INL/CON-23-74202-Revision-1

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March 2024

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Idaho National Laboratory
Idaho Falls, Idaho 83415

http://www.inl.gov

Prepared for the
U.S. Department of Energy
Under DOE Idaho Operations Office
Contract DE-AC07-05ID14517

Criticality Analysis of Fort Saint Vrain Spent Nuclear Fuel in the DOE Standard Canister – 24299

Benjamin L. Estrada[1], Kristina Y. Spencer[2], Evans D. Kitcher[2], and Daniel A. Thomas[2]

[1]Oregon State University, School of Nuclear Science and Engineering

[2]Idaho National Laboratory, Used Fuel Management Department

ABSTRACT

The U.S. Department of Energy (DOE) is responsible for managing over 300 types of spent nuclear fuel (SNF). To manage this large variety of fuel types, DOE plans to employ standardized canisters for the transportation, long-term storage, and eventual disposal of SNF. Idaho National Laboratory is currently supporting DOE's SNF Packaging Demonstration Project, in which Fort Saint Vrain (FSV) fuel assemblies will be loaded into a DOE Standard Canister. This paper presents criticality calculations demonstrating that all four or five FSV fuel assemblies loaded into the DOE Standard Canister will remain subcritical in any expected normal or credible abnormal conditions.

Previous criticality analyses were performed for one FSV fuel assembly and 12 Peach Bottom Core 2 fuel elements loaded into a DOE Standard Canister. This paper covers the criticality analysis performed for loading both four and five FSV fuel assemblies into a DOE Standard Canister. Various intact and degraded mode configurations were modeled in conducting the criticality calculations. This analysis encompassed three different configurations: (1) a single DOE Standard Canister loaded into a concrete storage overpack, (2) seven DOE Standard Canisters loaded into a concrete storage overpack, and (3) nine DOE Standard Canisters loaded into a concrete storage overpack. The overpack dimensions were varied for each of the three configurations, and transport, storage, and disposal scenarios were analyzed for each configuration.

For transport scenarios, a pair of degradation cases was analyzed. In the first case, the fuel compacts became degraded and were removed from the fuel block, then deposited at the bottom of a horizontally placed canister, thereby simulating a drop event. The canister was considered to remain intact. In the second case, the spacing between horizontally placed canisters in a nine-canister overpack was reduced such that the canisters were piled on top of each other, simulating a drop event. For this case, no degradation of the canister internals or fuel was considered.

For storage scenarios, the water moderator location in the system was varied to enable identification of the most reactive configurations. Dry and wet conditions were analyzed for the fuel materials, canister, and overpack. For disposal scenarios, two degradation cases were analyzed. In the first, the stainless-steel internals of the canister degraded to either hematite or goethite under both dry and wet conditions. In the second case, degraded FSV fuel formed a uranium-water slurry that filled the coolant/void holes. None of the cases presented exceeded the application specific upper subcritical limit.

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INTRODUCTION

The U.S. Department of Energy (DOE) is responsible for managing a wide variety of spent nuclear fuel (SNF). This SNF differs in terms of reactor type (light-water, heavy-water, or graphite-moderated), fuel enrichment, fuel element and assembly geometry, and materials. Additionally, less than 10% of DOE SNF has corresponding data to support thermal, structural, and criticality analyses [1]. Thus, DOE is pursuing a standardized canister for SNF transportation, storage, and disposal. The licensing strategy for this canister will be based around the reliability of its engineered systems, structures, and components.

The DOE Standard Canister comes in four available sizes: a diameter of either 45.7 or 61 cm, and a total length of 3.05 or 4.57 m. For loading the Fort Saint Vrain (FSV) fuel, the 45.7-cm-wide, 4.57-m-long DOE Standard Canister was chosen. The canister has a wall thickness of 0.9525 cm. The top and bottom impact plates are made of 316L stainless steel, and the top and bottom ends are sealed by dished heads, beyond which the canister wall extends a few extra inches. A basket structure sits in the canister and consists of six centering ribs arranged in a hexagonal formation, with five concentric rings spanning the height of the basket. The upper end has a vent port and plug used for draining, inerting, leak testing, venting, monitoring, and remote inspection. The DOE Standard Canister can accommodate up to five FSV fuel assemblies—four when a shield plug is included. Figure 1 shows an isometric and cross-sectional view of the two canister types with and without a shield plug. Table 1 describes the material composition of the 316L stainless steel used in the Monte Carlo N-Particle (MCNP) calculations.

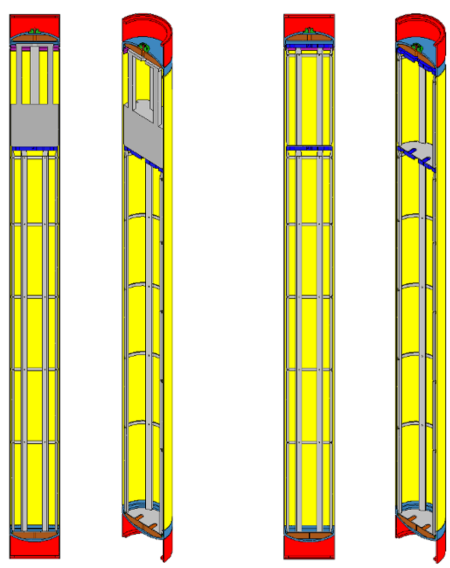

Figure 1. Cross-Sectional 3-D Model of the DOE Standard Canister.

Table 1. Composition of the 316L Stainless Steel [2].

Element/Isotope	Atomic Fraction
C	1.2003e-04
N	3.4308e-04
Si	1.7111e-03
P	6.9819e-05
S	4.5092e-05
Cr	1.5712e-02
Mn	1.7494e-03
Ni	9.8251e-03
Mo	1.2521e-03
Fe	5.6187e-02
Density: 7.98 g/cm^3	

The DOE Standard Canister has undergone extensive analysis and testing. Finite element analysis concluded that under both normal and credible pre-closure accident conditions, the canister will remain leak tight. Several canisters were drop tested per American National Standards Institute N14.510 criteria and did in fact remain leak tight, as expected [1]. Thus, for the transport scenarios covered in this criticality analysis, moderator exclusion is credited. The remainder of this paper summarizes the criticality analyses performed on various configurations and scenarios pertaining to FSV fuel loaded into DOE Standard Canisters.

CRITICALITY ANALYSES

This section describes the methods and assumptions employed in the criticality analyses. The cases and results are also presented in detail.

Methods

To perform the criticality calculations, MCNP version 6.2 was used to calculate the effective neutron multiplication factor (k_{eff}) of the various FSV SNF configurations in the DOE Standard Canister. The calculations were performed using the ENDF/B-VII.1 continuous-energy cross-section libraries. The Sawtooth high-performance computing cluster at Idaho National Laboratory was used to execute MCNP 6.2.

Assumptions

1. The description, dimensions, and material compositions of the FSV fuel assemblies were derived from [2].
2. Air was modeled as void because of its minimal effect as per the approach taken in [3].
3. The length of the fuel compacts was considered to be the length of the fuel assembly, rather than the actual (smaller) length. This afforded a larger void fraction and therefore the potential for more water in the fuel. The justification for this assumption is that it is more conservative [3].
4. Increase of fissionable materials in the container is not credited. Absorption of neutrons through materials like boric acid is not credited. Various scenarios consider changes in absorption, geometry, and interaction through fuel displacement and moderator ingress.
5. Unless stated otherwise, full water reflection (30 cm) was used in the MCNP models which is conservative.
6. The upper subcritical limit (USL) was calculated using Whisper, a sensitivity and uncertainty analyses package that compares models to criticality benchmarks [4]. The baseline USL value from Whisper stood at 0.97121. For transport scenarios, an additional subcriticality margin of 0.05 was incorporated, whereas storage and disposal scenarios incorporated an additional subcriticality margin of 0.02. This yielded a USL of 0.92171 for transport scenarios and 0.95171 for storage and disposal scenarios.

Description of a FSV Fuel Assembly[1]

The FSV fuel element, hexagonal in cross section, is 36.060 cm (14.172 in.) across flats by 79.2988 cm (31.22 in.) in height [2]. The standard element, the most reactive fuel assembly type, was modeled in MCNP. The fuel is contained in an array of holes that run parallel to the coolant channels and occupy alternating positions in a triangular array, whose pitch is approximately 18.8 mm (0.74 in.), within the graphite structure. A large coolant hole is positioned at the center of the element. At the four primary corners of the element are holes for accommodating burnable poison rods; these rods were added as required and did not always completely fill the hole. These burnable poison rods were replaced with graphite in the MCNP model. Figure 2 shows a cross-section view of a standard element.

The fuel blocks are made of nuclear-grade graphite, either type H-327 (needle-coke graphite) or type H-451. For the present research, H-327 was selected for its higher void fraction, which would allow for greater water saturation. The lateral alignment of the six-layered fuel element column in the core is maintained by a system of three graphite dowels located on the top face of each element. The bottom side of each fuel block features three dowel sockets for interlocking with the block underneath. These dowels are not simulated in the MCNP model. Table 2 and Table 3 provide the material compositions of the FSV fuel and graphite block, respectively.

1 The terms “fuel assembly” and “fuel element” are used interchangeably throughout this paper.

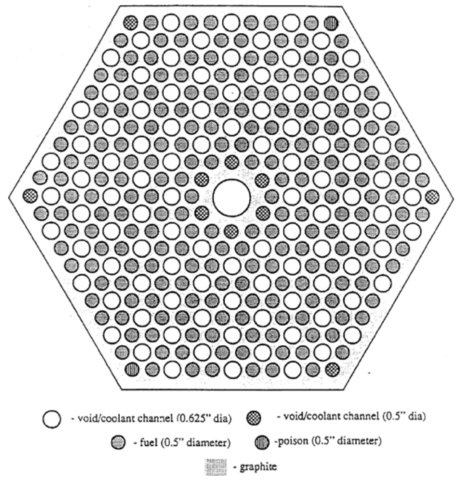

Figure 2. Cross-Section View of a FSV Fuel Assembly.

Table 2. FSV Fuel Composition [2].

Element/Isotope	Atomic Fraction
U-235	1.8036e-04
Th-232	1.3275e-03
Si	2.5451e-03
C	6.4756e-02
Pu-239	3.0929e-07
Density: 1.9911 g/cm^3	

Table 3. FSV Graphite Composition [2].

Element/Isotope	Atomic Fraction
C	1
Density: 1.72 g/cm^3	

Description of Scenarios

The present analysis investigated three different configurations: (1) a single DOE Standard Canister loaded into a concrete storage overpack, (2) seven DOE Standard Canisters loaded into a concrete storage overpack, and (3) nine DOE Standard Canisters loaded into a concrete storage overpack. The overpack dimensions were varied to accommodate the three different canister configurations. Table 4 lists the material composition of the concrete overpack.

Table 4. Concrete Overpack Composition [3].

Element/Isotope	**Atomic Fraction**
H	1.3742e-02
O	4.6056e-02
Na	1.7470e-03
Al	1.7450e-03
Si	1.6620e-03
Ca	1.5210e-03
Fe	3.4700e-03
Density = 2.3 g/cm^3	

Normal Conditions

This section describes the six base cases applied to FSV fuel assemblies loaded inside a DOE Standard Canister. For these base cases, there was no degradation or water in the canister, overpack, or fuel materials. This same scenario was applied to all three overpack configurations; namely the single-, seven-, and nine-canister configurations. Figure 3 shows the arrangement of the canisters within each overpack type. Figure 4 shows the MCNP models of four and five FSV fuel assemblies loaded into the DOE Standard Canister.

The color legend for Figure 3 and Figure 4 is as follows:

Green: water boundary

Teal: concrete overpack

Dark blue: stainless-steel liner, canister, and internals

Red: graphite fuel block

Yellow: fuel

White: void space.

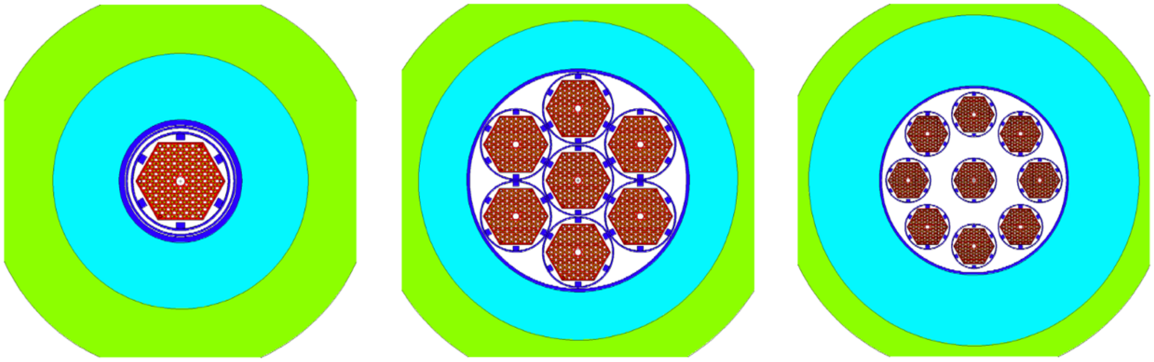

Figure 3. Single-, Seven-, and Nine-Canister Overpack Arrangements.

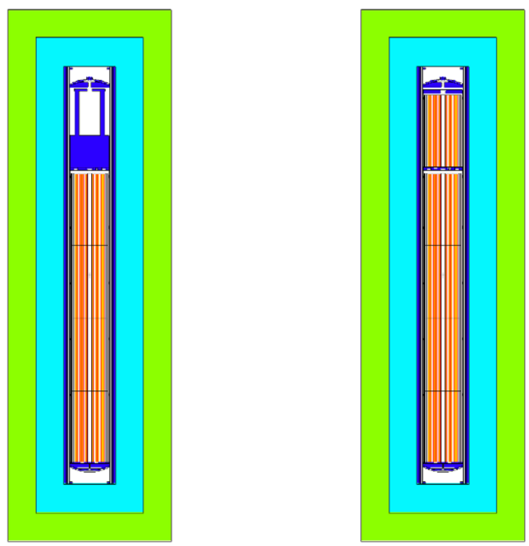

Figure 4. MCNP Models of Four and Five FSV Fuel Assemblies Loaded into the DOE Standard Canister.

Transport Scenarios

This section describes the cases analyzed for the transport scenarios. Some of the transport scenarios were derived from cases analyzed in [5]. For multi-canister overpack configurations, the scenarios were applied to all the DOE Standard Canisters in the overpack. In the first transport scenario, the fuel became degraded and then collected at the bottom of a horizontally placed canister and overpack. Here, one side of the hexagonal fuel assembly was positioned as the lowest point. This same case was also analyzed with the fuel assembly tilted 30 degrees, such that one of the hexagonal assembly vertices the lowest point. Slightly over 10% of the fuel was removed via the top of each fuel assembly.

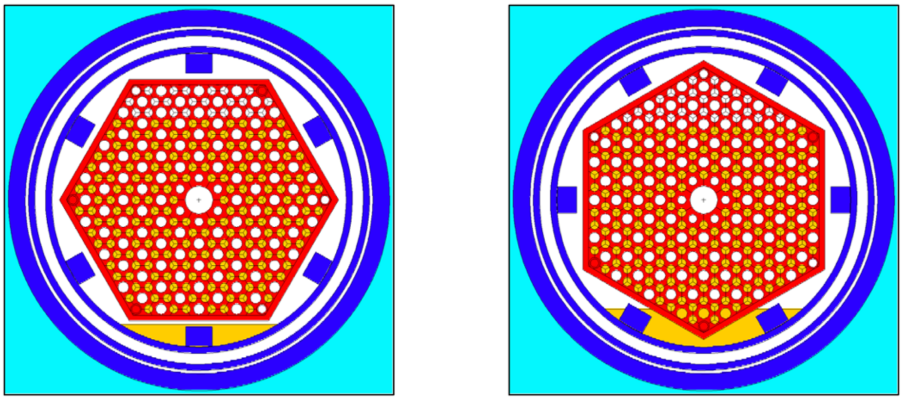

Figure 5. Cross Sections of Horizontally Placed DOE Standard Canisters with Degraded Fuel Collected at the Bottom.

In the second transport scenario, only the nine-canister overpack was analyzed. This scenario simulated a drop event that reduced the spacing between the canisters in the overpack. No fuel degradation or material rearrangement in the canister itself was considered. Figure 6 shows the crowded canister configuration post-drop.

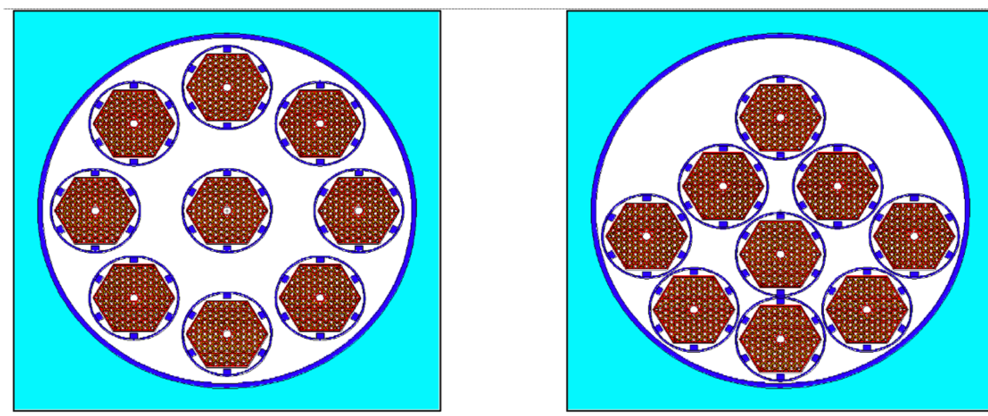

Figure 6. Cross Sections Before and After the Nine-Canister Overpack Drop Scenario.

Storage Scenarios

This section describes the cases analyzed for the storage scenarios. For multi-canister overpack configurations, the scenarios were applied to all the DOE Standard Canisters in the overpack. Moderator location was varied saturating the fuel materials, flooding the canister, flooding the overpack, and combinations thereof. These conditions were analyzed for the single-, seven-, and nine-canister overpack configurations. Fuel degradation was unaccounted for in any of the storage scenarios.

Disposal Scenarios

All the same cases covered in the storage scenarios were covered in the disposal scenarios as well. Some of the disposal scenarios were derived from cases analyzed in [5]. For multi-canister overpack configurations, the scenarios were applied to all the DOE Standard Canisters in the overpack. Two degradation scenarios were examined. In the first, about 10% of the original fissile uranium from each fuel assembly migrated to fill the coolant/void holes in the form of a uranium-water slurry. This is illustrated in Figure 7, with the uranium-water slurry being indicated in red. The results generated via this scenario are conservative, as in reality the uranium-water slurry would fill parts of the canister outside of the fuel assemblies. The value of 10% is based on findings collected via destructive post-irradiation examination of a spent FSV fuel assembly. The findings showed that around 0.3% of the fissile and 0.2% of the fertile microspheres had been damaged, and roughly 3% of the fuel compacts broken; therefore, 10% is a conservative value [2].

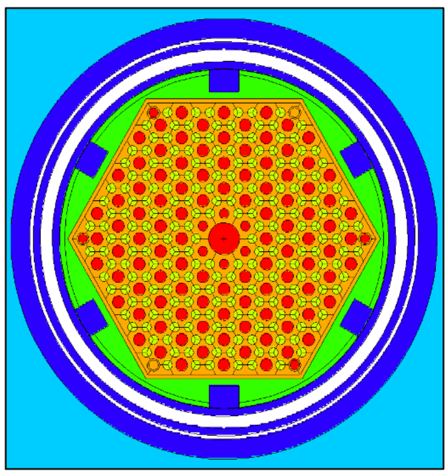

Figure 7. Cross Section of a Fuel Assembly in Which a Uranium-Water Slurry Has Filled the Coolant/Void Holes.

In the second scenario, derived from [3], the stainless-steel components of the canister and its internals became degraded. The iron in the stainless steel was substituted with hematite (Fe^2O^3) or goethite (Fe(OH)O), both of which are iron oxides. Additionally, moderator ingress was considered in both these degradation scenarios.

RESULTS

Normal Condition Results

Table 5 presents the results for the base cases. For the six base cases analyzed, the highest calculated k_{eff}, 0.34233, was for five FSV fuel assemblies loaded into the seven-canister overpack configuration, with a dry canister, dry overpack, and unsaturated fuel materials. This is partly because the seven-canister overpack configuration had very limited spacing between canisters. Notably, the differences in calculated k_{eff} are small when comparing four vs. five fuel assemblies loaded into the canisters.

Table 5. Calculated k_{eff} for the Base Cases.

Configuration	**k_{eff} + 2σ**		
	1 SC	7 SCs	9 SCs
Four FSV assemblies	0.12058	0.34092	0.27689
Five FSV assemblies	0.12074	**0.34233**	0.28441

Transport Scenario Results

Table 6 presents the results pertaining to the nine-canister overpack collapse. These results consider the moderator exclusion credited for the DOE Standard Canister, although moderator exclusion has not been licensed. Since moderator exclusion is credited for these cases, the fuel materials are unsaturated and the DOE Standard Canister is dry. The highest calculated k_{eff}, 0.3296, was for five FSV fuel assemblies loaded into a dry overpack.

Table 6. Calculated k_{eff} for the Nine-Canister Overpack Collapse.

Configuration		**k_{eff} + 2σ**
Four FSV assemblies	Dry overpack	0.3252
	Wet Overpack	0.26418
Five FSV assemblies	Dry overpack	**0.3296**
	Wet Overpack	0.26438

Table 7 presents the calculated k_{eff} results for the degradation scenario in which fuel collected at the bottom of a horizontal canister. These results consider the moderator exclusion credited for the DOE Standard Canister, although moderator exclusion has not been licensed. Since moderator exclusion is credited for these cases, the fuel materials are unsaturated and the DOE Standard Canister is dry. The highest calculated k_{eff}, 0.38794, was for four FSV fuel assemblies loaded into a dry seven-canister overpack.

Table 7. Calculated k_{eff} for Transport Scenarios Involving a Drop Event.

Configuration		**k_{eff} + 2σ**		
		1 SC	7 SCs	9 SCs
4 FSV assemblies	Dry overpack	0.12827	**0.38794**	0.31711
	Flooded overpack	0.18078	0.38071	0.24284
5 FSV assemblies	Dry overpack	0.12852	0.36116	0.29969
	Flooded overpack	0.18046	0.35565	0.22289

Table 8 presents the results for the same case but with the fuel assemblies tilted 30 degrees. In this scenario, the highest calculated k_{eff} was for five FSV fuel assemblies loaded into a dry seven-canister overpack.

Table 8. Calculated k_{eff} for Transport Scenarios Involving a Drop Event and Fuel Assemblies That Are Tilted 30 Degrees.

Configuration		**k_{eff} + 2σ**		
		1 SC	7 SCs	9 SCs
4 FSV assemblies	Dry overpack	0.24223	0.34951	0.28337
	Flooded overpack	0.17317	0.34466	0.21463
5 FSV assemblies	Dry overpack	0.12383	**0.35093**	0.29118
	Flooded overpack	0.17301	0.34485	0.2148

In all the cases presented, the seven-canister overpack had the highest k_{eff} of the three overpack types. This was likely due to the smaller spacing between canisters in the seven-canister overpack compared to the nine-canister overpack. In general, only small differences are seen when comparing four vs. five FSV fuel assemblies. The cases in which the fuel assembly vertices were the lowest point reflected a higher degree of reactivity than when the fuel assembly sides were the lowest point.

Storage Scenario Results

Table 9,

Table 10, and Table 11 show the calculated k_{eff} results for the storage scenarios pertaining to the single-, seven-, and nine-canister overpack configurations, respectively. The highest calculated k_{eff}, 0.94626, was for five FSV fuel assemblies in a dry seven-canister overpack, with saturated fuel materials and flooded canisters. Flooded canisters in a flooded overpack are less reactive than flooded canisters in a dry overpack likely due to neutrons that leave the canister continuing to be moderated to energies that preclude their re-entry into the canisters.

Table 9. Calculated k_{eff} for Storage Scenarios pertaining to the Single-Canister Overpack Configuration.

Configuration		**k_{eff} + 2σ**	
		Unsaturated	Saturated
4 FSV Assemblies	Dry canister in a dry overpack	0.12058	0.70998
	Dry canister in a fully flooded overpack	0.16528	0.68269
	Fully flooded canister in a dry overpack	0.74752	0.89833
	Fully flooded canister in a fully flooded overpack	0.72857	0.88744
5 FSV Assemblies	Dry canister in a dry overpack	0.12074	0.70979
	Dry canister in a fully flooded overpack	0.16554	0.68235
	Fully flooded canister in a dry overpack	0.74772	**0.89845**
	Fully flooded canister in a fully flooded overpack	0.72789	0.88757

Table 10. Calculated k_{eff} for Storage Scenarios pertaining to the Seven-Canister Overpack Configuration.

Configuration		**k_{eff} + 2σ**	
		Unsaturated	Saturated
4 FSV Assemblies	Dry canister in a dry overpack	0.34092	0.93005
	Dry canister in a fully flooded overpack	0.33145	0.80986
	Fully flooded canister in a dry overpack	0.83726	0.94594
	Fully flooded canister in a fully flooded overpack	0.78439	0.91848
5 FSV Assemblies	Dry canister in a dry overpack	0.34233	0.93036
	Dry canister in a fully flooded overpack	0.33244	0.8108
	Fully flooded canister in a dry overpack	0.83726	**0.94626**
	Fully flooded canister in a fully flooded overpack	0.7845	0.91794

Table 11. Calculated k_{eff} for Storage Scenarios pertaining to the Nine-Canister Overpack Configuration.

Configuration		$k_{eff} + 2\sigma$	
		Unsaturated	Saturated
4 FSV Assemblies	Dry canister in a dry overpack	0.27689	0.88459
	Dry canister in a fully flooded overpack	0.20416	0.68488
	Fully flooded canister in a dry overpack	0.82348	0.93884
	Fully flooded canister in a fully flooded overpack	0.72593	0.88651
5 FSV Assemblies	Dry canister in a dry overpack	0.28441	0.88774
	Dry canister in a fully flooded overpack	0.20445	0.68504
	Fully flooded canister in a dry overpack	0.82387	**0.93907**
	Fully flooded canister in a fully flooded overpack	0.72591	0.8866

Disposal Scenario Results

Table 12 shows the calculated k_{eff} results pertaining to the uranium-water slurry cases. The seven-canister configuration proved the most reactive of the three overpack configurations. The highest calculated k_{eff}, 0.94989, was for four FSV fuel assemblies in a dry seven-canister overpack, with a flooded canister.

Table 12. Calculated k_{eff} for the Uranium-Water Slurry Cases.

Configuration		$k_{eff} + 2\sigma$		
		1 SC	7 SCs	9 SCs
4 FSV Assemblies	Fully flooded canister in a dry overpack	0.90397	**0.94989**	0.94281
	Fully flooded canister in a fully flooded overpack	0.89331	0.92315	0.8921
5 FSV Assemblies	Fully flooded canister in a dry overpack	0.90403	0.94988	0.94289
	Fully flooded canister in a fully flooded overpack	0.89324	0.923	0.89202

Table 13 and Table 14 show the calculated k_{eff} for the hematite and goethite cases, respectively. The moderator location was varied in all the cases, but only the most reactive configurations are reported below, as these conditions bound the analysis. The most reactive configurations include saturated fuel materials, fully flooded DOE Standard Canisters, and a dry overpack. In general, the hematite cases produced a more reactive system, with the highest k_{eff}, 0.95033, being for four FSV fuel assemblies in a dry seven-canister overpack, with saturated fuel materials and flooded canisters. The hematite had a slightly greater effect on reactivity most likely due to being denser than the goethite.

Table 13. Calculated k_{eff} for the Hematite Cases.

Configuration		**k_{eff} + 2σ**		
		1 SC	7 SCs	9 SCs
4 FSV Assemblies	Fully flooded canister in a dry overpack	0.89984	**0.95033**	0.94249
	Fully flooded canister in a fully flooded overpack	0.89016	0.92212	0.88926
5 FSV Assemblies	Fully flooded canister in a dry overpack	0.90009	0.95026	0.94233
	Fully flooded canister in a fully flooded overpack	0.88965	0.92268	0.8898

Table 14. Calculated k_{eff} for the Goethite Cases.

Configuration		**k_{eff} + 2σ**		
		1 SC	7 SCs	9 SCs
4 FSV Assemblies	Fully flooded canister in a dry overpack	0.88937	0.93593	0.92923
	Fully flooded canister in a fully flooded overpack	0.88414	0.91419	0.88655
5 FSV Assemblies	Fully flooded canister in a dry overpack	0.88894	**0.93682**	0.92905
	Fully flooded canister in a fully flooded overpack	0.88504	0.91464	0.88651

CONCLUSIONS

This paper reported the criticality calculation results for transport, storage, and disposal scenarios applied to FSV fuel assemblies loaded into DOE Standard Canisters in various overpack configurations. Various degradation cases and moderator intrusion cases were analyzed in conducting the calculations. The cases were used to analyze fuel compact degradation, canister collapse within the nine-canister overpack, uranium-water slurry formation, stainless steel degradation, and moderator ingress into the DOE Standard Canister and overpack. The following statements summarize the key findings of the calculations. Loading four or five FSV fuel assemblies both generated results that were neutronically very similar. In general, the most reactive conditions involved saturated fuel materials, flooded canisters, and a dry overpack. This is the optimal moderation condition, where any additional water ingress in the system would result in a decrease in reactivity due to additional neutron absorption and scattering in the water. Saturating the fuel materials had the greatest effect on reactivity, since moderator was mixed directly with fuel. The seven-canister overpack was the most reactive of the three overpack types.

The highest calculated k_{eff}, 0.95033, was reported in the context of stainless steel becoming degraded into hematite, for four FSV fuel assemblies in a dry seven-canister overpack, with saturated fuel materials and flooded canisters. None of the presented cases exceeded the application-specific USL of 0.92171 for transport scenarios, or 0.95171 for storage and disposal scenarios.

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ACKNOWLEDGEMENTS

This research made use of the resources of the High-Performance Computing Center at Idaho National Laboratory, which is supported by the DOE Office of Nuclear Energy and the Nuclear Science User Facilities under contract no. DE-AC07-05ID14517.