Impact of Fuel Failure on Criticality Safety of Used Nuclear Fuel

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Abstract: Commercial used nuclear fuel (UNF) in the United States is expected to remain in storage for considerably longer periods than originally intended (e.g., <40 years). Extended storage (ES) time and irradiation of nuclear fuel 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, can 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 is not well understood. The objective of this work is to assess and quantify the impact of fuel reconfiguration due to fuel failure on criticality safety of UNF in storage and transportation casks. This effort is primarily motivated by concerns related to the potential for fuel degradation during ES periods and transportation following ES. The criticality analyses consider representative UNF designs and cask systems and a range of fuel enrichments, burnups, and cooling times. The various failed-fuel configurations considered are designed to bound the anticipated effects of individual rod and general cladding failure, fuel rod deformation, loss of neutron absorber materials, degradation of canister internals, and gross assembly failure. The results quantify the potential impact on criticality safety associated with fuel reconfiguration and may be used to guide future research, design, and regulatory activities. Although it can be concluded that the criticality safety impacts of fuel reconfiguration during transportation subsequent to ES are manageable, the results indicate that certain configurations can result in a large increase in the effective neutron multiplication factor, k_{eff}. Future work to inform decision making relative to which configurations are credible, and therefore need to be considered in a safety evaluation, is recommended.

Keywords: spent nuclear fuel, criticality safety, fuel reconfiguration, extended storage.

1. INTRODUCTION

This paper summarizes work performed to assess the impact of fuel reconfiguration due to fuel failure on the criticality safety of used nuclear fuel (UNF) in storage and transportation casks. This work is primarily motivated by concerns related to the potential for fuel degradation during extended storage (ES) periods and transportation following ES, but has relevance to other potential causes of fuel reconfiguration.

On-site storage of UNF in the United States had originally been expected to be short-term (e.g., <40 years). The potential need for longer-term UNF storage requires a review of the technical and regulatory issues related to the performance of UNF and associated systems during ES periods and transportation following ES. Extended storage time and irradiation of nuclear fuel 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, can result in changes to the geometric configuration of the fuel, which could adversely impact virtually all aspects of a UNF storage and transport system's performance, including thermal, radiation dose, criticality safety, containment, structural performance, and fuel handling and retrievability. The likelihood and potential extent of fuel reconfiguration during ES and the subsequent impact of reconfiguration on the safety of the UNF are not well understood. Therefore, a series of postulated configurations resulting from fuel failure was developed and analyzed from a criticality safety perspective. These configurations were developed with the goal of identifying the maximum possible reactivity increase. Hence, many of them may not be credible or physically possible. Based on available information, definitive conclusions regarding the credibility of the various configurations cannot be provided. The authors offer their opinions relative to credibility, but further work is needed to definitively classify the various configurations.

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The criticality safety requirements for dry storage and transportation of UNF in the United States are defined in 10 CFR Parts 72 and 71, respectively [1,2]. The Nuclear Regulatory Commission Standard Review Plans [3–5], which provide guidance for demonstrating compliance with the regulations, indicate that the effective neutron multiplication factor, k_{eff}, with at a 95% probability, 95% confidence interval, should not exceed 0.95 under all credible conditions during storage and transportation to demonstrate subcriticality by calculation. Hence, if fuel reconfiguration is determined to be credible, it must be considered in the criticality safety evaluation. Through quantifying the reactivity impact of various postulated fuel reconfigurations, the results of this work provide insight into the potential significance of fuel failure on criticality safety and could be used to develop an approach for addressing fuel reconfiguration on criticality safety of storage and transportation casks. Although the exact change in reactivity (Δk) resulting from credible reconfigurations is system dependent, knowledge of the magnitude of the change in representative systems can be used to determine the need for, and evaluate the merits of, options to address these conditions. For example, the current k_{eff} limit of 0.95 could be reduced by some amount to ensure that if fuel reconfiguration occurs, k_{eff} will not exceed 0.95. Alternatively, depending on the probability of fuel reconfiguration, it may be possible that a separate higher limit could be established to allow margin for the reactivity effect associated with fuel reconfiguration. This latter approach would be similar to the higher limit (i.e., 0.98) allowed for the unlikely optimum moderation condition in dry storage of fresh fuel under 10 CFR 50.68 [6]. In this case, the customary k_{eff} limit would still apply to all conditions involving intact fuel.

2. CONFIGURATIONS CONSIDERED

A series of configurations has been created to enable the assessment and quantification of the impacts of fuel reconfiguration on criticality safety. This analysis expands on previous work [7] by considering a broader range of fuel configurations, burnup values, and cooling times (i.e., time since final discharge from the reactor core). Each of the configurations included in this work will be compared to the related configurations in [7] to allow a basis of comparison with the previous results. These configurations do not represent the results of specific reconfiguration progressions; rather they are designed to be bounding of any reconfiguration conditions that could occur. All configurations are considered to be in a fully flooded condition to meet the current regulatory requirements for transportation of UNF in the United States. The configurations represent

- Rod failures
- Gross cladding failure
- Rod deformation
- Neutron absorber degradation/loss
- Canister internal or assembly hardware degradation
- Gross assembly failure

A range of rod failures is considered in two main categories: single and multiple rod failures. These rod failures are of interest due to the potential fuel rod failure mechanisms such as clad unzipping as discussed in [8]. In the flooded condition, the collapse of a fuel rod after cladding failure introduces additional moderation within the fuel lattice and will lead to an increase in neutron multiplication for undermoderated systems. For modeling rod failure configurations, each failed rod is assumed to have collapsed and fallen out of the lattice; hence, the cladding and fuel material is entirely removed from the model. Each unique fuel rod location in the assembly lattice is surveyed to determine the maximum reactivity consequence. The second category of configurations is the failure of multiple rods. The results of the single failed rod configurations are used to determine likely pairs of rods to maximize the increase in k_{eff} for two failed rod configurations. Additional rods are subsequently removed until no further increase in k_{eff} is observed. All fuel assemblies in the canister model are assumed to suffer the same rod failures in both the single and multiple rod failure configurations. The rod failure configurations are essentially the same as those in [7]. The multiple rod failure study is independent from that presented in [7], which may cause slight differences in the reported results.

The gross cladding failure configuration is the nonphysical, simultaneous removal of all fuel cladding material. Although this configuration is of interest in terms of a worst-case loss of cladding and comparison to previous work, no known mechanism could result in this configuration. The cladding and all guide, instrument, and/or water tubes are entirely removed from the model to examine the impact of this condition,

which introduces additional moderation within the fuel lattice and can lead to an increase in neutron multiplication. The rest of the fuel assembly model is unaffected, leaving the fissile material in unsupported cylinders in the intact fuel assembly geometry. All fuel assemblies in the canister model experience the cladding removal. This configuration is the same as performed in [7].

The rod deformation configuration is modeled as uniform rod pitch expansion constrained by the fuel storage cell walls for normal conditions during transportation. This configuration is of interest because fuel rod pitch control can be lost, for example with the failure of one or more structural grids. Fuel rod and assembly bowing result from radiation damage and fission product generation during power operation. The potential fuel rod pitch changes can lead to increased moderation and k_{eff}. A series of expanded lattices is modeled for each canister to demonstrate that the constrained pitch is still less than the optimum moderation condition. The expanded pitch cases are considered both with and without cladding, as was performed previously in [7].

Three neutron absorber damage or degradation configurations are considered. Neutron absorber damage and degradation are of interest as any loss of neutron absorber efficacy will lead directly to a k_{eff} increase. The first configuration considers a defect that removes all neutron absorber material in the panel over a 5 cm axial segment. The position of the defect is varied to determine the elevation that causes the maximum k_{eff} increase. The 5 cm defect size was chosen somewhat arbitrarily, so the sensitivity of the k_{eff} change to the size of the defect is investigated as well. The second configuration expands the defect from 5 cm to 10 cm in axial extent at the limiting elevation identified with the smaller defect. The center of the larger defect is maintained at the same elevation as the smaller defect. All neutron absorber panels in the canister are modeled with the same defect in both configurations. The third configuration is the removal of an entire neutron absorber panel near the center of the canister. The central location is selected to cause a significant increase in k_{eff}, though no effort is made to guarantee that the most reactive single panel has been removed. No neutron absorber degradation configurations were considered in [7].

The canister internal or assembly hardware degradation configuration is considered to allow the axial repositioning of fuel assemblies. The axial position of the assemblies is varied to examine the effect as a function of elevation, assuming that the canister internals and/or fuel assembly hardware, while potentially degraded, will likely maintain at least some integrity. The relocation of the fuel assemblies above or below the extent of the neutron absorber panel can result in a significant increase in k_{eff}. This configuration is largely the same as performed in [7].

Two gross assembly failure configurations are considered. Gross assembly failure would result in significant rearrangement of fuel and cladding material, which may lead to moderation conditions that cannot be achieved with an intact fuel assembly. Significant k_{eff} increases are possible if these configurations approach optimum moderation. One configuration is modeled as a uniform, dodecahedral array of fuel pellets. The pitch of the array is varied over a range of values so that the volume occupied by the array ranges up to nearly the entire internal volume of the canister. The overall fissile material mass is maintained in the pellet array so that no fuel is added or removed during the assembly failure configuration. This configuration is similar to the pellet array configuration from [7], except that fissile mass is maintained and the pellet array is allowed to extend beyond the poisoned region of the storage basket. The second gross assembly failure configuration is modeled by replacing the fuel assemblies with a homogeneous mixture of fuel, cladding, and water. The height of the mixture ranges from the full internal height of the canister to a compressed debris bed with no water included in the fuel and cladding mixture. This configuration may be more representative of the result of a gross assembly failure since the fuel pellets experience significant swelling and cracking during irradiation. Gross assembly failure may also lead to a relatively large number of small pieces of debris with behavior between the two extreme cases considered for the sake of modeling simplicity in these analyses. This configuration was not considered in [7].

A brief discussion of the credibility and relevance of each of these configurations to ES is presented in Table 1.

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

Configuration	Credibility and Relevance to ES Analyses
Single rod removal	Potentially credible as a result of cladding failure; relevant to ES analyses
Multiple rod removal	Potentially credible as a result of multiple cladding failures; relevant to ES analyses
Cladding removal	Nonphysical configuration that is not expected to be credible; relevant as bound of credible configuration to ES analyses
Uniform rod pitch expansion, clad	Potentially credible as a result of rod bowing or accident condition; relevant to ES analyses
Uniform rod pitch expansion, unclad	Nonphysical configuration that is not expected to be credible; relevant only as indication of magnitude of effect on ES analyses
Missing neutron absorber segment (5 cm)	Potentially credible as a result of neutron absorber degradation or manufacturing error; relevant to ES analyses
Missing neutron absorber segment (10 cm)	Potentially credible as a result of neutron absorber degradation or manufacturing error; relevant to ES analyses
Missing neutron absorber panel	Potentially credible as a result of a manufacturing error; relevant to all canister analyses, including ES
Axial displacement	Small misalignments potentially credible, larger misalignments potentially credible probably only in transportation accidents; small misalignments relevant to ES analysis, large misalignments potentially relevant to transportation accident analysis
Uniform pitch pellets	Nonphysical configuration that is not expected to be credible; relevant as bound of credible configuration to ES analyses
Homogeneous rubble	Potentially credible configuration as a result of gross assembly failure leading to fine debris particles; relevant to ES analyses
Optimum flooding (dry flux traps)	Credibility and relevance to ES analyses depend on canister design characteristics intended to guarantee flux trap flooding

3. FUEL AND CANISTER MODELING

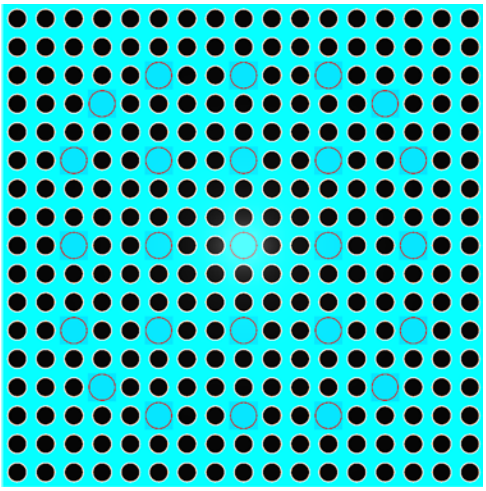
3.1. Fuel Assembly Models

Two fuel assembly designs are used in these analyses: one pressurized water reactor (PWR) type and one boiling water reactor (BWR) type. The designs chosen are intended to represent a large portion of the current inventory of discharged UNF as well as a significant portion of the fuel in use currently.

The PWR design selected is the Westinghouse 17×17 Optimized Fuel Assembly (OFA). Westinghouse 17×17 OFA is a fuel design commonly used in the commercial nuclear industry for the past 30 years. This common use makes it a good choice for a representative fuel assembly type for calculations in the PWR storage and transportation canisters. The cladding, instrument tube, and guide tubes are modeled as Zircaloy-4. Consistent with common practice for criticality safety evaluations of UNF, all other fuel assembly hardware, including grids and nozzles, is conservatively neglected. Unborated, unit-density water fills the gap between the pellet and cladding. Water in the pellet/clad gap is conservative for criticality calculations because it causes a slight increase in calculated k_{eff} values. In irradiated fuel, pellet swelling closes this gap and causes this assumption to be nonphysical. Fuel assembly dimensions are provided in Table 2, and a cross section of the assembly is shown in Figure 1.

Table 2. Westinghouse 17×17 OFA Dimensions Used in These Analyses[9]

Parameter	**Dimension (cm)**	**Dimension (in.)**
Pellet outer diameter	0.7844	0.3088
Fuel rod outer diameter	0.9144	0.360
Cladding thickness	0.0571	0.0225
Fuel rod pitch	1.2598	0.496
Active fuel height	365.76	144
Guide/instrument tube outer diameter	1.204	0.474
Guide/instrument tube thickness	0.0407	0.016
Fuel density	10.5216 g/cm^3 (96% theoretical density)	
Number of fuel rods	264	
Number of guide/instrument tubes	25	



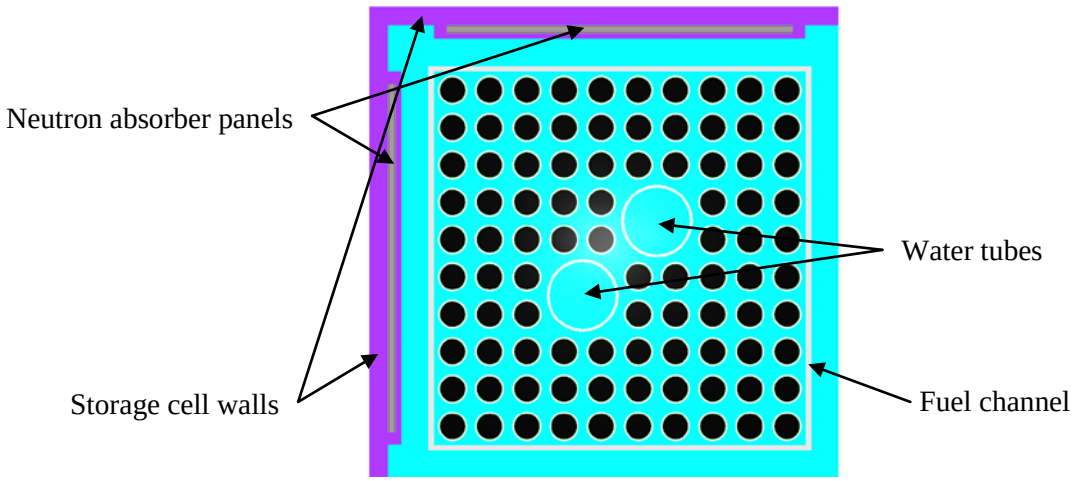
Note: Fuel shown in black; guide/instrument tubes are larger, water-filled tubes

Figure 1. Cross Section of 17×17 Optimized Fuel Assembly

The BWR design selected is a 10×10 design based on the GE14 fuel product. The 10×10 array is representative of existing BWR fuel assembly designs being used by the industry. The fuel assemblies are considered with a uniform initial enrichment in axial and radial directions. As simplifying assumptions for this analysis, no reduced enrichment axial blanket pellets are included, and no part-length rods are represented in the fuel assemblies. Part-length rods are common in BWR assembly designs, including the GE14 design. Unborated, unit-density water fills the gap between the fuel pellet and cladding. The cladding and water tubes are modeled as Zircaloy-4. BWR fuel cladding is usually Zircaloy-2, but this difference has negligible impact on the results of the calculations. Each water tube occupies four unit cells in the lattice, displacing a 2×2 region of fuel rods. All reconfiguration configurations except the pellet array gross assembly failure are repeated with and without the fuel assembly channel present. Consistent with common practice for criticality safety evaluations of UNF, all other fuel assembly hardware, including grids and nozzles, is conservatively neglected. Fuel assembly dimensions are provided in Table 3, and a cross section of the assembly is shown in Figure 2.

Table 3. GE 10×10 Assembly Dimensions Used in These Analyses[7]

Parameter	Dimension (cm)	Dimension (in.)
Pellet outer diameter	0.876	0.3449
Fuel rod outer diameter	1.026	0.404
Cladding thickness	0.066	0.026
Fuel rod pitch	1.295	0.510
Active fuel height	381	150
Water tube outer diameter	2.522	0.993
Water tube thickness	0.1	0.039
Fuel density	10.5216 g/cm^3 (96% theoretical density)	
Number of fuel rods	92	
Number of water tubes	2 (each displaces 4 fuel rods)	



Note: Fuel shown in black

Figure 2. Cross Section of GE 10×10 Fuel Assembly in MPC-68 Storage Cell

3.2. Canister Models

Three canister models based on the Holtec International HI-STAR 100 system are evaluated: the GBC-32 [9], the MPC-24, and the MPC-68 [10–12]. The GBC-32 canister is designed for the storage and transportation of 32 irradiated PWR fuel assemblies. The MPC-24 is designed for the transportation of 24 fresh PWR fuel assemblies and is considered in this effort to provide the reactivity effect of fuel reconfiguration on fresh PWR assemblies at the 5 wt % ^{235}U enrichment limit. Fresh fuel is being evaluated to explore the impact of reconfiguration from higher reactivity systems. The MPC-68 canister is designed for the transportation of 68 fresh BWR fuel bundles but is used here with UNF as well as fresh fuel.

The overall design of each of these canisters is similar. Each incorporates a stainless steel storage basket containing storage cells for individual fuel assemblies. Each storage cell also contains panels of boron carbide–aluminum metal matrix composite neutron absorber material. The radial and axial fuel positions vary somewhat among the canister designs. As mentioned above, all canister models are fully flooded to be consistent with regulatory requirements for the analysis of transportation packages.

3.3. Depletion Conditions

The depletion conditions used in this analysis are intended to be representative of conditions that would be used in a burnup credit analysis. Generic data are used in the PWR depletion conditions. The BWR depletion conditions are based on the operating history of a specific assembly [13], neglecting burnable absorbers and assuming entirely unrodded depletion. The depletion conditions for both PWR and BWR fuel are shown in Table 4.

Table 4. Depletion Conditions Used for PWR and BWR Fuel in These Analyses

Parameter	Value for PWR Depletions	Value for BWR Depletions
Fuel temperature	1100 K	840 K
Moderator temperature	610 K	512 K
Moderator density	0.63 g/cm^3	0.21–0.74 g/cm^3
Soluble boron concentration	1000 ppm	N/A (0 ppm)
Specific power and operating history	60 W/g, constant	30.31 W/g, constant
Fixed/removable burnable absorber	24 wet annular burnable absorber rodlets per assembly	N/A
Integral burnable absorber	None	None
Axial burnup profile	44.25 GWd/MTU: Profile 2[a] 70 GWd/MTU: Profile 1[a]	0.17–1.25[b]

[a] From Table 5 of [15].
[b] Based on data from [13].

Burnups ranging from fresh fuel to 70 GWd/MTU are considered. A range of post-irradiation cooling times from 5 years to 300 years is considered in these analyses for both PWR and BWR fuel, with explicit reconfiguration calculations at cooling times of 5, 80, and 300 years. The range of cooling times and the points selected for specific calculations are determined based on the behavior of k_{eff} as a function of time after discharge. The calculated behavior varies as described in [14] and is also a function of the isotopes that are included in the computational model. In general, k_{eff} drops from a few days after discharge to approximately 100 years after discharge as a result of the decay of ^{241}Pu and ^{155}Eu. From 100 years to more than 10,000 years after discharge, k_{eff} will increase because of the decay of ^{241}Am and ^{240}Pu. These analyses consider effects only to a period of 300 years after discharge. Longer time periods are studied for fuel disposal analyses but are not considered here. A complete discussion of the behavior of k_{eff} as a function of discharge time and nuclide set modeled is provided in [14].

The initial enrichment, burnup, and cooling time for each set of calculations performed in the GBC-32 and MPC-68 canisters are provided in Table 5. The MPC-24 canister considered only fresh fuel with an enrichment of 5 wt % ^{235}U. Each unique combination of enrichment, burnup, and cooling time is referred to subsequently as a single state point.

Table 5. Enrichment, Burnup, and Cooling Time for State Points in GBC-32 and MPC-68

GBC-32			MPC-68		
Enrichment (wt % ^{235}U)	**Burnups (GWd/MTU)**	**Cooling Time (years)**	**Enrichment (wt % ^{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

4. SOFTWARE CODES

This analysis requires a large number of k_{eff} calculations and also requires depletion calculations to generate the UNF compositions for the various burnups and cooling times considered. The SCALE code system [16] was used to perform these calculations.

The KENO V.a and KENO-VI Monte Carlo codes are used for k_{eff} calculations within the CSAS5 and CSAS6 sequences. Both codes use Monte Carlo transport to solve the k_{eff} eigenvalue problem. KENO-VI has the ability to represent complex geometric configurations and is used for the fuel pellet array and limiting fuel rod pitch expansion configurations. KENO V.a has a more limited geometry package but is significantly

faster because of the geometry limitations. KENO V.a is used for the majority of configurations considered in this analysis.

All depleted fuel isotopic compositions were generated with either the TRITON t-depl sequence or the STARBUCS sequence. The TRITON sequence couples the NEWT discrete ordinates code with the ORIGEN depletion module. The local fluxes calculated with NEWT are used to perform fuel depletion calculations with ORIGEN. The STARBUCS sequence uses the ORIGEN-ARP methodology to generate depleted fuel compositions and integrates the compositions into a KENO model to calculate k_{eff}.

5. RESULTS

This section presents the results of the analyses. The uncertainty in all calculated k_{eff} differences presented in this section is approximately 0.00014 (0.014%) Δk_{eff}, unless otherwise specified. The reported consequence is the difference in calculated k_{eff} values, $k_{reconfig} - k_{nominal}$. Positive numbers thus indicate an increase in k_{eff} for the reconfiguration scenario, which is expected for most configurations. The reported values are not divided by any k_{eff} values and therefore do not represent change in reactivity ($\Delta\rho$). A k_{eff} increase of 0.1% means an increase of 0.001 Δk from the reference k_{eff} value.

5.1. MPC-24

The impact of fuel reconfiguration on k_{eff} in the MPC-24 canister ranges from nearly zero to over 16.5% Δk_{eff} for the configurations considered, which are summarized in Table 6.

The single rod removal configurations lead to k_{eff} changes ranging from -0.03 to 0.15%. The limiting locations, those with the largest reactivity increases, are associated with the interior of the fuel assembly and are also diagonally adjacent to a guide or instrument tube location. These interior locations allow an increase in moderation within the lattice without an increase in neutron leakage. The locations that result in lower k_{eff} values are along the periphery of the assembly and increase leakage. The maximum increase for multiple rod failures is 2% Δk_{eff} with 48 rods removed. The k_{eff} increase as a function of rods removed is very close to linear from 2 to 16 rods removed, but the worth of additional rod removal decreases until the maximum is reached. As with single rod failure scenarios, interior locations result in larger increases. Large increases in k_{eff} are also associated with diagonally adjacent water holes; failed rods that are adjacent to either other failed rod locations or guide or instrument tubes have significantly lower impact on k_{eff}.

The uniform pitch expansion configuration to account for fuel rod deformation results in a maximum increase of 2.9% Δk_{eff} with cladding intact and 6.8% Δk_{eff} with cladding removed. The maximum k_{eff} value occurs with the fuel rods in contact with the storage cell walls. This indicates both that optimum moderation has not been achieved at these limited pitches and that the restriction imposed by the storage cell provides a limit to the increase in k_{eff} in this configuration.

The neutron absorber degradation or damage configurations range from 0.3 to 1.1% increase in k_{eff}. The limiting location for the neutron absorber defect is, as expected, at the midplane of the fuel assembly because only fresh fuel is modeled in the MPC-24. The reactivity increase is faster than linear as the defect size increases from 5 to 10 cm in height. The removal of a single panel does not result in as large a k_{eff} increase as the aligned gaps in all neutron absorber panels.

The axial misalignment configurations used to estimate the consequences of degraded canister internals or fuel assembly hardware result in an increase in k_{eff} of up to 7.1% Δk_{eff}. Misalignments toward the base plate do not expose enough fuel to result in k_{eff} increases larger than 0.05%, and misalignments toward the lid do not cause large k_{eff} increases until a misalignment of nearly 50 cm.

The k_{eff} increase associated with the gross assembly failure configurations is 8.2 to 13.6% Δk_{eff}. In both configurations, the maximum k_{eff} results from the entire interior volume of the cask being filled with debris, i.e., fuel and other materials. This indicates that optimum moderation has not been achieved in either gross assembly failure configurations. In this condition, a significant portion of the fuel debris is located above and below the neutron absorber panels in the fuel storage basket. The full axial volume available for debris would most likely be significantly reduced by the canister internal hardware used to maintain fuel assembly

axial position. The k_{eff} increase associated with both gross assembly failure scenarios would be significantly reduced if the debris were limited in axial extent to the neutron absorber region of the canister. As expected, the array of pellets has a larger consequence on k_{eff} than does a homogenized rubble mixture.

A preferential flooding configuration was also considered for the MPC-24 canister since the design of the fuel storage basket incorporates flux traps. The flooding of the fuel storage cells without coincident flooding of the flux traps results in an increase of 16.6% Δk_{eff}. This demonstrates clearly the importance of flooding the flux traps in any scenario that would also flood the fuel storage cells.

Table 6. Reconfiguration Consequence Summary for the MPC-24 Canister

Configuration	**Max. Change in k_{eff} (% Δk_{eff})**
Single rod removal	0.15
Multiple rod removal	2.01
Cladding removal	5.24
Uniform rod pitch expansion, clad	2.88
Uniform rod pitch expansion, unclad	6.83
Missing neutron absorber segment (5 cm)	0.35
Missing neutron absorber segment (10 cm)	1.07
Missing neutron absorber panel	0.44
Axial displacement	7.08
Uniform pitch pellets	13.56
Homogeneous rubble	8.23
Optimum Flooding (dry flux traps)	16.61

5.2. GBC-32

The impact of fuel reconfiguration on k_{eff} in the GBC-32 canister varies up to 22.2% Δk_{eff} for the configurations considered, which are summarized in Table 7. The second column shows the range in the k_{eff} increases for the limiting condition, for each of the state points.

The single rod failure configurations lead to k_{eff} changes ranging from -0.17 to 0.10% Δk_{eff}. The range of maximum k_{eff} changes across the seven burnup and cooling time state points is from 0.04 to 0.10%. The fresh 1.92 wt % ^{235}U case increases by only 0.04%, but all six of the irradiated fuel state points exhibit k_{eff} increases of 0.09 or 0.10%. The effect of increased burnup and cooling time is thus shown to be very small for single rod failure. The limiting failed rod locations are the same types of locations as discussed above for the 17×17 OFA fuel in the MPC-24 canister. For multiple rod failures, the range of k_{eff} changes is 0.03 to 1.87%. The fresh 1.92 wt % case manifests an increase of only 0.03% for two rods removed and decreases further with the removal of additional fuel rods. The k_{eff} increase for the fuel at 44,250 MWd/MTU burnup is 1.87% and for the fuel at 70,000 MWd/MTU varies slightly around 1.65%. The maximum k_{eff} increase occurs for fuel with 44,250 MWd/MTU burnup and 80 years cooling time and 44 rods removed. The multiple rod removal configurations show more sensitivity to burnup than the single rod removal configurations, though the sensitivity is not large. The failed rod patterns leading to large k_{eff} increases are similar to the limiting multiple rod failure patterns in the MPC-24 canister.

The impact of cladding removal ranges from 2.8 to 3.5% Δk_{eff}. The fresh fuel configuration shows the smallest increase, consistent with the single and multiple rod failure configurations. Larger variability exists among the various cooling times at 44,250 MWd/MTU burnup than at 70,000 MWd/MTU burnup. No consistent pattern of k_{eff} changes as a function of burnup or cooling time is evident.

The uniform pitch expansion configurations to account for fuel rod deformation result in maximum k_{eff} increases of 0.8 to 2.7% Δk_{eff} with cladding and 3.3 to 5.3% Δk_{eff} without cladding. As with the 17×17 OFA fuel in the MPC-24 canister, k_{eff} increases as the pitch is expanded from the nominal condition to the point at which the fuel rods are in contact with the storage cell walls. The smallest k_{eff} increases are again associated with the fresh fuel configurations. Among the various irradiated fuel state points, the increase in k_{eff} is smaller with increased cooling time and higher burnup. The fresh fuel included in the GBC-32 canister

models is 1.92 wt % ^{235}U compared to 5 wt % ^{235}U for the irradiated fuel, and this lower enrichment is likely the cause of the lower consequence for pitch expansion in fresh fuel. The effect of increased burnup in the irradiated fuel state points is significantly larger than the effect of increased cooling time.

The neutron absorber degradation or damage configurations cause k_{eff} increases of up to 2.6% Δk_{eff}. The limiting elevation for the neutron absorber defect is at the assembly midplane for the fresh fuel and near the top of the assembly for UNF. The increase in k_{eff} is slightly faster than linear as the defect gap height increases from 5 to 10 cm. The fresh fuel state point experiences the smallest increase in k_{eff} of the seven state points considered, which is consistent with the previous configurations discussed for this canister. The k_{eff} change exhibits small sensitivities to both increasing cooling time and burnup, resulting in larger increases in k_{eff} at the high burnup and cooling time state points. With the exception of the fresh fuel case, removal of an entire neutron absorber panel has a smaller impact than the 5 cm defect in all panels. The largest k_{eff} increase results from the removal of a panel in the fresh fuel case, which is the only configuration for which the fresh fuel state point is limiting in the GBC-32 canister.

The fuel assembly axial misalignment configurations cause k_{eff} increases of up to 17.4%. Small misalignments of the assemblies toward the base plate cause modest negative k_{eff} changes, indicating that some amount of neutron communication is occurring over the top of the neutron absorber panels for fuel from these state points. Misalignments toward the base plate cause significant increases in k_{eff} when the misalignment distance reaches 10 to 15 cm. Misalignments in the 5 to 10 cm range toward the canister lid cause k_{eff} increases. Larger sensitivity to upward misalignments is expected because the most reactive portion of the fuel assembly is near the top end because of the axial burnup distribution. The impact of fuel misalignment increases significantly between 5 and 80 years of cooling time but increases only slightly between 80 and 300 years of cooling time. The k_{eff} change is also increased at higher burnup for the same cooling time.

The k_{eff} change associated with the gross assembly failure configurations ranges from 6.7 to 22.2% Δk_{eff}. Large negative k_{eff} changes are observed in homogeneous rubble cases with low rubble volumes and a corresponding reduction in internal moderation. The largest increase is, as expected, associated with the uniform pellet array configuration. In both configurations, the fresh fuel state point experiences smaller increases in k_{eff} compared to the cases with used fuel. In both configurations, the k_{eff} increase is reduced at 70,000 MWd/MTU burnup compared to 44,250 MWd/MTU burnup. The k_{eff} increase is magnified in the homogeneous rubble case at higher cooling times, but no clear trend is evident for the k_{eff} increase as the cooling time is varied in the uniform pellet array state points.

Table 7. Reconfiguration Consequence Summary for the GBC-32 Canister

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

5.3. MPC-68

The impact of fuel reconfiguration on k_{eff} in the MPC-68 canister varies up to 35.6% Δk_{eff} for the configurations considered, which are summarized in Table 8. The second column shows the range of the k_{eff} increases for the most limiting condition for each of the state points considered.

The single rod failure configurations lead to k_{eff} changes ranging from -0.6 to 0.3% Δk_{eff}. The limiting location is in the symmetric location of (7,8)/(8,7), indexed from the corner pin nearest the neutron absorber panels in the storage cells. The neutron absorber panels are located next to the top and left faces of the assembly as shown in Figure 2. This position is surrounded by other fuel rods, thus allowing an increase in moderation without an associated increase in neutron leakage. The limiting configuration includes fresh fuel, though the irradiated fuel state points are essentially equally limiting. No trend is evident based on either burnup or cooling time. The increase in k_{eff} for multiple rod failures ranges from 0.5 to 2.4%. The maximum increase for each of the seven different fuel cases occurs for 16–20 rods removed. The smallest increase occurs for the fresh 5 wt % ^{235}U fuel. No significant trend is evident as a function of cooling time, and the 35,000 MWd/MTU burnup step experiences a larger increase than either 0 or 70,000 MWd/MTU. The largest increases in k_{eff} occur for fuel with the channel intact. The largest k_{eff} increases tend to come from patterns that leave intact rods near the water tubes in the middle of the assembly and along the periphery of the assembly. This configuration maximizes moderation within the lattice while minimizing the increase in neutron leakage. For both single and multiple rod removal scenarios, the channeled fuel leads to a larger k_{eff} increase than that in the unchanneled fuel. The removal of the channel causes a slight increase in the thermal neutron population in the base case, thus reducing the impact of additional thermalization caused by rod failures.

The removal of all fuel cladding material causes a k_{eff} increase of 4.7 to 5.0% Δk_{eff}. The fresh fuel case leads to the largest increase in k_{eff}. The effect lowers with increasing burnup but manifests no noticeable trends as a function of cooling time. As with the rod failure scenarios, the channeled fuel presents the limiting condition.

The uniform pitch expansion configuration to account for fuel rod deformation results in a maximum increase of 13.2% Δk_{eff} with cladding intact and 15.3% Δk_{eff} with cladding removed. The unchanneled case is limiting for the pitch expansion configurations because the removal of the channel allows for additional pitch expansion. The limiting condition occurs with the fuel rods in contact with the storage cell walls, again indicating that optimum pitch has not been reached before the expansion is constrained. The magnitude of the k_{eff} increase appears to be lessened with both higher burnup and higher cooling time.

The maximum increase in k_{eff} associated with the neutron absorber degradation or damage configurations is 6.4% Δk_{eff}. The limiting elevation for the defect is at the midplane for fresh fuel and near the top for irradiated fuel. The associated k_{eff} increase is much larger at 35,000 MWd/MTU than for fresh fuel, and it increases somewhat to the limiting condition of 70,000 MWd/MTU. No consistent trend is evident as a function of cooling time. The increase in k_{eff} is nearly linear with the increase in defect size from 5 to 10 cm. The removal of an entire neutron absorber panel causes the largest increase in k_{eff} for fresh fuel for the neutron absorber degradation configurations. The effect is reduced slightly at higher burnups, with no discernable trend as a function of cooling time.

The axial misalignment cases representing canister internal or fuel assembly hardware degradation cause k_{eff} changes ranging up to 20.8% Δk_{eff}. Larger k_{eff} increases occur for channeled fuel, and the effect increases with both higher burnup and longer cooling times. Significant k_{eff} increases can be caused by misalignment toward either the base plate or the lid. Lowering the fuel toward the base plate causes noticeable k_{eff} increases for misalignments greater than about 25 cm, while misalignment toward the lid has an impact with misalignments greater than about 8 cm.

The gross assembly failure configurations result in k_{eff} changes ranging from 17.2 to 35.6% Δk_{eff}. Large negative k_{eff} changes occur for homogeneous rubble cases with small rubble volumes, thus reducing or eliminating internal moderation in the debris bed. The largest increase is associated with the uniform pellet array configuration. In both configurations, the fresh fuel case yields smaller increases in k_{eff} compared to the irradiated fuel cases, and the k_{eff} change increases with burnup. The k_{eff} change also increases between 5 and 80 years of cooling time but does not change significantly between 80 and 300 years. The unchanneled case results in a larger k_{eff} increase for the homogenized rubble cases because, for the channeled cases, the channel

material is included in the debris, which reduces moderation. The channel is not included in the uniform pellet array cases.

Table 8. Reconfiguration Consequence Summary for the MPC-68 Canister

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

6. CONCLUSIONS

The impact of fuel reconfiguration due to fuel failure on criticality safety of UNF in storage and transportation casks was assessed and quantified. Although some of the configurations may have broader relevance, this effort was primarily motivated by concerns related to the potential for fuel degradation during ES periods and transportation following ES. The configurations studied in this analysis were selected to bound the potential reactivity increase associated with various proposed fuel reconfiguration mechanisms. The magnitude of the reactivity effects for some of the configurations clearly indicates the importance of material property data to provide an understanding of those configurations that represent credible physical conditions of UNF after ES.

Even without such data, it may be possible to eliminate several of the configurations considered in this paper that violate reasonable limits of physical likelihood or reality. This would be useful as these configurations may then be disregarded in assessing possible mitigation strategies necessary to provide confidence that UNF can be safely transported following ES. For example, the complete removal of all fuel cladding material is not credible as there is no known mechanism to remove the cladding from the fuel lattice. Similarly, there is no known mechanism by which the canister internal structure and fuel assembly hardware will degrade sufficiently for the fuelled portion of the assembly to experience significant axial displacement. Gross failure of all fuel assemblies in the canister also does not seem credible. Any shock significant enough to cause this level of damage to the fuel assemblies would also cause significant damage to the canister body and storage basket. There is no known mechanism to deliver a force capable of this level of damage in normal or accident transportation conditions.

The limiting k_{eff} increase for the MPC-24 canister, after eliminating configurations that the authors judge not to be credible, is slightly under 3% Δk_{eff} and corresponds to the rod deformation configuration. Even this increase is likely an overestimate of the reactivity impact given the improbability of uniform pitch expansion occurring throughout the axial fuel length and simultaneously in each assembly in the canister. Hence, based on these results, the reactivity increase appears small enough that the canister will remain subcritical provided the safety analysis demonstrates that k_{eff} will be less than 0.95 for intact fuel.

The maximum increase in k_{eff} for the GBC-32 canister, after eliminating configurations that the authors deem not credible, depends on the extent of axial misalignment that is judged as credible. If the misalignment distance could be shown to be only 10 cm, the k_{eff} increase would be approximately 5% Δk_{eff}; the effect is reduced to about 3% Δk_{eff} for a misalignment limited to 7 cm. Canister subcriticality can be demonstrated with the more limiting misalignment configurations and an intact fuel k_{eff} less than 0.95. Alternatively, the 3% Δk_{eff} increase could be offset with 8 to 12 GWd/MTU of additional burnup or 30 or more additional years

of cooling time for the configurations limited around 45 GWd/MTU and 5 to 80 years of cooling time. The canister k_{eff} with intact fuel at 70 GWd/MTU is low enough, approximately 0.85 and less, that even the extreme fuel reconfiguration configurations cannot introduce a large enough k_{eff} increase to reach criticality.

The MPC-68 canister results present more challenges. The limiting reactivity increase from the configurations judged by the authors to be credible is 13.2% Δk_{eff} and results from the rod deformation case. This can be reduced if only channeled fuel is considered or if it is determined that simultaneous maximum pitch expansion in all assemblies is not credible. Further steps will be required to demonstrate that fuel assembly array control will not be lost in or after ES. The axial misalignment and large neutron absorber panel defect cases also cause reactivity increases of 6 to 21% Δk_{eff}. Fuel assembly misalignments less than about 14 cm could yield reactivity increases of less than 3%, and neutron absorber defects of 5 cm or less also result in less than a 3% k_{eff} increase. If these three configurations can be addressed successfully, the MPC-68 canister would also qualify as subcritical in these fuel degradation configurations given a k_{eff} value analyzed to be less than 0.95 with intact fuel. A 3% increase in k_{eff} could be offset with 15 to 20 GWd/MTU of additional burnup. Additional fuel cooling time will not generate sufficient margin to account for this level of increase in k_{eff}. As with the GBC-32, the k_{eff} of the MPC-68 canister with intact fuel at 70 GWd/MTU is low enough, around 0.77 and less, that the increases in k_{eff} resulting from the configurations that are considered credible cannot cause criticality.

Based on the results presented in this paper, it may be concluded that the criticality safety impacts of fuel reconfiguration during transportation subsequent to a period of ES are manageable. However, future work is planned to (1) ensure that all relevant, credible configurations have been identified and sufficiently analyzed; (2) for irradiated fuel, quantify the reactivity impacts for burnup and initial enrichment conditions corresponding to expected limits (i.e., that correspond to k_{eff} of 0.95 for intact fuel); (3) incorporate material property and assembly behavior data during ES to justify the exclusion of configurations that are not credible; and (4) evaluate potential mitigation strategies for offsetting the increase in reactivity associated with credible fuel configurations. The end result of this planned work should provide a path to demonstrating that transportation of UNF following ES poses only manageable criticality risks.

References

[1] Title 10, *Code of Federal Regulations*, Part 72, 73 FR 63572, October 24, 2008.

[2] Title 10, *Code of Federal Regulations*, Part 71, 73 FR 63572, October 24, 2008.

[3] NUREG-1536, Revision 1, *Standard Review Plan for Spent Fuel Dry Storage Systems at a General License Facility*, Office of Nuclear Material Safety and Safeguards, July 2010.

[4] NUREG-1567, *Standard Review Plan for Spent Fuel Dry Storage Facilities*, Office of Nuclear Material Safety and Safeguards, March 2000.

[5] NUREG-1617, *Standard Review Plan for Transportation Packages for Spent Nuclear Fuel*, Office of Nuclear Material Safety and Safeguards, March 2000.

[6] Title 10, *Code of Federal Regulations*, Part 50.68, 71 FR 66648, November 16, 2006.

[7] Elam K R, Wagner J C, and Parks C V. *Effects of Fuel Failure on Criticality Safety and Radiation Dose for Spent Fuel Casks*, NUREG/CR-6835 (ORNL/TM-2002/255), prepared for the U.S. Nuclear Regulatory Commission by Oak Ridge National Laboratory, Oak Ridge, Tenn., September 2003.

[8] Stout R B and Leider H R (eds.). *Waste Form Characteristics Report, Revision 1*, UCRL-ID-108314, Version 1.3, Lawrence Livermore National Laboratory, July 1998.

[9] Wagner J C. *Computational Benchmark for Estimation of Reactivity Margin from Fission Products and Minor Actinides in PWR Burnup Credit*, NUREG/CR-6747 (ORNL/TM-2000/306), prepared for the U.S. Nuclear Regulatory Commission by Oak Ridge National Laboratory, Oak Ridge, Tenn., October 2001.

[10] *Safety Analysis Report for the Holtec International Storage, Transport, and Repository Cask System (HI-STAR 100 Cask System)*, Table of Contents to Chapter 1, Holtec Report HI-951251, Revision 10, Holtec International, August 2003, ADAMS Accession Number ML071940386.

[11] *Safety Analysis Report for the Holtec International Storage, Transport, and Repository Cask System (HI-STAR 100 Cask System)*, Chapter 2 through Chapter 4, Holtec Report HI-951251, Revision 10, Holtec International, August 2003, ADAMS Accession Number ML071940391.

[12] *Safety Analysis Report for the Holtec International Storage, Transport, and Repository Cask System (HI-STAR 100 Cask System)*, Chapter 5 to end, Holtec Report HI-951251, Revision 10, Holtec International, August 2003, ADAMS Accession Number ML071940408.

[13] Henderson D P et al. *Summary Report of Commercial Reactor Criticality Data for LaSalle Unit 1*, B00000000-01717-5705-00138, Civilian Radioactive Waste Management System Management & Operating Contractor, September 1999.

[14] Wagner J C and Parks C V. *Recommendations on the Credit for Cooling Time in PWR Burnup Credit Analyses*, NUREG/CR-6781 (ORNL/TM-2001/272), prepared for the U.S. Nuclear Regulatory Commission by Oak Ridge National Laboratory, Oak Ridge, Tenn., January 2003.

[15] Wagner J C, DeHart M D, and Parks C V. *Recommendations for Addressing Axial Burnup in PWR Burnup Credit Analyses*, NUREG/CR-6801 (ORNL/TM-2001/273) prepared for the U.S. Nuclear Regulatory Commission by Oak Ridge National Laboratory, Oak Ridge, Tenn., March 2003.

[16] *SCALE: A Comprehensive Modeling and Simulation Suite for Nuclear Safety Analysis and Design*, ORNL/TM-2005/39, Version 6.1, Oak Ridge National Laboratory, Oak Ridge, Tennessee, June 2011. Available from Radiation Safety Information Computational Center at Oak Ridge National Laboratory as CCC-785.