August 10, 2000

Paper
To be published in ***PROCEEDINGS***

Computational Physics and Engineering Division (10)

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Submitted to the
American Nuclear Society
ANS SPECTRUM 2000, International Conference on Nuclear and Hazardous Waste Management,
September 24–28, 2000,
Chattanooga, TN

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[†] Managed by UT-Battelle, LLC, under contract DE-AC05-00OR22725 with the U.S. Department of Energy.

SHIPPINGPORT PWR FUEL CRITICALITY ANALYSES FOR VIABILITY EVALUATION OF CODISPOSAL IN A GEOLOGIC REPOSITORY

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Abstract

The results from the criticality calculations for intact and degraded spent nuclear fuel (SNF) from the Department of Energy's (DOE's) Shippingport pressurized-water reactor (PWR) are reported. Shippingport PWR fuel is highly enriched uranium (HEU) oxide fuel that is slated for disposal in the potential monitored geologic repository at Yucca Mountain. The geochemical and physical processes that can breach the waste package and degrade the waste forms and other internal components are investigated.

INTRODUCTION

More than 250 forms of SNF are owned by DOE. Because of the variety of the spent nuclear fuel, the National Spent Nuclear Fuel Program has designated nine representative fuel groups for disposal criticality analyses based on fuel matrix, primary fissile isotope, and enrichment. Shippingport PWR fuel has been designated as the representative fuel for the HEU oxide fuel group. Demonstration that other fuels in this group are bounded by the Shippingport PWR fuel analysis remains a future task before acceptance of these fuel forms. The results of these analyses will be used to develop waste acceptance criteria. The items that are important to safety are identified based on the information provided by the National Spent Nuclear Fuel Program.

The analyses were performed according to the disposal criticality analysis methodology that was documented in a topical report[1] submitted to the Nuclear Regulatory Commission. Before the Shippingport PWR fuel is emplaced in the repository, the waste package must be shown to be viable for disposal of the Shippingport PWR fuel, considering the structural, thermal, shielding, and criticality aspects of the waste package. The methodology also includes analyzing the geochemical and physical processes that can cause the waste package to breach and degrade the waste forms. Therefore, the waste package is analyzed against the relevant design criteria for the respective disciplines. Addenda to the topical report will be required to establish the critical limit for DOE SNF once sufficient critical benchmarks are identified and performed. Meanwhile, an interim critical limit is established and used throughout this paper.

SHIPPINGPORT PWR CODISPOSAL WASTE PACKAGE

The waste package that holds the DOE SNF canister with Shippingport PWR fuel also contains five high-level waste (HLW) glass pour canisters and a carbon steel basket. The remainder of this paper will refer to the DOE SNF canister with the Shippingport PWR fuel as the SNF canister. The SNF canister is placed in a support tube that becomes the center of the waste

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package, as shown in Fig. 1. The five HLW canisters are evenly spaced around the SNF canister. The SNF canister is designed to hold one Shippingport PWR fuel assembly. The basket structure of the SNF canister comprises a stainless-steel rectangular grid that is a 208-mm square. An isometric of the SNF canister containing one Shippingport PWR fuel assembly is shown in Fig. 2.

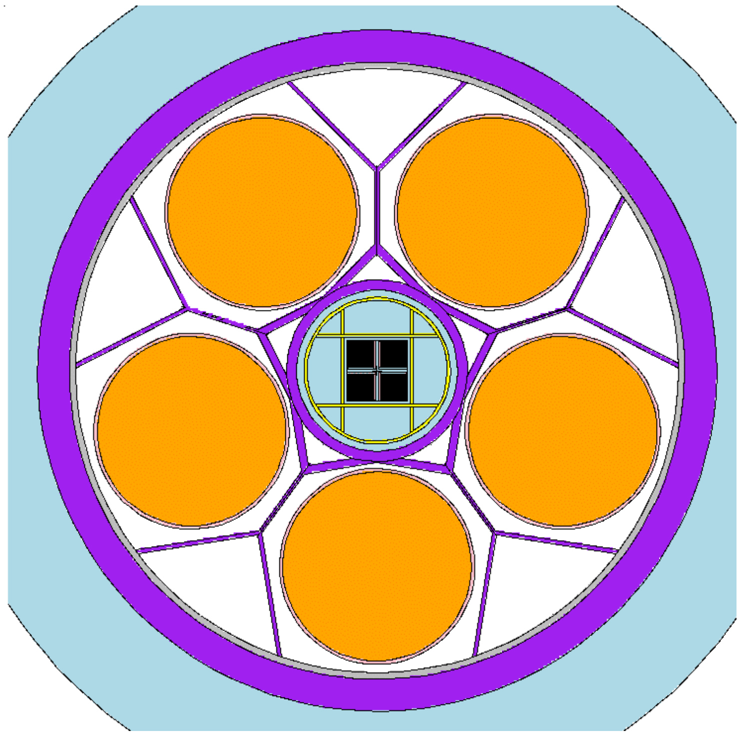

Fig. 1. 5-HLW/DOE SNF waste package with Shippingport PWR fuel assembly.

The waste package design is based on the preliminary waste package design contained in the Viability Assessment.[2] The outer barrier is made of a corrosion-allowance material, 100-mm-thick carbon steel. The corrosion-resistant inner barrier is fabricated from a 20-mm-thick high-nickel alloy. Both the top and bottom lids are also based on the two-barrier principle and use the same materials.

The Shippingport PWR was a “seed and blanket” reactor that underwent multiple modifications to provide higher thermal outputs. The blankets will be shipped and handled as bare assemblies. The low enrichments of the blankets (<1%) allow the use of the same packaging associated with either PWR or BWR commercial fuels. Therefore, this paper does not address the disposal of blanket assemblies in the monitored geologic repository.

Two seeds, Seed 1 and Seed 2, which had identical geometrical dimensions but different U-235 enrichment and chemical composition, were designed for Shippingport PWR Core 2 operation. The assembly is composed of Zircaloy-4 and consists of four sub-assemblies and a cruciform-shaped channel in the center to accommodate a control rod. Figure 3 shows the cross section of a single sub-assembly. Each sub-assembly is composed of 19 fuel plates and 20 channels. Each plate is formed by sandwiching an enriched U-Zr alloy strip between two Zircaloy-4 cover plates and four side strips. Note that there are five types of fuel plates located in the assembly: end (Y), transition (T), secondary (W), standard (R), and intermediate (L). As shown in Table I, the three assembly regions (i.e., Zones 1, 2, and 3) have different fissile loadings.

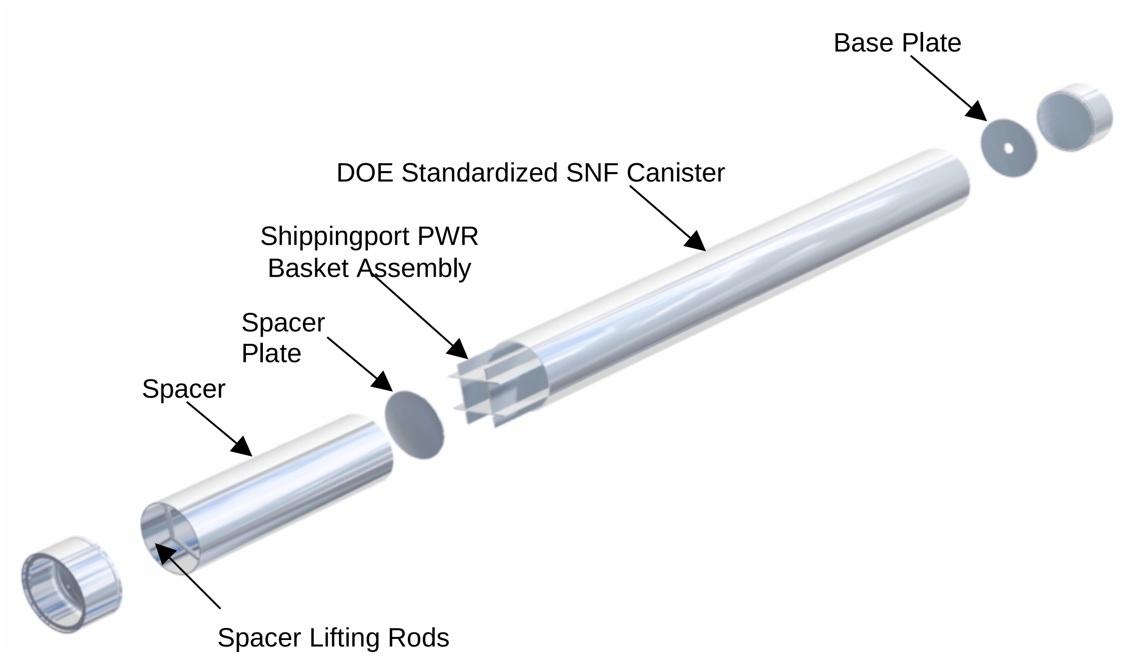

Fig. 2. Isometric view of the Shippingport PWR DOE SNF canister.

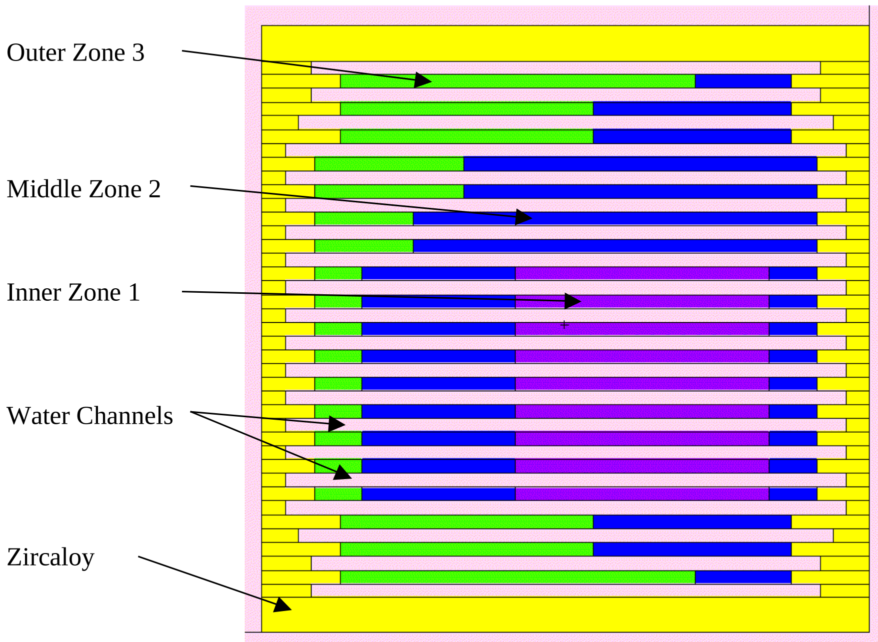

Fig. 3. Shippingport PWR Core 2 Seed 2 SNF sub-assembly cross section.

TABLE I

Geometry and Material Specifications for the Shippingport PWR Core 2 Seed 2 Assembly

Component	Material	Characteristic	Value
Assembly		Total mass (kg)	357
		Length (cm)	265.43
		Transverse dimensions (cm)	18.7325
Fuel plate		Active fuel length (cm)	246.38
Fuel wafer	UO_2-ZrO_2-CaO 93.2% U-235 beginning of life (BOL) enrichment	Length (cm)	2.07264
		Width (cm)	0.64008
		Thickness (cm)	0.09144
Fuel Zone 1	UO_2-ZrO_2-CaO	Weight (wt) % UO_2	54.9
		wt % CaO	5.2
		wt % ZrO_2	39.9
		Fissile loading (kg)	7.076
Fuel Zone 2	UO_2-ZrO_2-CaO	wt % UO_2	40.2
		wt % CaO	5.8
		wt % ZrO_2	54
		Fissile loading (kg)	8.987
Fuel Zone 3	UO_2-ZrO_2-CaO	wt % UO_2	26.5
		wt % CaO	6.4
		wt % ZrO_2	67.1
		Fissile loading (kg)	3.437
Borated stainless steel	SS 304	Mass (g)	6,001
	B-10	Mass (g)	26
	B-11	Mass (g)	114
Spacer rings	Inconel X	Mass (g)	546
Chrome plating	Cr	Mass (g)	325
Cladding	Zircaloy-4	--	--

Critical Limit

The worst-case bias, calculated from the MCNP simulations of the experiments applicable to Shippingport PWR fuel, is 0.02 (Refs. 3 and 4). This bias includes the bias in the method of calculation and the uncertainty in the experiments. Based on this bias, the interim critical limit is determined to be 0.93 after a 5% margin. This interim critical limit will be used until the addendum to the topical report is prepared to establish the final critical limit.

DEGRADATION AND GEOCHEMISTRY ANALYSES

The degradation analyses follow the general methodology[1] developed for application to all waste forms containing fissile material. This methodology evaluates potential critical configurations from the intact (geometrically intact components but otherwise breached waste package to include water as moderator) waste package through the completely degraded waste package. The waste package design developed for the intact configuration (at time of disposal) is used as the starting point. Sequences of events and/or processes of component degradation are developed. Standard scenarios from the master scenario list in the topical report are refined using unique fuel characteristics. Potentially critical configurations are identified for further analysis.

The EQ3/6 (Ref. 5) geochemistry code was used to determine the chemical composition of the solid degradation products. Particular emphasis was given to the chemical conditions that could lead to loss of neutron absorbers from the waste package and that would allow the fissile materials to remain. The DOE SNF canister with Shippingport PWR fuel does not contain any strong neutron absorbers, such as gadolinium, which is used for some of the other fuel types. Boron, which is a burnable poison that is an integral part of the fuel, is neglected in all criticality calculations.

EQ3/6 cases are constructed to span the range of possible fuel corrosion. The effects of steel corrosion, glass degradation, and fluid influx rate on uranium oxide dissolution are also investigated. Uranium loss from the waste package varied from 0.06 to 100% and was typically complete if greater than neutral pH's existed for any appreciable amount of time. At a given glass dissolution rate, uranium loss varies inversely with the influx of water.

INTACT AND DEGRADED COMPONENT CRITICALITY ANALYSES

The effective multiplication factors (k_{eff}) of the configurations evaluated are calculated using MCNP Version 4B2 (Ref. 6). All configurations assume the waste package is breached and flooded by water to create an optimum moderation environment. A number of parametric analyses were also run to address or bound the configuration classes. These parametric analyses addressed identification of optimum moderation, optimum spacing, and optimum fissile concentration.

The intact and degraded component criticality analyses consider a single Shippingport PWR assembly (Core 2, Seed 2) inside the DOE SNF canister, which contains a stainless steel Type 316L basket. Analyses consider optimum moderation, optimum distribution of fissile material and degradation products, and optimum reflection to determine the highest k_{eff} attainable by the system. Intact cases represent a breached but otherwise intact waste package, the SNF canister, and the fuel assembly. Degraded cases cover a range of degradation of waste package internals, HLW glass canisters, the SNF canister, and the fuel assembly.

In all cases the waste package is effectively water-reflected. A case was run to demonstrate that the environment outside the waste package, whether tuff, water, or a mixture, has no significant impact on the configuration k_{eff}. Instead of water reflection outside the waste package, reflective boundary conditions were used. The k_{eff} of the waste package with reflected boundary conditions (0.8408 ± 0.0011) was statistically identical to the k_{eff} of the water-reflected waste package (0.8415 ± 0.0011).

The effect of mineral deposits from the J-13 well water (which is the well water that is representative of the Yucca Mountain area), around the fuel assembly, between the plates, and the cruciform area is calculated. The results indicate that the mineral deposits from the J-13 well water have no significant effect on the k_{eff} of the system (results are within statistical uncertainty).

The intact component cases consider an intact fuel assembly in the intact SNF canister and intact waste package. Water intrusion into the void spaces in the assembly, the SNF canister, and the waste package is investigated. The worst case is when the water is in fuel wafer void space and plate void space. The SNF canister void space and the space between the SNF canister and the waste package center support tube are also flooded. The highest $k_{eff} + 2\sigma$ is 0.8819, with a water density of 1 g/cm^3.

The degraded component criticality calculations comprise degraded guide plates, clay accumulation inside the canister, degraded SNF canister and waste package, partially degraded fuel assembly in the intact SNF canister, partially degraded fuel assembly in degraded SNF canister, partially degraded fuel assembly with degraded canister and degraded waste package, and fully degraded fuel in degraded canister and degraded waste package. The most probable degradation path is identified as follows: Waste package is penetrated and flooded internally; waste package basket degrades; HLW glass canister shell and glass degrade; the SNF canister is penetrated and flooded; the SNF canister basket degrades; fuel assembly and plates stay intact and collect on the bottom of the degraded SNF canister or, if the SNF canister is degraded, collect near the bottom of the waste package.

The worst-case $k_{eff} + 2\sigma$ of 0.922 is obtained with degraded SNF canister and waste package internals. Clay from degraded glass surrounds the fuel assembly, as shown in Fig. 4. The fuel assembly coolant channel and cruciform areas are filled with water. The results that show the effect of clay, goethite, and water are given in Table II. Adding water or goethite to the clay decreases the k_{eff} by as much as 4%. Replacing clay with water or goethite altogether decreases k_{eff} by approximately 1%.

Also, the results from the criticality analysis for the degraded SNF canister (fissile material distributed in the waste package) indicate that the highest k_{eff} is achieved if the fuel and clay layers do not mix. Therefore, the amount of clay in the waste package has no effect on the bounding case, which is a layer of optimally moderated fuel not mixed with any clay. Although varying the amount of water mixed with the fuel changes the k_{eff}, the peak $k_{eff} + 2\sigma$ of the system is less than 0.85, which is well below the interim critical limit.

CONCLUSIONS

All conceivable aspects of intact and degraded configurations, including optimum moderation conditions, water intrusion into the fuel plates, and positioning of the fuel assembly were investigated. The results of 3-D Monte Carlo calculations from the intact and degraded component criticality analyses show that $k_{eff} + 2\sigma$ is less than 0.93 for one Shippingport PWR assembly in the DOE SNF canister. The configurations do not need any neutron absorber in the canister basket or elsewhere in the waste package, even without credit for burnable absorber (boron) that is present in the fuel assembly. With this design, there will be approximately 20 DOE SNF canisters loaded with Shippingport PWR SNF (Core 2 Seed 2), which corresponds to 20 waste packages.

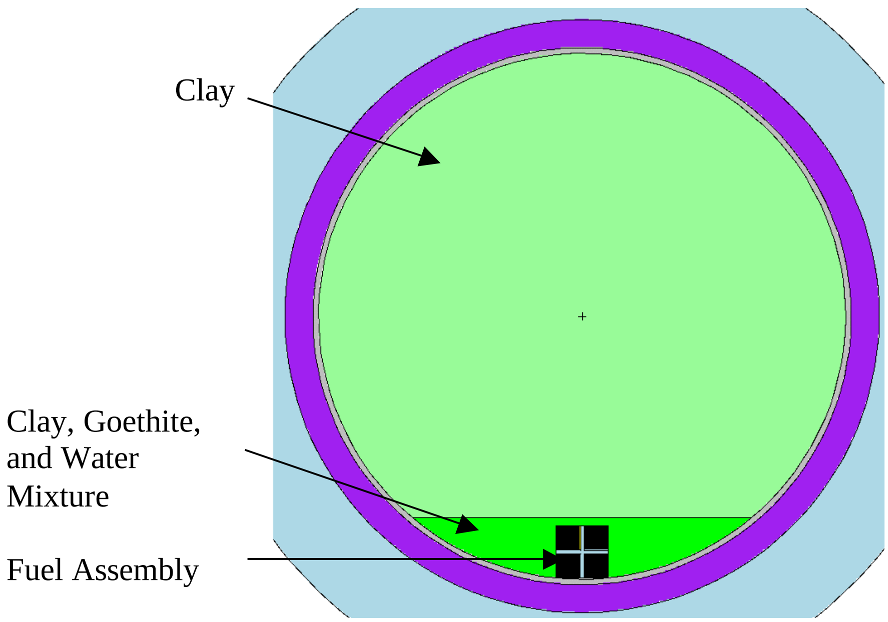

Fig. 4. Cross-sectional view of the intact fuel assembly in the degraded waste package.

TABLE II

Results for Intact Fuel Assembly with Degraded Canister and Degraded Waste Package

Goethite Fraction	Clay Fraction	Water Fraction	k_{eff}	σ	$k_{eff} \pm 2\sigma$
1.0[a]	0.0	0.0	0.9058	0.0010	0.9078
1.0[b]	0.0	0.0	0.8883	0.0011	0.8905
0.9	0.05	0.05	0.9034	0.0010	0.9054
0.7	0.00	0.3	0.9011	0.0010	0.9031
0.7	0.15	0.15	0.9039	0.0011	0.9061
0.7	0.30	0.0	0.9108	0.0010	0.9128
0.5	0.25	0.25	0.8999	0.0011	0.9021
0.3	0.35	0.35	0.8876	0.0011	0.8898
0.1	0.45	0.45	0.8881	0.0010	0.8901
0.0	1.0	0.0	0.9198	0.0011	0.922
0.0	0.0	1.0	0.9067	0.0010	0.9087

[a] Region above goethite filled with clay.
[b] Region above goethite filled with water.

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