

**OFFICE OF CIVILIAN RADIOACTIVE WASTE MANAGEMENT  
ANALYSIS/MODEL COVER SHEET**

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Page: 1 of 43

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00B	Technical back check and compliance check
00C	compliance back check and PCG core group check
00D	PCG compliance back check and Design Review
00E	Design Review back check
00	Initial Issue

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## **1. PURPOSE**

The purpose of this analysis is to develop a generic set of degradation scenarios and associated configurations for various Department of Energy (DOE) spent nuclear fuel (SNF) types when codisposed with the high-level waste (HLW) glass inside a waste package (WP). The degradation takes place inside the WP. These scenarios and configurations are developed as refinements of the standard degradation scenarios and potentially critical configuration classes given in Section 3.1 of the *Disposal Criticality Analysis Methodology Topical Report* (Ref. 1). Certain degradation scenarios and configurations will change when EDA II design is baselined. In accordance with AP-3.10Q, Revision 0, ICN 0, a work direction was developed, issued, and used in the preparation of this document (Ref. 13, p. 7).

## **2. QUALITY ASSURANCE**

This analysis was prepared in accordance with the DOE Office of Civilian Radioactive Waste Management System (OCRWM) Quality Assurance (QA) program. The information provided in this analysis will be used for evaluating the postclosure performance of the Monitored Geologic Repository (MGR) WP and engineered barrier segment. The QAP-2-3 (*Classification of Permanent Items*) evaluation entitled *Classification of the MGR DOE Spent Nuclear Fuel Disposal Container System* (Ref. 10, p. 5) has identified the WP as an MGR item important to radiological safety and waste isolation. The Waste Package Operations manager has evaluated the technical document development activity in accordance with QAP-2-0, *Conduct of Activities*. The QAP-2-0 activity evaluation, *DOE Spent Nuclear Fuel (SNF) - 2101 2310 M1-M8* (Ref. 11), has determined that the preparation and review of this technical document is subject to *Quality Assurance Requirements and Description* (Ref. 12) requirements. There is no determination of importance evaluation developed in accordance with Nevada Line Procedure, NLP-2-0, since the report does not involve any field activity.

Since unqualified inputs were used in the development of this analysis, they should be considered TBV (to be verified). This document will not directly support any procurement, fabrication, or construction activity, and therefore, the inputs and results are not required to be procedurally controlled as TBV and tracked in accordance with NLP-3-15. However, use of any data from this analysis for input into documents supporting procurement, fabrication, or construction is required to be controlled as TBV in accordance with appropriate procedures.

## **3. COMPUTER SOFTWARE AND MODEL USAGE**

No computer software or model is used for this analysis. Information on the various software packages and computer codes discussed in the text can be found in the referenced supporting engineering calculations in which they were used.

## **4. INPUTS**

Various inputs are used to develop the degradation scenarios and configurations. These inputs, in terms of parameters and criteria, are discussed below.

### **4.1 PARAMETERS**

#### **4.1.1 WP Characteristics**

As shown in Figure 4-1, the WP consists of an outer and an inner barrier. The outer barrier is made of A516 carbon steel (CS) and the inner barrier is made of Alloy 22 (Ref. 2, p. 5). Inside the WP, there is a web-shaped basket supporting structure that divides the interior of the WP into six compartments, five around the periphery and one in the center (center tube). A HLW glass canister is placed in each of the five peripheral compartments. Codisposed with the five HLW glass canisters is the DOE SNF canister in the center of the WP.

In the context of this analysis, the WP degradation process is associated with the degradation of materials. The parameters that need to be considered for degradation analysis characterize the different components and associated materials inside the WP. They are described below.

**WP Supporting Basket (Web) Structure**—As discussed above, the basket structure shown in Figure 4-1 divides the WP interior into six compartments, which provide the support and separation for the five peripheral HLW glass canisters and the DOE SNF canister in the center. The basket structure material is A516 CS.

**HLW Glass Canister**—As discussed above, there are five HLW glass canisters inside the WP. An example of a HLW glass canister is shown in Figure 4-2. The glass canister shell is made of 304L SS (stainless steel) (Ref. 2, p. 5). The glass chemical composition varies depending on where the HLW glass is made.

**DOE SNF Canister**—The DOE SNF canister is an 18- or a 24-inch-diameter cylindrical pipe; length is limited to no more than 3 m or 15 ft (depending on design). The 18-inch DOE SNF canister is to be placed in the center of the WP (Figure 4-1). The 24-inch DOE SNF canister will replace one of the five HLW glass canisters. The specification of the DOE SNF canister can be found in Reference 3. The DOE SNF canister contains the various SNF types to be stored in the repository. The outer shell of the DOE SNF canister is made of 316L SS (Ref. 3, p. 5).

**Waste Form (WF)**—WF refers to the HLW glass. The DOE spent nuclear fuel is referred to as SNF. Depending on the types of SNF to be stored, the SNF takes different forms and shapes (matrix). After SNF matrix has degraded, the fissile material is referred to as fissile waste form (FWF).

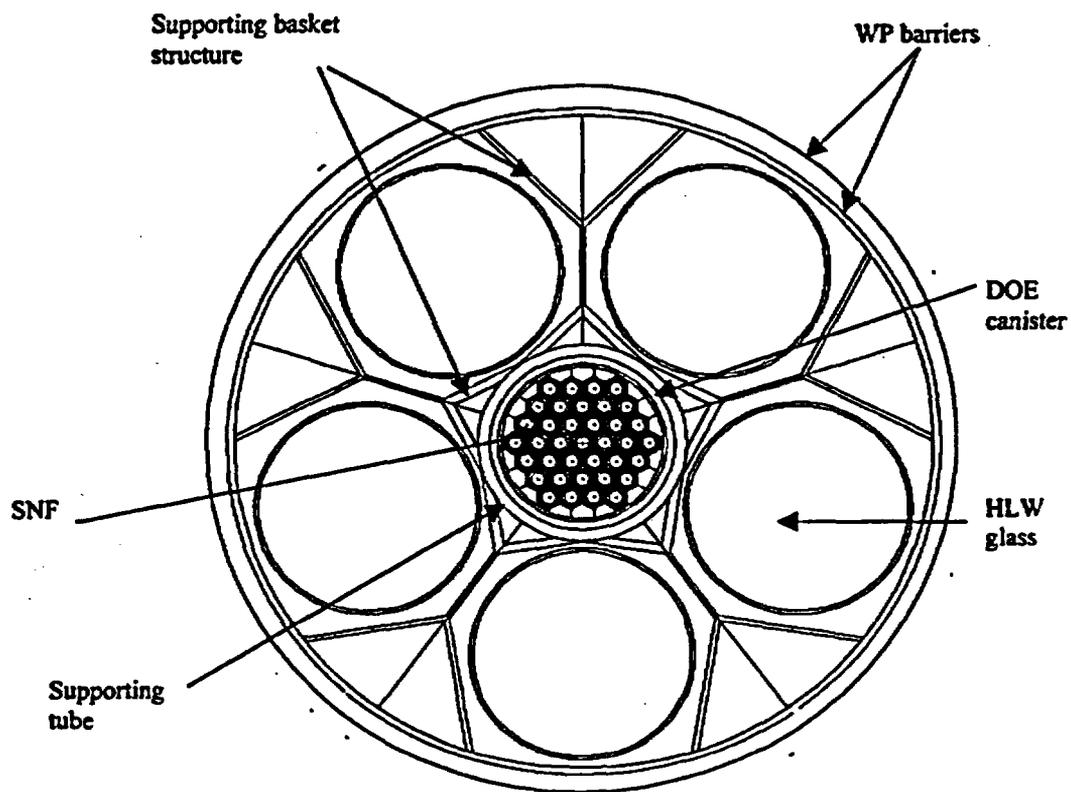
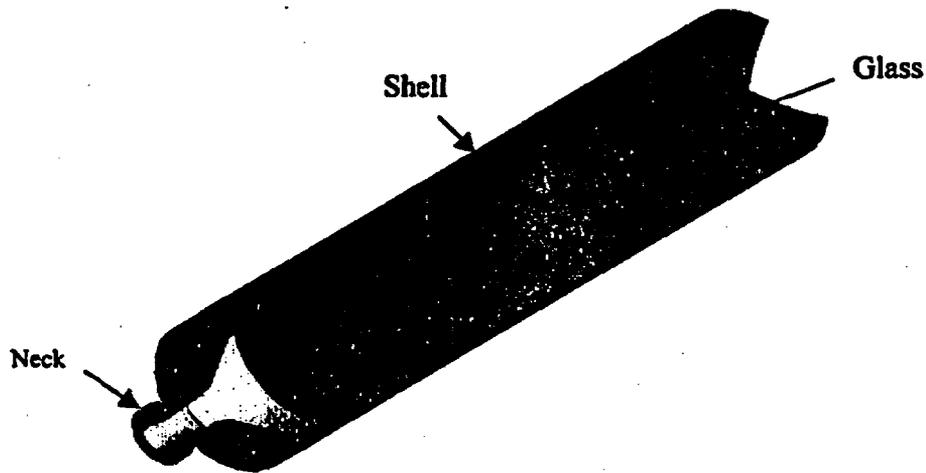


Figure 4-1. Cross Section of 5-HLW/DOE Spent Nuclear Fuel WP



**Figure 4-2. HLW Glass Canister**

#### 4.1.2 Degradation Rates

Reference 4 (pp. 17-18) provides the degradation rates for the various materials used in the WP and storage canisters. The degradation rates for the materials of interest are provided in Table 4-1.

Table 4-1. Degradation Rates for WP Components

Component	Material	Degradation Rate (moles/cm <sup>2</sup> -s) <sup>a</sup>	Degradation Rate (μm/y)
WP Inner Barrier	Alloy 22	Not Available	0.005 <sup>b</sup>
Web Inside WP	A516 CS	1.58E-11	35.0
HLW Glass	Glass	1.74E-13	Not Available
HLW Glass Canister	304L SS	4.58E-12	0.1
DOE SNF Canister	316L SS	4.55E-12	0.1

NOTES: <sup>a</sup> Average/typical of reported tests

<sup>b</sup> Reference 9, p. 3-87

#### 4.2 CRITERIA

No specific criteria are employed for this analysis.

#### 4.3 CODES AND STANDARDS

No specific codes and standards are required for this analysis.

## **5. ASSUMPTIONS**

- 1. It is assumed that all the degrading solid surfaces are constantly exposed to a volume of water equal to the void space of the WP. This corresponds to a WP filled with water. The basis for this assumption is that this model is conservative with respect to the removal of neutron absorber by flushing because a smaller volume of water would have a higher concentration of dissolved material, thereby more easily reaching the solubility limit so that the material would be precipitated rather than remaining in solution to be flushed out. If there were several small ponds instead of a big one, the surface area of solids exposed to aqueous attack would be correspondingly decreased, so that the rate of dissolution would be decreased. The extreme case of localized ponding occurs when the WP is penetrated at the bottom (as well as at the top). The water may then flow through the WP as a thin film over a limited set of solid surfaces, without ever ponding at all. Nevertheless, this film can be considered as a very localized pond with only a small fraction of the solid material contacting the water at any given time. Therefore, solid material would be dissolved at a slower rate than it would if the entire WP were flooded. This assumption is used in Section 6.2.2.**

## **6. ANALYSIS/MODEL**

### **6.1 MODELS**

#### **6.1.1 Degradation Scenarios**

##### **6.1.1.1 Standard Degradation Scenarios (for internal criticality)**

Degradation scenarios comprise a combination of features, events, and processes (FEPs) that result in degraded configurations to be evaluated for potential criticality (Ref. 1, p. 3-2).

Features are defined as topographic, stratigraphic, physical, or chemical characteristics of the site that may influence the configuration parameters, and thereby influence outcome of the criticality analysis. The principal examples of features applicable to internal criticality analysis are faults that may focus or block the flow of groundwater, thereby effecting the drip rate onto the WP. Processes are physical or chemical interactions that can occur between the emplaced material and the surroundings. Examples of processes include groundwater flow, corrosion, and precipitation. Events are similar to processes, but have a short duration, and possibly a more extreme intensity or effect on the emplaced material. Examples of events would be the sudden collapse of a basket due to rock-fall onto a WP.

A configuration is defined by a set of parameters characterizing the amount, and physical arrangement, at a specific location, of the materials that have a significant effect on criticality (e.g., fissile materials, neutron absorbing materials, reflecting materials, and moderators). The great variety of possible configurations is best understood by grouping them into classes. A configuration class is a set of similar configurations whose composition and geometry are defined by specific parameters that distinguish one class from another. Within a class, the configuration parameters may vary over a given range.

The internal degradation scenarios help define the classes of configurations that result from the effects of processes and events that degrade the contents of the WP, after the WP has been breached and the inert environment lost. The events and processes that most directly impact the potential for internal criticality include: (a) changes to a more reactive geometry, (b) accumulation/retention of moderator, and (c) separation of neutron absorbers from fissile material.

The Master Scenario List in the *Disposal Criticality Analysis Methodology Topical Report* (Ref. 1, pp. 3-2 through 3-8) provides discussions on a set of standard scenarios for the internal and external criticality. This list was developed by a process involving workshops and peer review. The standard scenarios and configuration classes are defined by the differences in degradation characteristics of the WP contents. For the purpose of scenario/configuration analysis, the WP contents are considered in two categories: the fissile waste form(s) (FWF) and other internal components (OICs). The latter category includes various structural, thermal, and neutron absorbing components of the intact basket, as well as any codisposed, non-fissile waste forms

such as the HLW glass. For codisposal WP criticality analysis, the OICs are further classified as inside versus outside the SNF canister.

All of the scenarios that can lead to internal criticality begin with aqueous breach of the WP. This breach can be fed by continued dripping of water, which leads eventually to the degradation of FWF and/or OICs of the WP. This degradation may permit neutron absorbing material to be mobilized (made soluble) and either flushed from the WP or displaced away from the fissile material, thereby increasing the probability of criticality.

The standard scenarios for internal criticality divide into two main groups:

- (1) The WP is breached on the top only, so the water flowing into the WP will build up a pond. This pond provides water for moderation to support a criticality. After a few hundred years of steady dripping, the water can overflow through the hole in the top of the WP, and thereby flush out any dissolved degradation products.
- (2) The WP is breached on the bottom as well as the top, so that water flows through the WP. Scenarios of this group do not directly provide water for moderation. Criticality is possible, however, if the WP bottom has holes and fills with corrosion products that can add water of hydration and/or can plug any holes in the bottom of the WP, permitting subsequent ponding.

For internal criticality scenarios, Reference 1 presents six generalized scenarios based on the accumulation of water and the relative degradation rates of the components inside the WP. The standard scenarios for the first group are designated as IP (internal package)-1, -2, and -3 depending on whether the fissile waste form degrades before the other WP internal components, degrades at approximately the same time, or degrades later.

The standard scenario groups IP-4 through IP-6 are associated with processes that have resulted in a WP that has penetrations in the bottom, thus preventing standing water in the WP. This flow-through removes soluble corrosion products at a faster rate, including any soluble neutron absorber. The standard scenario group IP-4 includes the situations in which FWF degrades faster than OICs. The standard scenario group IP-5 covers the situations where FWF and OICs degrade approximately at the same time. Finally, the standard scenario group IP-6 includes the situations in which OICs degrade faster than FWF under flow-through conditions.

The criticality potential is determined by the configurations resulting from the scenario groups discussed above. Several of the scenarios may lead to the same configuration class, particularly since the sequence of the individual component degradations is generally found to be unimportant. Section 6.1.2 will discuss in detail the standard configuration classes of the degraded WP that have potential for criticality, and will identify the scenarios (direct or indirect) that lead to them.

### **6.1.1.2 Degradation Processes**

This section presents the key degradation processes and the mechanisms, or factors, influencing the degradation. The possible degradation products are also discussed. These degradation processes, influencing factors, and degradation products are used to identify the different degradation configuration classes that are described in Section 6.1.2.

#### **6.1.1.2.1 WP Barriers**

The following description is based on the WP baseline Viability Assessment (VA) design (Ref. 5, p. 5-12). This section will be revised when the baseline design is changed. The data on WP barriers are for information purposes only

The WP outer barrier is made of A516 CS. The WP inner corrosion-resistant barrier is made of Alloy 22. As shown in Table 4-1, corrosion of Alloy 22 is very slow as compared to 304L SS and 316L SS.

For degradation to take place inside the WP, the WP outer and inner barrier will be penetrated first by the dripping water. After that the supporting web structure will be flooded and progressively corroded away.

WP criticality analysis uses the distribution of barrier breach times provided by the current M&O standard set of barrier corrosion calculations provided by the WAPDEG code (Ref. 6).

#### **6.1.1.2.2 Carbon Steel Supporting Structure**

The supporting structure inside the WP (outer web or basket) is made of carbon steel (A516 CS). It is designed to support the HLW glass canisters and the DOE SNF canister. Once water is inside the WP, A516 CS will degrade faster than 316L/304L SS (see Table 4-1). Given time, all of the carbon steel basket supporting materials would have degraded before the other types of steel materials have undergone significant general corrosion. The principal degradation product of carbon steel is iron oxide (hematite or goethite). The iron oxide is insoluble so it will probably collect at the bottom of the WP. Carbon steel is also susceptible to bulk corrosion from humid air or microbiologically influenced corrosion (MIC). If completely oxidized, the iron oxide corrosion product from the degradation of the carbon steel components will occupy almost twice the volume of the original components (Ref. 7, p. 28). This has the criticality control effect of displacing the water (away from the fissile material and/or out of the WP), thereby reducing the neutron moderation. The iron oxide is also a neutron absorbing material, but not as effective as the typical neutron absorbers, such as gadolinium.

**6.1.1.2.3 HLW Glass and Stainless Steel Canister**

The HLW glass is contained in an approximately 1-cm-thick cylindrical stainless steel (304L) canister with an outer diameter of approximately 610 mm and a nominal length of 3 m. It is filled to about 85% volume before cooling (Ref. 2, p. 5). Degradation scenarios for HLW glass have been subjected to geochemistry analysis, using the computer code EQ3/6 (Ref. 8, p. 54). The following is a qualitative description of the key results.

- (A) The silicon dioxide ( $\text{SiO}_2$ ) released by the degrading glass will be the principal constituent in the formation of clay within the WP. This clay will most likely start to accumulate at the bottom of the WP, but on top of the iron oxide from the previously degraded carbon steel. Any precipitated uranium (from the glass or degraded SNF) is incorporated into the clay in the form of insoluble uranyl silicate material (such as soddyite,  $(\text{UO}_2)_2\text{SiO}_4 \cdot 2\text{H}_2\text{O}$ ).
- (B) One corrosion product of the stainless steel shell of the HLW glass canister could be chromic acid, which could arise from the oxidation of the Cr in stainless steel, according to the charge balance equation:



If the effective oxygen potential is lowered slightly, chromate formation may be greatly inhibited, reducing acid production.

- (C) The HLW borosilicate glass contains significant amounts of the neutron absorber boron. However, the boron is highly soluble, and is, therefore, likely to be flushed from the WP as rapidly as the HLW glass degrades. As a result, it is not expected to have much impact on criticality. There is evidence that some fraction of the boron may adsorb onto clays and hydrous iron oxides, but this sorption is currently ignored for the sake of conservatism.
- (D) The HLW glass contains depleted uranium, which has a small, but significant, cross section for thermal neutron absorption. This is included in the criticality analysis, but the amount is not sufficient to have a major effect.
- (E) Because of its high alkalinity, the degrading HLW glass can increase the pH. This will, in turn, increase the solubility of U and Pu, and increase the probability of their being flushed out of the WP.

#### **6.1.1.2.4 Fissile Waste Form**

As mentioned above, U has some solubility, so some amount (usually small) can be flushed out of the WP. As the uranium degrades, it will mostly form the relatively insoluble hydrous uranium oxide (e.g., schoepite,  $\text{UO}_3 \cdot 2\text{H}_2\text{O}$ ) or uranium silicates (e.g., soddyite,  $(\text{UO}_2)_2\text{SiO}_4 \cdot 2\text{H}_2\text{O}$ ). The silicon comes mostly from the glass. Some uranium waste forms (such as metallic U, or highly fractured  $\text{UO}_2$  fuel) will react rapidly with water. On the other hand, some U waste forms (e.g., high-temperature ceramics or Zr-clad, coextruded forms) will be more resistant to corrosion than the more typical uranium dioxide.

#### **6.1.1.2.5 Flushing of Soluble Species from the WP**

The flushing process can occur in two ways. One way is through one or more penetrations near the top of the WP, when the bottom of the WP remains intact and water is ponding in the WP. There must also be circulation to carry dissolved degradation products near the upper surface of the ponding water (also called "bathtub"). The other way for flushing to occur is through the subsequent penetration at the bottom of the WP. This is also defined as flow-through flushing in the criticality topical report (Ref. 1, p. 3-4).

Drip rates can range from  $0.0015 \text{ m}^3/\text{y}$  to  $0.5 \text{ m}^3/\text{y}$  (Ref. 4, p. 21). With these drip rates, it is estimated that the range of time for the formation of the bathtub (provided there is no penetration of the bottom of the WP) can range from a thousand years down to about a few years. Since high drip rates tend to remove the more soluble neutron absorbing materials from the WP, criticality control must usually be provided by relatively insoluble neutron absorbing material.

#### **6.1.1.2.6 Reaction Enhancing Mechanisms/Processes**

##### **6.1.1.2.6.1 Internal Circulation**

Without internal water circulation, the corrosion process in the bathtub configuration is greatly retarded. The circulation serves three functions: (1) transporting dissolved oxygen from the free surface to the corroding surface covered with water, (2) removing dissolved corrosion products from the immediate vicinity of the corroding surfaces, and (3) moving the corrosion products to a flow path near the surface that carries them out of the WP. Potential drivers of internal circulation are the following: the dripping motion of the incoming water, the thermal convection due to the decay heat generated from the glass and the fissile waste form, and the bubbles resulted from the production of the hydrogen gas or the exsolution of dissolved  $\text{CO}_2$  as system pH changes. These potential mechanisms are discussed below.

The void space inside the WP consists of two parts: (1) the total volume of the WP minus the volume of the initial solids (called free void space) and (2) the pore space inside the material itself. This latter category applies primarily to low-density materials such as the clay or sludge formed from the degradation products. Expansion of the degraded steel (iron oxide) and the porosity formed in the degraded HLW glass clay can displace the space occupied by water, thus

reducing the void space inside the WP. To the extent that the expansion of corrosion products reduces the free void space, the volume available for internal circulation is reduced, thereby reducing the amount of such circulation. However, the reduced circulation may provide some enhancement of criticality control by limiting the loss of fissile and neutron absorbing materials. There is generally no credit taken for this process because the clay could fail to cover most of the corroding surfaces.

#### **6.1.1.2.6.2 Thermal Convection**

Decay heat released from the HLW glass and the fissile waste form can produce thermal gradients within the WP, which can drive buoyant convection to carry dissolved corrosion products to a flow path leading out of the WP. It should be noted that EDA II (the new Enhanced Design Alternative) will have at least 20,000 years before the first penetration, after which time there may not be enough heat to drive buoyant convection, particularly for the DOE SNF, which does not have much decay heat to begin with.

#### **6.1.1.2.6.3 Gas Bubbles**

Movement of degradation products inside the WP can be created by gas bubbles such as hydrogen or CO<sub>2</sub> exsolved from the solution by changes in pH condition. Hydrogen gas can be produced by the normal degradation process or by the microbiological corrosion process. If the buoyant convection of these gas bubbles is sufficiently strong, fluid may be entrained, thereby moving dissolved degradation products, similar to thermal convection. However, preliminary calculations indicate that such gas bubbles would not provide as much movement as diffusion.

#### **6.1.1.2.6.4 Diffusion**

The transport of oxidants into, and reduced species away from, the zones of active corrosion can be enhanced by molecular diffusion. This can be large enough to support nominal reaction rates if the distances are sufficiently small (~10 cm in liquid water or a medium with high porosity). The diffusion mechanism will be the dominant driver of corrosion after 20,000 to 30,000 years when the decay heat has declined to such an extent that it can no longer drive buoyant convection.

#### **6.1.1.2.6.5 Drop Kinetics**

A strong motion imparted by the incoming water drops could drive a circulation. However, drips into water pools tend to affect the surface most strongly, except when the drips have a significantly higher density than the pool upon which they impinge. This cannot occur in the WP situation because the ponding water is the same as the dripping water, except for the addition of dissolved material, which will make it heavier than the dripping water. The motion activated by dripping may cause some movement of the aqueous degradation products inside the WP, but the movement is not deep enough to reach most of the corroding surfaces in the bathtub configuration.

**6.1.1.2.7 Effects of pH and Fugacities (partial pressure) of CO<sub>2</sub> and O<sub>2</sub>**

High pH (alkalinity) increases the solubility of Pu and U. In the codisposal WP, the most likely source of high pH is the alkalinity in dissolving HLW glass. The quantity of Pu and U released from the WP is determined from geochemistry calculations (EQ3/6 computer code). A low pH (acid condition) will increase the solubility of the generally insoluble neutron absorber such as gadolinium (Gd). The release of Gd from the WP is determined from geochemistry calculations (EQ3/6). In the codisposal WP, the most likely source of low pH is the oxidation of Cr from stainless steel (of the HLW canisters and the DOE SNF canister) to the dichromate ion, which is responsible for chromic acid. Such acidification will end when all of the stainless steel has been oxidized (50,000 to 100,000 years after aqueous breach of the WP). During the period of low pH, a relatively soluble form of Gd (Gd oxide) could be lost due to flushing or leaking discussed above.

The solubility of actinides is especially enhanced due to the formation of aqueous actinide carbonate complexes if the CO<sub>2</sub> fugacity is maintained to ambient levels or higher.

The oxygen fugacity has both direct and indirect effects on the solubility and removal of neutron absorbers, such as Gd and actinides. For example, aqueous carbonate complexes of Pu (VI) are much more stable than those of Pu (V); the former is much more soluble than the latter. Therefore, lowering the oxygen activity slightly, to levels typical of desert soils, can greatly reduce the solubility of Pu by reducing the amount of the more oxidized Pu (VI) relative to the amount of Pu (V). In addition, a modest lowering of the effective oxygen fugacity may greatly reduce the acid production when stainless steel degrades because, at lower oxygen fugacities, insoluble Cr (III, VI) oxides can form, reducing the acid production that accompanies formation of chromate ion.

**6.1.1.2.8 Settlement, Mixing, or Separation of Degradation Products**

The different components inside the WP show some variation in corrosion rates and other aspects of the degradation processes (discussed above). The concern, with respect to criticality, is the separation of the neutron absorber from the fissile materials. In general, since the carbon steel (A516) will degrade first, the iron oxide formed will be the first to settle at the bottom of the WP followed by the settlement of the other steel materials. According to Stokes Law, the settling rates depend on the densities and diameters of the corrosion product particles. However, differential settling due to density and diameter differences is probably not going to be an important effect because, with the low rates of production of the various alteration materials and a potential for thousands of years separation between the times of maximum production of one corrosion product versus another, the minutes-to-weeks settling times of particles in water will be relatively insignificant.

**6.1.1.2.9 Localized Degradation****6.1.1.2.9.1 Degradation by Bacteria**

Microorganisms can influence corrosion in a variety of ways. Formation of localized corrosion cells, the production of mineral and organic acids, ammonia production, and sulfate reduction are just a few of the mechanisms by which bacteria, fungi, and algae can influence corrosion. Corrosion may develop when localized cells are formed due to biofilms developing on metal surfaces. The oxidation of iron is not a requirement for the development of a localized corrosion cell.

The degradation configurations are different between the direct oxidation corrosion and the bacterial corrosion. The direct oxidation corrosion can be both localized (pitting) and bulk. The MIC is localized only. The principal effects of MIC are the following:

- (A) Enhanced corrosion of the carbon steel outer barrier of the VA WP design, as shown in the *Total System Performance Assessment-Viability Assessment (TSPA-VA)* analysis (Ref. 9, p. 3-84). This is not expected to be much of an effect on the new EDA II design, which has no carbon steel.
- (B) Earlier collapse of the carbon steel pedestal supporting the WP.-Collapse of the pedestal can cause the WP to sit directly on the invert, which, in turn, can speed up MIC at the WP bottom because the invert contains moisture.

Thus MIC can decrease the time for WP penetration but is not likely to have any influence on criticality.

**6.1.1.2.9.2 Crevice, Galvanic, and Stress Corrosion**

Crevice corrosion is a particular form of pitting which occurs between adjoining surfaces, usually due to oxygen concentration cell effects. Galvanic corrosion requires two different types of metals making contact; it is also known as bimetallic corrosion. Stress corrosion occurs when a highly stressed area becomes anodic with respect to the adjacent metal. The large cathode-to-anodic area ratio causes rapid penetration along the stressed areas. The anodic dissolution, together with the tensile stresses, tends to pull the metal apart, causing rapid cracking.

Inside the WP there are several types of steel materials. They join together and make direct contact in many locations. Thus, possibilities of crevice, galvanic, and stress corrosion do exist in many locations inside the WP. However, since these types of corruptions act only at boundaries between metals, they will be local in nature and cause only small increments of degradation of the components carrying the neutron absorber inside the WP. This is further discussed in Section 6.2.

### **6.1.2 Configuration Classes**

The following paragraphs list and discuss the configuration classes that have the potential for criticality (Ref. 1, p. 3-8). These configuration classes result from the standard scenarios presented in Section 6.1.1.1. The configuration classes are intended to comprehensively represent the configurations that can result from physically realizable scenarios. As presented here, the configuration classes do not distinguish between WP internal components inside versus outside the DOE SNF canister. Such distinctions will be given with the application of the configuration classes to the codisposal WP in Section 6.2.2.

**(1) Configuration Class 1**

The WP internal basket (outside the DOE SNF canister) degraded but SNF relatively intact and sitting at the bottom of the WP, surrounded by, and/or beneath, the basket corrosion products. This configuration class is reached from the standard scenario IP-3.

**(2) Configuration Class 2**

Both basket and SNF degraded. The corrosion product composition is a mixture of fissile material, clay, and iron oxides. It is more complex than for configuration class 1, and is determined by geochemistry calculations. This configuration class is most directly reached from the standard scenario IP-2, in which all the WP components are degrading at the same time. However, after many tens of thousands of years, the standard scenarios IP-1 and IP-3, in which the SNF degrades before or after the other components, respectively, can lead to this configuration when the latter catches up with the former.

**(3) Configuration Class 3**

Fissile material moved some distance from the neutron absorber, which remains in the WP. This configuration class can be reached from the standard scenario IP-1.

**(4) Configuration Class 4**

Fissile material accumulates at the bottom of the WP, together with moderator provided by water trapped in clay. The clay composition is determined by geochemistry calculations. FWF can degrade at any time. This configuration can be reached by any of the standard scenarios, although the standard scenarios IP-2 and IP-5 lead by the most direct path; the only requirement is that there be a large amount of HLW glass in the WP (as in the codisposal WP) to form the clay.

**(5) Configuration Class 5**

In configuration class 5, as discussed in class 4 above, the moderator is provided by water trapped in clay, but in this case the fissile material is distributed throughout a major fraction of the WP volume. Fissile material is incorporated into the clay, similar to configuration class 4, but with the fissile material not at the bottom of the package. Generally, the mixture would be spread throughout most of the WP volume, but it could vary in composition, so that the fissile material could be confined to one or more layers.

This configuration class can only be reached if the FWF degrades faster than the OIC (particularly the HLW glass canisters) and the degraded fissile material remains in place to be locked in by its own hydration or by the hydration of the OICs. Therefore, it is only reached directly by the standard scenario IP-4 or indirectly after the standard scenario IP-1.

**(6) Configuration Class 6**

In this class, the FWF has degraded in place with OIC intact. This configuration class is of interest if the degradation of the FWF can distribute the fissile material into a more reactive geometry than the intact FWF (but not necessarily moved away from the neutron absorber, as in configuration class 3). This is particularly true for the case of highly enriched SNF. This configuration can be reached by the standard scenario IP-1.

It should also be noted that configuration classes 1, 2, 4, and 5 imply removal of the neutron absorber from the WP, while in configuration classes 3 and 6 the fissile material is simply moved away from the absorber or into a more reactive geometry. The application of these configuration classes to the DOE SNF canister discussed in Section 6.2 will emphasize the ones that form clay from the HLW glass. Such behavior is specified in the definitions of configuration classes 4 and 5, but is an implicit possibility in configuration classes 1 and 2, as well.

The comprehensive evaluation of disposal criticality for any fissile waste form must include variations of the standard scenarios and configurations to ensure that no credible degradation scenario will be neglected.

### **6.1.3 Events with Configuration-Changing Potential**

These are the events that could, under proper conditions, re-arrange the geometry of the fissile material, or increase the separation between fissile material and neutron absorber, sufficiently to change a configuration from just below critical to significantly above critical. Some of these events can be sudden events. Any configuration reached by these mechanisms could have been reached by a slower, gradual process. These events do not significantly affect the probability of a criticality. They can, however, affect the transient dynamics of a criticality, because they are drivers of reactivity insertion rate.

#### **6.1.3.1 Seismic Event**

A seismic event can dislodge degradation product particles (like iron oxide) that are performing a criticality control function such as moderator displacement or neutron absorption. If this dislodging leads to the displacement between the fissile material and neutron absorber causing a positive reactivity increase, it can produce a transient criticality. There is a potential for sudden change of some configurations by facilitating the collapse of the partially degraded inner supporting structures. But this event will not generate a new class of configurations. It will simply make a transition to a group of configurations that is normally reached after a much longer time. Furthermore, any collapsed configuration will generally have lower  $k_{eff}$  because of the more limited space available for moderation in the collapsed configuration.

#### **6.1.3.2 Rockfall**

This event will not generate a new class of configurations. Due to the possible shock on the WP, it will simply make a transition to a group of configurations that is normally reached after a much longer time. Furthermore, any collapse due to rockfall can reduce  $k_{eff}$  because of moderator exclusion, as described in the previous item. Rockfalls are normal hazard that would likely be exacerbated by seismic events. As mentioned above, the resultant WP internal configurations are already included in the configuration classes considered in the present analysis.

#### **6.1.3.3 Volcanic Eruption**

Volcanic lava pouring into a WP could provide sufficient moderator for criticality if the WP had an opening already. However, the probability of a volcanic event is so small to begin with that when combined with the small probability of finding a WP, or stack of assemblies, in the appropriate geometry, there will be very little probability for a consequent criticality. The volcanic material may also alter the geochemistry of the drift, but not in any obviously negative way.

#### **6.1.3.4 Structural Collapse**

This event is also similar to a seismic event in the potential for dislodging particles. It is also similar to a rockfall event, in being likely to bring fissile material into a more condensed geometry, and, hence, less critical. The comments mentioned above (Section 6.1.3.2) apply also for this event.

#### **6.1.3.5 Tilting**

WP tilting can cause redistribution of the degradation products inside the package, which could potentially, result in a more favorable geometry for criticality. Tilting can also result from a sudden event like the seismic or structural collapse, but can be also attained in a gradual mode. If the tilting angle is sufficiently large, the configurations obtained are generally different from the standard classes and need to be assessed separately.

### **6.2 ANALYSIS**

The objective of this analysis is to identify and describe the generic configurations of the degraded codisposal WP that have a potential for internal criticality. The standard degradation scenarios from Section 6.1.1.1 have been investigated in a systematic manner with respect to the processes and events presented in Section 6.1.1.2. The configurations resulting from the degradation processes that directly impact the potential for criticality (involving changes to a more reactive geometry; accumulation/retention of moderator; and separation of neutron absorbers from fissile material) have been grouped in configuration classes that are refinements of the configuration classes delineated in Section 6.1.2. The resultant configuration class refinements and their possible variations are presented as a guideline for the specific degradation criticality analysis to be performed for each particular type of SNF.

#### **6.2.1 Hydrology Conditions Influencing the Degradation Scenarios**

The following list of hydrology conditions covers all the possibilities that can affect the WP. The list applies to all scenarios that include the breach of both the WP and the DOE SNF canister.

**Flow regime:**

Continuous dripping

Intermittent dripping

Humidity only

**Breach location:**

Top (upper half) only

Bottom (lower half) only

Top and bottom

The behavior resulting from these conditions can be grouped as follows:

**Continuous and Intermittent Dripping**—The effect of intermittent dripping is similar to that of continuous dripping, with the following distinctions:

- Intermittent dripping may require longer times to fill and flush the WP. This has the same effect as lowering the average drip rate.
- Pondered water may evaporate in the times between dripping episodes. This will increase the concentration of dissolved ions in the remaining water. It may also leave a solid residue in those locations where the water evaporates completely. Both of these effects are considered as part of the geochemistry calculations (EQ3/6).

**Humid Only**—The resulting scenarios and configurations are independent of breach location. These cases can affect only minor relocation of material within the WP (primarily due to structural collapse). The relocations are similar to a subset of those that can be caused by dripping. With humid corrosion, the bulk degradation process will be much slower than that with aqueous corrosion. Therefore, since criticality is only affected by bulk relocation of neutronically significant materials, the increased probability of criticality provided by the humid-only corrosion scenarios will take effect only at very long times (upwards of 100,000 years).

**Top Breach Only**—If all the WP breaches are in the upper half only, the WP will fill with water to the level of the lowest breach after sufficient dripping time. This may also cause the DOE SNF canister to fill with water. Variations are possible with partial filling, depending on the breach located furthest below the top of the package.

**Bottom Breach Only**—If breaches occur in the lower half of the WP, there can be no significant flow of water into the WP by this mechanism unless the highest breach is below the height of any ponding in the drift. Even with the capillary action, the accumulation of water inside the WP will not be significant. Since the drift is designed to preclude the possibility of water ponding in the drift (with drains, etc.), corrosion from this mechanism is extremely unlikely. Since this alternative is unlikely to produce significant degradation, it is not necessary to distinguish the location of the breach in the DOE SNF canister.

**Top and Bottom Breach**—As mentioned previously, rapid degradation of solids containing neutronically significant elements may be provided when both top and bottom are breached, for both the WP and the DOE SNF canister. However, for such scenarios to lead to criticality, there must be some plugging of the holes in the bottom, so that water can eventually accumulate in the WP to provide neutron moderation. (It is not necessary for the holes in the bottom of the DOE SNF canister to plug, because the level of ponding water [or clay] in the DOE SNF canister will generally approximate the level immediately outside in the WP.) Such accumulation can be either as standing water (bathtub) or incorporated into degradation products as water of hydration

(clay or sludge). The DOE codisposal WP is the one with the greatest potential for this type of behavior because of its large amount of HLW glass as compared to the commercial SNF WP.

### **6.2.2 Generic Scenarios/Configurations Refinements for Codisposal WP**

Based on the discussions presented in Section 6.1, the generic degradation scenarios have been applied for the codisposal WP and the relevant configurations identified and analyzed. The different hydrology conditions considered for each scenario (particularly drip rates and patterns) will lead to variations of the resulting configurations. They are described and subdivided into configuration class refinements that represent sub-groupings within the general configuration classes presented in Section 6.1.2. Refinements of the configuration classes result also from the specific design of the codisposal WP. The presence of the DOE SNF canister inside the WP permits, by applying the standard degradation scenarios to it, the development of specific refinements within some of the configuration classes. For each configuration class refinement the following are given: sequence of the degradation processes, composition of the degradation products, and their relative positions inside the WP.

For many of the refinements it is appropriate to specify further variations according to the following parameters: (a) possible geometry of the form containing the fissile material, (b) separation between fissile material and neutron absorber, (c) amount of neutron absorber remaining in the WP, (d) plugging of the holes in the bottom of the WP, and (e) amount of water trapped in the glass clay or degradation product sludge.

This analysis addresses each standard scenario in order to identify all the representative configurations to be used in the criticality analysis. Note that, given the complex structure of the codisposal WP, distinction will be made in the analysis between the outer basket structure (outside the DOE SNF canister supporting HLW glass canisters) and the DOE SNF canister internal supporting structure that holds the SNF.

Based on the above, detailed discussion on the different refined configurations resulting from each of the degradation scenario groups, i.e., IP-1, IP-2, etc., are presented below along with the representative configuration figures. The WF in these figures is non-specific and is for illustration purpose only. Different SNF type will result in different degradation configurations.

The configuration refinements resulting from each scenario have also been codified for convenience by adding letters to the standard scenario denomination. However, in the description of each refinement, the corresponding class of configurations (from Section 6.1.2) that include the refinement is explicitly indicated.

**(IP-1) Configurations Resulting from Degradation Scenarios in which the SNF Degrades Before the OICs-**For IP-1 scenarios, the SNF degrades faster than the surrounding components, i.e., DOE SNF canister, HLW glass, and the supporting baskets inside and outside the DOE SNF canister. The WP and DOE SNF canister are considered breached at the top and flooded with water. The resultant configuration class refinements and their relevant variations with respect to criticality are presented as follows.

**(IP-1-A) SNF Degraded, DOE SNF Canister and Internal Supporting Structure not Degraded-**In this configuration class refinement, the DOE SNF canister interior is flooded but not degraded. The configurations result from the application of IP-1 scenario to the DOE SNF canister. Inside the DOE SNF canister, the supporting internals are in place but the SNF has degraded. Degradation of SNF implies that the support structure of the individual assemblies (spacer grids or exterior channels) has collapsed from degradation and the forms containing the fuel matrix (typically pins or plates) are contained in the compartments of the inner structure. The neutron absorber remains with its carrier (typically stainless steel structure). The degradation materials are distributed at the bottom of each inner structure compartment. The configurations obtained have the potential for a more reactive geometry with respect to criticality, especially for the highly enriched SNF. Since the SNF degrades in place, this configuration group is a refinement of the configuration class 6, as described in Section 6.1.2.

The possible variations of this configuration having an impact on criticality are as follows:

- (A) Configurations with partial degradation of the SNF (configurations at different stages of the SNF degradation, e.g., degraded fuel assemblies, degraded fuel cladding, and degraded fuel matrix).**
- (B) Configurations with partial/total degradation of the HLW canisters, which implies total degradation of the carbon steel supporting structure in the WP.**

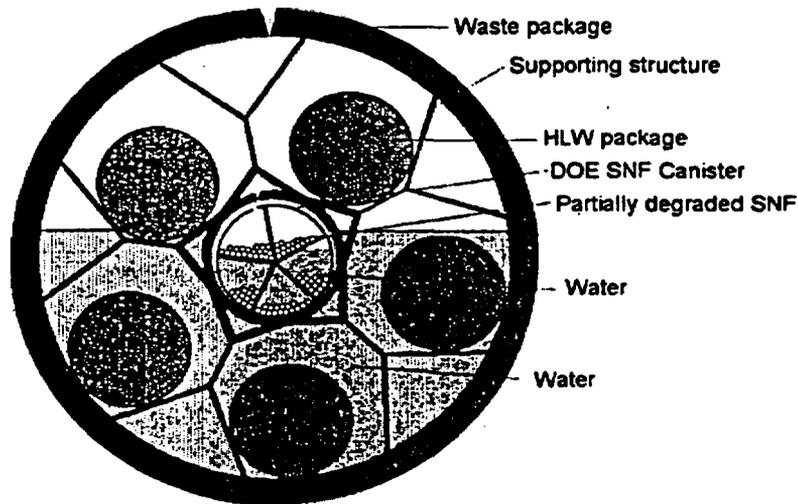


Figure 6-1. WP with SNF Degraded, DOE SNF Canister and Its Internal Supporting Structure not Degraded

**(IP-1-B) SNF Degraded, DOE SNF Canister Supporting Structure Partially Degraded**—In this configuration refinement group, obtained also by applying the standard scenario IP-1 to the DOE SNF canister, some of the inner supporting structures (inside the flooded DOE SNF canister) have partially degraded (e.g., localized corrosion). As a result, some degraded SNF could fall to the bottom of the DOE SNF canister and be separated from the neutron absorber. The evolution toward this group of configurations is enhanced by the events that can produce sudden modifications of the WP geometry, as those described in Section 6.1.3. More precisely, the localized corrosion could weaken the material of the supporting structure inside DOE SNF canister. Its collapse could then be triggered by a seismic disturbance or rockfall. This configuration group is a refinement of the configuration class 3 described in Section 6.1.2. Its increased potential for criticality is generally a result of separation of the fissile form from the neutron absorber.

The possible variations of this configuration having an impact on criticality are as follows:

- (A) Various combinations of degraded SNF at the bottom of DOE SNF canister.
- (B) Configurations with different quantities of neutron absorber trapped within the degraded SNF (most probable configurations).
- (C) Configurations including partial/total degradation of the structures outside the DOE SNF canister.

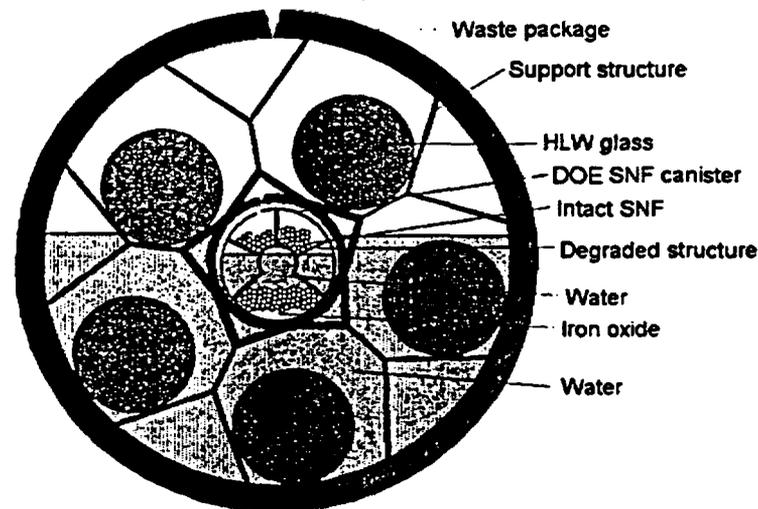


Figure 6-2. WP with SNF Matrix Degraded, DOE SNF Canister Supporting Structure Partially Degraded

**(IP-1-C) All WP Components Degraded**—This configuration group results from the subsequent degradation of the WP internals and HLW canisters after the above intermediate configurations have been reached. It also represents the final configuration obtained by applying scenario IP-2 to the whole WP. The composition of the mixture is dependent on the environmental conditions and availability of materials. The specific composition is calculated by a geochemistry analysis code (currently EQ3/6) with the environmental parameters such as drip rate and temperature as input. The configuration can be described as including the fissile material confined in one or more layers within the degradation products collected at the bottom of the WP. The neutron absorber can be partially separated in a different layer. The clay from the degraded HLW glass and WP internals forms a thick layer that includes the layers of the completely degraded SNF canister. These configurations are refinements of the configuration class 2 from Section 6.1.2. Both geometry of the fissile materials and separation of the neutron absorber affect the criticality potential.

The possible variations of this configuration having an impact on criticality are as follows:

- (A) Configuration with a DOE SNF canister not completely degraded containing fully degraded SNF and internals placed in the mass of degradation products from HLW glass and WP internals.
- (B) Configurations with the dissolved neutron absorber flushed out of the WP.

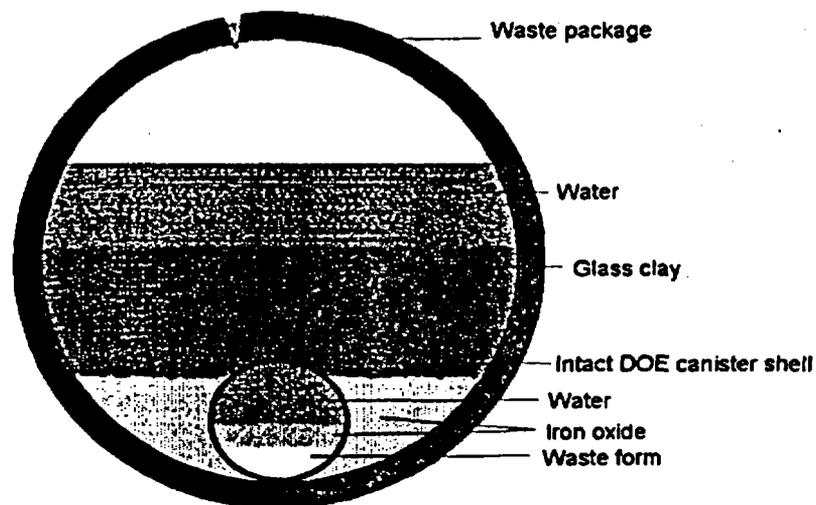


Figure 6-3. WP with its Internals Degraded, DOE SNF Canister Intact, SNF Degraded

- (IP-2) Configurations Resulting from Degradation Scenarios in which WP Components Degrade concurrently with the SNF**
- (IP-2-A) All WP Components Degraded**—The components of the flooded WP including the SNF will be degrading at the same time. The configurations result by applying the IP-2 scenario to the whole WP. The final composition inside the WP will be a mixture of fissile material, clay, and iron oxides. The characteristic of this group of configurations is the relative dispersal of the fissile material in the mass of the corrosion products and degraded constituents. Both DOE SNF canister's degraded components and the degradation products from HLW glass and supporting structure will collect at the bottom of WP. The specific parameters of these configurations are dictated by the amount of each constituent calculated by the geochemistry analysis code, taking into account the hydrology conditions and the materials affected by aqueous attack. This group of configurations is also a refinement of configuration class 2. The criticality concern associated with this class of configurations is due to the presence of the fissile material and moderator in a modified geometry, coupled with the possible separation from the neutron absorber (either by physical displacement or by flushing from the WP).

The possible variations of this configuration having an impact on criticality are as follows:

- (A) Configurations with different compositions of the layers, including the water content.
- (B) Configurations with the dissolved neutron absorbers flushed out of the WP.

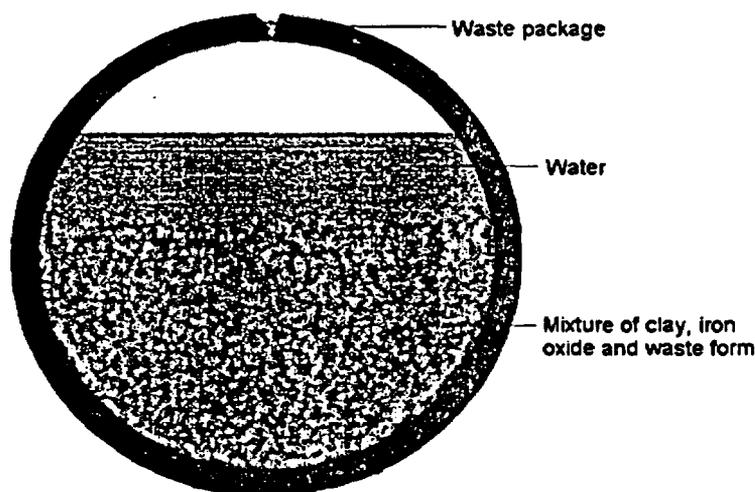


Figure 6-4. All Components Degraded with Mixture of Clay, Iron Oxide, and Degraded SNF

- (IP-3) **Configurations Resulting from Degradation Scenarios in which the SNF Degrades After the OICs**—The components external to flooded DOE SNF canister will be the first ones exposed to aqueous attack, and will start to degrade first. The carbon steel of the WP structural web supporting the HLW canisters will degrade fastest, and leave a significant amount of iron oxide in the bottom of the WP. Much of the HLW glass will degrade before the DOE SNF canister is breached, and the silica released will form a clay layer at the bottom of the WP (mostly above the initial iron oxide layer).
- (IP-3-A) **Degraded DOE SNF Canister Internal Structure; Intact SNF and DOE SNF Canister Shell; Degraded WP Basket Structure and HLW Glass Canister(s)**—In this configuration, which results after the application of scenario IP-3 to the flooded DOE SNF canister, the supporting structure inside the DOE SNF canister degrades before the SNF. The intact SNF falls to the bottom of DOE SNF canister. This configuration is characterized by the intact SNF stacked at the bottom of the DOE SNF canister, surrounded by degradation materials from stainless steel and neutron

absorber. Partial separation of the neutron absorber is possible: it is more likely if combined with the category of events described in Section 6.1.3. This configuration group is a refinement of configuration class 1 described in Section 6.1.2. The configurations are relatively insensitive to whether the materials outside the DOE SNF canister are degraded or not. Modified geometry and separation from the neutron absorber make this group of configurations susceptible to criticality.

The possible variations of this configuration having an impact on criticality are as follows:

- (A) Configurations with various arrangements of the intact SNF at the bottom of the DOE SNF canister.
- (B) Configurations with variations in the distribution of the degraded neutron absorbers.
- (C) Configurations with the dissolved neutron absorbers flushed out of the WP. Note that this configuration is the most likely to cause criticality unless positive measures are taken to ensure the insolubility of the neutron absorber material.

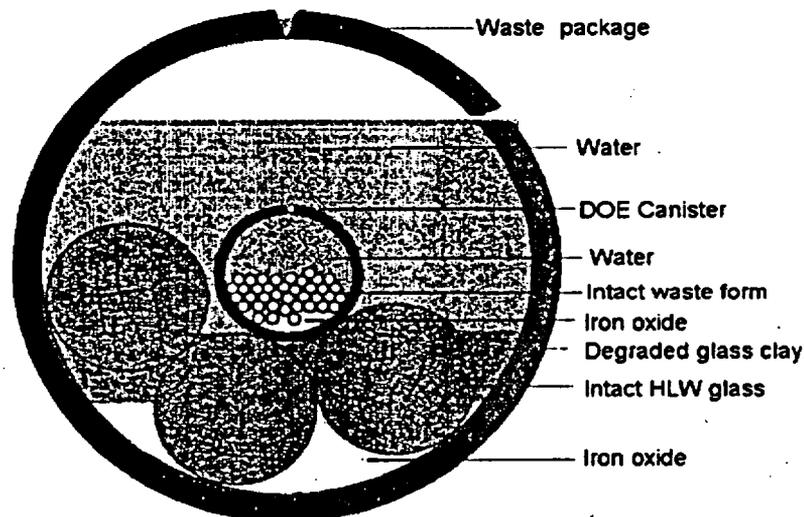


Figure 6-5. Degraded DOE SNF Canister Internal Structure: Intact SNF and DOE SNF Canister Shell: Degraded WP Basket Structure and HLW Glass Canister(s)

- (IP-3-B) Degraded WP Basket Structure, HLW Glass Canister(s), and DOE SNF Canister; Intact SNF—In this configuration, which results from the application of scenario IP-3 to the whole WP, all the WP internal structure materials and the HLW

glass are degraded first, followed by the degradation of the DOE SNF canister and the supporting structure inside. If the SNF stays in solid form due to its high resistance to bulk corrosion (possible for certain types of SNF), it can fall to the bottom of WP, break into small pieces (due to localized corrosion), scatter, and mix with the glass clay and steel degradation materials. If the SNF matrix stays intact, the configuration may be characterized by the intact SNF matrix stacked at the bottom of the WP, surrounded by clay and layers of steel degradation materials. This configuration group is a refinement of the configuration class 1 described in Section 6.1.2, but has a lower potential for criticality compared with the configuration group IP-3-A above (the fissile material is usually more dispersed).

The possible variations of this configuration having an impact on criticality are as follows:

- (A) Configurations with various arrangements of intact SNF at the bottom of the WP.
- (B) Configurations including subsequent degradation stages of the SNF matrix (e.g., spacer grids, cladding, fuel matrix).
- (C) Configurations with variations in the distribution of the degraded neutron absorbers.
- (D) Configurations with the dissolved neutron absorbers flushed out of the WP.

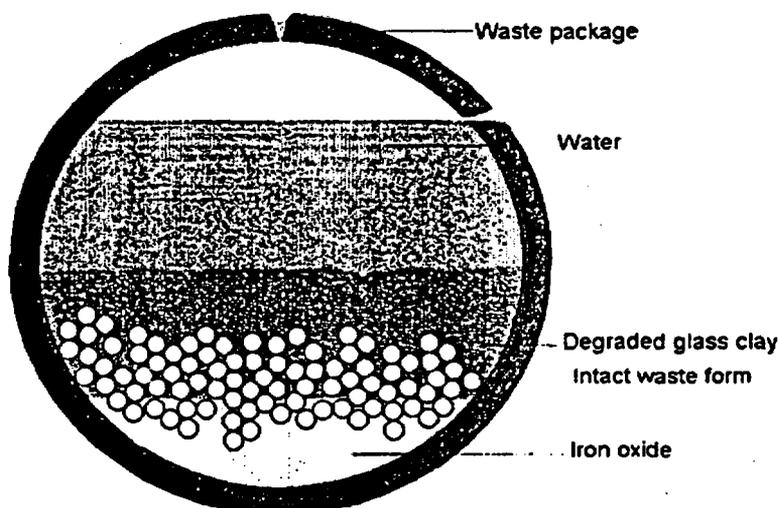


Figure 6-6. Degraded WP Basket Structure, HLW Glass Canister(s), and DOE SNF Canister; Intact FWF

**(IP-3-C) All WP Components Degraded**—The final stage of scenario IP-3 applied to the entire WP is a configuration group with all degraded materials inside the WP, but with the degraded FWF layer confined at the bottom. The configurations are similar in many respects to those resulting from scenarios IP-1 and IP-2, and represent a refinement of the configuration class 2.

The possible variations of this configuration having an impact on criticality are as follows:

(A) Configurations with variations in the localization of the degraded neutron absorbers.

(B) Configurations with the dissolved neutron absorbers flushed out of the WP.

**(IP-4) Configurations Resulting from Flow-through Degradation Scenarios in which the SNF Degrades Before the OIC**—For this scenario, the SNF is degraded faster than the surrounding components with flow-through conditions. The scenario IP-4 is applied to the entire WP. The difference from scenario IP-1 is the fact that both the bottom and top of the WP and DOE SNF canister are penetrated. This condition may allow water to flush dissolved material out of the WP at a higher rate than if the water were ponding and the dissolved material could only exit the WP after circulating from the dissolving surface to the location where water is flowing out of the package.

**(IP-4-A) SNF Degraded, DOE SNF Canister Shell not Fully Degraded**—The degradation products of the fissile material remain in place in a relatively immobilized form to be locked by its own hydration or by hydration of the DOE SNF canister internals. The other WP internals are degraded and included in the resultant clay or sludge. Moderator is also provided by the water trapped in clay. This configuration can be reached directly by scenario IP-4 and indirectly after scenario IP-1 if the bottom of the WP is subsequently penetrated. The composition of the mixture can be calculated by specific geochemistry analysis (see also Assumption 1). The corresponding configuration class for this group is class 5 from Section 6.1.2.

The possible variations of this configuration having an impact on criticality are as follows:

(A) Configurations with partial removal of dissolved neutron absorbers.

(B) Configurations with various locations of the DOE SNF canister inside the clay volume.

(C) A configuration resulting from a subsequent plugging (by clay) of the WP exit hole.

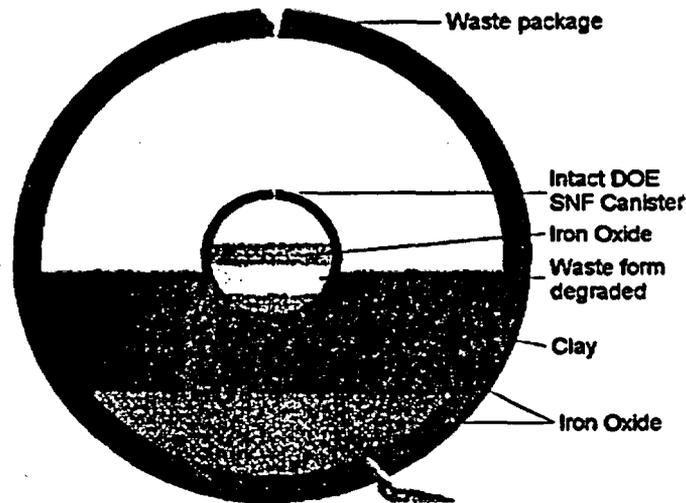


Figure 6-7. FWF Degraded, DOE SNF Canister Shell not Fully Degraded

- (IP-4-B) All WP Components Degraded**—The difference from the similar group of configurations analyzed for scenario IP-1 is the fact that for the IP-4 configurations the neutron moderator is provided either by water trapped in clay or by hydration of metal corrosion products. Also the composition of the mixture calculated from geochemistry analysis could be different due to a locally faster removal of soluble degradation products (see also Assumption 1). The fissile material is spread over a larger fraction of the WP volume, and can be situated anywhere in the layers of clay and degradation materials. These configurations occur as a subsequent stage of the scenarios leading to the previous group and can also be categorized as refinements of the configuration class 5.
- (IP-5) Configurations Resulting From Flow-through Degradation Scenarios in which WP Components Including the SNF, Will Be Degrading Concurrently**
- (IP-5-A) All WP Components Degraded**—The characteristics of these configurations are similar to the group of configurations resulting from scenario IP-2 above. The main difference is the faster rate of flow-through flushing, which can change the composition of the sludge or clay and remove the soluble products at a faster rate. The moderator is provided either by the water trapped in clay or by hydration of metal corrosion products. The fissile material accumulates at the bottom of the WP. The configurations can also be reached indirectly from any other scenarios since the degradation of HLW glass will result in a large amount of clay in any scenario. The configurations in this group are a refinement of configuration class 4.

The possible variations of this configuration having an impact on criticality are as follows:

- (A) Configurations with removal of dissolved neutron absorber.
- (B) A configuration resulting from a subsequent plugging (by clay) of the WP exit hole.

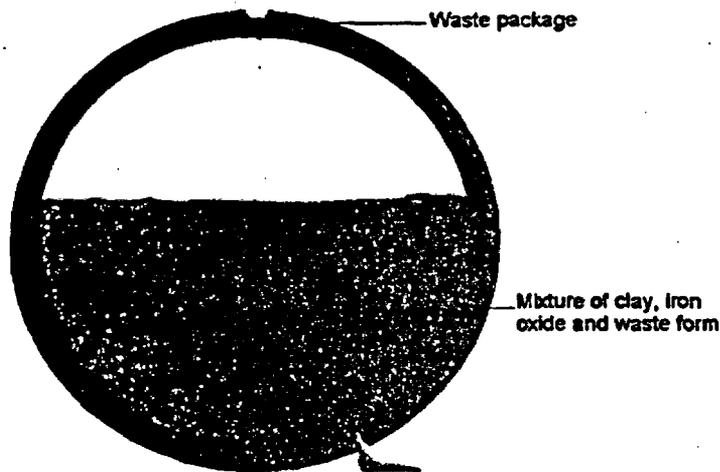


Figure 6-8. All WP Components Degraded with Mixture of Clay, Iron Oxide, and FWF

**(IP-6) Configurations Resulting from Flow-through Degradation Scenarios in which the SNF Degrades After the OIC**

**(IP-6-A) All WP Components Degraded**—There are no significant differences in the characteristics of the configurations obtained from this scenario with the previous group. The intermediate stage would have the SNF degraded in place with less hydration, which is covered in IP-3. The degraded fissile material is disposed in layers situated mainly at the bottom of the WP. The soluble neutron absorbers can be flushed out or, if insoluble, dispersed in the mixture of hydrated corrosion products or confined in layers. The composition of the mixture inside WP is calculated by geochemistry calculations. The configurations belong also to configuration class 4 described in Section 6.1.2. The principal determinant of criticality is the presence of the moderator (water) in the hydrated products.

The possible variations of this configuration having an impact on criticality are as follows:

- (A) Configurations with removal of soluble neutron absorber.
- (B) A configuration resulting from a subsequent plugging (by clay) of the WP exit hole.

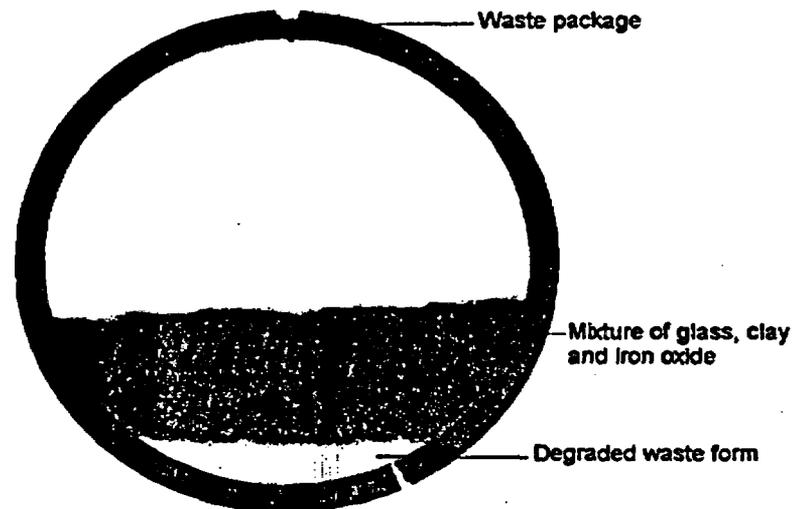


Figure 6-9. All WP Internal Components Degraded with Degraded FWF at the Bottom of WP

### 6.2.3 WP Tilting

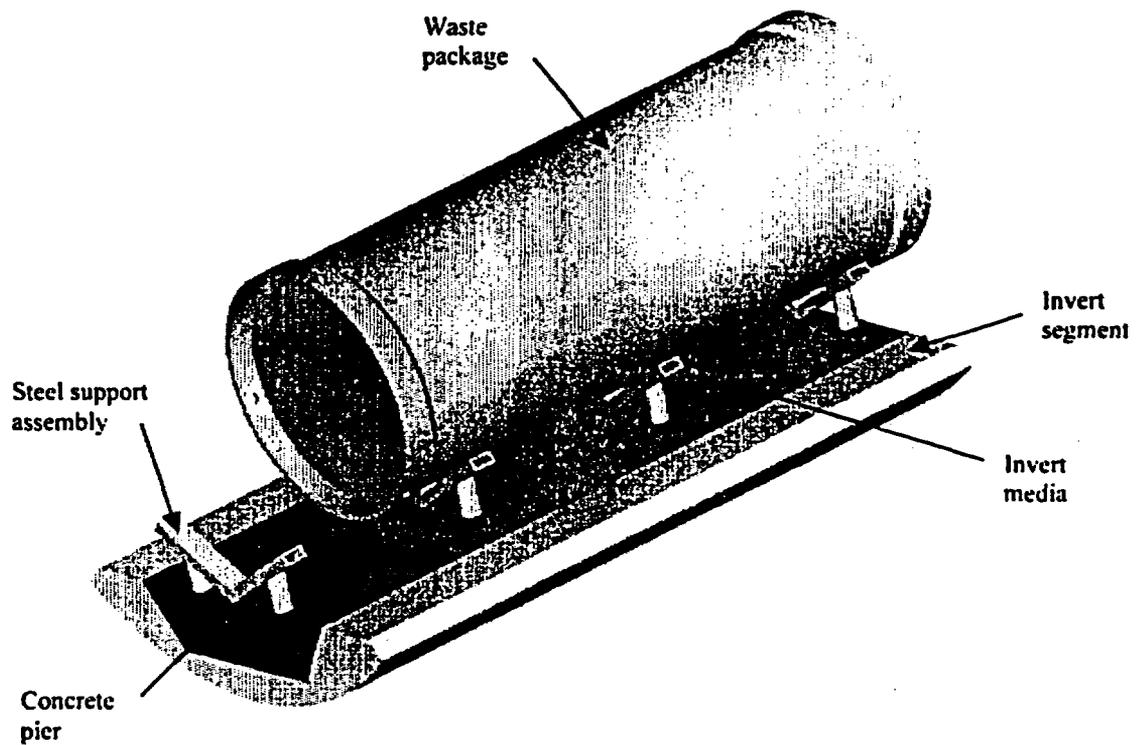
Tilt angle has great influence on the distribution of degraded products inside the WP. Tilting can result in changing the concentrations of the fissile materials and the neutron absorber and also the separation between them, i.e., potentially a more favorable geometry for criticality.

A preliminary analysis of WP tilt for the commercial SNF indicates that the most probable angle of tilt for the WP, relative to the ground of the repository drift, is very small. To evaluate the impact of a small angle of tilt on the degradation configurations for DOE SNF, three possibilities are considered: (1) intact DOE SNF canister and intact SNF inside, (2) intact DOE SNF canister with degraded OICs and SNF inside, and (3) degraded DOE SNF canister and degraded SNF. For the first case, no angle of tilt can cause any change or degradation since the WP is designed to maintain its internal arrangement in any orientation. For the second and third cases, the extent of the impact of tilting on the configuration would depend on the type of SNF. However significant redistribution of the degradation products inside the WP is not expected for a small angle of tilt.

For a large tilt angle of the WP, the impact could be significant in terms of the concentration of the fissile materials and separation of the fissile materials from neutron absorbers due to redistribution. However, as shown in Figure 6-10 (for a VA design), the occurrence of a large tilt angle requires the following events:

- (A) The steel support at the center of WP is intact and the other supports have degraded (this configuration results in the largest angle of tilt).
- (B) The concrete pier has degraded and collapsed.
- (C) The invert media has degraded and collapsed.

Obviously, the probability for all of the above events happening collectively is very small.



**Figure 6-10. Emplacement Drift Segment (VA Design)**

## **7. CONCLUSIONS**

Based on the systematic analysis of the standard degradation scenarios and associated configurations presented in the *Disposal Criticality Analysis Methodology Topical Report*, a comprehensive set of refinements for the codisposal WP can be developed to encompass all foreseeable events and processes. The refinements are identified by considering the entire spectrum of degradation scenarios applied to the DOE SNF canister and/or to the entire WP in conjunction with the specific degradation processes and initial hydrology conditions.

For many of the refinements with potential for internal criticality, further variations can be specified according to the following parameters:

- Geometry of the fissile material in degraded form
- Separation between the fissile material and neutron absorber
- Amount of the neutron absorber available in the WP
- Plugging of holes in the bottom of the WP
- Amount of water trapped in clay or degradation product sludge.

The resultant configuration class refinements and their variations will serve as a guideline for the specific degradation criticality analysis to be performed for each particular type of DOE SNF.

**8. REFERENCES**

1. Civilian Radioactive Waste Management System Management & Operating Contractor (CRWMS M&O) 1998. *Disposal Criticality Analysis Methodology Topical Report*. B00000000-01717-5705-00095 REV 00. Las Vegas, Nevada: CRWMS M&O. ACC: MOL.19980918.0005.
2. CRWMS M&O 1998. *Evaluation of Codisposal Viability for Aluminum-Clad DOE-Owned Spent Fuel: Phase II, Degraded Codisposal Waste Package Internal Criticality*. BBA000000-01717-5705-00017 REV 01. Las Vegas, Nevada: CRWMS M&O. ACC: MOL.19980701.0782.
3. Department of Energy (DOE) 1998. *Preliminary Design Specification for Department of Energy Standardized Spent Nuclear Fuel Canisters, Volume 1- Design Specification*. DOE/SNF/REP-011, Revision 0. Washington, D.C.: DOE. TIC: 240539.
4. CRWMS M&O 1998. *EQ6 Calculations for Chemical Degradation of Fast Flux Test Facility (FFTF) Waste Packages*. BBA000000-01717-0210-00028 REV 00. Las Vegas, Nevada: CRWMS M&O. ACC: MOL.19981229.0081.
5. DOE, Office of Civilian Radioactive Waste Management (OCRWM) 1998. *Viability Assessment of a Repository at Yucca Mountain, Volume 2- Preliminary Design Concept for the Repository and Waste Package*. DOE/RW-0508. Las Vegas, Nevada: DOE, OCRWM. ACC: MOL.19981007.0029.
6. CRWMS M&O 1998. *Software Routine Report for WAPDEG (Version 3.09)*. CSCI:30048 v 3.09. DI: 30048-2999 REV 02. Las Vegas, Nevada: CRWMS M&O. ACC: MOL.19981012.0224.
7. CRWMS M&O 1997. *Criticality Evaluation of Degraded Internal Configurations for the PWR AUCF WP Designs*. BBA000000-01717-0200-00056 REV 00. Las Vegas, Nevada: CRWMS M&O. ACC: MOL.19971231.0251.
8. CRWMS M&O 1998. *Geochemical and Physical Analysis of Degradation Modes of HEU SNF in a Codisposal Waste Package with HLW Canisters*. BBA000000-01717-0200-00059 REV 01. Las Vegas, Nevada: CRWMS M&O. ACC: MOL.19980624.0325.
9. DOE OCRWM 1998. *Viability Assessment of a Repository at Yucca Mountain, Volume 3- Total System Performance Assessment*. DOE/RW-0508. Las Vegas, Nevada: DOE OCRWM. ACC: MOL.19981007.0030.
10. CRWMS M&O 1999. *Classification of the MGR DOE Spent Nuclear Fuel Disposal Container System*. ANL-EDC-SE-000001 REV 00. Las Vegas, Nevada: CRWMS M&O. ACC: MOL.19990928.0141.

**Title: Generic Degradation Scenario and Configuration Analysis for DOE Codisposal Waste Package**

**Document Identifier: BBA000000-01717-0200-00071 REV 00**

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11. CRWMS M&O 1999. *Activity Evaluation, DOE Spent nuclear Fuel (SNF) – 2101 2310 M1–M8*. WP-12. Las Vegas, Nevada: CRWMS M&O. ACC: MOL.19991001.0154.
12. DOE 1998. *Quality Assurance Requirements and Description*. DOE/RW-0333P, Revision 8. Washington, D.C.: U.S. Government Printing Office. ACC: MOL.19980601.0022.
13. CRWMS M&O 1999. *Analysis And Models, AP-3.10Q*. Revision 0, ICN 0. Las Vegas, Nevada: CRWMS M&O. ACC: MOL.19990225.0335.

**9. ATTACHMENTS**

None.