7. INTACT AND DEGRADED CRITICALITY ANALYSES

7.1 USE OF COMPUTER SOFTWARE

The Monte Carlo code, MCNP, Version 4B2, is used to calculate the effective multiplication factor of the waste package. This code identified as CSCI 30033 V4B2LV was obtained from SCM in accordance with appropriate procedures, and is qualified as documented in the SQR for the MCNP, Version 4B2 (CRWMS M&O 1998i).

7.2 DESIGN ANALYSIS

The calculation method used to perform the criticality calculations consisted of using the MCNP Version 4B2 code (LANL 1997) to calculate the k_{eff} for various geometrical configurations of FFTF fuel in the 5-HLW/DOE SNF Long waste package. The k_{eff} results represent the average combined collision, absorption, and track-length estimator from the MCNP calculations. The standard deviation represents the standard deviation of k_{eff} about the average combined collision, absorption, and track-length estimate due to the Monte-Carlo-calculation statistics. The calculations are performed using continuous energy cross-section libraries that are part of the qualified MCNP code system (CSCI 30033 V4B2LV). All calculations are performed with fresh-fuel isotopics (Assumption 2.3.5.1).

The issue of minor actinides, which are fast-fissionable and non-fissile, is investigated. The critical mass of Np-237 moderated and reflected by granite is 45,000 g, and that for Am at 10,000 years is 78,900 g (ORNL 1978). The DOE SNF canister with either six assemblies or five assemblies and an Ident-69 pin container has a total of approximately 720 g Np-237 and 804 g Am-241, as a result of 150 MWd/kg exposure and decay of all Pu-241 into Np-237 (Bergsman 1994). Due to these very low quantities (less than 2% of required minimum critical mass), these minor actinides do not present a potential for criticality, and therefore, have not been included in the criticality calculations.

7.3 CALCULATIONS AND RESULTS – PART I: INTACT CRITICALITY ANALYSIS

A detailed description of the Monte Carlo representations, the method of solution, and the results are provided in CRWMS M&O (1999e). Results for the intact criticality analysis are derived from two cases: one with an Ident-69 pin container in the center position of the basket inside the DOE SNF canister (see Figures ES-1 and 2-4), and the other, with a DFA in the center position (see Figure 7-1). In all cases, the other five positions in the basket contain DFAs. When the DOE SNF canister basket is doped with Gd, the amount of Gd is given in terms of the weight percent of the DOE SNF canister basket with 1% corresponding to 3.852 kg of Gd in the basket.

In this section, the criticality analyses for intact configurations are discussed. Although the components (pins, cladding, assembly, and DOE SNF canister) are considered structurally intact, water intrusion into the components is allowed to determine the highest k_{eff} resulting from optimum moderation.

First, the most reactive assemblies based on the fuel type and optimum moderation are determined. Optimal spacing and optimum number of fuel pins in an Ident-69 pin container are also determined for configurations that involve an Ident-69 pin container. Then, the DOE SNF canister configurations containing either six DFAs or five DFAs and an Ident-69 pin container are analyzed with respect to optimum moderation by assuming complete or differential flooding. Optimum positions are also determined by changing the positions of the assemblies, the Ident-69 pin container, and the DOE SNF canister. Due to the long time periods considered in degraded calculations, the decay of plutonium isotopes must be considered. Pu-239 decays to U-235 with a half-life of 24,100 years (Parrington et al. 1996, pp. 48, 49). Pu-240 decays to U-236 with a half-life of 6,560 years. Pu-241 decays to Np-237 with an effective half-life of 447.1 years. The k_{eff} of the system changes because of Pu-240 absorber decay and Pu-239 fissile decay. Therefore, the nuclide contents are modified to account for the plutonium decay effects in order to identify the most reactive isotopic composition. After scoping calculations, 0 years; 24,100 years; 48,200 years; and 241,000 years are selected as the time steps at which the plutonium decay effects are investigated. At 24,100 years, approximately 92% of the Pu-240 has decayed to U-236, practically all Pu-241 has decayed to Np-237, and only 50% of the Pu-239 has decayed to U-235. At 48,200 years, more than 99% of the Pu-240 has decayed to U-236, practically all Pu-241 has decayed to Np-237, and 75% of the Pu-239 has decayed to U-235. At 241,000 years, more than 99.9% of the Pu-239 has decayed to U-235 and all other plutonium isotopes are essentially zero. The final configurations that result in k_{eff} greater than the established interim critical limit of 0.93 are further analyzed to determine the minimum amount of absorber required to reduce the k_{eff} below the interim critical limit.

7.3.1 Determination of Most Reactive Assemblies

Several comparison calculations are performed to determine the type of fuel elements that results in the highest k_{eff}. Types 3.2 and 4.1 DFAs (see Table 2-4) are compared because they contain the lowest and the highest fissile loading of the four DFA types, respectively. The results show that the Type 4.1 DFAs are more reactive and result in approximately 4% higher k_{eff} than the Type 3.2 DFAs (CRWMS M&O 1999e, p. 19). Therefore, Type 4.1 DFAs are used for the remainder of the analyses.

Water intrusion into the fuel pins was also investigated. Based on the calculation results, it was concluded that water intrusion into the fuel pins causes a 2% increase in k_{eff} (CRWMS M&O 1999e, Table 6-13). Therefore, all fuel pins are modeled with water occupying all void spaces inside the fuel pins.

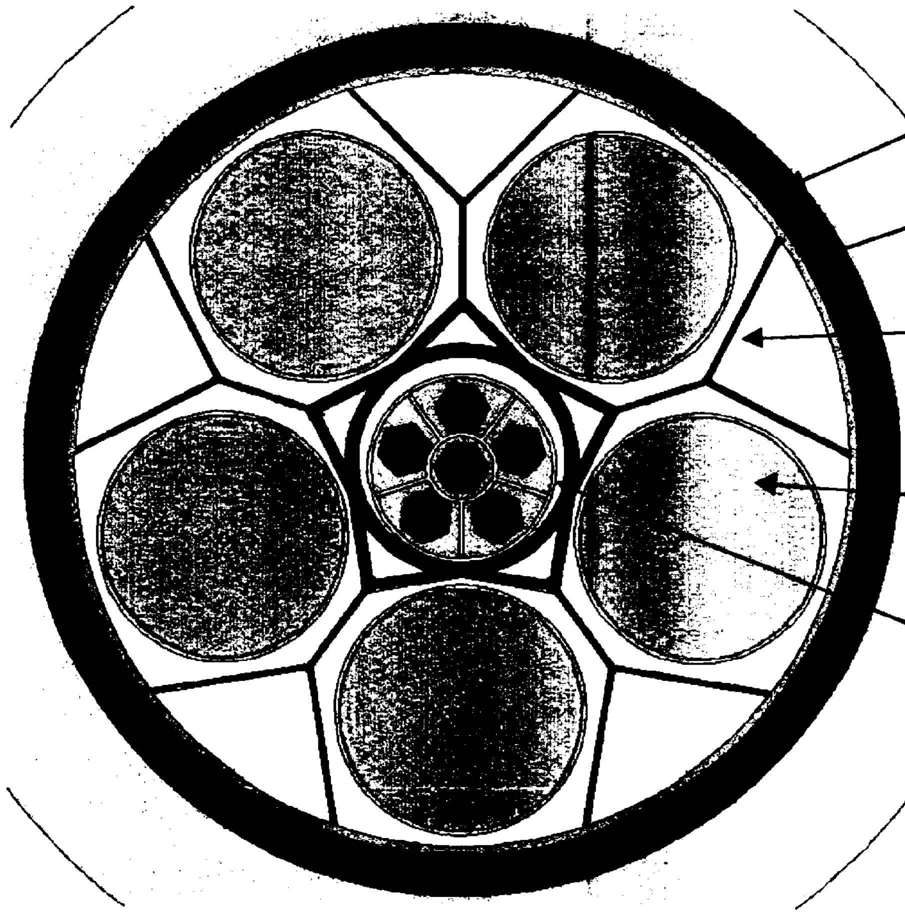


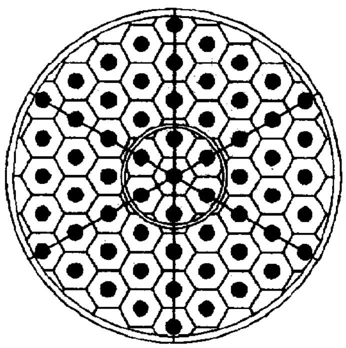
Figure 7-1. Cross Section of 5-HLW/DOE SNF Long Waste Package with Six DFAs

7.3.2 Optimal Spacing and Optimum Number of Fuel Pins in an Ident-69 Pin Container

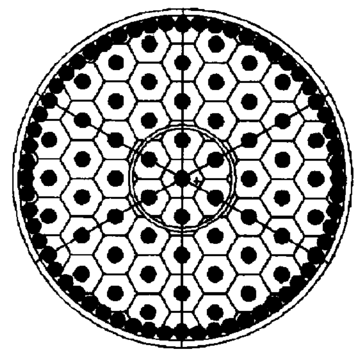
Due to the variety of loading possibilities and varying number of pins in the Ident-69 pin containers, a bounding Ident-69 pin container configuration has to be determined. The Ident-69 pin container is analyzed with respect to the optimal number of fuel pins and the optimal spacing between fuel pins. The array shape is also varied between hexagonal and square.

The pins are placed in the array with uniform spacing filling the entire Ident-69 container, neglecting the inner duct (center tube) of the Ident-69 container. The container is analyzed as fully flooded. The highest $k_{eff} + 2\sigma$ of 0.7222 is obtained with a pitch of 1.25 cm with equivalent total number of fuel pins of approximately 109 (including partial pins) in a hexagonal array (CRWMS M&O 1999e, Table 6-8). This uniform array is used to demonstrate that the interim critical limit of 0.93 is met and is shown in Figure 7-2a.

An extremely conservative alternate configuration involves a nonuniform distribution of pins in the Ident-69 pin container. In this configuration, the Ident-69 pin container with the uniform array of pins is modified to include a ring of fuel pins around the inside perimeter of the Ident-69 pin container as shown in Figure 7-2b. This most reactive case has 60 pins around the outer edge of the container plus six pins placed just outside the inside duct with a total of 145 fuel pins and a k_{eff} + 2σ of 0.7321 (CRWMS M&O 1999e, Table 6-9). This Ident-69 pin container with optimum number of pins in a uniform array with a ring of fuel pins around the inside perimeter of the container is referred to as the reflected array Ident-69 pin container in this document. This configuration is used for comparison and sensitivity analysis, but not in demonstration that the interim critical limit of 0.93 is met.



(a)
Uniform array



(b)
Reflected array

Figure 7-2. Fuel Pin Configuration for Ident-69 Pin container Representations

The reflected array Ident-69 container with a k_{eff} + 2σ of 0.7321, is then modeled in the basket of the DOE SNF canister surrounded by five DFAs. Since the basket and additional fuel is being placed around the Ident-69 container, the spacing of the fuel pins inside the Ident-69 container must be varied to determine if a significantly more reactive configuration can be found. The results show that k_{eff} is essentially constant for values of the pitch ranging from 1.40 to 1.60 cm (recall that the original pitch is 0.72644 cm), and decreases as the pitch decreases with a maximum k_{eff} + 2σ of 0.9343 for a pitch of 1.4 cm (CRWMS M&O 1999e, Table 6-11). This configuration did not include any Gd.

7.3.3 Optimum Moderation in the Waste Package and DOE SNF canister

If the waste package internal space (excluding all components such as HLW canisters and DOE SNF canister) is void instead of being flooded with water, the k_{eff} is approximately 1% higher (CRWMS M&O 1999e, Table 6-13). This is due to the fact that the carbon steel support tube acts as a reflector when the waste package internal space is void. When this space is flooded, the water slows the neutrons down, thereby increasing the absorption of neutrons in other waste package components such as the basket.

The effect of differential flooding in the Ident-69 pin container, the DOE SNF canister, and the waste package (CRWMS M&O 1999e, Table 6-16) (i.e., only the Ident-69 pin container, only the DOE SNF canister, or only the waste package is flooded) is also investigated by changing the density of the water from 0 g/cm^3 (void) to 1 g/cm^3 (flooded) gradually in these components. The results indicated that flooding (water at 1 g/cm^3 density) the Ident-69 pin container increases k_{eff} by approximately 16% (CRWMS M&O 1999e, Table 6-17) and flooding the DOE SNF canister increases k_{eff} by approximately 18% (CRWMS M&O 1999e, Table 6-18). Therefore, in all configurations in the following sections the Ident-69 pin container, the assemblies, and the DOE SNF canister are modeled as being flooded whereas the waste package internal cavity space is modeled as void.

7.3.4 DOE SNF Canister in the Waste Package

The center position of the basket contains either a DFA or an Ident-69 pin container. The DOE SNF canister is placed in the center position in the waste package and is surrounded by five HLW glass canisters as shown in Figure 7-1. Cases are investigated where the canister is either centered in the waste package or offset from the center to account for settling due to gravity. This change in canister position has no effect on the k_{eff} of the system (results are within 1σ). Also varying levels of flooding and different spacings (between assemblies in outer basket positions and either an Ident-69 or another assembly occupying the inner basket position) are investigated. In all cases, even though the environment outside the waste package, whether tuff, water, or a mixture, has no significant impact on the configuration k_{eff}, the waste package is water reflected. The amount of outgoing neutrons penetrating the waste package barriers is less than 1% of the total number of neutrons in the system; and typically less than 0.2% based on the evaluation of the neutron activity reported in the outputs. When the factor of four attenuation through the waste package barriers is factored in, even mirror reflection of these neutrons would have no statistically significant effect. Hence, having a different reflector (e.g., tuff, rock, clay, etc.) on the outside of the waste package would have negligible or no effect on the results.

The maximum $k_{eff} + 2\sigma$ for six DFAs is 0.908 (CRWMS M&O 1999f, Table 6-21). This k_{eff} is obtained when fuel pins, fuel assemblies, and the DOE SNF canister are flooded and the plutonium isotopes are decayed for 48,200 years, which corresponds to two half-lives of Pu-239 isotope. The analysis of the results indicates that for the intact criticality configurations the k_{eff} increases by as much as 5% after approximately 48,200 years of plutonium decay. No Gd was required for this configuration.

The maximum $k_{eff} + 2\sigma$ for five DFAs and a reflected array Ident-69 pin container is 1.001 with the plutonium isotopes decayed for 48,200 years, and no Gd in the DOE SNF canister basket (CRWMS M&O 1999f, Table 6-21). The maximum $k_{eff} + 2\sigma$ for five DFAs and a uniform array Ident-69 pin container is 0.894 (CRWMS M&O 1999f, Table 6-21). This k_{eff} is obtained when the fuel pins, the fuel assemblies, the uniform array Ident-69 pin container, and the DOE SNF canister are flooded, the plutonium isotopes are decayed for 48,200 years, and 0.5 wt% (1.93 kg) Gd uniformly distributed in the DOE SNF canister basket.

7.3.5 Summary

In this section the worst-case configurations are determined for intact criticality. The worst-case configurations are obtained when the entire contents of the DOE SNF canister including fuel pins, assemblies, and the Ident-69 pin container, if present, are flooded and the waste package internal cavity is dry. The plutonium isotopes are also decayed to their daughter isotopes, which result in the highest k_{eff} after approximately 48,200 years. The results show that the configuration of six DFAs in the DOE SNF canister does not need any absorber in the basket or elsewhere in the waste package to achieve a $k_{eff} + 2\sigma$ of ≤ 0.93. For the cases that include an Ident-69 container and five DFAs, 0.5 wt% (1.93 kg) Gd must be uniformly distributed on (e.g., flame deposit), or in, the entire DOE SNF canister basket to achieve a $k_{eff} + 2\sigma$ of ≤ 0.93.

7.4 CALCULATIONS AND RESULTS – PART II: SCENARIOS WITH FISSILE MATERIAL RETAINED IN DOE SNF CANISTER

A detailed description of the Monte Carlo representations, the method of solution, and the results are provided in CRWMS M&O (1999f). From the intact configuration results discussed in Section 7.3, the presence of an Ident-69 pin container in the center position is shown to result in higher k_{eff} than the presence of a DFA. Therefore, the focus of degraded calculations is on the configurations including an Ident-69 pin container in the center position. Results from the calculations for the partial degradation in the DOE SNF canister can be divided into three general categories depending upon the level of degradation of the fuel components. The categories are defined as follows: partially degraded DFAs and an intact Ident-69 pin container; completely degraded DFAs and an intact Ident-69 container; and DFAs and an Ident-69 container, both completely degraded. In the first two categories, the basket may or may not be intact. However, in the third category, the entire contents of the (intact) DOE SNF canister are degraded, including the basket. Additional calculations are performed with the center position of the basket of the DOE SNF canister containing a DFA rather than an Ident-69 container.

In the configurations investigated in this section, the waste package carbon steel basket and the HLW glass canisters are considered intact. Degradation inside the DOE SNF canister, which is stainless steel Type 316L, is extremely unlikely while the waste package carbon steel basket remains intact. However, the calculations indicate that the position of the DOE SNF canister in the waste package (centered in the clay that would form from the degradation of the waste package basket and HLW glass, or at the bottom against the inner barrier) has no effect on k_{eff} since the results are within statistical uncertainty (CRWMS M&O 1999f, Table 6-18 and CRWMS M&O 1999g, Table 6.1-1).

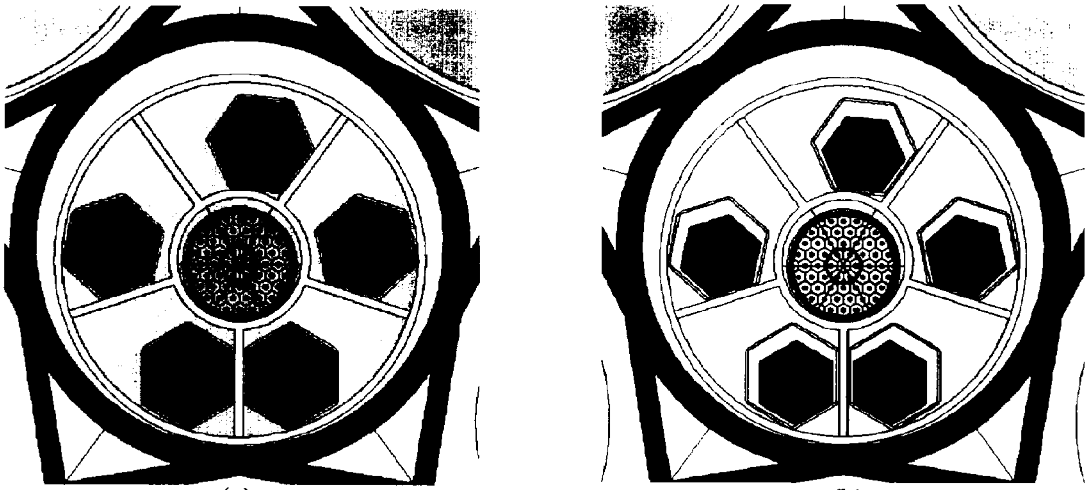
In analyzing the configurations described above, parametric studies have been performed to determine the optimum moderation and configuration. These parametrics include optimizing the moderation in the DOE SNF canister by varying the amount of water in the degradation products, and by varying the density of water in the degradation products; varying the amount of absorbers (both Gd and Fe_2O_3); and varying the position of remaining intact elements (e.g., the fuel pins, the Ident-69 pin container, etc.). The plutonium decay effects due to long times considered in performing the criticality calculations are also determined. As explained in Section 7.3, all configurations are analyzed with respect to the plutonium decay effects at 0 years, 24,100 years, 48,200 years, and 241,000 years.

Some of the configurations in the following sections include an intact Ident-69 pin container while all other DOE SNF canister components and all DFAs are degraded. The configurations with an intact Ident-69 pin container are the most reactive configurations. Although the water intrusion into the DOE SNF canister will cause some degradation in the Ident-69 pin container shell, due to its position in the canister it is possible that the Ident-69 pin container will stay intact longer than all other components inside the DOE SNF canister. The Ident-69 pin container resides in a 10 mm thick stainless steel Type 316L tube, which is the central section of the DOE SNF canister basket. The maximum clearance between the DOE SNF canister basket and this tube is 11.7 mm when the waste package is horizontally emplaced. The average clearance is 5.85 mm. After water intrusion into the DOE SNF canister and therefore into this clearance space, the outside of the Ident-69 pin container and the inside wall of this center tube will corrode. The corrosion products (FeOOH and/or Fe_2O_3) will take more space, since they have a lower density, by expanding into the clearance space between the DOE SNF canister basket center tube and the Ident-69 pin container. This may exclude water from the clearance space and stop the corrosion in between the center tube and the Ident-69 pin container. This may create an approximately 19 mm thick shell that is composed of the center tube, corrosion layer, and the Ident-69 pin container. This thick shell may take longer to degrade, thereby allowing the fuel pins inside the Ident-69 pin container to stay in their most reactive configuration longer than all other DOE SNF canister components and DFAs.

In the description of the configurations, the term "degraded fuel" is used generically to represent the degradation products of the fuel.

7.4.1 Degradation Inside the DFAs

The effect of degraded fuel pin clips/spacers in the DFAs is calculated by varying the fuel pin pitch. Only reduction of fuel pin pitch is considered in the analyses, as there are no known physical mechanisms for expanding the pitch. This configuration has five DFAs and a reflected array Ident-69 pin container as shown in Figure 7-3a. The pitch is held uniform within the DFAs in all cases and the pins inside the Ident-69 pin container remain intact. This configuration is described in Section 6.2.1.1 and corresponds to the configuration class 3. As the spacing between the fuel pins decreases, the k_{eff} decreases – with the original pitch of the DFA being the most reactive. Reducing the pitch decreases the k_{eff} by as much as 10%. The maximum $k_{eff} + 2\sigma$ of the system is 0.8950 with the original pitch and 0.1% Gd (0.381 kg) in the DOE SNF canister basket (CRWMS M&O 1999f, Table 6-1).



(a) Degraded fuel pin clips/spacers

(b) Partially degraded fuel pin cladding

Figure 7-3. Degradation Inside the DFAs

The effect of partially degraded fuel pin cladding in the DFAs is analyzed with a parametric on the fuel pin pitch. This configuration involves five DFAs and a reflected array Ident-69 pin container as shown in Figure 7-3b. The fuel pins remain radially separated while the cladding thickness is reduced since goethite sludge surrounds the pins and takes the place of the cladding. The volume fraction of water in the sludge determines the separation between the fuel pins. The maximum volume fractions of water considered for each fraction of remaining cladding correspond to the original pin pitch for the DFAs. The plutonium decay effects are investigated at four decay times described in Section 7.3. Cladding degradation increases k_{eff} by as much as 3%. The maximum $k_{eff} + 2\sigma$ with 0.1% (0.381 kg) Gd in the DOE SNF canister basket is 0.9592 after approximately 48,200 years of plutonium radioactive decay (CRWMS M&O 1999f, Tables 6-2 and 6-20). (Note that the difference in $k_{eff} + 2\sigma$ between this configuration and the configuration described in previous paragraph appears to be more than 3%. This is due to the plutonium decay effects, which are taken into account for this configuration only). The minimum required Gd content for this configuration was identified as 2% (7.62 kg) to reduce the maximum $k_{eff} + 2\sigma$ to 0.9222.

A parametric study on pellet axial spacing is performed by analyzing the fuel pellets dispersed in the goethite sludge, which is formed from the complete degradation of the fuel pin cladding. The maximum radial separation for the pellets is assumed to be the same as for the fuel pin spacing of an intact DFA. The water volume fraction in the sludge is varied to give differing pellet separations. This configuration involves five DFAs and a uniform array Ident-69 pin container as shown in Figure 7-4. The results show that an axial separation of 1 cm and a radial separation of 0.72644 cm (original pitch) give the highest k_{eff}. The configurations with 2% (7.62) Gd in the entire basket, and five DFAs and a uniform array Ident-69 pin container (intact) result in a maximum $k_{eff} + 2\sigma$ of 0.8977 after 48,200 years of plutonium decay (CRWMS M&O 1999f, Section 6.1.3 and Table 6-20). The configurations with 2% (7.62 kg) Gd in the entire basket and six DFAs result in a maximum $k_{eff} + 2\sigma$ of 0.8810 after 48,200 years of plutonium decay

(CRWMS M&O 1999f, Table 6-20). The results corresponding to different times for six DFAs, and five DFAs and a uniform array Ident-69 pin container are shown in Figure 7-5.

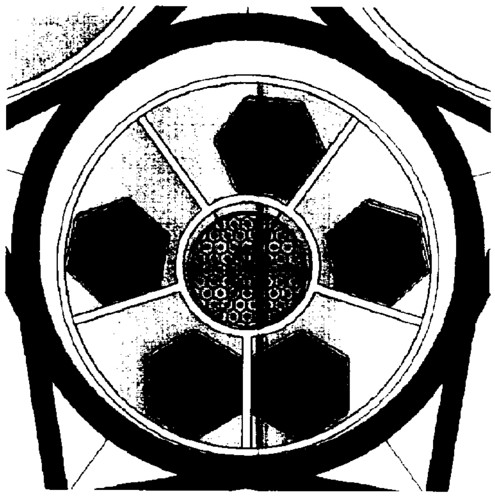


Figure 7-4. Axially Separated Fuel Pellets Inside the DFAs with Reflected Array Ident-69 Pin Container

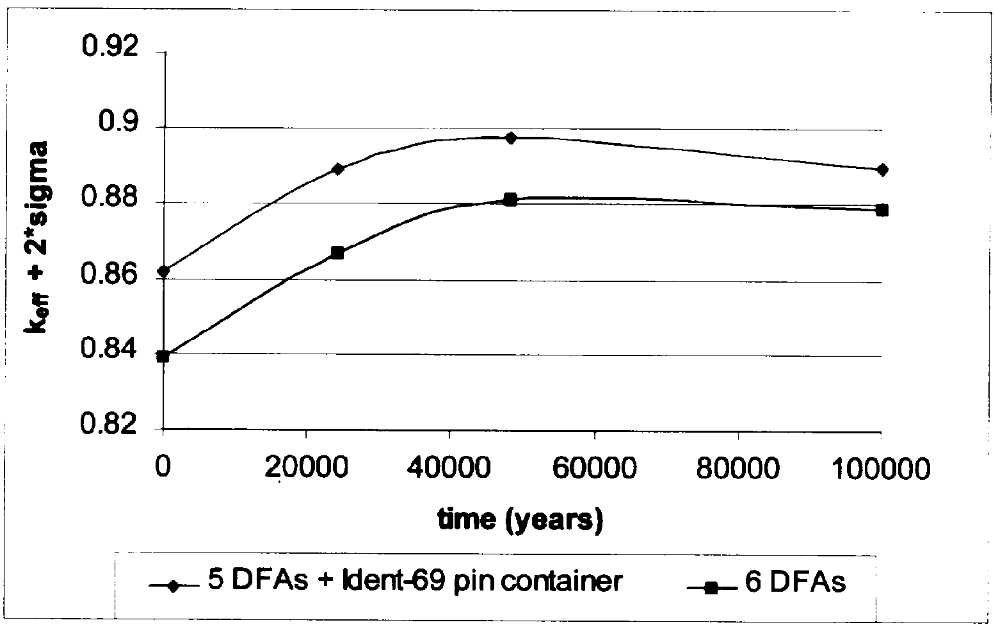
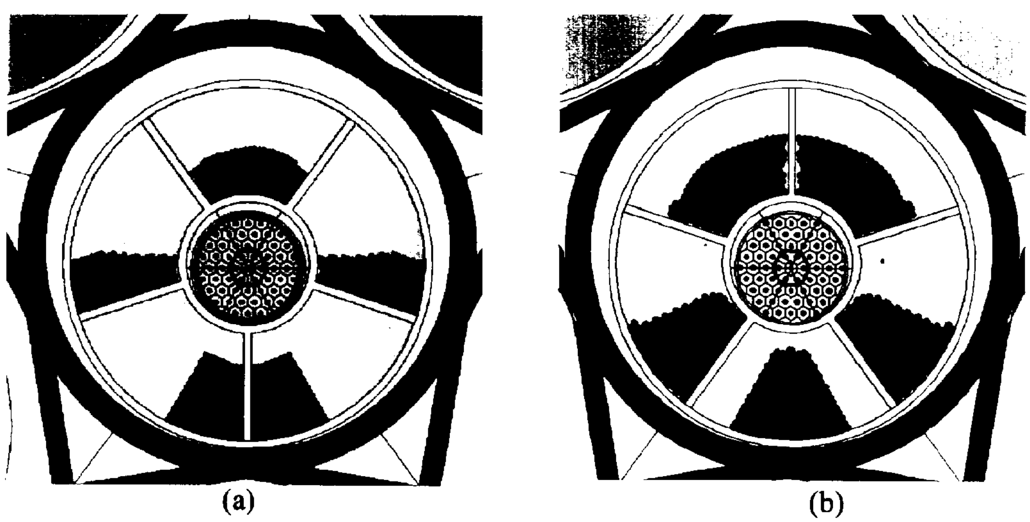


Figure 7-5. Plutonium Decay Effects for Six DFAs and Five DFAs and a Uniform Array Ident-69 Pin Container

7.4.2 Degraded DFA Ducts

These analyses consider loose pins settling in each position of the basket as a result of the degradation of the assembly ducts and fuel pin clips/spacers. Since the assembly duct is eight times as thick as the cladding, this is an unlikely configuration. This configuration has five DFAs and a reflected array Ident-69 pin container as shown in Figure 7-6a. The orientation of the DOE SNF canister is also varied. The placement of fuel pins in the DOE SNF canister basket is either irregular (triangular and square array) or random to account for the pins having fallen from a DFA. This configuration is described in Section 6.2.1.1, and corresponds to the configuration class 3. The results show that the maximum $k_{eff} + 2\sigma$ is 0.9167 after 48,200 years of plutonium decay (CRWMS M&O 1999f, Tables 6-5 and 6-20). The minimum amount of Gd required is 0.1% (0.3811 kg) of the DOE SNF canister basket.

The effects of degradation of fuel pin cladding and axial separation of fuel pellets with degraded fuel pin clips/spacers, and degraded assembly ducts are also analyzed. This configuration has five DFAs and a uniform array Ident-69 pin container as shown in Figure 7-6b. Individual fuel pellets are placed in each of the positions of the intact basket. The corrosion products from the ducts would be expected to surround the fuel pellets but are neglected for these cases. The degradation products from the cladding surround the fuel pellets, which are assumed to be axially aligned, and separate the pellets in the radial direction depending on the volume fraction of water in the sludge. In no case is this separation greater than that of the fuel pins in the intact DFA. The plutonium decay effects are investigated at four decay times. The results show that an axial separation of 0.6 cm and completely degraded fuel pin cladding with the original pitch produces the largest value of k_{eff} after 48,200 years of plutonium decay. The minimum amount of Gd required is 3% (11.43 kg) in the entire DOE SNF canister basket, and the maximum $k_{eff} + 2\sigma$ is 0.9295 with 3% (11.43 kg) Gd. If one of the DFAs is removed, the maximum $k_{eff} + 2\sigma$ is 0.8843 with 2% (7.62 kg) Gd (CRWMS M&O 1999f, Tables 6-6 and 6-20).



(a) (b)

Figure 7-6. Degraded Assembly Ducts Inside Intact DOE SNF Canister Basket

7.4.3 Degraded Basket and Intact SNF

The cases where the basket is fully degraded with all other fuel components intact are analyzed. This configuration is not considered credible, as the basket structure is approximately three times thicker than the assembly ducts and the Ident-69 container. The DFA ducts and the Ident-69 container will naturally degrade before the basket structure. These cases are presented to provide insight into the role of the Ident-69 container and the measures that can be taken to mitigate the contribution of the Ident-69 container to the overall reactivity of the system. In these cases, the DFAs and the Ident-69 container or the center DFA are at the bottom of the DOE SNF canister and the degradation products, with varying water volume fractions, are settled around the fuel components. The cases with six DFAs in the DOE SNF canister as well as the cases with an Ident-69 container with a uniform array of pins surrounded by five DFAs are analyzed. This configuration is described in Section 6.2.1.2 and corresponds to the configuration class 1.

The results support the conclusion that the Ident-69 pin container is driving the system neutronically, and that the Gd placed in the DOE SNF canister is not very efficient when all DFAs and the Ident-69 pin container are close enough to touch each other, since the interaction between the DFAs and the Ident-69 pin container is mostly through fast neutrons (CRWMS M&O 1999f, Tables 6-7 and 6-20). The $k_{eff} + 2\sigma$ for the system with a uniform array Ident-69 pin container surrounded by five DFAs is 0.9272. The minimum amount of Gd required for this configuration is 4% (15.24 kg).

7.4.4 Intact Fuel Pins in DOE SNF Canister with Degraded Basket and Assembly Ducts

The results for intact fuel pins with a degraded basket, degraded assembly ducts, and degraded fuel pin clips/spacers are analyzed. Fuel pins surround the uniform array Ident-69 container, if present, and the minimum distance between the outer edge of the Ident-69 container and the DOE SNF canister is varied. This configuration is described in Section 6.2.1.2 and corresponds to the configuration class 1. This configuration is shown in Figure 7-7. The results show that 2% (7.62 kg) Gd is sufficient to reduce the $k_{eff} + 2\sigma$ below 0.93 (CRWMS M&O 1999f, Section 6.1.7).

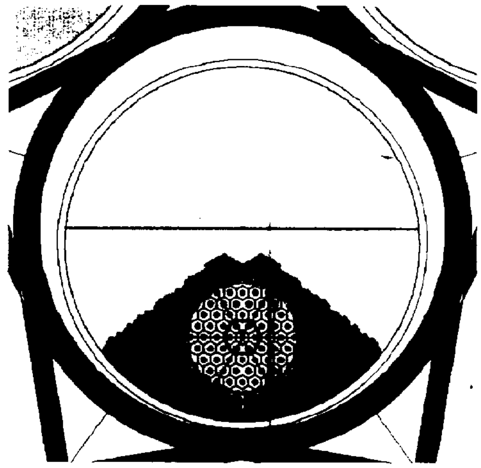


Figure 7-7. Intact Fuel Pins in DOE SNF Canister with Degraded Basket and Assembly Ducts

7.4.5 DOE SNF Canister Containing an Intact Ident-69 Container and Five Degraded DFAs

As described in Section 7.4, the Ident-69 pin container may stay intact long after all DFAs and the DOE SNF canister basket are degraded. The effect of intact versus degraded Ident-69 pin container is analyzed. The results show that the waste package with completely degraded DFAs is the most reactive when the Ident-69 pin container is intact (CRWMS M&O 1999f, Tables 6-11 and 6-12).

The effect of components outside the DOE SNF canister is investigated by neglecting the waste package (thereby neglecting the waste package basket and HLW canisters). The results indicate that the intact waste package configurations result in approximately 2% higher k_{eff} (CRWMS M&O 1999f, Tables 6-11 and 6-14). As indicated in Section 7.4, the degradation of the stainless steel DOE SNF canister internal components before the carbon steel waste package basket structure is extremely unlikely.

The effect of degraded fuel slurry length, which is along the length of the DOE SNF canister, on the k_{eff} is investigated for the configurations with and without Gd at four plutonium radioactive decay times. The results indicate that if the basket contains Gd then the shorter fuel slurries are more reactive, whereas if the basket contains no Gd the longer slurries are more reactive (CRWMS M&O 1999f, Section 6.1.9). The maximum $k_{eff} + 2\sigma$ is 0.9209 with 2.5% (8.45 kg) Gd in the DOE SNF canister basket after 48,200 years of plutonium decay (CRWMS M&O 1999f, Tables 6-11 and 6-20). The $k_{eff} + 2\sigma$ is 0.9333 with 2.0% (6.76 kg) Gd.

The configurations for a DOE SNF canister containing an intact uniform array Ident-69 container and degraded fuel from the DFAs are further analyzed. The DOE SNF canister is placed in the intact waste package. The configuration is shown in Figure 7-8. These configurations are described in Section 6.2.1.2 and correspond to the configuration class 1. The fuel in the Ident-69 container is centered in the fuel slurry, which is 0.9144 m (3 ft) long and exactly aligns with the fuel slurry from the DFAs. The Ident-69 pin container centered in the fuel slurry (densities are similar) results in the highest k_{eff} (CRWMS M&O 1999f, Table 6-14). A range of values of goethite volume fractions from 0.746 to 0.472 is investigated. The larger values of volume fraction are greater than the represented maximum of 0.6 and show the sensitivity of the results to this value, whereas the smallest value corresponds to a sludge volume that radially fills the DOE SNF canister for the length of the fuel slurry. The results indicated that larger goethite volume fractions result in higher k_{eff} (CRWMS M&O 1999f, Table 6-14).

A search on optimum moderation in the sludge was also performed. The worst-case identified in the previous paragraph was used as the starting point. The effect of water content in the degraded fuel sludge and in the goethite adjacent to the fuel is determined by again considering the case with the Ident-69 container centered in the fuel sludge and varying the amount of water in the degraded fuel mixture and in the adjacent goethite mixture. The remaining volume fraction within the fuel is treated as void. The results show that water content in the fuel sludge and in the goethite adjacent to the fuel affects the k_{eff} by as much as 2%, and the optimum moderation is achieved with water at 1 g/cm^3 density in the sludge to fill the entire DOE SNF canister (CRWMS M&O 1999f, Table 6-16). The worst-case in this set is, therefore, the same as the worst-case that was used as the starting point.

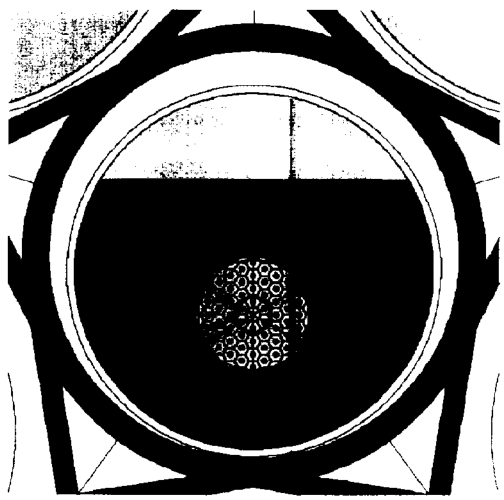


Figure 7-8. Intact Ident-69 Container and Five Fully Degraded DFAs

7.4.6 DOE SNF Canister Containing a Degraded Ident-69 Container and Five Degraded DFAs in the Waste Package

Results for a fully degraded Ident-69 container that holds various numbers of fuel pins (maximum 217 fuel pins) and five degraded DFAs are analyzed. The degraded Ident-69 pin container with 217 fuel pins is equivalent to a degraded DFA; therefore, this configuration also covers the DOE SNF canister with six completely degraded DFAs. These results are for a 0.9144 m (3 ft) fuel slurry and a basket that contains 2% Gd (7.62 kg). The space not occupied by fuel slurry or goethite in the DOE SNF canister is filled with water at 1 g/cm^3 density. The goethite volume in the fuel sludge is varied from 60% to a low of 45.71% corresponding to a volume that radially fills the DOE SNF canister for a 0.9144 m (3 ft) length. Vacant space in the waste package is treated as a void. The waste package is fully reflected by water. This configuration is described in Section 6.2.1.2 and corresponds to the configuration class 1. The configuration is shown in Figure 7-9. The results show that the highest $k_{eff} + 2\sigma$ is 0.920 with 217 fuel pins in the Ident-69 pin container, 45.71% goethite volume fractions, and 2% (7.62 kg) Gd in the DOE SNF canister basket (CRWMS M&O 1999f, Section 6.1.10.2).

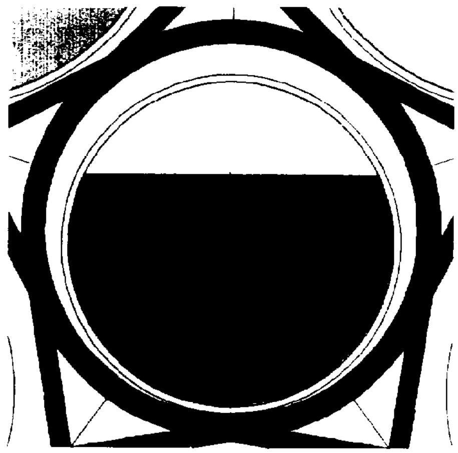


Figure 7-9. DOE SNF Canister Containing a Degraded Ident-69 Container and Five Fully Degraded DFAs

7.4.7 DOE SNF Canister Containing Degraded Fuel or Fuel Components with the Waste Package Contents Degraded

The contents of the waste package external to the DOE SNF canister are now analyzed as completely degraded. The contents of the DOE SNF canister are taken to be same as the most reactive case in Section 7.4.5. Recall that the most reactive case in Section 7.4.5 required 2.5% (8.45 kg) Gd in the DOE SNF canister basket and resulted in $k_{eff} + 2\sigma$ of 0.9209. The position of the DOE SNF canister in the clay formed from the HLW glass (HLW glass degrades to a clay like material, "clayey", that will be referred to simply as clay throughout this document) and the water content of that clay are the parameters that are varied. The plutonium decay effects are also investigated at four decay times described in Section 7.3. The position of the canister (center of the waste package versus bottom of the waste package) effects k_{eff} by less than 1% with the highest being the bottom position. The water volume in the clay does not affect the results since all results are within statistical uncertainty indicating that the clay is a good reflector with or without water (CRWMS M&O 1999f, Table 6-18).

The results indicate that even with 6% (20.28 kg) Gd in the DOE SNF canister basket, the $k_{eff} + 2\sigma$ is 0.9510 after 24,100 years of plutonium decay. Therefore, the number of DFAs needs to be reduced from five to four and 2.75% (9.29 kg) Gd needs to be added to reduce $k_{eff} + 2\sigma$ below the interim critical limit of 0.93. This configuration results in the highest $k_{eff} + 2\sigma$ of 0.9269 after 24,100 years of plutonium decay (CRWMS M&O 1999f, Tables 6-18 and 6-20). The results for different times are shown in Figure 7-10. These results also support the conclusion that the Ident-69 pin container is driving the system neutronically. This configuration is the limiting case driving the design/loading solution.

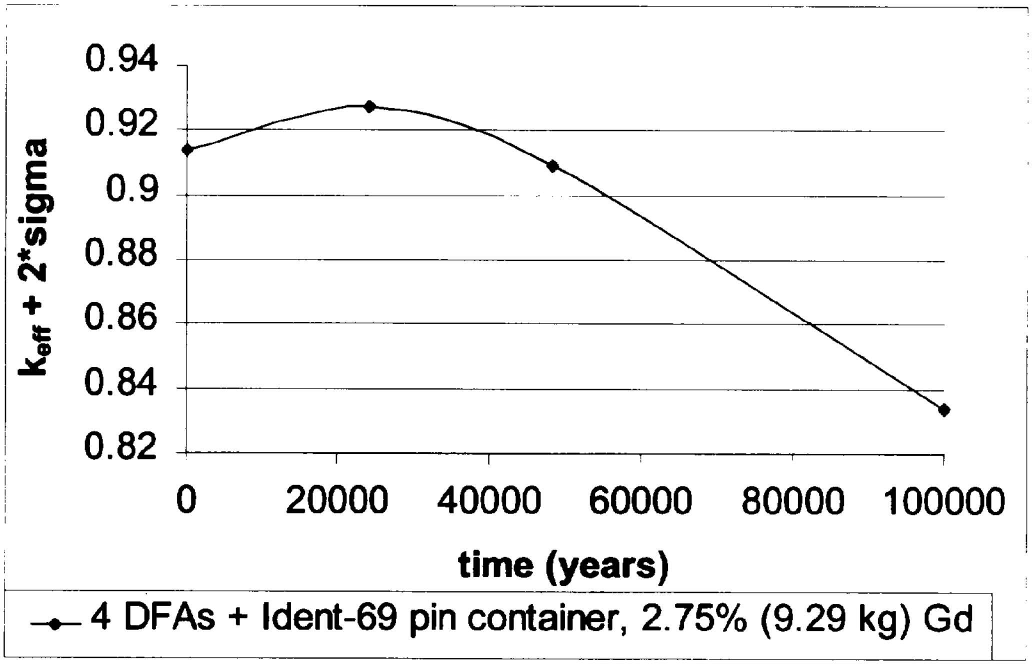


Figure 7-10. Plutonium Decay Effects for Four DFAs and a Uniform Array Ident-69 Pin Container

7.4.8 DOE SNF Canister with Degraded FFTF Fuel and Surrounded by Degraded HLW

In this section, the waste package with degraded HLW canisters and degraded SNF is analyzed. This configuration is described in Section 6.2.1.3 and corresponds to the configuration class 5. The DOE SNF canister shell is represented as being intact, and confines the SNF. The DOE SNF canister contents are completely homogenized and distributed inside the DOE SNF canister. This is different from the previous configurations in that the fuel length is not preserved during homogenization. Instead, the degraded FFTF fuel (equivalent fissile amount of six DFAs, which is the maximum amount in an FFTF DOE SNF canister) is distributed into the homogenized mixture axially and radially.

The effect of the position of the DOE SNF canister is investigated by placing the DOE SNF canister either in the middle or on the bottom of the waste package as shown in Figure 7-11. The amount of water in the clay, the amount of water in the fuel, the minimum amount of absorber required, and flooding in the DOE SNF canister are among the parameters that are varied.

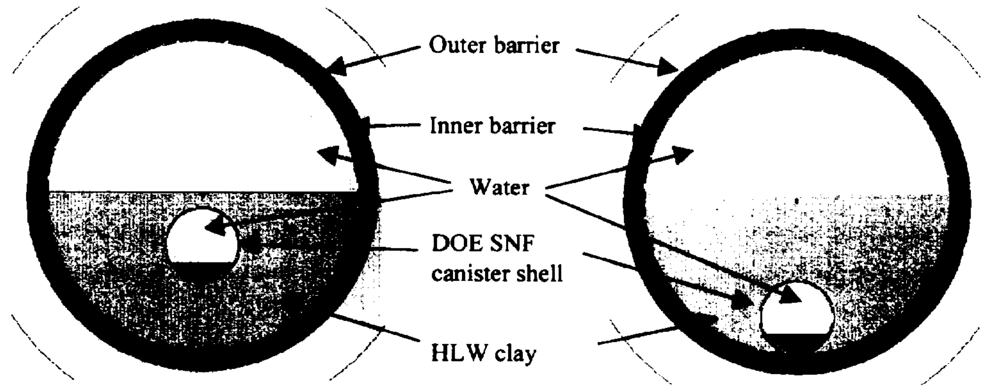


Figure 7-11. Cross-sectional View of the DOE SNF Canister Settled in the Middle and on the Bottom of the WP

7.4.8.1 Degraded FFTF Mixture in a Flooded DOE SNF Canister

In investigating the intact DOE SNF canister shell with the degraded FFTF fuel settled at the bottom of the flooded canister, the percentage of water in the clay (along with the volume of clay) is increased. The position of the DOE SNF canister in the waste package is also varied (Figure 7-11). The results show that the $k_{eff} + 2\sigma$ is less than 0.3 for all cases (CRWMS M&O 1999g, Section 6.1), and the position of the DOE SNF canister in the waste package has no effect on criticality (CRWMS M&O 1999g, Table 6.1-1 and CRWMS M&O 1999f, Table 6-18).

The next configuration investigated is an intact DOE SNF canister shell having degraded FFTF fuel located in the center of the waste package, with the FFTF fuel mixed with different amounts of water. The k_{eff} of a degraded waste package as a function of the amount of water in the hematite is investigated. In all of these cases, the clay is not diluted. Results of the variations show that the $k_{eff} + 2\sigma$ is less than 0.6 for all cases (CRWMS M&O 1999g, Section 6.1). In this configuration, the optimal moderation of the waste package is achieved when the fuel contains 50-65% by volume water.

7.4.8.2 Minimum Mass of Gd Required

If some of the main absorbers (Gd and Fe_2O_3) are lost, the k_{eff} of the waste package will increase. In the configurations investigated, some of the principal absorbers have been removed. Also the DOE SNF canister shell is intact in the middle of the waste package.

With all of the Fe_2O_3 remaining in the waste package, the minimal mass of Gd needed in the DOE SNF canister to meet the interim critical limit in such a configuration is 0.1% Gd (0.387 kg) (CRWMS M&O 1999g, Section 6.1). This configuration results in a $k_{eff} + 2\sigma$ of 0.9217. In the absence of Fe_2O_3, 2% (7.7 kg) Gd is required to be distributed in the DOE SNF canister. This configuration results in a $k_{eff} + 2\sigma$ of 0.6288 at time zero, which corresponds to the time of disposal (CRWMS M&O 1999g, Tables 6.1-3 and 6.4-1). If all the Gd is driven from the waste package and all the fuel are to remain in the DOE SNF canister, the interim critical limit may be exceeded. However, geochemistry results indicate that maximum Gd loss is less than 0.7% in 100,000 years (see Section 6.4). Therefore, this configuration is not a concern for criticality.

7.5 CALCULATIONS AND RESULTS – PART III: SCENARIOS WITH FISSILE MATERIAL DISTRIBUTED IN WASTE PACKAGE

A detailed description of the Monte Carlo representations, the method of solution, and the results are provided in CRWMS M&O (1999g). This section documents the criticality analyses that are performed for a degraded 5-HLW/DOE SNF Long waste package containing FFTF fuel in the DOE SNF canister. Sections 7.5.1 and 7.5.2 present the k_{eff} results for different scenarios in which the degradation external to the DOE SNF canister is investigated. These scenarios include the following: (1) the degraded DOE SNF canister on top of the degraded HLW; and (2) degraded HLW on top of degraded DOE SNF canister. Since all configurations consider completely degraded fuel, the worst-case is achieved with the maximum amount of fissile elements in the DOE SNF canister. This is obtained by assuming that all basket locations are filled with a DFA (a total of six DFAs).

In analyzing the configurations from the two scenarios described above, parametric studies have been performed to determine the optimum moderation and configuration. These parametrics include varying the amount of water in the clay and fuel layers, varying the density of water in the clay and fuel layers, varying the amount of absorbers (both Gd and Fe_2O_3), and varying the amount of clay mixed with the fuel layer. The bounding results are not dependent on the retention of the clay in the waste package, since the Fe_2O_3-fuel mixture with no clay is included. The plutonium decay effects due to long times considered in performing the criticality calculations are also determined.

7.5.1 Degraded DOE SNF Canister above Settled HLW Clay

This section describes the calculations that assume the HLW degrades and settles before the DOE SNF canister. The degraded HLW forms a clay material that is collected at the bottom of the waste package, and the degraded FFTF SNF deposits in a layer at the top of the clay material, as shown in Figure 7-12. This section also investigates the k_{eff} of the waste package for different degrees of hydration of both the FFTF SNF and the HLW clay layers (CRWMS M&O 1999g, Section 6.2). These configurations are described in Section 6.2.1.4 and correspond to the configuration class 5.

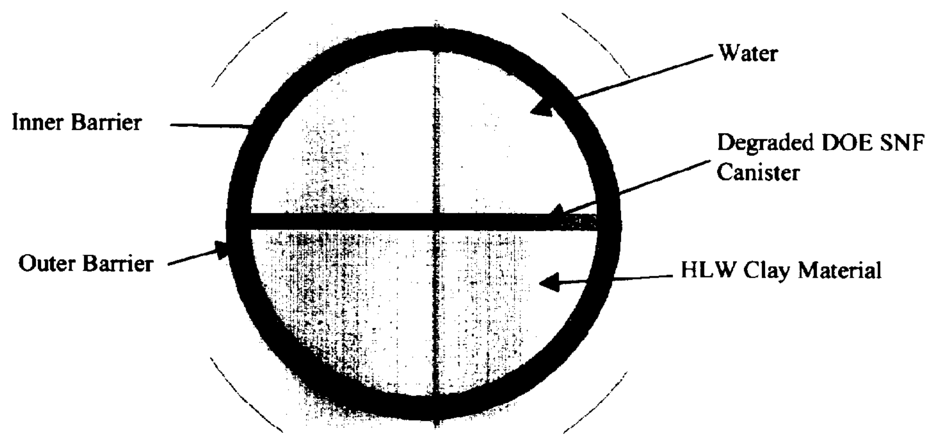


Figure 7-12. Degraded DOE SNF on Top of the Degraded HLW Glass Clay

The following configurations are investigated: the amount of water in the clay layer varies and the fuel is modeled with no free-water fraction; the amount of water in the FFTF SNF layer varies, the HLW clay material is modeled with no free-water (however, it does contain some hydrogen in the form of hydrates) to maximize the potential volume of the degraded FFTF fuel in the layer above the HLW clay; the HLW clay and the fuel layer fill the entire waste package so there is no void space (Figure 7-13) and the density of the water is varied within the clay and/or the fuel; the layer of fuel and the layer of HLW glass are mixed partially or totally as shown in Figure 7-14, any available void space in the waste package is flooded with water; the waste package contains a mixture of FFTF SNF, HLW, and water so that the inner volume of the waste package is filled. All these configurations are also investigated with respect to the plutonium decay effects at four decay times described in Section 7.3.

The results show that the $k_{eff} + 2\sigma$ of the configurations investigated are all below 0.5 with 2% (7.62 kg) Gd. When Gd is present, the k_{eff} of the system decreases as plutonium isotopes decay. In these configurations, even if all the Gd is driven out of the waste package, the $k_{eff} + 2\sigma$ of the system is still below the interim critical limit of 0.93 with a maximum of 0.9025 after 24,100 years of plutonium radioactive decay.

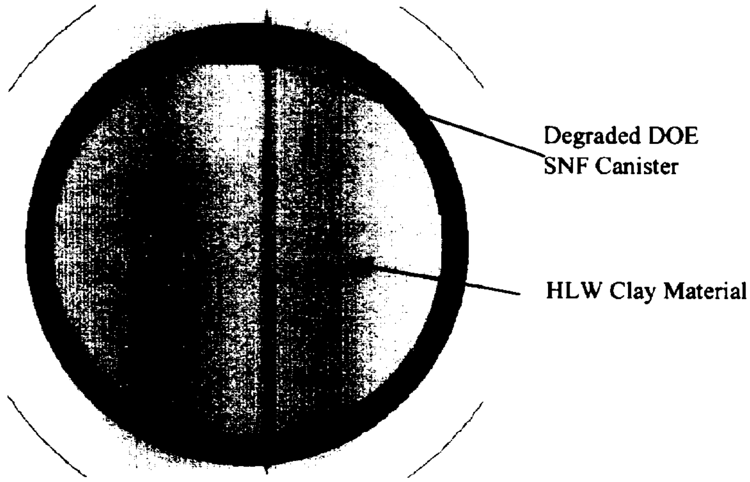


Figure 7-13. WP Filled with HLW Clay Material Layer and FFTF SNF Layer

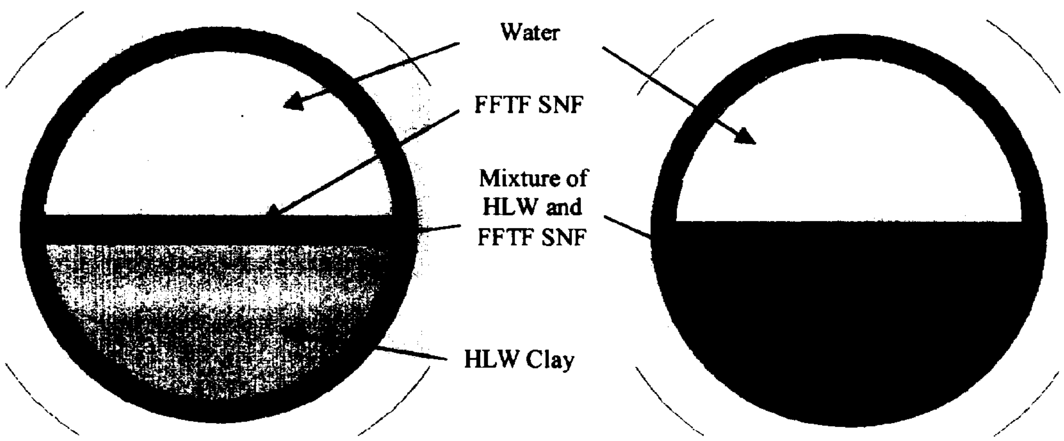


Figure 7-14. Layer of Fuel Mixed with the Layer of HLW Clay

7.5.2 Degraded DOE SNF Canister Settled at the Bottom

This section describes the calculations performed assuming the DOE SNF canister sinks to the bottom of the degraded HLW clay during the degradation process. As the DOE SNF canister degrades, some of the HLW clay and the FFTF SNF will mix as shown in Figure 7-15. The water fractions in the bottom layer and in the clay material are represented as being the same (CRWMS M&O 1999g, Section 6.3). These configurations are described in Section 6.2.1.5 and correspond to the configuration class 4. The results indicate that the highest k_{eff} is achieved if the fuel and clay layers do not mix. Even without any credit for Gd or iron oxide, the maximum $k_{eff} + 2\sigma$ of the system is 0.9145 after 24,100 years of plutonium decay.

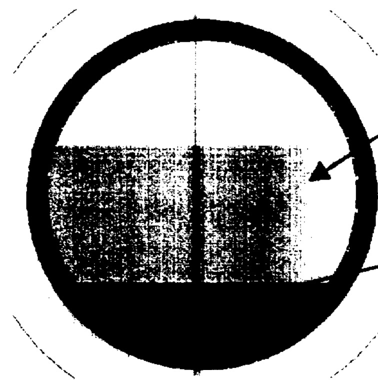


Figure 7-15. Degraded DOE SNF Mixed with HLW Glass Clay at the Bottom of the WP

The Pu-239 neutron fission cross section is somewhat higher than the U-235 neutron fission cross section in the thermal energy range. Pu-239 has a fission resonance at 0.3 eV, which is an order of magnitude higher than the corresponding U-235 resonance at approximately 0.18 eV. The total number of neutrons emitted by Pu-239 fission (ν) is approximately 15% higher than the total number of neutrons emitted by U-235. Total capture of neutrons that are in the thermal range by Pu-240 is approximately three orders of magnitude higher than total capture of neutrons by U-236, which is the isotope Pu-240 decays to.

The results from considering the effect of Pu decay indicate that for homogenous layers of fuel and clay, if Gd is present in the waste package, the k_{eff} is maximum at time zero and decreases in time. When Gd is present, the thermal neutrons are absorbed by Gd rather than by Pu-240. Therefore, Pu-240 decay has no significant effect on k_{eff}. However, as Pu-239 decays to U-235, the k_{eff} decreases. If the Gd is not present, the decay of Pu-240 reduces the overall neutron absorption (Pu-240 is a much stronger absorber than U-236). As a consequence, the k_{eff} peaks at approximately 24,100 years. At that time, approximately 92% of the Pu-240 has decayed to U-236 and only 50% of the Pu-239 has decayed to U-235. As more Pu-239 decays to U-235, k_{eff} decreases.

7.6 SUMMARY

Six DFAs with 2% (7.62 kg) Gd in the DOE SNF canister basket can be disposed of in the waste package without any criticality concerns. However, the waste packages with an Ident-69 pin container must have one of the basket locations blocked so that only four DFAs can be disposed of with the Ident-69 container, and at least 9.29 kg of Gd must be distributed on (e.g., flame deposit), or in the DOE SNF canister basket.

8. CONCLUSIONS

8.1 STRUCTURAL ANALYSIS

The results from the 2-D FEA calculations given in Section 3.3 show that there is sufficient clearance between the inner diameter of the support tube and the outer diameter of the DOE SNF canister for the DOE SNF canister to be removed from the waste package after a tipover DBE, which results in the bounding dynamic load.

The maximum deformations in each component of the waste package are acceptable. The outer barrier is directly exposed to a dynamic impact with an essentially unyielding surface. Therefore, local plastic deformations are unavoidable on the outer surface. Similarly, the basket support structure receives the direct impacts of pour canisters, which result in limited permanent deformations of the basket plates. The pour canisters remain intact after the impact.

The results given in Section 3.3.3 show that there would be no interference between any of the fuel assemblies and the basket structure inside the DOE SNF canister. Thus, the waste package will be able to be unloaded after a tipover DBE.

In the light of the above discussions, it is concluded that the performance of the 5-HLW/DOE SNF Long waste package design is structurally acceptable when exposed to a tipover event, which is the bounding DBE within the criteria specified in the SDD, as long as the 3400 kg DOE SNF canister loaded mass limit is not exceeded.

8.2 THERMAL ANALYSIS

Based on the 2-D FEA calculations given in Section 4, the FFTF waste package satisfies all relevant governing criteria, as listed in Table 8-1. The maximum temperatures are shown in Table 8-1. The HLW glass dominates the thermal heat output of the waste package. The HLW glass and FFTF fuel temperatures are below the limits.

Table 8-1. FFTF Codisposal WP Thermal Results and Governing Criteria

WP Metric	SDD Criterion	FFTF Codisposal WP Value
Maximum waste package heat output	< 18,000 W	13,533 W
Maximum HLW temperature	< 400 °C	247.6 °C
Maximum DOE SNF temperature in codisposal waste package	< (TBD-179)	280.3 °C

8.3 SHIELDING ANALYSIS

The results of 3-D Monte Carlo dose rate calculations show that maximum dose rate on the outer surfaces of waste package is below the 355 rem/h design limit by a factor of approximately 23. The highest dose rate is only 15.9 ± 1.9 rem/h. The primary gamma dose rate dominates the neutron dose rate by approximately three orders of magnitude. The presence of the FFTF DOE SNF canister in the center of the waste package reduces the axial dose rate by as much as 50%.

8.4 GEOCHEMISTRY ANALYSIS

The degradation analyses followed the general methodology developed for application to all waste forms containing fissile material that evaluates potential critical configurations from intact through degraded. Sequences of events and/or processes of component degradation were developed. Standard scenarios from the master scenario list in the topical report were refined using unique fuel characteristics. Potentially critical configurations were identified and analyzed.

The cases that evaluate the alkaline regime produce the highest Gd loss which is $\leq 0.7\%$ in $\geq 100{,}000$ years. When the glass is allowed to degrade rapidly, the alkaline conditions produce high uranium and plutonium loss (up to 100%), reducing the chances of internal criticality.

The cases that evaluate the effect of exposing the Gd, Pu, and U to long-lived acidic conditions (pH ~5 to 6) show no loss of Gd (due primarily to the use of $GdPO_4$ instead of Gd_2O_3), and the highest fissile loss is less than 3% of either Pu or U.

8.5 INTACT AND DEGRADED CRITICALITY ANALYSES

All aspects of intact configurations, including optimum moderation conditions, absorber distribution, water intrusion into the fuel pins, and positioning of the DFAs and the Ident-69 pin container were investigated. The results of 3-D Monte Carlo calculations from the intact criticality analysis show that the requirement of $k_{eff} + 2\sigma$ less than or equal to 0.93 is satisfied for six DFAs in the DOE SNF canister. This configuration does not need any Gd in the basket or elsewhere in the waste package to meet this requirement. For the cases that include an Ident-69 container (uniform array) and five DFAs, the DOE SNF canister basket must contain 0.5% (1.93 kg) Gd uniformly distributed over the entire basket.

A number of parametric analyses were run to address or bound the configuration classes discussed in Section 6.2.1. These parametric analyses addressed identification of optimum moderation, optimum spacing, optimum fissile concentration, decay of Pu isotopes, and absorber concentration/ distribution requirements.

The results from the criticality analysis for the intact DOE SNF canister show that the criteria of $k_{eff} + 2\sigma$ less than or equal to 0.93 is satisfied with the following restrictions. For the cases that include an Ident-69 container, all degradation configurations result in $k_{eff} + 2\sigma$ of less than or equal to 0.93 with 2.75 wt% Gd on or in the DOE SNF canister basket as long as only four DFAs are included in the package. All degradation configurations for six DFAs in the DOE SNF canister result in $k_{eff} + 2\sigma$ of less than or equal to 0.93 if the Gd content is at least 2 wt%.

The results from the criticality analysis for the degraded DOE 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 0.5, which is well below the interim critical limit. Even without any credit for Gd or iron oxide, the maximum $k_{eff} + 2\sigma$ of the system is below the interim critical limit.

In summary, the DOE SNF canister can contain six DFAs, which corresponds to the maximum number of basket locations, with at least 7.62 kg of Gd distributed on (e.g., flame deposit), or in the DOE SNF canister basket. However, the DOE SNF canister with the Ident-69 pin container must have one of the basket locations blocked so that only four DFAs can be disposed of with the Ident-69 container with at least 9.29 kg of Gd on, or in the DOE SNF canister basket. With this design, there will be approximately 64 DOE SNF canisters with FFTF SNF, which corresponds to 64 waste packages. Alternatively, the Ident-69 pin container could be filled with iron shot, thereby allowing five DFAs to be disposed of with the Ident-69 pin container. With this design, there will be approximately 58 DOE SNF canisters with FFTF SNF, which corresponds to 58 waste packages.

8.6 ITEMS IMPORTANT TO SAFETY

As part of the criticality licensing strategy, items that are important to safety will be identified during evaluation of the representative fuel type designated by the NSNFP. As a result of the analyses performed for the evaluation of the codisposal viability of MOX (FFTF) DOE-owned fuel, several items are identified as important to safety. DOE SNF canister shell is naturally an item that is important to safety since it confines the fissile elements to a specific geometry and location within the waste package. The basket that was designed for the DOE SNF canister containing the FFTF fuel is also an important safety item since it confines the fissile elements to a specific geometry and location within the DOE SNF canister. The DOE SNF canister basket also provides thermal neutron absorption due to its high iron content. The DOE SNF canister loaded weight, which must be less than 3400 kg, is also an important safety item. Based on the conclusions derived in Section 8.5, some small amount of neutron absorber will have to be distributed on or in the DOE SNF canister basket. Therefore, the absorber material that will be placed on or in the basket is also an item important to safety. All calculations are based on assemblies with 217 fuel pins. It was shown, in Section 7.3 (intact criticality analysis), that having a fewer number of fuel pins, which in turn results in increased fuel pin pitch, results in higher k_{eff}. On the other hand, it was shown in Sections 7.4 and 7.5 (degraded criticality) that having more fuel pins increases the k_{eff}. It was also shown in Section 7 that degraded configurations with fuel pellets spread out axially and radially bound the intact configurations. The degraded configurations include varying degrees of degradation resulting in many different geometric configurations and fissile distributions. Therefore, these degraded configurations also bound the other types of MOX fuels as long as the limits on mass and enrichment are not exceeded. The total mass of fissile elements (U-235 and Pu-239) in an assembly should not exceed the one used in deriving the conclusions in this report, which is 8.6 kg per assembly, with total fissile to U-238 ratio of 0.34 or less. All analyses are based on the fuel pin type that has the highest plutonium enrichment (enriched in Pu-239) and the highest plutonium loading per pin. In Section 7, it was shown that as the total amount of Pu-240 decreases with radioactive decay, the k_{eff} increases. Since Pu-240 was decayed, the fraction of Pu-239 in plutonium is not a factor that is important to safety.

The shielding source terms and thermal heat output of the fuel assemblies must not exceed the ones used in the analyses. Specifically, the total gamma sources from the HLW glass and the fuel assembly must not exceed 4.94E+15 gammas/sec/canister and 1.84E+15 gammas/sec/assembly, respectively. HLW glass thermal power should not exceed 2,540 W. Alternatively, it must be demonstrated that HLW glass canisters and/or fuel assemblies with higher shielding source terms or thermal heat outputs will not result in violation of the required criteria.

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