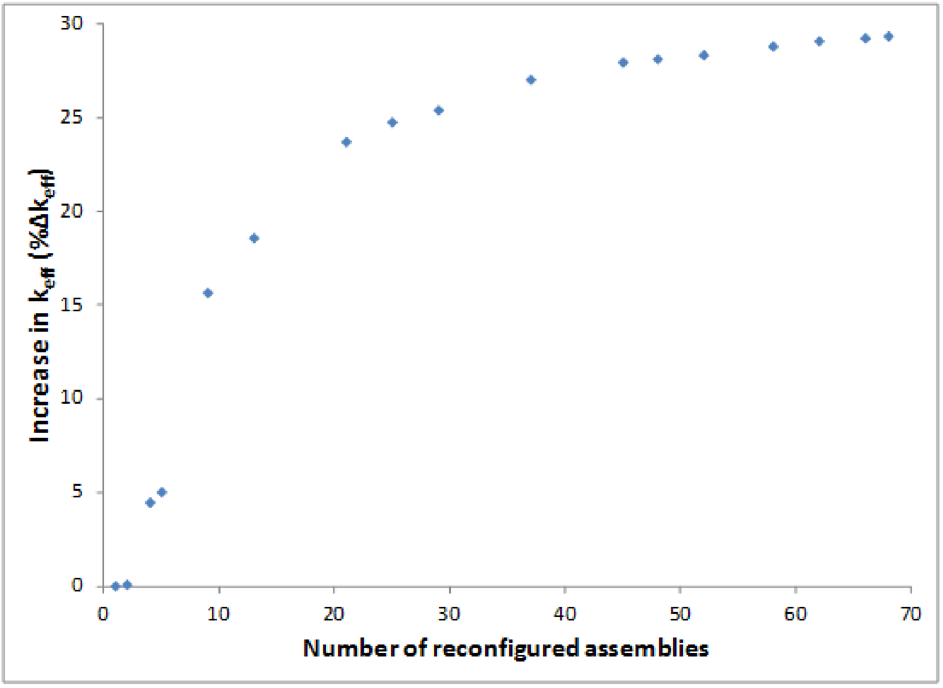

Figure 3. Change in k_{eff} in MPC-68, homogeneous rubble configuration of gross assembly failure (5 w/o initial enrichment, 35 GWd/MTU burnup, 5 year cooling).

The degradation mechanisms related to UNF in ES or experiencing high burnup are not expected to be random, but deterministic modeling may be too conservative. Other factors, such as thermal load, may drive high-burnup UNF to be loaded near the edges of a canister. These more realistic loadings would lead to a lower impact on k_{eff} by dispersing the locations of the failed assemblies within the canister. The locations of the reconfigured UNF would not be expected to be distributed randomly, but an examination of the impact of random reconfigurations should provide an estimate of the minimum k_{eff} change associated with a particular configuration involving a fixed number of failed UNF assemblies. The realistic impact can therefore be expected to be somewhere between the two estimates.

A series of 25 calculations is performed in which four assemblies are randomly selected to experience reconfiguration into the limiting homogeneous rubble configuration in the MPC-68 canister. These calculations use fuel compositions for fuel with a burnup of 70 GWd/MTU and a 300-year cooling time. These compositions lead to the largest increase in k_{eff}, relative to the base case, for all burnup and cooling time combinations considered for homogeneous rubble resulting from BWR fuel. The increase in k_{eff} for four reconfigured assemblies in the center of the canister is 6.95% Δk_{eff}. The use of four assemblies is somewhat arbitrary but is selected because the increase in k_{eff} is significant. The increase in k_{eff} for each randomly generated case is provided in Table 10. A histogram of the results with a superimposed normal distribution is shown in Figure 4. While some deviations from the ideal normal distribution are evident, the set of k_{eff} changes tests as normal with a 10 bin chi-square normality test. The normal distribution of Δk_{eff} values allows the use of statistical functions derived assuming a normal distribution of data.

The average change in k_{eff} is a reduction of about 0.20% Δk_{eff}, and the standard deviation is approximately 0.25% Δk_{eff}. The largest increase in k_{eff} is 0.14 Δk_{eff}. The one-sided tolerance factor for 95% probability of a 95% confidence interval assuming a normal distribution of 25 samples is 2.292, from [13]. The 95/95 upper bound for the reactivity increase for four random assemblies is 0.37%. This represents a significant reduction in the k_{eff} impact compared to the bounding condition of four reconfigured assemblies in the center of the cask. These results are based on only a cursory examination of the effects of random assembly selection, but the results indicate a significant reduction in the k_{eff} if the reconfigured assemblies are randomly distributed in the canister.

Table 10. Change in k_{eff} for four randomly selected reconfigured assemblies, 25 realizations

Increase in k_{eff} (%Δk_{eff})				
-0.02	0.14	-0.04	0.13	-0.33
-0.19	0.09	-0.29	-0.13	-0.19
0.04	-0.75	-0.47	-0.66	-0.38
-0.06	-0.23	-0.19	-0.02	-0.22
-0.01	-0.03	-0.73	-0.13	-0.37

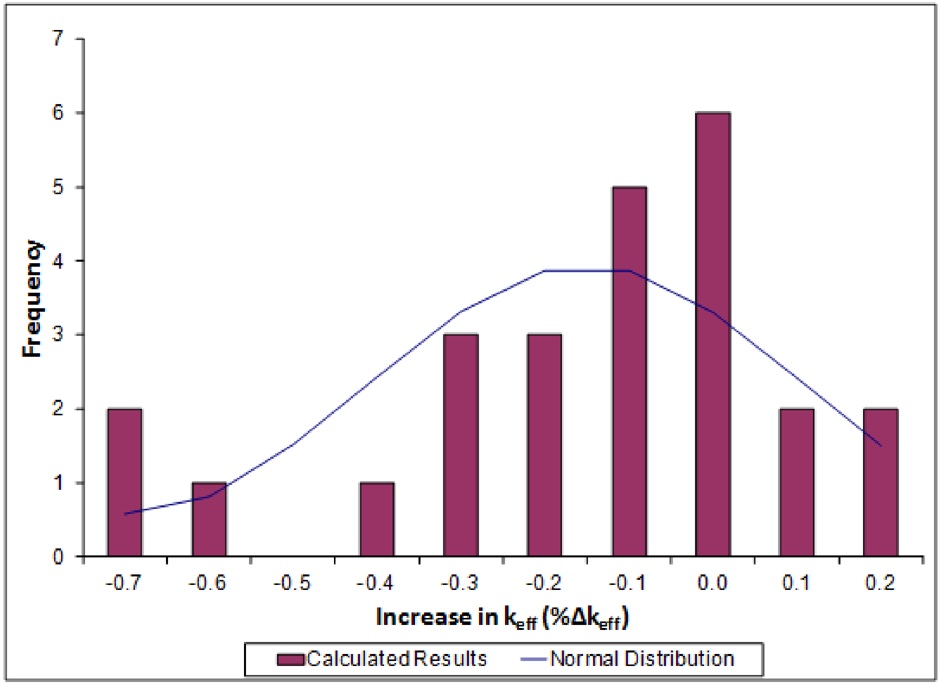

Figure 4. Histogram of increases in k_{eff} for 25 random samples of four reconfigured assemblies.

CONCLUSIONS

The work presented here focuses on two main areas: modeling of part-length rods in BWR fuel and examining the increase in k_{eff} due to fuel reconfiguration of varying numbers of fuel assemblies. Both of these areas are extensions of previous work documented in [1 – 3].

The impact of reconfiguration for a BWR fuel assembly with part-lengths rods was investigated and determined to be smaller than that of an assembly with full-length rods, for most configurations considered. Therefore, the results generated in prior work are potentially conservative estimates of the criticality safety impact of BWR fuel reconfiguration. Many of the configurations considered experience greater k_{eff} increases with burned fuel than with fresh fuel, relative to the base case, so the impact of UNF with differing axial burnup profiles caused by the part-length features should be examined in the future.

The effect of fuel reconfiguration as a function of the number of assemblies experiencing fuel failure was investigated for both the PWR and BWR canisters in this work. The majority of the increase in k_{eff} is caused by a relatively small number of reconfigured fuel assemblies if they are near each other and near the center of the canister. The effect was also investigated assuming the degraded assemblies were randomly distributed in the canister. While the random distribution of degraded assemblies results in smaller increases in $k_{eff,}$ it is unclear that such configurations are realistic given that the characteristics of the fuel of the fuel assemblies are likely correlated.

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