

# Calculation Cover Sheet

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## Table of Contents

<u>Item</u>	<u>Page</u>
1. PURPOSE .....	5
2. METHOD.....	5
3. ASSUMPTIONS .....	6
4. USE OF COMPUTER SOFTWARE .....	9
4.1 EQ3/6 Software Package .....	9
4.2 Software Routines for Chaining Successive EQ6 Cases .....	10
4.2.1 Files bldinput.bat (for HP), CSCI# 30044 V1.0.....	10
4.2.2 File bldinput.c, CSCI# 30045 V1.0.....	11
4.2.3 Files nxtinput.bat (for HP), CSCI# 30046 V1.0, and nxti_bat.c (for PC), CSCI# 30046 V1.1.....	11
4.2.4 File nxtinput.c (for both HP and PC), CSCI# 30047 V1.0.....	11
4.2.5 Files Allpost.bat (for HP), CSCI# 30050 V1.0 and Allp_bat.c (for PC), CSCI# 30050 V1.1 .....	11
4.2.6 Files PostprocP.c (for HP), CSCI# 30049 V1.1, and postprocP.c (for PC), CSCI# 30049 V1.2 .....	11
4.2.7 Files Lastpost.c (for both HP and PC), CSCI# 30051 V1.0.....	11
4.3 Pro/Engineer version 17.0 .....	12
4.4 Spreadsheets .....	12
4.5 Software Approved for QA Work .....	12
5. CALCULATIONS .....	12
5.1 Calculation Inputs.....	12
5.1.1 WP Materials and Performance Parameters.....	12
5.1.1.1 Chemical Characteristics of Representative Spent Nuclear Fuel (SNF) Waste Packages.....	13
5.1.1.2 Chemical Composition of J-13 Well Water .....	18
5.1.1.3 Drip Rate of J-13 Water into a Waste Package .....	19
5.1.1.4 Densities and Molecular Weights of Solids .....	21
5.1.1.5 Atomic Weights .....	22
5.2 Data Conversion .....	22
5.2.1 Mole Fractions of Elements in SNF.....	22
5.2.2 Atom Fractions of Elements in Basket Metals.....	25
5.2.3 Degradation Rates.....	26
5.2.4 Calculation of Equilibrium Constants for Rhodium Species .....	27
5.2.5 Calculations of Volumes and Surface Areas of Basket Materials.....	28
5.3 EQ6 Calculations and Scenarios Modeled .....	28
5.3.1 Degradation of Basket Only.....	29
5.3.2 Simultaneous Degradation of Basket and LEU SNF .....	33
5.3.3 Degradation of SNF after Degradation of Basket .....	45
6. RESULTS .....	51
7. REFERENCES.....	53
8. ATTACHMENTS .....	55

## Tables

<u>Item</u>	<u>Page</u>
Table 5.1.1.1-1. Elemental Composition in Gram-atoms/Assembly for 4.9%, 34 GWd/MTU B&W 15x15 PWR LEU Fuel Assembly .....	13
Table 5.1.1.1-2. Elemental Composition in Gram-atoms/Assembly for 4.0%, 35.6 GWd/MTU 15x15 Westinghouse PWR MOX Fuel Assembly .....	14
Table 5.1.1.1-3. Dimensions for Basket Components .....	16
Table 5.1.1.1-4. Basket Dimensions for Westinghouse Vantage 5 17x17 Assembly .....	16
Table 5.1.1.1-5. Metal Compositions, Weight Percent .....	17
Table 5.1.1.1-6. Metal Corrosion Rates .....	18
Table 5.1.1.1-7. Metal Densities .....	18
Table 5.1.1.1-8. 21 PWR LEU or PWR MOX Waste Package Dimensions .....	18
Table 5.1.1.2-1. Composition of J-13 Well Water .....	19
Table 5.1.1.3-1. Correlation between Percolation Rate and Drip Rate onto a Waste Package (Data Taken from Tables 2.3-49 and 2.3-50 of Ref. 21) .....	20
Table 5.1.1.4-1. Densities and Molecular Weights of Precipitated Solids .....	21
Table 5.1.1.4-2. Miscellaneous Constants .....	22
Table 5.1.1.4-3. Thermodynamic Data .....	22
Table 5.2.1-1. Elemental Composition in Atom Fraction for 21 B&W 15x15 PWR LEU Assemblies with 4.9%, 34 GWd/MTU .....	23
Table 5.2.1-2. Elemental Composition in Atom Fraction for 4.0%, 35.6 GWd/MTU 17x17 Westinghouse MOX SNF Fuel Assembly .....	24
Table 5.2.2-1. Atom Fractions for A516 .....	25
Table 5.2.2-2. Atom Fractions for Borated SS .....	25
Table 5.2.2-3. Atom Fractions for Al Alloy .....	26
Table 5.2.3-1. Molecular Weights of Reactants .....	26
Table 5.2.3-2. Reaction Rates of Reactants .....	27
Table 5.2.3-3. Moles and Surface Areas of Reactants/kg Water .....	27
Table 5.2.4-1. Equilibrium Constants for Rh Species at 25°C .....	28
Table 5.2.5-1. Calculation of Volumes for PWR MOX Waste Package .....	28
Table 5.3.1.1-1. Comparison of PWR LEU Basket Corrosion at Low Drip Rate with Corrosion at Mean Rate .....	33
Table 5.3.2-1. Percentages of Selected Elements Remaining as Solids in the Degraded PWR LEU Waste Package at Various Times -- Case Corresponds to Simultaneous Degradation of Basket and SNF. Hematite Present <sup>2</sup> . Drip Rate 0.15 m <sup>3</sup> /yr. ....	34
Table 5.3.2-2. Concentrations of Selected Elements in the Degraded PWR LEU Waste Package at Various Times -- Case Corresponds to Simultaneous Degradation of Basket and SNF. Hematite Present* <sup>2</sup> Drip Rate was 0.15 m <sup>3</sup> /yr. Molalities .....	37
Table 5.3.2-3. Concentrations of Selected Elements in the Degraded PWR LEU Waste Package at Various Times -- Case Corresponds to Simultaneous Degradation of Basket and SNF. Hematite Suppressed* <sup>2</sup> Drip Rate was 0.15 m <sup>3</sup> /yr. Molalities .....	39
Table 5.3.3-1. Percentages of Selected Elements Remaining in the Degraded PWR LEU Waste Package at Various Times -- Case Corresponds to Breaching of Zircaloy and Initiation of SNF Degradation After Basket Fully Degraded <sup>2</sup> Drip Rate 0.15 m <sup>3</sup> /yr. ....	46
Table 5.3.3-2. Percentages of Selected Elements Remaining in the Degraded PWR MOX Waste Package at Various Times -- Breaching of Zircaloy and Initiation of SNF Degradation After Basket Fully Degraded. Drip Rate 0.15 m <sup>3</sup> /yr. <sup>2</sup> .....	48
Table 5.3.3-3. Percentages of Selected Elements Remaining in the Degraded PWR MOX Waste Package at Various Times -- Breaching of Zircaloy and Initiation of SNF Degradation After Basket Fully Degraded. Drip Rate 0.015 m <sup>3</sup> /yr. <sup>2</sup> .....	50

<u>Item</u>	<u>Figures</u>	<u>Page</u>
Figure 5.1.1.3-1. Percolation to drip rate correlation.....		20
Figure 5.3.1-1. Volume percentages of void space in a 21 PWR LEU waste package occupied by principal minerals precipitated, Zircaloy intact.....		31
Figure 5.3.1-2. Masses of principal corrosion product solids in a 21 PWR LEU waste package, Zircaloy intact.....		32
Figure 5.3.2-1. Percent of selected elements remaining in solid phases in a 21 PWR LEU waste package; Zircaloy breached early, hematite present. ....		35
Figure 5.3.2-2. Volume percentages of void space in a 21 PWR LEU waste package occupied by principal minerals precipitated; Zircaloy breached early, hematite present. ....		36
Figure 5.3.2-3. Masses of principal corrosion product solids in a 21 PWR LEU waste package; Zircaloy breached early, hematite present.....		37
Figure 5.3.2-4. Aqueous concentrations (molalities) of selected elements in a 21 PWR LEU waste package; Zircaloy breached early, hematite present.....		38
Figure 5.3.2-5. Volume percentages of void space in a 21 PWR LEU waste package occupied by principal minerals precipitated; Zircaloy breached early, goethite present.....		40
Figure 5.3.2-6. Masses of principal corrosion product solids in a 21 PWR LEU waste package; Zircaloy breached early, goethite present. ....		41
Figure 5.3.2-7. Percent of selected elements remaining in solid phases in a 21 PWR LEU waste package; Zircaloy breached early, goethite present. ....		42
Figure 5.3.2-8. Aqueous concentrations (molalities) of selected elements in a 21 PWR LEU waste package; Zircaloy breached early, goethite present.....		43
Figure 5.3.2-9. Percent of selected elements remaining in solid phases in a 21 PWR MOX waste package; Zircaloy breached early, hematite present, mean drip rate. ....		44
Figure 5.3.2-10. Percent of selected elements remaining in solid phases in a 21 PWR MOX waste package; Zircaloy breached early, hematite present, high drip rate.....		45
Figure 5.3.3-1. Percent of selected elements remaining in solid phases in a 21 PWR LEU waste package; Zircaloy breached late, mean drip rate.....		47
Figure 5.3.3-2. Percent of selected elements remaining in solid phases in a 21 PWR MOX waste package; Zircaloy breached late, mean drip rate.....		49
Figure 5.3.3-3. Percent of selected elements remaining in solid phases in a 21 PWR MOX waste package; Zircaloy breached late, low drip rate. ....		51

## 1. Purpose

The Monitored Geologic Repository (MGR) Waste Package Operations of the Civilian Radioactive Waste Management System Management & Operating (CRWMS M&O) contractor performed calculations to provide input to the design of a waste package (WP). This document analyzes the degradation processes of two types of pressurized water reactor (PWR) spent nuclear fuel (SNF):

- Fuel fabricated from low enriched uranium oxide, which has been used, or will be used, in commercial nuclear power plants. This SNF is referred to as LEU (low enriched uranium) SNF.
- Fuel fabricated from plutonium oxide and uranium oxide, which may be used in commercial nuclear power plants in the future. This fuel has not yet been fabricated. It is referred to as MOX (mixed oxide) SNF.

The specific objectives were to determine the geochemical conditions under which:

- 1) The criticality control material suggested for this design will remain in the degraded waste package after the corrosion/dissolution of its initial form (such that it can be effective in preventing criticality), and
- 2) The fissile plutonium and uranium will be carried out of the degraded waste package by infiltrating water (such that internal criticality is no longer possible, but the possibility of external criticality may be enhanced).

The results will be used to determine the nominal chemical composition for the criticality evaluations of the waste package design, and to suggest the range of parametric variations for additional evaluations. These chemical compositions (and consequent criticality evaluations) are determined for time periods up to 100,000 years because it is considered likely that the US Nuclear Regulatory Commission will require demonstration of criticality control for longer than 10,000 years. This longer time frame extends the calculations closer to the 1 million years time horizon recently recommended by the National Academy of Sciences to the Environmental Protection Agency for performance assessment related to a nuclear repository (National Research Council, 1995, Ref. 1).

Boron (B) in the form of borated stainless steel was included in the calculations, as were various neutron absorbing fission products, notably Gd and Nd. These elements are important for inclusion in calculations of WP internal criticality. The results of this analysis will be used to ensure that the type and amount of criticality control material used in the waste package design will prevent criticality.

## 2. Method

The method used for this analysis involves the following steps:

Use of basic EQ3/6 (software package, see Section 4.1) capability for tracing the progress of reactions with evolution of the chemistry, including the estimation of the concentrations remaining in solution and the composition of the precipitated solids. (EQ3 is used to set up EQ6 calculations; it does not simulate reaction progress.)

Evaluation of available data on the range of dissolution rates for the materials involved, to be used as material/species input for each time step.

Use of "pseudo flow-through" mode in which:

- 1) Water is added continuously to the waste package and builds up in the waste package over a sequence of time steps (typically 15 to 18 steps per sequence, except for the initial sequence). The first sequence typically ranges from 200 to 600 steps. The duration of a time step modeled for the individual EQ6 time steps range from 0.01 seconds to 1000 days as determined automatically by the

first sequence typically ranges from 200 to 600 steps. The duration of a time step modeled for the individual EQ6 time steps range from 0.01 seconds to 1000 days as determined automatically by the program. The modeled duration of a sequence, including the initial sequence, stays constant within the limits imposed internally by the program. This time is determined from the selected drip rate, e.g., 0.15 m<sup>3</sup>/yr entering the WP, and the percentage of added water selected. This percentage is set at 10% at the beginning of a set of runs, and typically increased to 100% to enable modeling of very long times after initial relatively rapid chemical changes have settled down to a quasi-steady state.

- 2) Flushing action (removal of water added during one EQ6 sequence) is simulated by specifying smaller amounts of water and solutes for input to the next EQ6 sequence than were present at the end of the preceding sequence. The mass of water simulated as removed equals the mass of water added, adjusted for water calculated to enter, or released from, solids. Solutes are removed in proportion to their concentrations in that mass of water.

Determination of fissile concentrations in solution as a function of time (from the output of EQ6 sequences over times up to or somewhat greater than 100,000 years).

Calculation of the amount of fissile material released from the waste package as a function of time (which thereby reduces the chance of criticality within the waste package).

Determination of concentrations of neutron absorbers, such as B and Gd, in solution as a function of time (from the output of EQ6 sequences over times up to or somewhat greater than 100,000 years).

Calculation of the amount of neutron absorbers retained within the waste package as a function of time.

Further detail on the specific methods employed for each step is available in Section 5 of this set of calculations.

### 3. Assumptions

All assumptions are for preliminary design; these assumptions will require verification before this analysis can be used to support procurement, fabrication, or construction activities. All assumptions are used throughout Section 5.

- 3.1 It is assumed that J-13 well water fills all voids within waste packages. It is further assumed that the composition of this water will remain as given in Harrer et al., 1990 (Ref. 2) for up to 100,000 years. The basis for the first part of this assumption is that it provides the maximum degradation rate with the potential for the fastest flushing of the neutron absorber from the DOE SNF canister and from the waste package, and is, thereby conservative. The basis for the second part of the assumption is that there is no basis for predicting any change in this composition over a 100,000-year time period, although for a few thousand years after waste emplacement the composition may differ because of perturbations resulting from reactions with engineered materials and from the thermal pulse. These are not taken into account in this calculation because the corrosion allowance and corrosion resistant barriers are not expected to breach until after that perturbed period. Therefore, the early perturbation is not relevant to the calculations reported in this document. See Assumption 3.3.
- 3.2 It is assumed that the density of J-13 well water is 1.0 g/cm<sup>3</sup>. The basis is that for dilute solutions, the density differs extremely little from that for pure water and that any differences are insignificant in respect to other uncertainties in the data and calculations. Moreover, this number is used only initially in EQ3/6 to convert concentrations of dissolved substances from parts per million to molalities.
- 3.3 The assumption that the water entering the waste package can be approximated by the J-13 water implicitly assumes: (1) that the infiltrating water will have only a minimal contact, if any at all, with undegraded

metal in the corrosion allowance barrier, and (2) that any effects of contact with the drift liner will be minimal after a few thousand years. The basis for the first part of this assumption is that the water should move rapidly enough through openings in the waste package barriers that its residence time in the corroded barrier will be too small for significant reaction to occur. Furthermore, the water flowing through the barriers will be in contact with the corrosion products left from the barrier corrosion that created the holes in the first place, but these corrosion products will closely resemble iron oxides and hydroxides in the overlying rock. Consequently, the water should already be close to equilibrium with these compounds and would be unaffected by further contact with them, even if it flowed slowly enough to permit significant reaction. The second part of this assumption is justified by the following: (1) The drift liner at the top of the drift is expected to collapse with the roof support well before 1000 years. (2) The water flowing through the concrete liner, dominantly along fractures, will be in contact with the degradation products of the liner which will have come close to equilibrium with the water moving through the rock above the repository. Interaction of water in the fractures with any undegraded concrete between fractures would be minimal owing to the slow rate of diffusion through the matrix compared to rate of flow through fractures.

- 3.4 It is assumed water may circulate freely enough in the partially degraded WP that all degraded solid products may react with each other through the aqueous solution medium. The basis is that this provides one bound for the extent of chemical interactions within the WP and conservatively simulates potential preferential loss of neutron absorbers from the waste package by facilitating contact of any acid, which may result from corrosion of steel, with neutron absorbers in spent fuel.
- 3.5 It has been assumed that the database supplied with the EQ3/6 computer package is sufficiently accurate for the purposes of this report. The basis is that the data have been carefully scrutinized by many experts over the course of several decades and carefully selected by Lawrence Livermore National Laboratory (LLNL) for incorporation into the data base (Wolery, 1992a, Ref. 3; Daveler and Wolery, 1992, Ref. 4; Wolery, 1992b, Ref. 5; Wolery and Daveler, 1992, Ref. 6). These databases are periodically updated and/or new databases added, such as one including extensive data on the lanthanides (Spahiu and Bruno, 1995, Ref. 7). Every run of either EQ3 or EQ6 documents automatically which database is used. The databases include references internally for the sources of the data. The reader is referred to this documentation, included in electronic files labeled data0 that accompany this report, for details. Nevertheless, this review and documentation do not absolutely guarantee that all the data are adequate.
- 3.6 In general it is assumed that chromium and molybdenum will oxidize fully to chromate (or dichromate) and molybdate, respectively. This is based on the available thermodynamic data, which indicate that in the presence of air the chromium and molybdenum would both oxidize to the +6 valence state. Laboratory observation of the corrosion of Cr and Mo containing steels and alloys, however, indicates that any such oxidation would be extremely slow. It in fact may not occur at a significant rate in respect to the time frame of interest. For the present analyses, the assumption is made that over the times of concern the oxidation will occur. This is conservative for times of several thousand years after waste package breach, when the high pH solution from any drift liner effects, has been flushed out of the waste package. Acidification of the water will enhance solubility and transport of neutron absorbers out of the WP thereby separating it preferentially from fissile material.
- 3.7 It is assumed that the inner corrosion resistant barrier will react so slowly with the infiltrating water as to have negligible effect on the chemistry. The bases consist of the facts that this metal corrodes very slowly compared: (1) to other reactions in the waste package, and (2) to the rate at which soluble corrosion products will likely be flushed from the package.
- 3.8 It is assumed that gases in the solution in the waste package will remain in equilibrium with the ambient atmosphere outside the waste package. In other words, it is assumed that there is sufficient contact with the gas phase in the repository to maintain equilibrium with the CO<sub>2</sub> and O<sub>2</sub> present, whether or not this be the

hence on the solubility of uranium, gadolinium, and other elements. As discussed in CRWMS M&O, 1997a (Ref. 8), the measured composition of J-13 water is not in equilibrium with the partial pressure of CO<sub>2</sub> in the atmosphere. By adjusting the average measured composition of the water slightly, well within the standard deviation of the measurements, it is possible to determine a partial pressure of CO<sub>2</sub> nearly ten times atmospheric (Yang, et al., 1996, Ref. 9, Table 8, and Weast, 1977, Ref. 10, p. F-210), with which this water was apparently in equilibrium at depth in the well. Computer runs j13avg1.3o, j13avg19.3o, j13avg20.6o, and j13avg21.6o (provided on tape, CRWMS M&O, 1998a, Ref. 11) show the details of these adjustments. This high partial pressure is close to the maximum found by measurement of the rock gas composition (Yang, et al., 1996, Ref. 9, Table 8). Therefore this high partial pressure was conservatively chosen for the computer runs used in this analysis. The basis for this assumption is that it minimizes the pH and thereby conservatively maximizes the solubility of Gd and the likelihood that this neutron absorber can be separated from the U. The high CO<sub>2</sub> tends to increase the concentration of free carbonate ion and its complexation with the dissolved U (uranyl ion), thereby tending to increase the solubility of U, but this is moderated by the reduction of the pH. There is little overall net effect for otherwise comparable conditions.

- 3.9 It is assumed that all solids that are deposited remain in place; no solids are entrained or otherwise re-mobilized, except possibly by dissolving at a later time. The basis for this assumption is that it conservatively maximizes the size of potential deposits of fissile material inside the WP.
- 3.10 It is assumed that the corrosion rates will not be significantly enhanced by biologically mediated corrosion. The bases for this assumption are that even at the time that the repository is closed there will be little organic material present to serve as nutrients for biological activity and that by the time the corrosion barriers are breached essentially all of such material will most likely have decayed to carbon dioxide and dissipated. Whereas a few organisms can use CO<sub>2</sub> directly as a nutrient and two other essential factors necessary for biological activity are present (water and an energy source, in this case chemical disequilibrium between the metal and atmospheric oxygen), the impact on corrosion is likely to be low and the effect on the chemistry of fissile isotopes and neutron absorbers is expected to be negligible.
- 3.11 It is assumed that sufficient decay heat is retained within the waste package over times of interest to cause convective circulation and mixing of the water inside the package. The basis for this assumption is discussed in CRWMS M&O, 1996 (Ref. 12, p. 5-7).
- 3.12 It is assumed that the alkalinity reported in analyses of J-13 water correspond to bicarbonate (HCO<sub>3</sub><sup>-</sup>) alkalinity. Contributors to alkalinity in J-13 water, in addition to bicarbonate, potentially include borate, phosphate, and silicate. However, at pH less than 9 the contribution of silicate will be small, and in any case the concentrations of all three of these components in J-13 water is small. Fluoride ion will not contribute to a typical measured alkalinity because the titration will not be carried out to a sufficiently low pH for its influence to be detectable. Nitrate will likewise not contribute. The validity of this assumption is justified by the observation that the calculated electrical neutrality, using the assumption, is zero within the analytical uncertainty, as it should be. The same assumption is implicitly made by Harrar et al., 1990 (Ref. 2, Table 4.1, p. 4.2).
- 3.13 It is assumed that the rate of entry of water into, as well as the rate of egress from, a waste package is equal to the rate at which water drips onto the package. For most of the time frame of interest, i.e., long after the corrosion barriers become largely degraded, it is more reasonable to assume that all or most of the drip will enter the degraded package than to assume that a significant portion will instead be diverted around the remains. Diversion of the water with a consequent lower entry rate has not been incorporated into the present calculations.
- 3.14 It is assumed that the most insoluble solids for a fissile radionuclide will form, i.e., that equilibrium will be

- 3.14 It is assumed that the most insoluble solids for a fissile radionuclide will form, i.e., that equilibrium will be reached. This is conservative for internal criticality because the assumption will lead to simulation for maximal retention of fissile material within the waste package.
- 3.15 It was assumed that the degradation rate for alloy SB-209 A96061 T4 (hereafter referred to as Al alloy) is such that the alloy will last for 200 years. The corrosion rate under conditions applicable to Yucca Mountain appears not to be well known. However, common experience derived from observations of the durability of aluminum window frames and other widely used aluminum items indicates that it will persist for several decades. On the other hand corrosion of the aluminum does occur, as evidenced by the buildup of white solid products over such time frames. This suggests that the alloy will corrode entirely in a few centuries. The exact lifetime of the alloy is of only minor importance to the chemical simulation so long as it is modeled as corroding much faster than the stainless steels.

#### **4. Use of Computer Software**

This section describes the computer software used to carry out the analysis.

##### **4.1 EQ3/6 Software Package**

The EQ3/6 software package originated in the mid-1970's at Northwestern University (Wolery, 1992a, Ref. 3). Since 1978 Lawrence Livermore National Laboratory has been responsible for its maintenance. It has most recently been maintained under the sponsorship of the Civilian Radioactive Waste Management Program of the U.S. Department of Energy. The major components of the EQ3/6 package include: EQ3NR, a speciation-solubility code; EQ6, a reaction path code which models water/rock interaction or fluid mixing in either a pure reaction progress mode or a time mode; EQPT, a data file preprocessor; EQLIB, a supporting software library; and several (>5) supporting thermodynamic data files. The software deals with the concepts of the thermodynamic equilibrium, thermodynamic disequilibrium, and reaction kinetics. The supporting data files contain both standard state and activity coefficient-related data. Most of the data files support the use of the Davies or B-dot equations for the activity coefficients; two others support the use of Pitzer's equations. The temperature range of the thermodynamic data on the data files varies from 25 °C only for some species to a full range of 0-300 °C for others. EQPT takes a formatted data file (a data0 file) and writes an unformatted near-equivalent called a data1 file, which is actually the form read by EQ3NR and EQ6. EQ3NR is useful for analyzing groundwater chemistry data, calculating solubility limits and determining whether certain reactions are in states of partial equilibrium or disequilibrium. EQ3NR is also required to initialize an EQ6 calculation.

EQ6 models the consequences of reacting an aqueous solution with a set of reactants which react irreversibly. It can also model fluid mixing and the consequences of changes in temperature. This code operates both in a pure reaction progress frame and in a time frame. In a time frame calculation, the user specifies rate laws for the progress of the irreversible reactions. Otherwise, only relative rates are specified. EQ3NR and EQ6 use a hybrid Newton-Raphson technique to make thermodynamic calculations. This is supported by a set of algorithms which create and optimize starting values. EQ6 uses an ordinary differential equation integration algorithm to solve rate equations in time mode. The codes in the EQ3/6 package are written in FORTRAN 77 and have been developed to run under the UNIX operating system on computers ranging from workstations to supercomputers. Further information on the codes of the EQ3/6 package is provided in Wolery (1992a and 1992b, Refs. 3 and 5), Daveler and Wolery (1992, Ref. 4), and Wolery and Daveler (1992, Ref. 6).

In this study EQ3/6 was used to provide:

- 1) a general overview of the nature of chemical reactions to be expected,
- 2) the degradation products likely to result from corrosion of the waste forms and canisters, and
- 3) an indication of the minerals, and their amounts, likely to precipitate within the WP.

The programs have not been used outside the range of parameters for which they have been verified. The EQ3/6 calculations reported in this document used version 7.2b of the code, which is appropriate for the application, and were executed on the Hewlett-Packard (HP) 9000 Series 735 workstation and on Pentium personal computers (PCs). The source codes were obtained from Software Configuration Management in accordance with M&O QAP-SI-3.

The EQ3/6 package has been verified by its present custodian, Lawrence Livermore National Laboratory, and has been installed under the Management and Operating Contractor Quality Administrative Procedure (M&O QAP-SI-3) prior to performing the calculations reported in Section 5. However, the documentation (the Installation and Test Report) for this installation has not yet received all required signatures. Therefore all the results are considered "to be verified" (TBV) with respect to any design or procurement decisions or specifications.

## **4.2 Software Routines for Chaining Successive EQ6 Cases**

The following software routines were developed specifically for this study for the purpose of facilitating the setup and execution of successive cases of EQ6, by transforming the output of one case to the input of the following case. An individual EQ6 run diluted the solution constituents to reflect the inflow of fresh water and the routines periodically remove water and solutes corresponding to the inflow. The routines also read the output of one run and reformat it as input for the next run. The data reformatting aspect of these routines was verified by visual inspection in accordance with QAP-SI-0, 5.3.2C by an individual independent of the person doing the original development. The mathematical algorithms for these routines are given in Attachment I. An individual independent of the person doing the original development verified the calculations by hand in accordance with QAP-SI-0, 5.3.2C. Both the program and the hand calculation are documented in Attachment II, in accordance with QAP-SI-0, 5.3.2D. The routines were originally developed for a Hewlett-Packard HP 6000 computer (UNIX operating system), and were subsequently modified slightly for use on PCs. Both versions have been checked. The CSCI numbers apply to both the HP and the corresponding PC versions. Both file names are provided in Section 4.2 subsections below.

### **4.2.1 Files bldinput.bat (for HP), CSCI# 30044 V1.0**

This is a routine which does the following:

- 1) runs the program bldinput.c which builds the initial input (bldinput.out) for the sequence of EQ6 runs,
- 2) executes the initial iteration of EQ6,
- 3) runs the program (nxtinput.c) to transfer the output from one iteration to the input of the next iteration,
- 4) runs the next iteration of EQ6, and

condition occurs (which causes `nextinput.c` to write an error message to a file which is read and interpreted by this script file).

(This HP routine is actually not needed, inasmuch as others can accomplish the same result. A corresponding routine was not implemented for PCs.)

#### **4.2.2 File `bldinput.c`, CSCI# 30045 V1.0**

This C program builds the EQ3/6 input from a template and an input file containing filename (internally, it's called "root" in the supplementary input file, "bldinput.in"), date, and maximum simulation time. (This HP routine is actually not needed, inasmuch as `nextinput.c` can accomplish the same result. A corresponding routine was not implemented for PCs.)

#### **4.2.3 Files `nextinput.bat` (for HP), CSCI# 30046 V1.0, and `nexti.bat.c` (for PC), CSCI# 30046 V1.1**

This shell script runs the same iteration loop as `bldinput.bat`, but starts from the output of a previous iteration.

#### **4.2.4 File `nextinput.c` (for both HP and PC), CSCI# 30047 V1.0**

This C program reads the output and pickup (program file names) files of an EQ3/6 iteration and generates the input file for the next iteration. In this process it makes two basic data changes:

- 1) the amounts of all the species in solution are reduced to simulate the flushing out of an amount of solution corresponding to an infusion of fresh J-13 water into the waste package as calculated by EQ6, and
- 2) some alternative species are switched into, or out of, the basis set for the chemical reactions, according to which member of the alternative set has achieved the largest concentration.

#### **4.2.5 Files `Allpost.bat` (for HP), CSCI# 30050 V1.0 and `Allp.bat.c` (for PC), CSCI# 30050 V1.1**

This shell script operates in essentially the same way as do `bldinput.bat` and `nextinput.bat`, but in addition runs the C program `postproc.c` and deletes the allout files produced by these programs after the desired data have been extracted. This deletion avoids complete filling of available file space.

#### **4.2.6 Files `PostprocP.c` (for HP), CSCI# 30049 V1.1, and `postprocP.c` (for PC), CSCI# 30049 V1.2**

This C program was originally written for a different problem, and was modified to expand its capabilities for the present application. The expanded "P" version was verified in the same manner as was the original. This C program locates specific data outputs in the concatenated EQ6 output files generated by running the programs, `bldinput.c` and `nextinput.c`, and copies the selected data to a separate file to facilitate analysis and entry into spreadsheets.

#### **4.2.7 Files `Lastpost.c` (for both HP and PC), CSCI# 30051 V1.0**

This C program processes the output of `allpost.bat` and reduces the still extensive output to a form more amenable to plotting by selecting only every tenth output line.

### 4.3 Pro/Engineer version 17.0

Pro/Engineer is drafting software that is used to produce WP drawings and is not required to be qualified under the M&O QAP SI series procedures. Based on the component dimensions used to create the drawings, Pro/Engineer provides the option of determining the volume, surface area, and other parameters for the component. This Pro/Engineer volume information for the 21 PWR LEU WP components is included as Attachment III, and is summarized in Table 5.1.1.1-3.

### 4.4 Spreadsheets

Spreadsheet analyses were performed with Microsoft Excel version 97, loaded on a PC. The specific spreadsheets used for results reported in this document are included for reference on electronic tape (Ref. 11).

### 4.5 Software Approved for QA Work

The software package, EQ3/6, Version 7.2b, was approved for quality assurance (QA) work by LLNL (Memorandum to File from Royce E. Monks, dated March 28, 1997, QA designator 97/026). Before computer runs were performed, the codes were installed and tested on the computers used in accordance with the requirements of CRWMS M&O, 1997b (Ref. 13). However, the documentation for this installation and testing has not yet been completed. The input files used are echoed in the output files. The output files are listed in Ref. 11.

## 5. Calculations

The general scheme of the calculations starts with obtaining data for compositions, amounts, surface areas, and reaction rates of the various components of the PWR LEU and PWR MOX waste packages. These quantities are recalculated to the form required for entry into EQ6; mostly this consists of making such conversions as weight percentages of elements or component oxides to mole fractions of elements, degradation rates in micrometers/year into moles per square centimeter per second, etc. Attached spreadsheets (Ref. 11) provide details of these calculations. The final part of the input to EQ6 consists of the composition of J-13 well water together with a rate of influx into the waste package that corresponds to suitably chosen percolation rates into a drift and drip rate into a waste package (see Section 5.1.1.3). From time to time the water added to the waste package from this simulated influx is removed, together with its solutes, to approximate reactive flow and transport through the waste package via routines described in Section 4.2.1. The EQ6 output provides the results of modeling of the chemical degradation of the waste package, or components thereof. Sometimes the degradation of the waste package is divided into phases, e.g., degradation of basket materials before breach of the Zircaloy cladding and exposure of the spent fuel to the water. The results include the compositions and amounts of solid products and of substances in solution. Details of the results are presented below and in Ref. 11.

The number of digits cited for values converted from English to metric units does not indicate the accuracy; it is an artifact of the conversion process.

### 5.1 Calculation Inputs

#### 5.1.1 WP Materials and Performance Parameters

This section provides a brief overview of the chemical characteristics of PWR LEU and PWR MOX waste packages. The emphasis is on the chemical composition and reactivity, rather than on the physical configurations within different waste packages, although the configurations were used for volume calculations to determine the overall chemistries and surface areas. Material nomenclature used throughout this document is: SA-516 K02700

(hereafter referred to as A516), SB-575 N06022 (hereafter referred to as Alloy 22), SB-209 A96061 T4 (hereafter referred to as Al alloy), and SS316B6A less 20% boron (hereafter referred to as borated SS).

**5.1.1.1 Chemical Characteristics of Representative Spent Nuclear Fuel (SNF) Waste Packages**

A commercial spent fuel waste package will consist of 21 PWR LEU or 21 PWR MOX assemblies of spent fuel held in a basket and placed inside a corrosion barrier. The design for the corrosion barrier itself specifies an outer corrosion allowance and an inner corrosion resistant metal. For modeling the chemical behavior of this system, the chemical compositions of each of these materials, their masses, their surface areas, and their corrosion or degradation rates are required. As explained in Assumptions 3.1, 3.3, and 3.7, an exception is made for the materials of the corrosion barrier and for Zircaloy cladding, which are not included in the modeling. Tables 5.1.1.1-1 shows data for commercial SNF. Tables 5.1.1.1-3 through 5.1.1.1-7 show the data used that are specific to SNF, both LEU and MOX.

<b>Table 5.1.1.1-1. Elemental Composition in Gram-atoms/Assembly for 4.9%, 34 GWD/MTU B&amp;W 15x15 PWR LEU Fuel Assembly</b>						
Element	Age of Fuel		Element	Age of Fuel		
	10000.0 yr	25000.0 yr		10000.0 yr	25000.0 yr	
He	9.21E+00	1.40E+01	Y	2.71E+00	2.71E+00	
Tl	1.03E-13	2.37E-13	Zr	2.10E+01	2.09E+01	
Pb	7.67E-04	5.80E-03	Nb	1.16E-02	2.88E-02	
Bi	5.41E-05	6.87E-04	Mo	1.65E+01	1.65E+01	
Po	9.32E-08	2.53E-07	Tc	3.73E+00	3.55E+00	
At	2.33E-17	1.06E-16	Ru	9.90E+00	1.01E+01	
Rn	2.58E-09	6.98E-09	Rh	2.16E+00	2.16E+00	
Fr	2.19E-13	9.81E-13	Pd	5.03E+00	5.02E+00	
Ra	3.94E-04	1.07E-03	Ag	3.09E-01	3.10E-01	
Ac	2.43E-07	5.52E-07	Cd	2.85E-01	2.85E-01	
Th	2.77E-02	6.56E-02	In	5.45E-03	5.45E-03	
Pa	3.65E-04	8.25E-04	Sn	1.73E-01	1.67E-01	
U	1.86E+03	1.87E+03	Sb	3.02E-02	3.02E-02	
Np	3.67E+00	3.65E+00	Te	1.68E+00	1.68E+00	
Pu	1.21E+01	7.44E+00	I	7.83E-01	7.82E-01	
Am	4.72E-02	1.15E-02	Xe	1.74E+01	1.74E+01	
Cm	4.83E-04	1.39E-04	Cs	6.91E+00	6.89E+00	
Bk	4.26E-25	2.35E-25	Ba	9.58E+00	9.59E+00	
Cf	4.86E-14	4.64E-19	La	4.25E+00	4.25E+00	
H	0.00E+00	0.00E+00	Ce	8.32E+00	8.32E+00	
Li	2.02E-05	2.02E-05	Pr	3.87E+00	3.87E+00	
Be	7.30E-06	7.26E-06	Nd	1.36E+01	1.36E+01	
C	2.71E-07	4.41E-08	Pm	0.00E+00	0.00E+00	
Zn	5.09E-08	5.09E-08	Sm	2.74E+00	2.74E+00	
Ga	4.53E-07	4.53E-07	Eu	3.94E-01	3.94E-01	

Ge	2.51E-03	2.51E-03	Gd	2.93E-01	2.93E-01
As	7.46E-04	7.46E-04	Tb	5.21E-03	5.21E-03
Se	3.34E-01	3.33E-01	Dy	2.49E-03	2.49E-03
Br	1.23E-01	1.23E-01	Ho	1.21E-04	1.21E-04
Kr	2.07E+00	2.07E+00	Er	2.50E-05	2.50E-05
Rb	2.14E+00	2.14E+00	Tm	6.86E-09	6.86E-09
Sr	2.04E+00	2.04E+00	Yb	1.59E-08	1.59E-08
Ref. CRWMS M&O, 1997c (Ref. 14)					

The data in Table 5.1.1.1-1 provided input to EQ6 runs. The actual input to EQ6 was reduced from the data in this table by deleting noble gases and constituents comprising less than 0.1 atom percent of the total and modified by adding oxygen equivalent to the initial U inventory (two gram-atoms of oxygen for every gram-atom of uranium). Table 5.2.1-1 shows the calculation for oxygen and the reduced data set. The weight of the SNF in one assembly is taken as 526.38 kg (CRWMS M&O, 1997c, Ref. 14).

A waste package for spent PWR MOX fuel closely resembles that for PWR LEU spent fuel. It will consist of 21 MOX assemblies of spent fuel held in a basket and placed inside a corrosion barrier. The design for the corrosion barrier itself specifies an outer corrosion allowance and an inner corrosion resistant metal. For modeling of the chemical behavior of this system, the chemical compositions of each of these materials, their masses, their surface areas, and their corrosion or degradation rates are required. An exception is made, however, for the materials of the corrosion barrier, as explained in Assumptions 3.1, 3.3, and 3.7. Table 5.1.1.1-2 shows the data used that are specific to PWR MOX SNF.

**Table 5.1.1.1-2. Elemental Composition in Gram-atoms/Assembly for 4.0%, 35.6 GWd/MTU 15x15 Westinghouse PWR MOX Fuel Assembly**

Element	Age of Fuel		Element	Age of Fuel	
	10000.0 yr	25000.0 yr		10000.0 yr	25000.0 yr
H	1.28E-02	1.28E-02	Te	1.91E+00	1.93E+00
He	3.59E+01	4.81E+01	I	1.11E+00	1.11E+00
Li	9.44E+00	9.44E+00	Xe	1.76E+01	1.76E+01
Be	3.65E-04	3.64E-04	Cs	6.15E+00	6.14E+00
B	9.27E-07	2.31E-06	Ba	8.80E+00	8.81E+00
C	3.53E-05	3.51E-05	La	3.62E+00	3.62E+00
N	3.28E-11	4.45E-11	Ce	7.05E+00	7.05E+00
O	8.39E-12	8.39E-12	Pr	3.33E+00	3.33E+00
F	2.11E-18	2.11E-18	Nd	1.09E+01	1.09E+01
Ne	2.22E-08	2.22E-08	Pm	0.00E+00	0.00E+00
Na	9.72E-10	9.72E-10	Sm	2.79E+00	2.79E+00
Mg	2.31E-03	2.31E-03	Eu	5.45E-01	5.45E-01
Al	7.37E-10	7.37E-10	Gd	5.14E-01	5.14E-01
Si	8.73E-02	8.73E-02	Tb	1.40E-02	1.40E-02
P	3.13E-14	3.13E-14	Dy	7.48E-03	7.48E-03
S	2.05E-18	2.05E-18	Ho	4.09E-04	4.09E-04
Zn	1.28E-07	1.28E-07	Er	9.06E-05	9.07E-05
Ga	1.05E-06	1.05E-06	Tm	2.10E-08	2.10E-08

**Title:** EQ6 Calculations for Chemical Degradation of PWR LEU and PWR MOX Spent Fuel Waste Packages

**Document Identifier:** BBA000000-01717-0210-00009 REV 00

**Page 15 of 57**

Ge	1.83E-03	1.83E-03	Yb	5.34E-08	5.34E-08
As	6.60E-04	6.60E-04	T	1.84E-14	7.80E-14
Se	2.40E-01	2.39E-01	Pb	2.23E-04	1.75E-03
Br	9.81E-02	9.89E-02	Bi	1.21E-04	1.59E-03
Kr	1.06E+00	1.06E+00	Po	2.84E-08	7.78E-08
Rb	1.03E+00	1.03E+00	At	5.31E-17	2.47E-16
Sr	9.24E-01	9.24E-01	Rn	7.84E-10	2.15E-09
Y	1.16E+00	1.16E+00	Fr	4.85E-13	2.25E-12
Zr	1.29E+01	1.29E+01	Ra	1.20E-04	3.28E-04
Nb	7.50E-03	1.87E-02	Ac	3.48E-08	1.43E-07
Mo	1.45E+01	1.45E+01	Th	9.49E-03	2.62E-02
Tc	3.47E+00	3.30E+00	Pa	5.04E-05	2.06E-04
Ru	1.20E+01	1.21E+01	U	1.67E+03	1.69E+03
Rh	3.26E+00	3.26E+00	Np	8.62E+00	8.58E+00
Pd	1.10E+01	1.10E+01	Pu	2.93E+01	1.75E+01
Ag	8.09E-01	8.12E-01	Am	1.79E-01	4.36E-02
Cd	8.40E-01	8.40E-01	Cm	3.39E-03	9.83E-04
In	9.11E-03	9.11E-03	Bk	9.35E-25	5.15E-25
Sn	4.09E+01	4.09E+01	Cf	1.29E-13	1.22E-18
Sb	7.24E-02	7.24E-02			
Ref. CRWMS M&O, 1998b (Ref. 15)					

The data in Table 5.1.1.1-2 provided input to EQ6 runs. The actual input to EQ6 was reduced from the data in this table by deleting noble gases and constituents comprising less than 0.1 atom percent of the total and modified by adding oxygen equivalent to the initial U inventory. Table 5.2.1-2 shows the calculation for oxygen and the reduced data set. The weight of the PWR MOX SNF is taken as the sum of the light elements, 4.89 kg, actinides, 407 kg, fission products, 15.2 kg (all from CRWMS M&O, 1998b, Ref. 15), and the weight of the oxygen (calculated in Table 5.2.1-2).

Tables 5.1.1.1-3 and 5.1.1.1-4 show the basic dimensional data from which the volumes of the various components and the void space in the waste packages were calculated. Table 5.1.1.1-5 includes data on metal compositions, Table 5.1.1.1-6 tabulates the metal corrosion rates, Table 5.1.1.1-7 shows metal densities, and Table 5.1.1.1-8 includes overall waste package dimensions.

Basket	Material	Volume, mm <sup>3</sup>	Surf. Area, mm <sup>2</sup>	Number per WP
A-Guide	CS	8.10E+06	1.68E+06	16
B-Guide	CS	9.20E+05	2.08E+05	32
Corner Guide	CS	5.34E+06	1.10E+06	16
Corner Stiffener	CS	2.95E+05	6.74E+04	32
Side Cover	CS	5.01E+05	1.16E+05	4
A-Plate	BSS	9.47E+06	2.77E+06	8
B-Plate	BSS	9.47E+06	2.77E+06	8
C-Plate	BSS	5.69E+06	1.67E+06	16
D-Plate	Al	6.74E+06	2.74E+06	8
E-Plate	Al	6.74E+06	2.74E+06	8
Tube	CS	2.09E+07	8.36E+06	21
CS = A516				
BSS = Borated SS				
Al = Al alloy				
Data from calculations using Pro/Engineer (Attachment III)				

Item	Size, inches	Page in Ref. 16
Pellet OD	0.3088	2.1.2.2-3
Rod OD	0.36	2.1.2.2-3
Assy Length	160.1	2.1.2.2-3
Guide Tube OD	0.474	2.1.2.2-3
Active Fuel Length	144	2.1.2.2-3
Clad ID	0.315	2.1.2.2-3
End Fitting Mass	12.5 kg	2.1.2.1-10
Ref. Stout and Leider, 1997 (Ref. 16)		

**Table 5.1.1.1-5. Metal Compositions, Weight Percent**

Element	A516	Borated SS	Al Alloy
Fe	98.535%	60.639%	0.700%
B10	-	0.231%	-
B11	-	1.053%	-
B10 + B11	-	1.284%	-
Cr	-	19.061%	0.195%
Ni	-	13.543%	-
Mn	0.900%	2.006%	0.150%
Mg	-	-	1.000%
Mo	-	2.508%	-
Zn	-	-	0.250%
N	-	0.100%	-
S	0.035%	0.030%	-
Si	0.275%	0.752%	0.600%
P	0.035%	0.045%	-
C	0.220%	0.030%	-
O	-	-	-
Cu	-	-	0.275%
Ti	-	-	0.150%
Al	-	-	96.680%
Co	-	-	-
50% Nb + 50% Ta	-	-	-
Zr	-	-	-
Sn	-	-	-
V	-	-	-
W	-	-	-
Density (g/cm <sup>3</sup> )	7.832	7.745	2.713
Reference	12	12	12, 17

	Corrosion Rate, mm/yr			
	High (5%)	Mean	Low (95%)	
A516	0.1	0.035	0.01	CRWMS M&O, 1995 (Ref. 18)
Borated SS	0.0025	0.00025	0.00005	CRWMS M&O, 1997c (Ref. 14, pp. 11-13)

Material	Density, kg/m <sup>3</sup>	Reference
A516	7832	CRWMS M&O, 1996b (Ref. 28)
Borated SS	7745	CRWMS M&O, 1996b (Ref. 28)
Al alloy	2713	ASME Code Table NF-2 (Ref. 17)
C 22	8691	CRWMS M&O, 1996b (Ref. 28)

Parameter	Value	Units
WP Inner Diameter	1.4234	M
WP Inner Length	4.585	M
Fuel Assembly Volume	0.081	m <sup>3</sup>
Data from CRWMS M&O, 1997c (Ref. 14) and CRWMS M&O, 1997d (Ref. 19)		

The surface area for both LEU SNF and MOX SNF is taken to be 39.6 cm<sup>2</sup>/g (CRWMS M&O, 1995, Ref.14, p. 6-3). The degradation rate for both LEU SNF and MOX SNF is taken to be 1.24 g/m<sup>2</sup>/yr (CRWMS M&O, 1997e, Ref. 20). This is the rate reported for the mid range of both carbonate concentration and pH.

**5.1.1.2 Chemical Composition of J-13 Well Water**

It was assumed that the water composition entering the waste package would be the same as for water from well J-13 (Assumptions 3.1 and 3.3). This water has been analyzed repeatedly over a span of at least two decades (Harrer, et al., 1990, Ref. 2). This composition is reproduced in Table 5.1.1.2-1.

Component	Units**
Na <sup>+</sup>	45.8
K <sup>+</sup>	5.04
Ca <sup>++</sup>	13.0
Mg <sup>++</sup>	2.01
NO <sub>3</sub> <sup>-</sup>	8.78
Cl <sup>-</sup>	7.14
F <sup>-</sup>	2.18
SO <sub>4</sub> <sup>-</sup>	18.4
Si	28.5
PO <sub>4</sub> <sup>-</sup>	0.12
Alkalinity*	128.9
pH	7.41
* Assumed to be HCO <sub>3</sub> <sup>-</sup>	
** mg/L, except for pH	
Ref. Harrer, et al., 1990, Ref. 2	

### 5.1.1.3 Drip Rate of J-13 Water into a Waste Package

It is assumed (Assumption 3.13) that the drip rate onto a waste package is the same as the rate at which water flows through the waste package. The drip rate is taken from a correlation between percolation rate and drip rate. Specifically percolation rates of 40 mm/yr and 8 mm/yr correlate with drip rates onto the waste package of 0.15 m<sup>3</sup>/yr and 0.015 m<sup>3</sup>/yr, respectively.

Data for the rate of influx of J-13 water into a waste package were taken from Ho and Wilson, 1998 (Ref. 21). Table 5.1.1.3-1 provides the data from this preliminary report, and Figure 5.1.1.3-1 shows the information graphically. Statements on p. 2.3-105 of Ref. 21 indicate that the drip rates correspond to an area considerably larger than the horizontal (as emplaced) cross-sectional area of waste packages. The rationale is that, in some poorly defined manner, such as movement through rubble that will fall on top of a WP, water from this larger area may drip onto the WP. A minimum rate of 0.015 m<sup>3</sup>/yr and an approximate median value of 0.15 m<sup>3</sup>/yr were chosen from these data for use in the present calculations. The maximum drip rate in Ref. 21 (p. 2.3-106) was set to a large value, at 10 standard deviations above the mean. The reader is referred to that document for the rationale.

**Table 5.1.1.3-1. Correlation between Percolation Rate and Drip Rate onto a Waste Package (Data Taken from Tables 2.3-49 and 2.3-50 of Ref. 21)**

Percolation rate, mm/yr	Mean drip rate, m <sup>3</sup> /yr	Standard Deviation (SD)	Mean + 10 SD
3.9	0.0123	0.0159	0.1713
9.2	0.0125	0.0866	0.8785
14.6	0.0366	0.283	2.8666
73.2	0.323	0.408	4.403
213	1.2	0.4	5.2

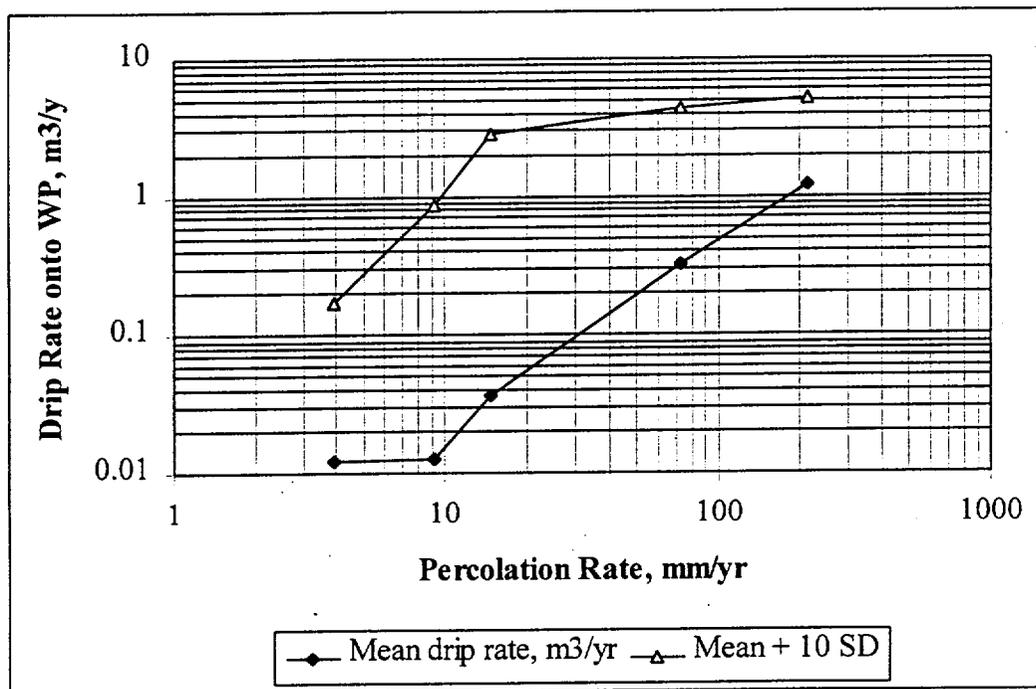


Figure 5.1.1.3-1. Percolation to drip rate correlation.

**Title:** EQ6 Calculations for Chemical Degradation of PWR LEU and PWR MOX Spent Fuel Waste Packages**Document Identifier:** BBA000000-01717-0210-00009 REV 00**Page 21 of 57****5.1.1.4 Densities and Molecular Weights of Solids**

For input to criticality calculations conversions one must convert moles of solids, simulated to form, to solid volumes. Table 5.1.1.4-1 provides some of these data.

**Table 5.1.1.4-1. Densities and Molecular Weights of Precipitated Solids**

Solid	Density, kg/m <sup>3</sup>	Molecular Weight <sup>c</sup>	Mol. Vol., cm <sup>3</sup> /mol <sup>c</sup>	Calc. Dens., g/cm <sup>3</sup>
Diaspore (AlOOH)	3400 <sup>a</sup>	59.988	17.760	3.378
Hematite (Fe <sub>2</sub> O <sub>3</sub> )	5240 <sup>b</sup>	159.692	30.274	5.275
Pyrolusite (MnO <sub>2</sub> )	5060 <sup>a</sup>	86.937	17.181	5.060a
Goethite (FeOOH)		88.854	20.820	4.268
Ni <sub>2</sub> SiO <sub>4</sub>		209.463	42.610	4.916
Nontronite-Ca		424.293	131.100	3.236
Nontronite-K		430.583	135.270	3.183
Nontronite-Mg		421.691	129.760	3.250
Nontronite-Na		425.267	132.110	3.219

References:

<sup>a</sup> Roberts, et al., 1974 (Ref. 22)

<sup>b</sup> Weast, 1977 (Ref. 10)

<sup>c</sup> Ref. 11 (EQ3/6 Data base, data0.nuc.R8), g/mole, except for pyrolusite, which is calculated from the density and molecular weight.

Table 5.1.1.4-2 provides constants required for these conversions, and Table 5.1.1.4-3 provides thermodynamic data required for calculation of equilibrium constants for Rh.

Constant	Value	Reference
Ideal Gas Constant	83143200 erg/K/mole	10, p. F-241
Conversion, erg to cal	41840000 erg/cal	10, p F-305
Conversion, °C to K	273.15 (to be added to °C)	10, p. F-128

Substance	Delta H°, kcal/mole	Delta G°, kcal/mole	S°, cal/°K/mole	Reference	Page
Rh	0	0	7.53	23	93
Rh <sup>+++</sup>		55.3		24	215
RhO		-16		24	215
Rh <sub>2</sub> O		-19.1		24	215
Rh <sub>2</sub> O <sub>3</sub>	-82		26.5	23 & 24, resp.	93 & 215, resp.
RhCl		-12.4		24	215
RhCl <sub>2</sub>		-26.4		24	215
RhCl <sub>3</sub>	-71.5		33	23 & 24, resp.	93 & 215, resp.
RhCl <sub>6</sub> <sup>---</sup>	-202.8		50	23 & 24, resp.	93 & 215, resp.
H <sub>2</sub> O		-56.687		25	13
Cl <sup>-</sup>		-31.371		25	24
H <sub>2</sub> (g)		0		25	12
O <sub>2</sub> (g)		0		25	11
Cl <sub>2</sub> (g)		0		25	24

**5.1.1.5 Atomic Weights**

Atomic weights were taken from CRWMS M&O, 1996b (Ref. 28) and Walker, et al., 1989 (Ref. 26). These are listed in Ref. 11 (spreadsheet volmas21c, sheet VOLMASS).

**5.2 Data Conversion**

The data presented in Section 5.1 are largely not in a form suitable for entry into EQ3/6. This section presents the conversions and combinations required for input to the computer codes. Ref. 11 includes the spreadsheets for the calculations. This section includes only the results and related discussion.

**5.2.1 Mole Fractions of Elements in SNF**

These calculations started with the numbers of gram-atoms for the spent fuels presented in Tables 5.1.1.1-1 and 5.1.1.1-2 and the weights of the SNF. The noble gases, He, Ne, Ar, Kr, and Xe and H were deleted because they are volatile and will not be retained within the waste package following breach, except possibly for a small amount of the hydrogen, which, however, will be insignificant compared to the amount of hydrogen in the water. In addition an amount of oxygen equivalent to the uranium originally present in UO<sub>2</sub> in LEU SNF, or, in the case of MOX SNF,

UO<sub>2</sub> NpO<sub>2</sub>, PuO<sub>2</sub>, and AmO<sub>2</sub>. In other words two gram-atoms of O were added for every gram-atom of U, Np, Pu, and Am. The list of elements included in the calculation was also reduced by deleting those that constitute less than 0.1 atom percent of the total. This markedly reduces the number of elements to be considered and results in significantly improved efficiency for the running of EQ6. Tables 5.2.1-1 and 5.2.1-2 show the atom fractions for the elements used for the calculations. These values were entered directly into the EQ6 input files.

Element	Atom fraction	
	10000 yrs	25000 yrs
U	3.15799E-01	3.17218E-01
Np	6.23109E-04	6.19168E-04
Pu	2.05439E-03	1.26209E-03
Am	8.01383E-06	1.95080E-06
Mo	2.80144E-03	2.79898E-03
Tc	6.33296E-04	6.02205E-04
Ru	1.68087E-03	1.71332E-03
Rh	3.66735E-04	3.66412E-04
Ag	5.24634E-05	5.25869E-05
Nd	2.30907E-03	2.30704E-03
Sm	4.65210E-04	4.64800E-04
Eu	6.68951E-05	6.68363E-05
Gd	4.97469E-05	4.97031E-05
Rb	3.63339E-04	3.63019E-04
Sr	3.46360E-04	3.46056E-04
Y	4.60116E-04	4.59711E-04
Zr	3.56548E-03	3.54538E-03
Pd	8.54016E-04	8.51569E-04
Cs	1.17321E-03	1.16879E-03
Ba	1.62654E-03	1.62680E-03
La	7.21584E-04	7.20950E-04
Ce	1.41261E-03	1.41136E-03
Pr	6.57066E-04	6.56488E-04
O	6.61909E-01	6.61327E-01
Total	1.00E+00	1.00E+00

<b>Table 5.2.1-2. Elemental Composition in Atom Fraction for 4.0%, 35.6 GWd/MTU 17x17 Westinghouse MOX SNF Fuel Assembly</b>		
Element	Atom fraction	
	10000 yrs	25000 yrs
Li	1.78390E-03	0.00000E+00
O	6.47906E-01	6.48089E-01
Rb	1.94641E-04	1.94696E-04
Sr	1.74610E-04	1.74659E-04
Y	2.19208E-04	2.19269E-04
Zr	2.43774E-03	2.43843E-03
Mo	2.74009E-03	2.74087E-03
Tc	6.55733E-04	6.23784E-04
Ru	2.26766E-03	2.28721E-03
Rh	6.16049E-04	6.16223E-04
Pd	2.07869E-03	2.07928E-03
Ag	1.52878E-04	1.53489E-04
Sn	7.73217E-03	7.73209E-03
Cs	1.16218E-03	1.16062E-03
Ba	1.66295E-03	1.66531E-03
La	6.84079E-04	6.84272E-04
Ce	1.33225E-03	1.33263E-03
Pr	6.29277E-04	6.29455E-04
Nd	2.05980E-03	2.06038E-03
Sm	5.27232E-04	5.27381E-04
Eu	1.02990E-04	1.03019E-04
Gd	9.71316E-05	9.71591E-05
U	3.15583E-01	3.19453E-01
Np	1.62894E-03	1.62184E-03
Pu	5.53688E-03	3.30794E-03
Am	3.38260E-05	8.24151E-06
Total	1.00E+00	1.00E+00

### 5.2.2 Atom Fractions of Elements in Basket Metals

These calculations are straight forward conversions from weight percentages of elements in the metals to atom fractions. Details are in Ref. 11. The results in Tables 5.2.2-1 through 5.2.2-3 are entered directly into EQ6 input files.

Element	Atom fr.
Fe	0.9742064
Mn	0.0090454
S	0.0006044
P	0.0006239
Si	0.0054063
C	0.0101134
Total	1

Element	Atom fr.
B	0.0623405
C	0.0013154
N	0.0037597
Si	0.0140616
P	0.0016906
S	0.0004942
Cr	0.1924212
Mn	0.01917
Fe	0.5699404
Ni	0.1210848
Mo	0.0137216
Total	1

**Table 5.2.2-3. Atom Fractions for Al Alloy**

Element	Atom fr.
Fe	0.0034132
Mn	0.0007435
Mg	0.0112008
Zn	0.0010414
Si	0.0058174
Cu	0.0011786
Ti	0.0008528
Al	0.9757523
Total	1

**5.2.3 Degradation Rates**

The degradation rates, as well as the rate of influx of water, must be converted to moles/cm<sup>2</sup>/sec for entry into EQ6. The data presented in Section 5.1.1.1 (e.g., Table 5.1.1.1-5), however, are for millimeters/yr for metals, g/m<sup>2</sup>/yr for SNF, and m<sup>3</sup>/yr for rate of addition of water. These conversions are all relatively simple. The conversion to moles is accomplished by determining the number of gram-atoms in some known weight of the material. For example, for the metals a weight of 100 g was taken and the number of gram-atoms of each element determined and summed. Then the weight, 100 g, divided by the number of gram-atoms yields the "molecular weight". Parallel calculations were made for the SNF and the water, even though different total weights were used for the SNF. The "molecular weights" determined in this way are listed in Table 5.2.3-1. (See Ref. 11 for details of the calculations.) (The "molecular weights" for the SNF are not actually needed because the "molecular weight" is determined by dividing the weight of SNF in an assembly by the number of gram-atoms in the assembly, as reported above in Section 5.2. The number of moles of SNF in an assembly is then calculated by dividing the weight of SNF in an assembly by the "molecular weight", which, of course, simply returns the number of gram-atoms per assembly.)

**Table 5.2.3-1. Molecular Weights of Reactants**

Reactant	Mol. Wt.
A516	55.215412
Borated SS	52.490083
Al alloy	27.231379
LEU SNF	90.00
MOX SNF	91.16
Water	18.00

The values of molecular weight enable the conversion of grams to moles. For metals the weight corroded is obtained from taking arbitrarily a 1 cm<sup>2</sup> area and multiplying by the corrosion rate converted from micrometers to cm to get the volume corroded, and by the density, to get g/cm<sup>2</sup>/yr. Reaction rate for water is taken equal to the rate of influx, using the assumed density of 1 g/cm<sup>3</sup> (Assumption 3.2) to convert volume to weight. The remaining conversions involve only years to seconds. Table 5.2.3-2 compiles the results. (See Ref. 11 for details of the

calculations.) It is assumed that the Al alloy will last for 200 years, and the degradation rate was adjusted to match that lifetime. See Assumption 3.15.

**Table 5.2.3-2. Reaction Rates of Reactants**

Reactant	Drip rate	Rate *
A516		1.573E-11
Borated SS		1.169E-13
Al alloy		1.263E-11
LEU SNF		4.419E-14
MOX SNF		4.419E-14
Water	0.5m <sup>3</sup> /yr	1.934E-07
Water	0.15m <sup>3</sup> /yr	5.803E-08
Water	0.015m <sup>3</sup> /yr	5.803E-09

\* Moles/cm<sup>2</sup>/sec

The final pieces of data needed to characterize the reactants are the surface areas and moles of reactants. These must both be normalized to one kg of solvent for convenient use in EQ6 (other choices may be possible, but would be more awkward). For these purposes the dimensions of the various components of the waste package and fuel are utilized to determine the masses (from volume and density) and to determine the surface areas of the basket metals and the volume of the SNF. The volumes of these solids are then subtracted from the internal volume of the waste package to determine the volume of void space, which is assumed to be filled by J-13 water (Assumption 3.1). The masses of the metals and SNF are then divided by the mass of water, in kg, to achieve the normalization. Similarly, the surface areas of metals are normalized. The surface area of the SNF in cm<sup>2</sup> is taken equal to 39.6 times the weight in grams in accordance with the ratio adopted in CRWMS M&O, 1995 (Ref. 18). Table 5.2.3-3 shows the results of these calculations, which are detailed in Ref. 11.

**Table 5.2.3-3. Moles and Surface Areas of Reactants/kg Water**

Reactant	Moles	Area, cm <sup>2</sup>
A516	21.64	504.16
Borated SS	7.86	156.01
Al alloy	2.36	96.42
LEU SNF	27.21	9.62E+04
MOX SNF	24.77	7.92E+04
Water*	1.00E+06	1

\* Values arbitrary

## 5.2.4 Calculation of Equilibrium Constants for Rhodium Species

Table 5.2.4-1 compiles the results of the calculation of equilibrium constants for Rh species starting from the master

basis species in the EQ3/6 data base. Full details of the calculation are provided in Ref. 11.

**Table 5.2.4-1. Equilibrium Constants for Rh Species at 25°C**

Species	Log K (base 10)
Rh	21.79
RhO	10.06
Rh2O	14.79
Rh2O3	-1.49
RhCl	14.92
RhCl2	6.88
RhCl3	-12.39
RhCl6---	-15.99

**5.2.5 Calculations of Volumes and Surface Areas of Basket Materials**

The volumes of basket materials, including the void volume, and surface areas are mostly calculated in spreadsheets included in spreadsheet volmas21 in Ref. 11. However, a small portion of these calculations, specifically for the MOX SNF waste package, were done separately in V5moxvol. This spreadsheet is also included in Ref. 11 and included here as Table 5.2.5-1.

**Table 5.2.5-1. Calculation of Volumes for PWR MOX Waste Package**

Item	Size <sup>1</sup> or Number			
Pellet OD	0.784352			
Guide Tubes/Assembly	25	endfitting mass	12.5	kg
Rods/Assembly	264	endfitting vol	1602.564	cm <sup>3</sup>
Rod OD	0.9144			
Assembly Length	406.654	Assy. Volume	84070.78	cm <sup>3</sup>
Guide Tube OD	1.22428	12 Assy. Vol.	1008849	cm <sup>3</sup>
Active Fuel Length	365.76	Total Fuel Vol.	46656.49	cm <sup>3</sup> /assy
Clad ID	0.8001			
Volume for 21 Assemblies			1.765486289	cm <sup>3</sup>
Surface Area of Fuel	238191.5921			cm <sup>2</sup>
<sup>1</sup> cm, converted from inches in Table 5.1.1.1-4				
Density of steel for endfitting, 7.8 g/cm <sup>3</sup> , from CRWMS M&O, 1996b (Ref. 28)				

**5.3 EQ6 Calculations and Scenarios Modeled**

Three basic types of scenarios were simulated. The first simulation is for a case in which the Zircaloy cladding does not fail throughout the period of regulatory concern. In other words the degradation modeling considers only the

degradation of the basket materials. Results of this simulation are shown in Figures 5.3.1-1 and 5.3.1-2. The simulation indicates that the iron will degrade to hematite, although goethite is a likely alternative, and virtually no loss of the Fe or Mn from the degraded package. Retention of Ni is very variable, evidently depending strongly on the pH history. Cr, Mo, and Tc are simulated to oxidize to soluble acid radicals and to be flushed from the package. Consequently the pH is modestly decreased.

The second type modeled consisted of cases in which the basket and fuel were exposed to water simultaneously. This is the other extreme in which the Zircaloy is fully breached immediately. For these cases the simulations show very similar results in respect to the basket materials. The fuel degrades mostly to insoluble products. A small proportion of the U is dissolved and flushed away, and a large proportion of the Gd is removed. Tables 5.3.2-1 through 5.3.2-3 and Figures 5.3.2-1 through 5.3.2-8 summarize these results. One set of runs for this type of scenario was made with suppression of hematite with the result that goethite is predicted instead. In view of the observation that goethite more commonly constitutes the bulk of the corrosion products of iron and steel, this simulation may be more realistic. The pH history differs slightly from that when hematite is simulated to form, and does to a minor extent hasten the predicted dissolution of Am and Np. The rare earth elements are comparably affected in the two cases, when account is taken of the fact that any concentration less than about  $1.0E-06$  molal means that effectively the rare earth element has been flushed from the system.

The final type of situation modeled an intermediate case in which the all the Zircaloy cladding would breach just after all the basket materials had fully degraded. This case isolates the interaction of the SNF from that of the degradation of the metals. Initially the pH rises slightly, evidently owing to the release of positively charged ions (cations), such as  $UO_2^{++}$ , at a slightly higher net rate than the release of negatively charged ions (anions). Because electrical neutrality must be maintained, this requires the generation of an equivalent amount of hydroxide ion,  $OH^-$ , which means that pH will rise. This situation does not persist for long, however, because as soon as the cation concentrations rise a little, the cations precipitate as insoluble compounds as they are released from the waste. Under that situation, they have no effect on the pH. However, the release of the anions, notably of Mo, Cr, and Tc, continues and the pH decreases to about 6.2, where it stays in a quasi-steady state until all of the waste is degraded. Thereafter, it rises to the normal pH of J-13 water as water continues to course through the degraded waste package. Beyond that time very little is simulated to happen; there is a slow conversion of one uranium and one Gd compound to others with no simulated (within the accuracy of the calculations) further loss of either. A little Gd is dissolved and flushed out at the lowest pHs achieved. To emphasize the potential effect of the low pH period some runs were made at the slowest drip rate. This did lower the minimum pH, but not enough to have much impact on the removal of Gd or U. Tables 5.3.3-1 and 5.3.3-2 summarize these results. Full details of all the calculations are included in Ref. 11.

### 5.3.1 Degradation of Basket Only

The chemical results of interest to criticality calculations for this scenario consist of the masses and volumes of solids containing Fe, Al, Ni, Mn, Si, and water. The data from the EQ6 runs for the solids, together with their densities, permit calculation of the volumes of solids and the percentage of the void space occupied by each solid. Figures 5.3.1-1 and 5.3.1-2 show the results of these calculations. The void space is calculated as that originally present plus the volume of the basket metals that have been corroded as a function of time. The increase in the volume of hematite over the first 100 years arises primarily from the corrosion of the A516. A small amount of the iron clay, nontronite, is also simulated to occur over this time frame, as is a small volume of pyrolusite,  $MnO_2$ . At about 100 years the A516 is predicted to be completely corroded, as is reflected in the sudden change in the rates of change of the space occupied by hematite, nontronite, and pyrolusite. The diaspore,  $AlOOH$ , derives from the corrosion of the Al alloy. The pH changes result from complex interactions among all the solid and aqueous species present. Many of these effects are not apparent in Figure 5.3.1-1; for example, the  $Ni_2SiO_4$ , derived from corrosion of the borated SS, first forms, then dissolves, then resumes formation at about 165 years. From 100 years to about 14,000 years the pH remains nearly constant as a consequence of the balance between flushing by through-flowing J-13 water as it admixes with water already present, acid production from corrosion of the borated SS, and the solids

**Title:** EQ6 Calculations for Chemical Degradation of PWR LEU and PWR MOX Spent Fuel Waste Packages

**Document Identifier:** BBA000000-01717-0210-00009 REV 00

**Page 30 of 57**

present, some of which act as buffering agents. During this time frame the diaspore and clay are simulated to dissolve very slowly; hematite and pyrolusite slowly increase. Thereafter, the pH rises quickly to the value in the inflowing J-13 water, and a slow conversion of diaspore and hematite to nontronite, with silica deriving from the J-13 water, takes place. (The loss of hematite is not evident in the figure, but the more detailed output files show this decrease. The shift from dissolution to precipitation of nontronite results from the change in pH.) With the complete corrosion of the borated SS the increase in  $\text{Ni}_2\text{SiO}_4$  ceases. Full details of the calculations are provided in spreadsheets in Ref. 11.

Essentially all of the Fe and Mn originally present in the basket materials are retained as insoluble solids. About one third of the Ni is retained. A small part of the Fe is simulated to become incorporated into the ferric iron clay, nontronite, as a consequence of the interaction with Al initially present predominantly as the Al alloy and with silica brought in as a solute in the infiltrating J-13 water.  $\text{Ni}_2\text{SiO}_4$  is simulated to form in very small amount shortly after breach of the WP, but to be dissolved away during the period of lowest pH. Later, as pH rises, the Ni released during further metal corrosion forms a new precipitate and remains insoluble.

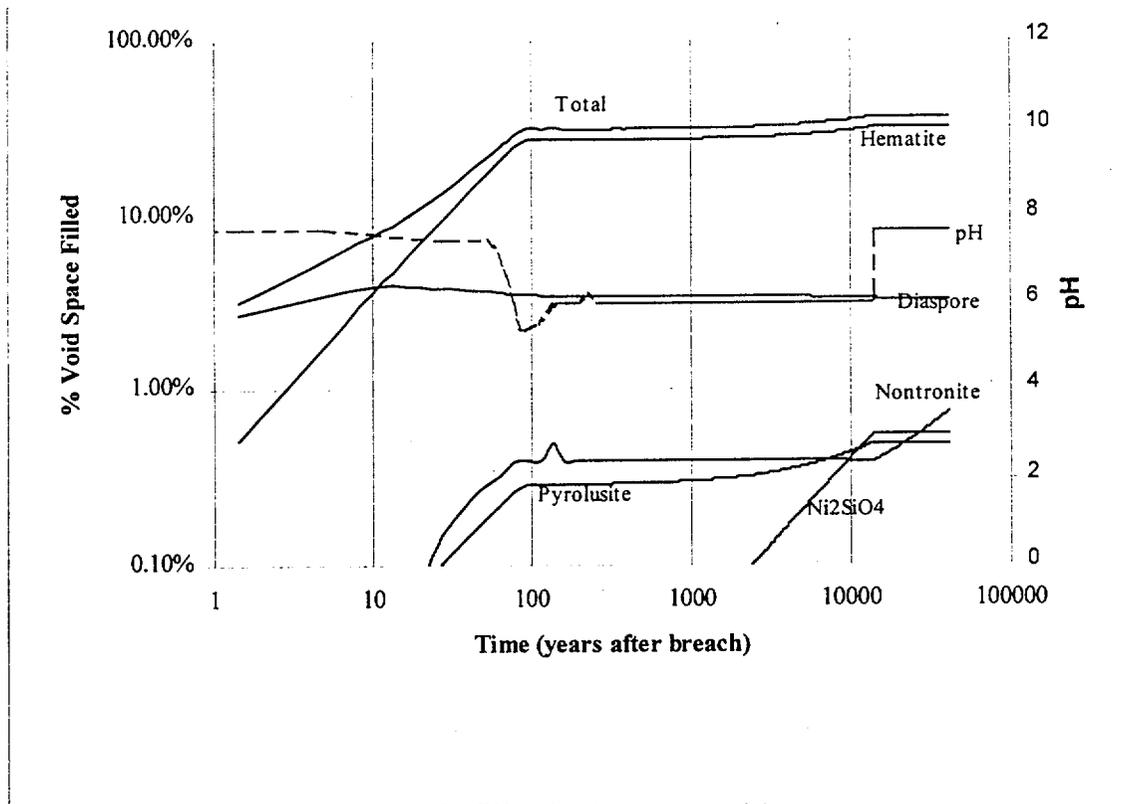


Figure 5.3.1-1. Volume percentages of void space in a 21 PWR LEU waste package occupied by principal minerals precipitated, Zircaloy intact. This figure shows the simulated history for degradation of the basket materials only. Drip rate was 0.15 m<sup>3</sup>/yr. (Run set PWR0\_15. See Ref. 11, file Name.doc for naming conventions.) (Figure copied from spreadsheet volmas21c.xls, sheet PWR.)

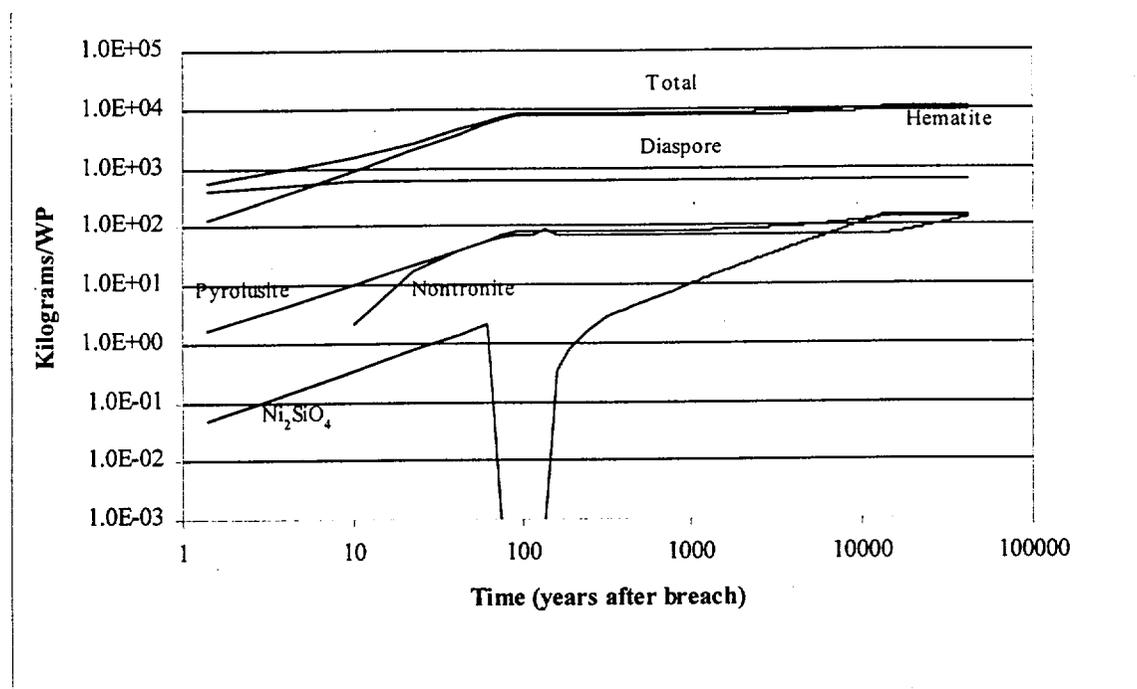


Figure 5.3.1-2. Masses of principal corrosion product solids in a 21 PWR LEU waste package, Zircaloy intact. This figure shows the simulated history for degradation of the basket materials only. Drip rate was  $0.15 \text{ m}^3/\text{yr}$ . (Run set PWR0\_15)

(Figure copied from spreadsheet volmas21c.xls, sheet PWR.)

The first case run in this investigation was performed for an average corrosion rate for each of the basket metals and a mean drip rate into the WP of  $0.15 \text{ m}^3/\text{yr}$  (Run PWR0\_15ahI). This run indicated complete corrosion of all the metals in the basket by about 1400 years. Because of the simulated acid production arising from the oxidation of the Cr and Mo in the borated SS, the pH decreased. The flushing rate, however, limited this decrease to about pH 5.5. A more conservative case would lower the pH further, as was demonstrated by using the lower drip rate of  $0.015 \text{ m}^3/\text{yr}$  (Run PWR0\_15ahsII). In this case the pH decreased to about 5.2, owing to the slower removal of acid from the WP. However, because the borated SS was fully corroded in about 1400 years, the pH subsequently rose to 6.6 by 4400 years, as the acid solution was flushed out and replaced by the admixture of slightly alkaline fresh J-13 water. From chemical principles it was expected that the results from these two runs would provide nearly identical amounts of precipitated solids, unless only small amounts that are sensitive to the pH should form. The limited comparison shown in Table 5.3.1.1-1 bears this out. These indicated, on the basis of chemical principles, that a more conservative simulation would use a slower corrosion rate for the borated SS in order to prolong the period of low pH. This was done, using a corrosion rate of 0.025 micrometer/yr for the borated SS, which was fully corroded at about 13,600 years, and the mean drip rate of  $0.15 \text{ m}^3/\text{yr}$  in the run set PWR0\_15II.

Table 5.3.1.1-1 shows a comparison of some of the output data for these three cases. The main result to be drawn from these runs is that the differences in corrosion rate and drip rate have very minimal effect on the amounts of iron or aluminum retained in the WP as solids, as is shown by the amounts simulated at times after all the borated SS has corroded. Reasons for the more complex behavior for the other solids were discussed above.

Table 5.3.1.1-1. Comparison of PWR LEU Basket Corrosion at Low Drip Rate with Corrosion at Mean Rate						
Drip Rate of 0.015m <sup>3</sup> /yr <sup>a</sup> Corrosion rate of Borated SS 0.25 micrometer/yr <sup>b</sup>						
1000s of Years	pH	Hematite	Diaspore	Pyrolusite	Ni <sub>2</sub> SiO <sub>4</sub>	Smectite
0.45	5.23	11.24	2.29	0.25	3.25E-04	4.48E-02
1.04	5.17	12.19	2.29	0.31	1.26E-03	5.52E-02
1.99	5.47	12.73	2.28	0.35	1.74E-03	6.12E-02
3.03	6.07	12.73	2.28	0.35	1.89E-03	6.09E-02
4.01	6.51	12.73	2.28	0.35	2.18E-03	6.02E-02
4.41	6.56	12.73	2.28	0.35	2.37E-03	5.98E-02
Drip Rate of 0.15m <sup>3</sup> /yr <sup>a</sup> Corrosion rate of Borated SS 0.25 micrometer/yr <sup>c</sup>						
0.44	5.53	11.23	2.29	0.25	4.52E-04	4.45E-02
Drip Rate of 0.15m <sup>3</sup> /yr <sup>a</sup> Corrosion rate of Borated SS 0.025 micrometer/yr <sup>d</sup>						
1.04	6.02	10.68	2.29	0.21	1.10E-01	3.60E-02
1.99	6.02	10.84	2.29	0.22	2.25E-02	3.59E-02
3.03	6.01	11.01	2.29	0.23	3.46E-03	3.59E-02
4.01	6.01	11.17	2.29	0.24	4.59E-03	3.60E-02
4.41	6.01	11.24	2.29	0.25	5.05E-03	3.60E-02
13.60	6.01	12.75	2.29	0.16	1.98E-02	2.01E-01
<sup>a</sup> Units for solids are moles/kg of water in a WP						
<sup>b</sup> EQ6 runs PWR0_015ahsl						
<sup>c</sup> EQ6 run PWRah0_15						
<sup>d</sup> EQ6 run PWR0_15						

**5.3.2 Simultaneous Degradation of Basket and LEU SNF**

Table 5.3.2-1 shows percentages of selected elements of special interest for criticality computations at various times post-breach of the corrosion barriers. These data are for LEU SNF. Mo and Tc are effectively removed as soluble corrosion products from the WP as the fuel degrades. Consequently, they will be absent from the WP, except for very minor amounts of adsorbed species or minute traces left in solution, e.g., as a consequence of incomplete mixing of water within the WP, soon after the SNF is fully degraded. Full data sets are included in Ref. 11.

The data in this table show only the percentages retained as solids. Early in the degradation a few percent of the elements present in the original inventory may be present in solution in the WP, and may later precipitate before these elements are flushed out. Thus, occasionally the table shows a decrease in the percentage retained, owing to a partial dissolution of a solid, followed by an increase. Data in Table 5.3.2-1 are for a set of runs in which hematite was not suppressed; the simulation predicts its formation.

**Table 5.3.2-1. Percentages of Selected Elements Remaining as Solids in the Degraded PWR LEU Waste Package at Various Times -- Case Corresponds to Simultaneous Degradation of Basket and SNF. Hematite Present<sup>2</sup>. Drip Rate 0.15 m<sup>3</sup>/yr.**

Time <sup>1</sup>	U	Np	Pu	Am	Ru	Rh	Ag	Nd	Sm	Eu	Gd
0.000	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
0.072	100.00	99.79	100.00	90.63	100.00	100.00	98.28	99.93	99.91	99.94	99.84
0.101	100.00	99.49	100.00	50.12	100.00	100.00	96.83	99.90	99.64	99.61	98.98
0.203	100.00	97.62	100.00	0.00	100.00	100.00	91.32	99.49	92.69	90.13	75.79
0.219	100.00	97.56	100.00	0.00	100.00	100.00	92.50	99.54	93.61	91.67	79.25
0.529	100.00	95.72	99.93	0.00	99.94	99.86	91.39	99.27	88.38	90.90	77.76
0.892	99.82	92.94	99.93	0.00	99.94	99.86	90.20	99.15	86.12	88.54	71.86
2.34	99.81	81.57	99.93	0.00	99.94	99.86	85.25	98.76	78.13	80.19	51.07
5.24	99.80	58.17	99.93	0.00	99.94	99.86	75.49	97.92	60.84	62.19	25.07
10.3	99.78	16.83	99.93	0.00	99.94	99.86	58.28	96.41	35.06	30.17	8.82
12.5	99.79	0.00	99.93	0.00	99.94	99.86	50.94	95.77	28.99	16.35	6.27
20.3	99.38	0.00	99.93	0.00	99.94	99.86	26.10	95.39	26.38	7.95	5.29
30.1	98.89	0.00	99.93	0.00	99.94	99.86	0.00	95.35	26.08	7.04	5.18
40.0	98.38	0.00	99.93	0.00	99.94	99.86	0.00	95.33	25.80	6.13	5.07
50.2	97.87	0.00	99.93	0.00	99.94	99.86	0.00	95.30	25.51	5.19	4.96
60.0	97.34	0.00	99.93	0.00	99.94	99.86	0.00	95.28	25.22	4.28	4.86
70.2	96.83	0.00	99.93	0.00	99.94	99.86	0.00	95.24	24.94	3.34	4.75
79.0	96.48	0.00	99.93	0.00	99.94	99.86	0.00	95.22	24.70	2.53	4.67

<sup>1</sup> Time in thousands of years after breach.  
<sup>2</sup> Data extracted from spreadsheet PWRSF0\_15.xls, sheet minerals.

Figure 5.3.2-1 shows the complete simulated history for these elements for the PWR LEU case in which hematite forms. It shows the rapid removal of Am, and the early flushing out of Np. Eu, Sm, and Gd are decreased to small percentages of their original inventory, but only a small percentage of Nd is removed. Nearly all of the Pu and U are retained. Full details are included in Ref. 11 in files in set PWRSF0\_15, and summary data are in Ref. 11 (spreadsheet PWRSF0\_15.lastpost.xls, sheet minerals).

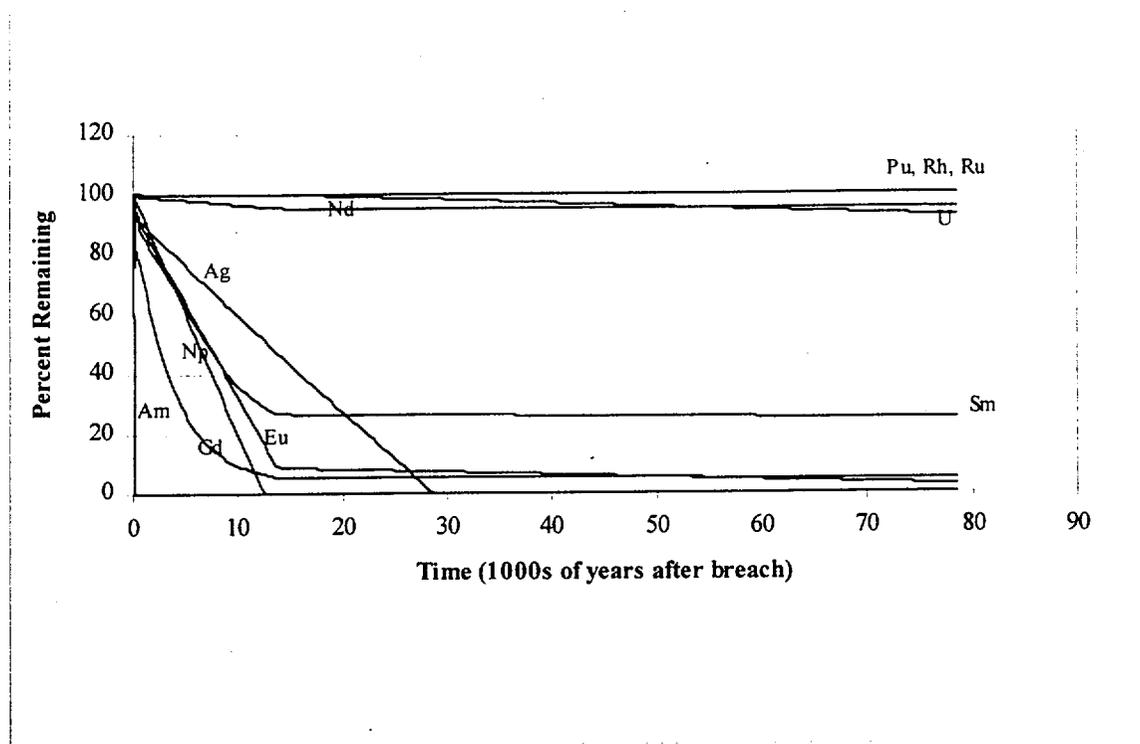


Figure 5.3.2-1. Percent of selected elements remaining in solid phases in a 21 PWR LEU waste package; Zircaloy breached early, hematite present.

This figure shows the entire simulated history of retention of elements of principal interest for criticality during simultaneous degradation of PWR LEU SNF and basket. Hematite is present. Drip rate was  $0.15 \text{ m}^3/\text{yr}$ . The lines for Pu, Rh, and Ru coincide with the 100% line. Am is dissolved out quickly, such that the line for it nearly coincides with the zero time gridline.

(Figure copied from spreadsheet PWRSF0\_15.xls, sheet minerals.)

The solubilities of all the lanthanides (Gd, Nd, Sm, and Eu) are all very similar; the different histories reflect differences in their initial inventories in the waste.

The data for the solids, together with their densities, permit calculation of the volumes of solids and the percentage of the void space occupied by each solid. Figure 5.3.2-2 shows the results of these calculations. The void space is calculated as that originally present plus the volume of the basket metals that have been corroded as a function of time. The increase in the volume of hematite over the first 100 years arises primarily from the corrosion of the A516. Unlike the case for the basket only corroding, nontronite, is not simulated to occur. Probably this happens on account of a small effect on the pH, making hematite and/or diasporite a little less soluble, thereby robbing the nontronite of elements that must be at a high enough concentration for it to precipitate. The pH could also affect the silica concentration slightly, thereby allowing too much to be flushed out to permit the formation of silicates. This would apply also to  $\text{Ni}_2\text{SiO}_4$ , which is also simulated to be absent in this case. A small volume of pyrolusite,  $\text{MnO}_2$  is still modeled as forming. At about 100 years the A516 is predicted to be completely corroded, as is reflected in the sudden change in the rates of change of the space occupied by the hematite. The diasporite,  $\text{AlOOH}$ , derives from the corrosion of the Al alloy. The pH changes result from complex interactions among all the solid and aqueous species present. The major solids, hematite and diasporite, remain essentially the same as in the absence of simulated

waste degradation. Consequently, virtually all of the Fe and Al initially present in the steel and Al alloy remain in the waste package. The small amounts of Ca, Mg, K, and Na that were predicted to be present in solids in the case of basket degradation only are absent. About one fourth of the Ni is retained as trevorite,  $NiFe_2O_4$ .

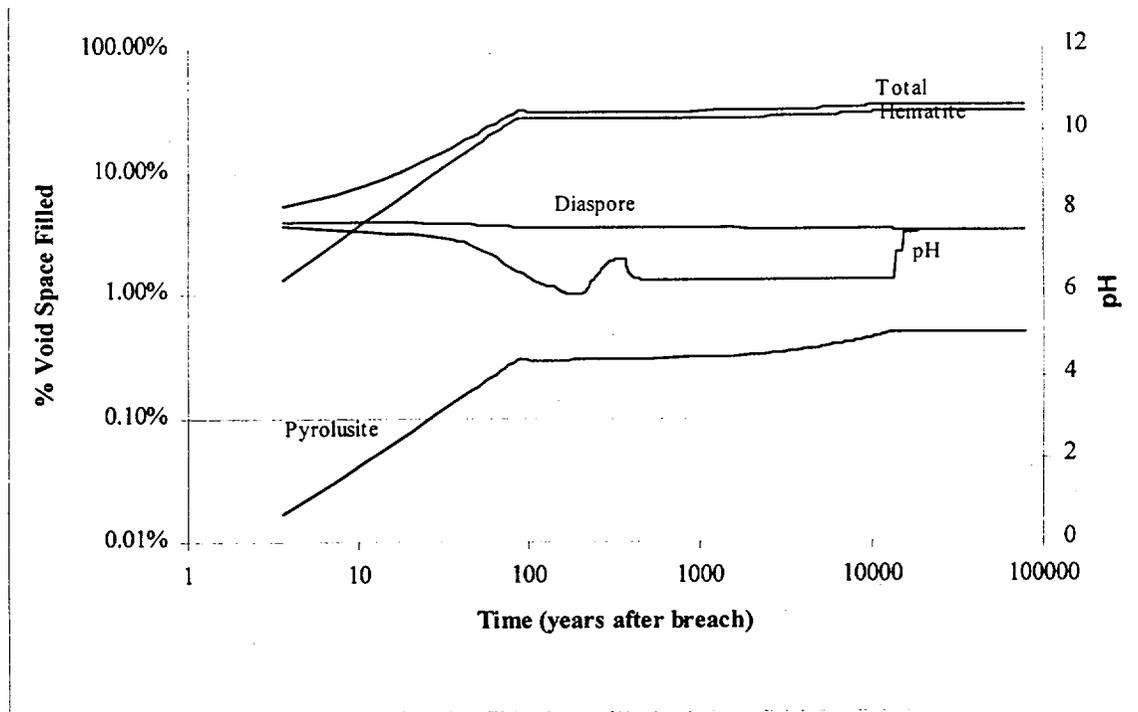


Figure 5.3.2-2. Volume percentages of void space in a 21 PWR LEU waste package occupied by principal minerals precipitated; Zircaloy breached early, hematite present. This figure shows percentage of void space occupied by most of the solids produced during the degradation of the 21 PWR LEU waste package for simultaneous corrosion of basket and SNF. Hematite is present. Drip rate was  $0.15 \text{ m}^3/\text{yr}$ .

(Figure copied from spreadsheet volmas21c, sheet PWRSF.)

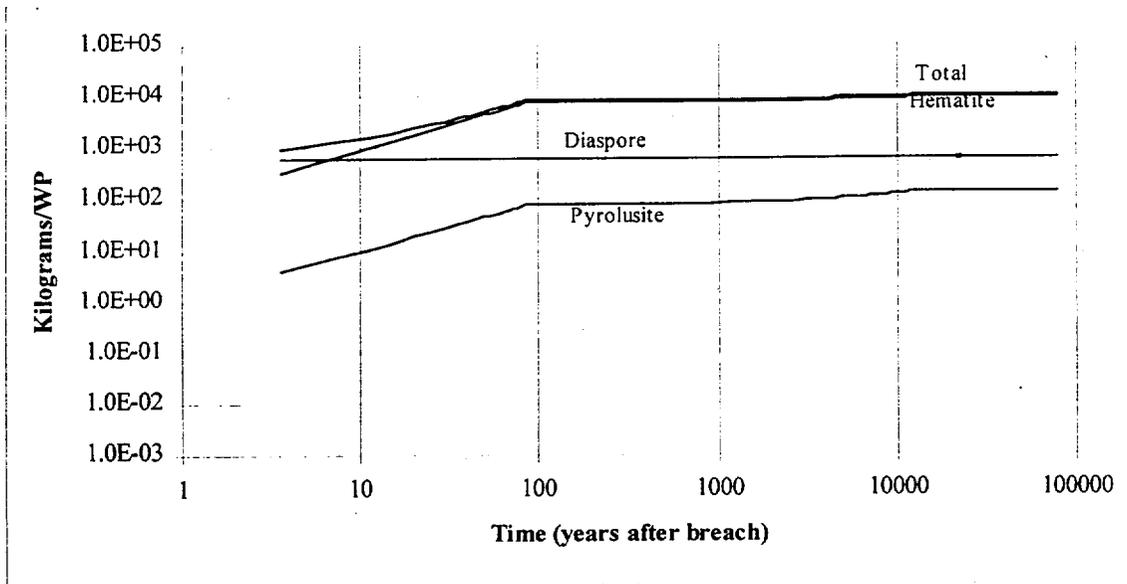


Figure 5.3.2-3. Masses of principal corrosion product solids in a 21 PWR LEU waste package; Zircaloy breached early, hematite present.

This figure shows the total masses of most of the solids produced during the degradation of the 21 PWR LEU waste package for simultaneous corrosion of basket and SNF. Hematite is present. Drip rate was 0.15 m<sup>3</sup>/yr. (Figure copied from spreadsheet volmas21c, sheet PWRSF.)

Table 5.3.2-2 provides the pH and concentrations of U, Np, Pu, Am, Nd, Sm, Eu, Gd, and B at the same times as entered in Table 5.3.2-1. Figure 5.3.2-4 shows the complete time history for the pH and U, Gd, and B concentrations.

**Table 5.3.2-2. Concentrations of Selected Elements in the Degraded PWR LEU Waste Package at Various Times -- Case Corresponds to Simultaneous Degradation of Basket and SNF. Hematite Present\*<sup>2</sup> Drip Rate was 0.15 m<sup>3</sup>/yr. Molalities.**

Time <sup>1</sup>	pH	U	Np	Pu	Am	B	Nd	Sm	Eu	Gd
0.000	7.64E+00	1.00E-14	1.00E-10	1.00E-14	1.00E-10	1.24E-05	1.00E-14	1.00E-10	1.00E-10	1.00E-14
0.07	6.74E+00	2.21E-05	1.78E-05	1.64E-12	3.19E-06	1.02E-03	8.60E-07	3.96E-06	6.75E-07	1.24E-06
0.101	6.38E+00	1.18E-05	4.08E-05	3.19E-12	1.55E-05	1.10E-03	6.25E-06	2.55E-05	4.69E-06	8.76E-06
0.203	5.98E+00	8.02E-06	1.03E-04	7.47E-12	8.67E-06	1.15E-03	8.43E-05	3.26E-04	6.44E-05	1.17E-04
0.219	6.11E+00	8.57E-06	7.30E-05	5.39E-12	5.29E-06	1.13E-03	2.86E-05	1.11E-04	1.95E-05	3.69E-05
0.529	6.35E+00	1.06E-05	4.08E-05	3.21E-12	4.17E-10	1.10E-03	8.04E-06	3.23E-05	4.65E-06	8.49E-06
0.892	6.35E+00	1.07E-05	3.94E-05	3.09E-12	1.00E-14	1.10E-03	4.91E-06	2.03E-05	3.05E-06	5.88E-06
2.34	6.33E+00	1.04E-05	4.12E-05	3.22E-12	1.00E-14	1.10E-03	5.55E-06	2.28E-05	3.42E-06	5.53E-06
5.24	6.33E+00	1.04E-05	4.15E-05	3.23E-12	1.00E-14	1.10E-03	5.63E-06	2.31E-05	3.46E-06	2.44E-06
10.3	6.33E+00	1.04E-05	4.16E-05	3.24E-12	1.00E-14	1.10E-03	5.69E-06	1.30E-05	3.50E-06	6.24E-07
12.5	6.32E+00	1.03E-05	4.04E-05	3.27E-12	1.00E-14	1.10E-03	5.75E-06	8.85E-06	3.53E-06	3.66E-07
20.3	7.53E+00	1.35E-04	1.00E-14	7.49E-13	1.00E-14	1.24E-05	5.18E-08	1.15E-07	5.10E-08	4.63E-09

30.1	7.53E+00	1.35E-04	1.00E-14	7.49E-13	1.00E-14	1.24E-05	5.18E-08	1.13E-07	5.10E-08	4.53E-09
40.0	7.53E+00	1.35E-04	1.00E-14	7.49E-13	1.00E-14	1.24E-05	5.18E-08	1.12E-07	5.10E-08	4.42E-09
50.2	7.53E+00	1.35E-04	1.00E-14	7.49E-13	1.00E-14	1.24E-05	5.18E-08	1.10E-07	5.10E-08	4.32E-09
60.0	7.53E+00	1.35E-04	1.00E-14	7.49E-13	1.00E-14	1.24E-05	5.18E-08	1.09E-07	5.10E-08	4.22E-09
70.2	7.53E+00	1.35E-04	1.00E-14	7.49E-13	1.00E-14	1.24E-05	5.18E-08	1.07E-07	5.10E-08	4.12E-09
79.0	7.53E+00	1.35E-04	1.00E-14	7.49E-13	1.00E-14	1.24E-05	5.18E-08	1.06E-07	5.10E-08	4.04E-09

<sup>1</sup> Time in thousands of years after breach. \* Concentrations equal to or less than 1.00E-14 are reported as 1.00E-14.

<sup>2</sup> Data extracted from spreadsheet PWRSF0\_15, sheet elements and PWRSF0\_15 EQ6 summary files.

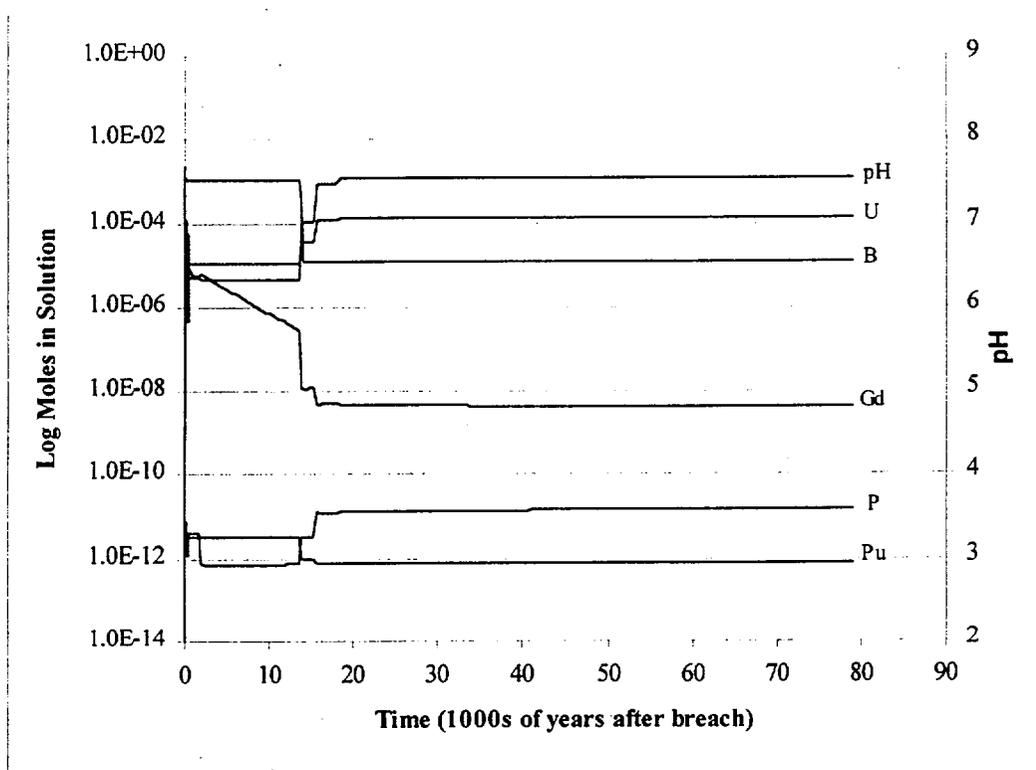


Figure 5.3.2-4. Aqueous concentrations (molalities) of selected elements in a 21 PWR LEU waste package; Zircaloy breached early, hematite present.

This figure shows aqueous concentrations of several of the most significant elements as a function of time following waste package breach for the 21 PWR LEU waste package for simultaneous corrosion of basket and SNF. Hematite is present. Drip rate was 0.15 m<sup>3</sup>/yr.

(Figure copied from spreadsheet PWRSF0\_15, sheet elements.)

Table 5.3.2-3 and Figure 5.3.2-5 show data for a case that is parallel to that for Table 5.3.2-1, except that in this case hematite was suppressed and goethite is simulated to form instead. Mo and Tc are effectively removed as soluble corrosion products from the WP as the fuel degrades. The runs show minor differences in the solution chemistry, such as the pH, which cause major changes in how long Np and the rare earths remain in the WP. Full details are included in Ref. 11 in files in set PWRnHSF0\_15, and summary data are in Ref. 11 (spreadsheet PWRnHSF0\_15.lastpost.xls, sheet elements).

**Table 5.3.2-3. Concentrations of Selected Elements in the Degraded PWR LEU Waste Package at Various Times -- Case Corresponds to Simultaneous Degradation of Basket and SNF. Hematite Suppressed\*<sup>2</sup> Drip Rate was 0.15 m<sup>3</sup>/yr. Molalities.**

Time <sup>1</sup>	pH	U	Np	Pu	Am	B	Nd	Sm	Eu	Gd
0.00	7.64E+00	1.00E-14	1.00E-14	1.00E-14	1.00E-14	1.24E-05	1.00E-14	1.00E-14	1.00E-14	1.00E-14
0.04	7.33E+00	1.02E-04	5.13E-06	8.33E-13	3.52E-07	7.81E-04	9.55E-08	5.42E-07	8.95E-08	1.56E-07
0.09	6.47E+00	1.32E-05	3.26E-05	2.62E-12	1.28E-05	1.11E-03	3.66E-06	1.52E-05	2.78E-06	5.18E-06
0.12	6.03E+00	8.27E-06	9.06E-05	6.61E-12	1.25E-05	1.15E-03	5.82E-05	2.25E-04	4.39E-05	8.01E-05
0.23	6.06E+00	8.18E-06	7.99E-05	5.86E-12	3.82E-06	1.12E-03	3.49E-05	1.37E-04	2.26E-05	4.31E-05
0.55	6.08E+00	8.12E-06	7.48E-05	5.58E-12	1.86E-10	1.10E-03	3.99E-05	1.56E-04	2.22E-05	3.59E-05
0.90	6.02E+00	7.81E-06	8.37E-05	6.14E-12	1.00E-14	1.10E-03	3.86E-05	1.51E-04	2.26E-05	1.88E-05
1.21	6.02E+00	7.80E-06	8.39E-05	6.16E-12	1.00E-14	1.10E-03	3.88E-05	1.52E-04	2.22E-05	1.13E-05
1.82	6.00E+00	7.72E-06	8.80E-05	6.44E-12	1.00E-14	1.10E-03	4.45E-05	1.06E-04	4.11E-06	4.11E-06
2.37	5.99E+00	7.68E-06	9.03E-05	6.61E-12	1.00E-14	1.10E-03	4.80E-05	6.14E-05	1.60E-05	1.73E-06
4.14	5.95E+00	7.60E-06	9.73E-05	7.11E-12	1.00E-14	1.10E-03	6.03E-05	1.18E-05	1.00E-14	1.40E-07
5.02	5.94E+00	7.58E-06	1.01E-04	7.40E-12	1.00E-14	1.10E-03	6.80E-05	5.04E-06	1.00E-14	4.46E-08
5.70	5.93E+00	7.58E-06	7.72E-05	7.53E-12	1.00E-14	1.10E-03	7.18E-05	3.25E-06	1.00E-14	2.44E-08
10.21	5.92E+00	7.59E-06	1.00E-14	7.80E-12	1.00E-14	1.10E-03	7.99E-05	6.68E-07	1.00E-14	2.29E-09
15.30	6.99E+00	3.31E-05	1.00E-14	1.06E-12	1.00E-14	1.24E-05	2.53E-07	1.32E-09	1.00E-14	2.74E-12
20.16	7.53E+00	1.34E-04	1.00E-14	7.49E-13	1.00E-14	1.24E-05	5.19E-08	3.61E-10	1.00E-14	8.31E-13
30.36	7.53E+00	1.34E-04	1.00E-14	7.49E-13	1.00E-14	1.24E-05	5.19E-08	3.60E-10	1.00E-14	8.28E-13
44.57	7.53E+00	1.34E-04	1.00E-14	7.49E-13	1.00E-14	1.24E-05	5.19E-08	3.59E-10	1.00E-14	8.24E-13

<sup>1</sup> Time in thousands of years after breach. \* Concentrations equal to or less than 1.00E-14 are reported as 1.00E-14.

<sup>2</sup> Data extracted from spreadsheet PWRSF0\_15nH, sheet elements and PWRSF0\_15nH EQ6 summary files.

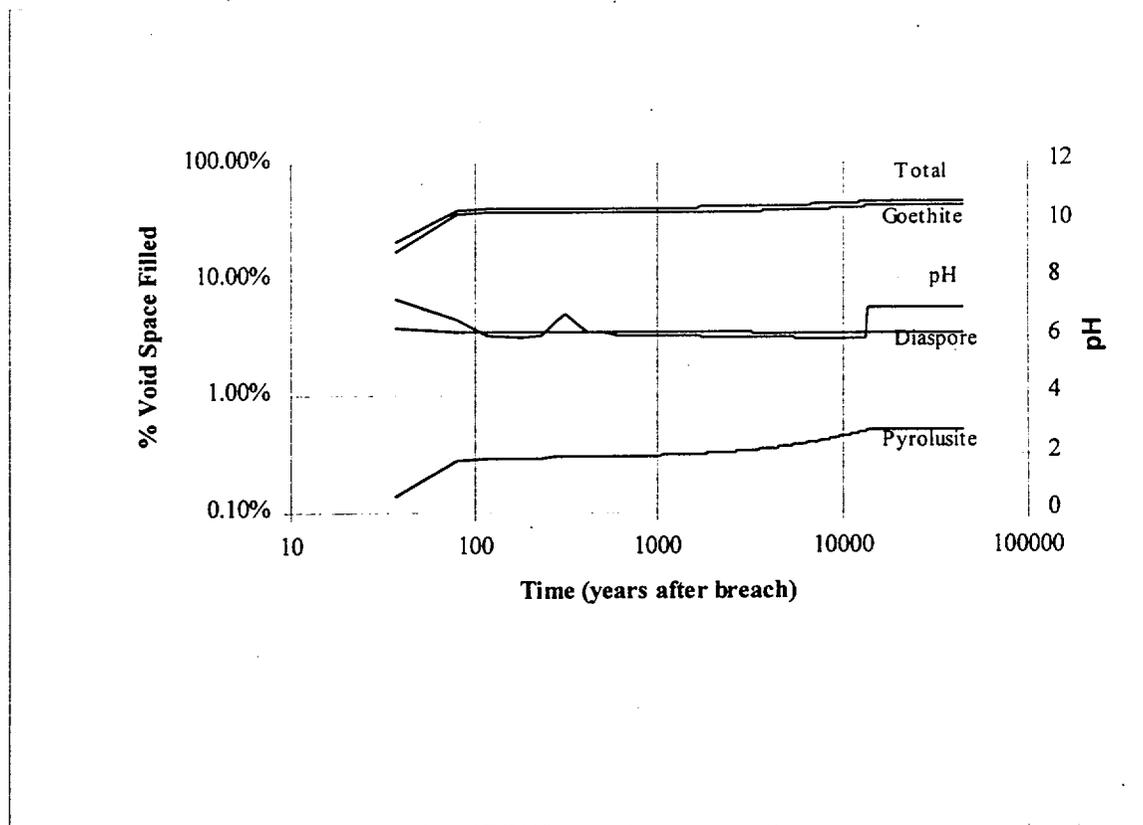


Figure 5.3.2-5. Volume percentages of void space in a 21 PWR LEU waste package occupied by principal minerals precipitated; Zircaloy breached early, goethite present.

This figure shows percentage of void space occupied by most of the solids produced during the degradation of the 21 PWR LEU waste package for simultaneous corrosion of basket and SNF. Goethite is present. Drip rate was 0.15 m<sup>3</sup>/yr.

(Figure copied from spreadsheet volmas21c.xls, sheet PWRSFnH.)

**Title:** EQ6 Calculations for Chemical Degradation of PWR LEU and PWR MOX Spent Fuel Waste Packages

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**Page 41 of 57**

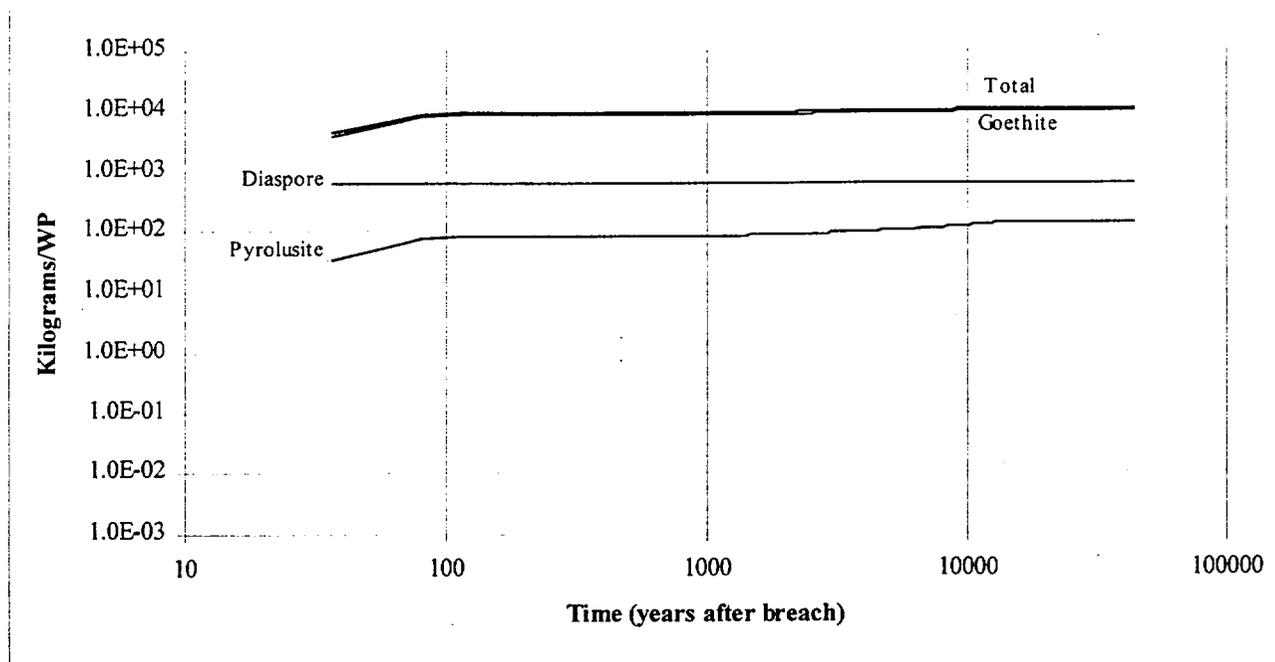


Figure 5.3.2-6. Masses of principal corrosion product solids in a 21 PWR LEU waste package; Zircaloy breached early, goethite present. This figure shows the total masses of most of the solids produced during the degradation of the 21 PWR LEU waste package for simultaneous corrosion of basket and SNF. Goethite is present. Drip rate was 0.15 m<sup>3</sup>/yr. (Figure copied from spreadsheet volmas21c.xls, sheet PWRSFnH.)

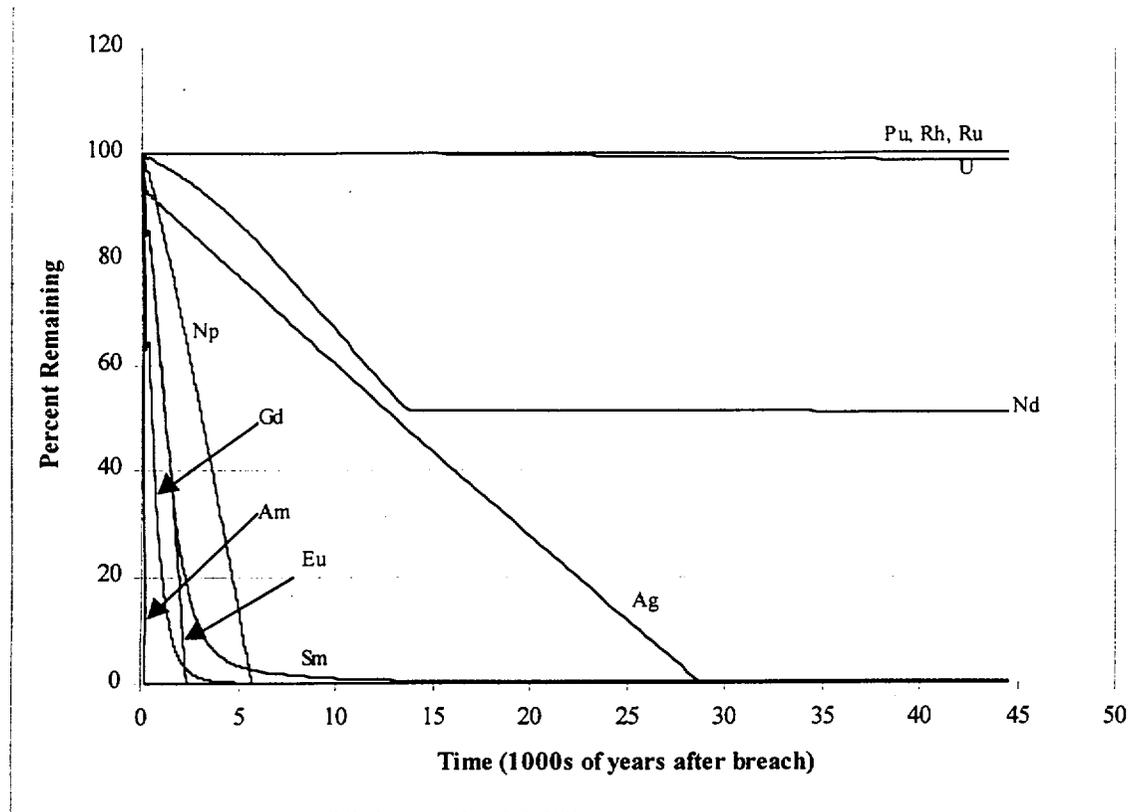


Figure 5.3.2-7. Percent of selected elements remaining in solid phases in a 21 PWR LEU waste package; Zircaloy breached early, goethite present.

This figure shows the entire simulated history of retention of elements of principal interest for criticality during simultaneous degradation of PWR LEU SNF and basket. Goethite is present. Drip rate was 0.15 m<sup>3</sup>/yr. The lines for Pu, Rh, and Ru coincide with the 100% line. Am is dissolved out quickly, such that the line for it nearly coincides with the zero time gridline. Drip rate was 0.15 m<sup>3</sup>/yr.

(Figure copied from spreadsheet PWRSF0\_15nH.xls, sheet minerals.)

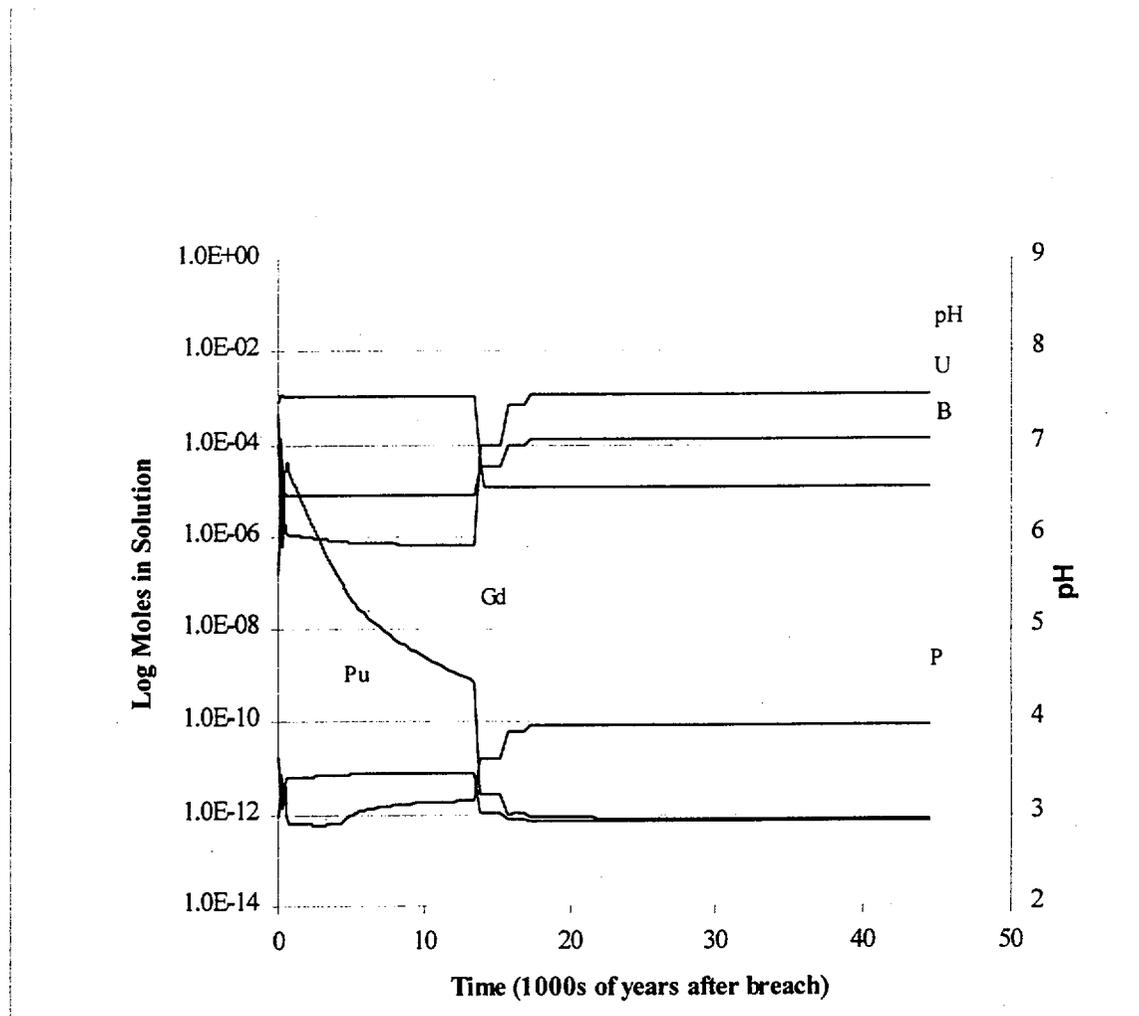


Figure 5.3.2-8. Aqueous concentrations (molalities) of selected elements in a 21 PWR LEU waste package; Zircaloy breached early, goethite present. This figure shows aqueous concentrations of several of the most significant elements as a function of time following waste package breach for the 21 PWR LEU waste package for simultaneous corrosion of basket and SNF. Goethite is present. Drip rate was 0.15 m<sup>3</sup>/yr. (Figure copied from spreadsheet PWRSF0\_15nH.xls, sheet elements.)

Results for a PWR MOX spent fuel package closely resemble those for the PWR LEU fuel. The major differences are in the earlier or larger percentage removal of Ag and the lanthanides for the PWR LEU case. Table 5.3.2-4 and Figure 5.3.2-9 show the percentages of principal isotopes that remain in the WP as a function of time. Full details are included in Ref. 11 in files in set MOXSF0\_15, and summary data are in Ref. 11 (spreadsheet MOXSF0\_15.lastpost.xls, sheet sum).

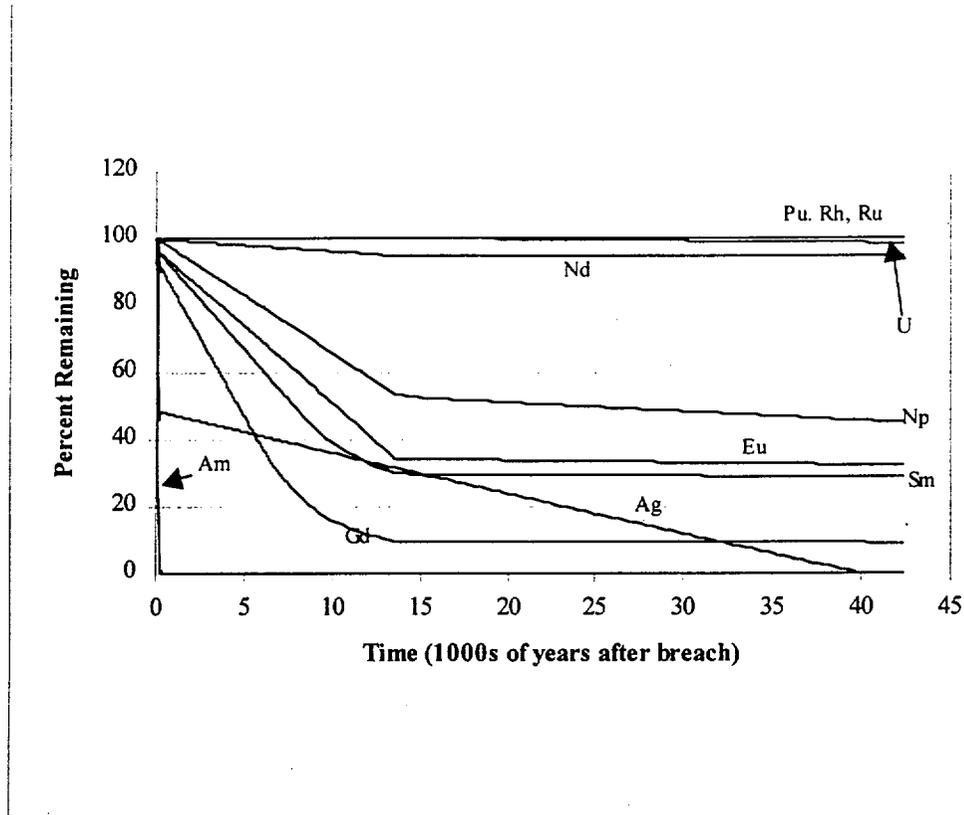


Figure 5.3.2-9. Percent of selected elements remaining in solid phases in a 21 PWR MOX waste package; Zircaloy breached early, hematite present, mean drip rate.

This figure shows the entire simulated history of retention of elements of principal interest for criticality during simultaneous degradation of PWR MOX SNF and basket. Hematite is present. Drip rate was 0.15 m<sup>3</sup>/yr. The lines for Pu, Rh, and Ru coincide with the 100% line. Am is dissolved out quickly, such that the line for it nearly coincides with the zero time gridline.

(Figure copied from spreadsheet MOXSF0\_151.lastpost.xls, sheet sum.)

The effect of different infiltration, or drip, rates was investigated partly by using a slower rate following degradation of the basket material, as described in Section 5.3.3, and partly by a relatively short series of runs at a drip rate of 0.5 m<sup>3</sup>/yr. The results of this latter set, for PWR MOX SNF, are shown in Figure 5.3.2-10. Comparison with Figure 5.3.2-9 shows that there are essentially no differences for Pu, U, Nd, Rh, and Ru. Am is retained a little longer at the higher infiltration rate, and Ag is initially removed less rapidly, but in the longer term is removed sooner. A closer examination of the output data shows that the rate of removal of Ag for the 0.5 m<sup>3</sup>/yr drip rate is very close to 3 1/3 times faster than at the 0.15 m<sup>3</sup>/yr drip rate, i.e., in proportion to the drip rate. This is consistent with the removal being controlled by the solubility of the silver solid, AgCl. The lanthanides, most notably the Gd, are simulated to be removed significantly less rapidly at the higher drip rate.

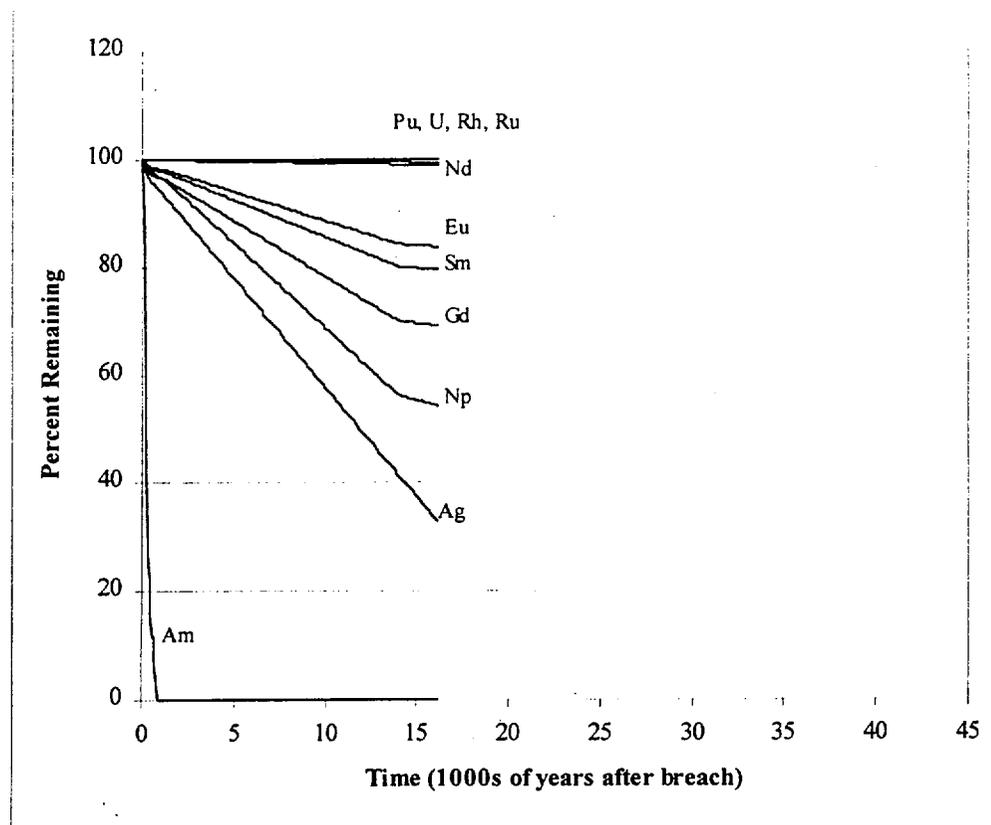


Figure 5.3.2-10. Percent of selected elements remaining in solid phases in a 21 PWR MOX waste package; Zircaloy breached early, hematite present, high drip rate.

This figure shows the entire simulated history of retention of elements of principal interest for criticality during simultaneous degradation of PWR MOX SNF and basket. Hematite is present. Drip rate was  $0.5 \text{ m}^3/\text{yr}$ . The lines for Pu, Rh, and Ru coincide with the 100% line. Am is dissolved out quickly, such that the line for it nearly coincides with the zero time gridline.

(Figure copied from spreadsheet MOXSF0\_5.xls, sheet sum.)

### 5.3.3 Degradation of SNF after Degradation of Basket

Three different scenarios were calculated for the start of degradation of the spent fuel after all the basket materials had corroded. The first considered PWR LEU SNF at the mean drip rate of  $0.15 \text{ m}^3/\text{yr}$  entering the WP, and the second the parallel case for PWR MOX SNF. The case for PWR LEU SNF was run only far enough to confirm that the chemical evolution would be essentially the same as for the case when the basket and SNF degrade simultaneously. The third case was for PWR MOX SNF, but with a minimal drip rate of  $0.015 \text{ m}^3/\text{yr}$ . This case was run to investigate whether a lower drip rate would be more conservative, owing to the expected longer-lasting low pH for a lower drip rate, thereby possibly enabling a greater leaching and removal of Gd absorber from the WP. The simulation did in fact show the expected pH effect (e.g., pH 7.37 for the slow drip rate at 16,700 years as compared with pH 7.53 for the mean drip rate at the same time). However, even in the slow drip rate case the pH rose rapidly enough that the solubility of Gd became minimal and the removal rate from the WP was dominated by the slow drip rate, rather than the approximately 30% higher solubility. Consequently, the rate of removal was

substantially slower for a drip rate of 0.015 m<sup>3</sup>/yr following complete corrosion of the basket, as shown by a comparison of the data in Tables 5.3.3-2 and 5.3.3-3. The solubility of Pu for the slow drip rate case was only about 3% higher than for the mean drip rate, but that for U was about 40% lower, presumably because of the greater formation of uranyl carbonate complexes at the higher pH for the faster drip rate. (This could not be checked owing to the impracticality of retaining dozens of very large (up to several gigabytes in size) complete output files.) The pH rises following the complete degradation of the basket because of the influx of the slightly alkaline J-13 and lack of any further generation of acid from borated SS corrosion. The case, in which the drip rate decreases upon full corrosion of the basket, would correspond to a rapid climate change to a drier environment that happened to coincide approximately with the end of the degradation of the metals in the basket.

Table 5.3.3-1 shows percentages of selected elements retained as solids at various times post-breach of the corrosion barriers for the first of these cases. The first 13,800 years are the same as for the degradation of the basket materials alone, as discussed in Section 5.3.1. Those details are not repeated here. The rest of the data summarize the chemical evolution after the basket materials are corroded and at which time the Zircaloy cladding is simulated to have breached and the degradation of the PWR LEU SNF begun. Full data sets are included in Ref. 11 (file set PWRSFpd0\_15). Figure 5.3.3-1 displays these results graphically.

Time <sup>1</sup>	U	Np	Pu	Am	Ru	Rh	Ag	Nd	Sm	Eu	Gd
0	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
0.465	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
13.8	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
14.00	100.00	98.54	100.00	21.30	99.99	100.01	94.49	99.90	97.86	97.36	93.34
15.00	99.96	97.18	100.01	0.00	100.00	99.99	90.94	99.86	97.04	96.41	90.96
16.00	99.90	96.53	100.01	0.00	100.00	99.99	87.72	99.85	96.96	96.30	90.74
17.00	99.85	95.87	100.01	0.00	100.00	99.99	84.58	99.85	96.88	96.24	90.52
20.29	99.10	0.00	99.93	0.00	99.94	99.86	26.10	95.39	26.38	7.95	5.29
25.02	98.55	0.00	99.93	0.00	99.94	99.86	11.19	95.36	26.24	7.51	5.23
28.67	98.14	0.00	99.93	0.00	99.94	99.86	0.00	95.36	26.13	7.17	5.19
39.95	96.79	0.00	99.93	0.00	99.94	99.86	0.00	95.33	25.80	6.13	5.07
50.16	95.60	0.00	99.93	0.00	99.94	99.86	0.00	95.30	25.51	5.19	4.96
60.01	94.42	0.00	99.93	0.00	99.94	99.86	0.00	95.28	25.22	4.28	4.86
70.20	93.23	0.00	99.93	0.00	99.94	99.86	0.00	95.24	24.94	3.34	4.75
78.58	92.25	0.00	99.93	0.00	99.94	99.86	0.00	95.22	24.70	2.57	4.67

<sup>1</sup> Time in thousands of years after breach.  
<sup>2</sup> Data extracted from spreadsheet PWRSFpd.xls, sheet minerals.

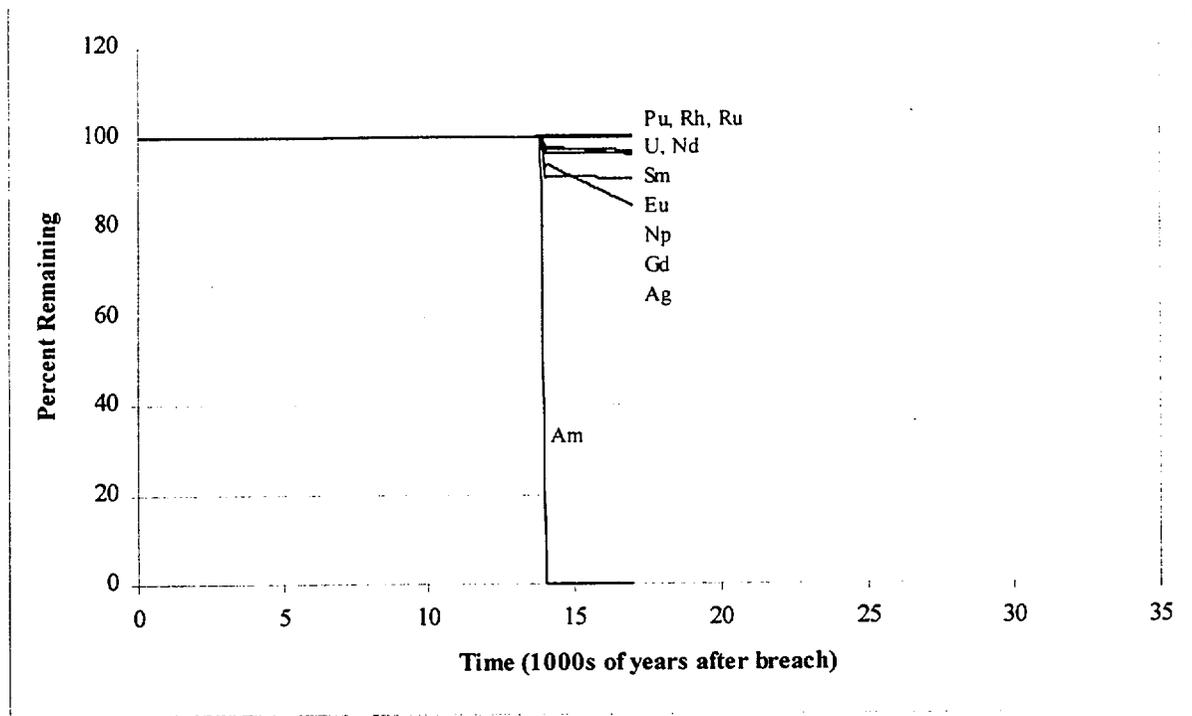


Figure 5.3.3-1. Percent of selected elements remaining in solid phases in a 21 PWR LEU waste package; Zircaloy breached late, mean drip rate.

This figure shows the entire simulated history of retention of elements of principal interest for criticality. This case simulates breach of the Zircaloy cladding only after the basket is completely corroded. Consequently, none of the elements is lost from the WP before that time, about 13,700 years. Hematite is present. Drip rate was 0.15 m<sup>3</sup>/yr. The lines for Pu, Rh, and Ru coincide with the 100% line. Am is dissolved out quickly after waste package breach.

(Figure copied from spreadsheet PWRSFpd.xls, sheet minerals.)

Table 5.3.3-2 and Figure 5.3.3-2 show the parallel case for PWR MOX SNF. Full data sets are included in Ref. 11, data set MOXpda0\_15.

**Table 5.3.3-2. Percentages of Selected Elements Remaining in the Degraded PWR MOX Waste Package at Various Times -- Breaching of Zircaloy and Initiation of SNF Degradation After Basket Fully Degraded. Drip Rate 0.15 m<sup>3</sup>/yr.<sup>2</sup>**

Time <sup>1</sup>	U	Np	Pu	Am	Ru	Rh	Ag	Nd	Sm	Eu	Gd
0	100	100	100	100	100	100	100	100	100	100	100
0.32	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
13.69	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
14.00	99.99	99.10	99.99	5.70	99.99	99.99	50.76	99.86	97.81	98.01	96.04
16.48	99.85	98.42	99.99	0.00	99.99	99.99	47.82	99.84	97.60	97.85	95.70
17.41	99.80	98.18	99.99	0.00	99.99	99.99	46.71	99.84	97.53	97.77	95.59
18.64	99.73	97.85	99.99	0.00	99.99	99.99	45.24	99.83	97.43	97.70	95.40
22.98	99.49	96.68	99.99	0.00	99.99	99.99	40.08	99.82	97.10	97.42	94.85
25.14	99.36	96.11	99.99	0.00	99.99	99.99	37.51	99.81	96.92	97.27	94.55
31.95	98.98	94.27	99.99	0.00	99.99	99.99	29.41	99.80	96.39	96.83	93.67

<sup>1</sup> Time in thousands of years after breach.  
<sup>2</sup> Data extracted from spreadsheet PWRpda0\_15.xls, sheet minerals.

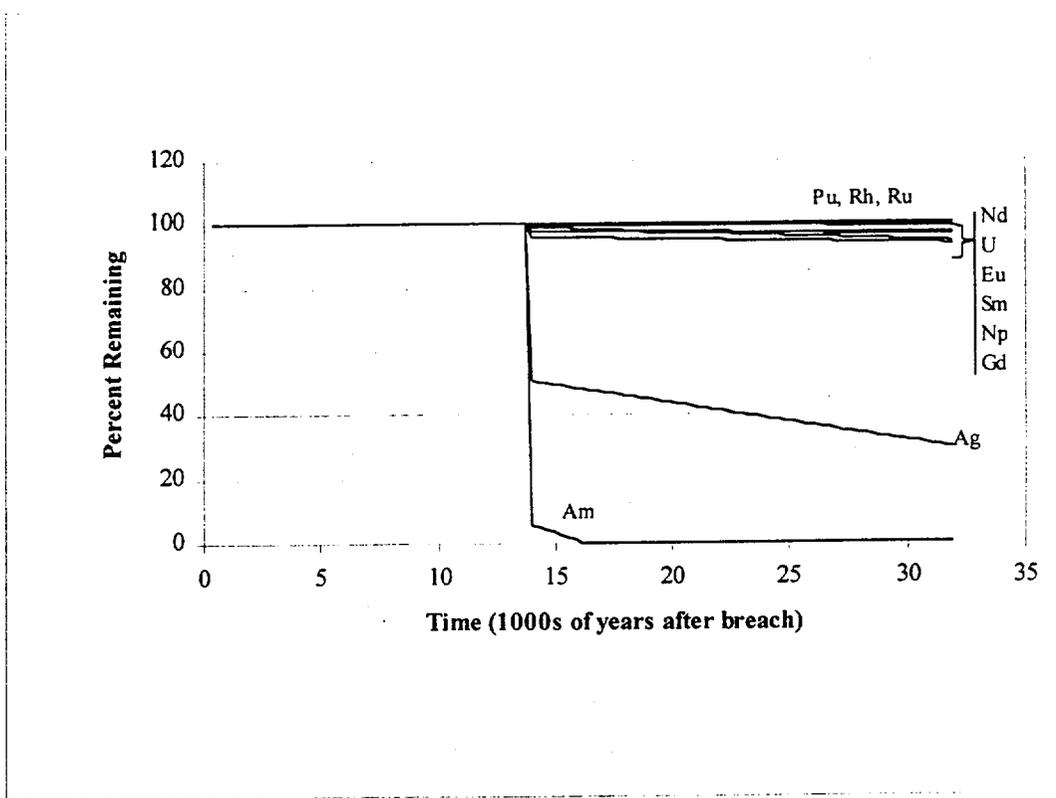


Figure 5.3.3-2. Percent of selected elements remaining in solid phases in a 21 PWR MOX waste package; Zircaloy breached late, mean drip rate.

This figure shows the entire simulated history of retention of elements of principal interest for criticality. This case simulates breach of the Zircaloy cladding only after the basket is completely corroded. Consequently, none of the elements is lost from the WP before that time, about 13,700 years. Hematite is present. Drip rate was 0.15 m<sup>3</sup>/yr. The lines for Pu, Rh, and Ru coincide with the 100% line. Am is dissolved out quickly after waste package breach.

(Figure copied from spreadsheet MOXpda1.xls, sheet minerals.)

Table 5.3.3-3 and Figure 5.3.3-3 show the results for the third case, degradation of PWR MOX SNF at a drip rate of 0.015 m<sup>3</sup>/yr immediately following the complete corrosion of the basket.

**Table 5.3.3-3. Percentages of Selected Elements Remaining in the Degraded PWR MOX Waste Package at Various Times -- Breaching of Zircaloy and Initiation of SNF Degradation After Basket Fully Degraded. Drip Rate 0.015 m<sup>3</sup>/yr<sup>2</sup>**

Time <sup>1</sup>	U	Np	Pu	Am	Ru	Rh	Ag	Nd	Sm	Eu	Gd
0	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
0.651	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
16.70	100.00	99.27	100.00	6.43	99.99	100.00	28.93	99.80	96.83	96.09	92.84
19.98	99.98	99.20	100.00	5.49	99.99	100.00	28.54	99.79	96.80	96.05	92.81
29.82	99.93	98.92	100.00	2.93	99.99	100.00	27.38	99.79	96.73	95.97	92.67
42.93	99.85	98.57	100.00	0.00	99.99	100.00	25.81	99.78	96.63	95.89	92.50
78.96	99.64	97.60	100.00	0.00	99.99	100.00	21.53	99.78	96.35	95.66	92.03
101.90	99.51	96.98	100.00	0.00	99.99	100.00	18.80	99.77	96.16	95.50	91.73
200.20	98.96	94.34	100.00	0.00	99.99	100.00	7.11	99.72	95.39	94.87	90.41
262.50	98.61	92.67	100.00	0.00	99.99	100.00	0.00	99.70	94.91	94.44	89.57
301.70	98.39	91.60	100.00	0.00	99.99	100.00	0.00	99.70	94.60	94.21	89.07
400.50	97.83	88.97	100.00	0.00	99.99	100.00	0.00	99.66	93.82	93.54	87.75
495.60	97.30	86.40	100.00	0.00	99.99	100.00	0.00	99.62	93.07	92.92	86.50

<sup>1</sup> Time in thousands of years after breach.  
<sup>2</sup> Data extracted from spreadsheet MOXPdswa.xls, sheet sum.

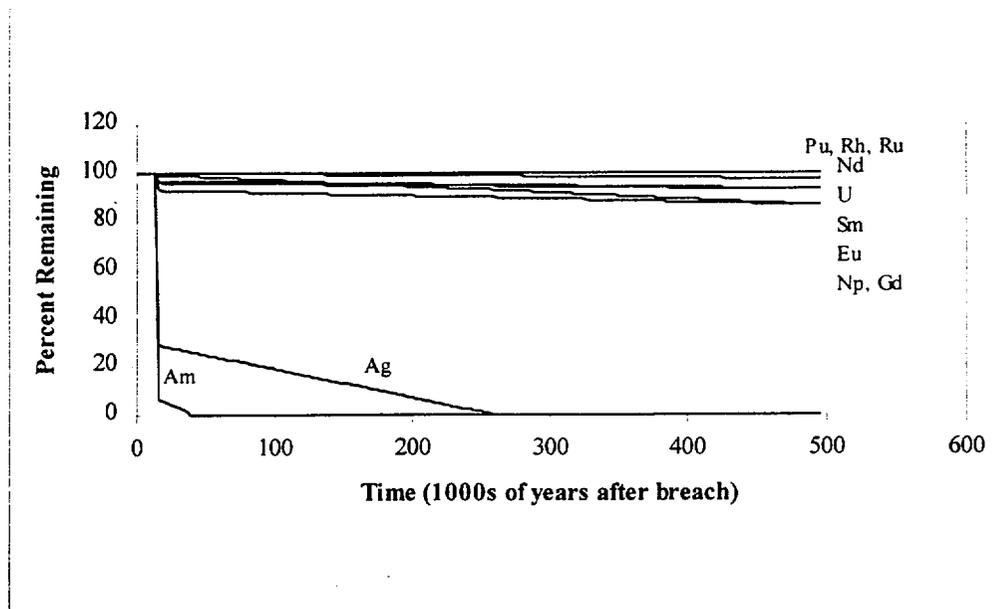


Figure 5.3.3-3. Percent of selected elements remaining in solid phases in a 21 PWR MOX waste package; Zircaloy breached late, low drip rate.

This figure shows the entire simulated history of retention of elements of principal interest for criticality. This case simulates breach of the Zircaloy cladding only after the basket is completely corroded. Consequently, none of the elements is lost from the WP before that time, about 13,700 years. Hematite is present. Drip rate was  $0.015 \text{ m}^3/\text{yr}$ . The lines for Pu, Rh, and Ru coincide with the 100% line. Am is dissolved out quickly after waste package breach.

(Figure copied from spreadsheet MOXPdswa.xls, sheet sum.)

## 6. Results

A principal objective of the calculations was to assess chemical circumstances that could lead to removal of neutron absorbers from the waste package, thereby increasing the probability that a nuclear criticality could occur within the waste package. This was investigated by setting up some initial cases, examining the results to identify the reasons for the chemical changes during degradation of waste package materials and flushing by J-13 water, and finally setting up additional cases that were expected to lead to a greater removal of neutron absorbers, such as gadolinium, while retaining as much fissile material as possible. In other words successive cases were designed to increase the conservatism. Nevertheless, the differences in the results were in all instances small.

Most of the Fe and Mn initially present in the metals are simulated to be retained. The situation for Ni is more complex. Evidently its retention depends strongly on the pH history, especially during the first several thousand years. The percentage retained may be as low as 6%, e.g., for a fast corrosion rate of the borated SS at a drip rate of  $0.15 \text{ m}^3/\text{yr}$ , or as high as 83%, e.g., for simultaneous degradation of the basket and PWR MOX SNF with a mean corrosion rate for the borated SS and the high drip rate of  $0.5 \text{ m}^3/\text{yr}$ . In most runs the percentage simulated to be retained at very long times was in the range of 25% to 33%. During the early history for cases in which SNF is not exposed to the water the corrosion product is predicted to be  $\text{Ni}_2\text{SiO}_4$ , but later this transforms to trevorite,  $\text{NiFe}_2\text{O}_4$ , the only form found after SNF begins to degrade. Another interesting difference is the predicted formation of minor

amounts of nontronite clay in the absence of degradation of SNF, but not when the SNF also degrades. This also probably relates to slight differences in pH. Neither of these differences is very significant in view of the small amounts of these solids.

All or most of the Gd, Sm, and Eu are simulated to be removed for those cases in which the borated SS and SNF degrade simultaneously, but most of the Nd is modeled as retained. See Figures 5.3.2-1, 5.3.2-5, and 5.3.2-9. This results not from significant differences in their solubilities, but from the differences in their initial inventories in the SNF. All of the Am is simulated to be removed very quickly, and all of the Np to be flushed out of the LEU SNF WP in less than 15,000 years, and more than half from the MOX SNF WP in 50,000 years. Nearly all of the U is retained, and, within the numerical precision, all of the Pu is kept. The small amounts of Ru and Rh likewise appear to be completely retained. Silver evidently will dissolve slowly and be removed in less than 40,000 years.

For the cases which simulate the complete corrosion of the borated SS prior to the start of the degradation of the SNF, essentially all of the lanthanides, specifically, Nd, Sm, Eu, and Gd would be retained within the WP. Am is still modeled to be removed rapidly, and the Ag is also dissolved and flushed out, but more slowly. The case for a slow drip rate, after basket corrosion, the pH is lower for an extended time and the Gd is modestly more soluble than for the mean drip rate, but the slowness of the flushing results in a slower removal of all elements from the waste package.

Detailed results of specific cases are presented in Section 5.

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## 8. Attachments

Attachment I. Algorithms for the C Programs (15 pages)

Attachment II. Review of the C Programs in Accordance with QAP-SI-0 (Ref. 27) (1 page)

Attachment III. Pro-Engineer Output (15 pages)

### List of Files on the Colorado Trakker Tape (Ref. 11)

DATA0N~1 R8	2,298,907	07-29-98	9:08a	data0.nuc.R8
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J13INF~1 XLS	18,432	07-23-98	4:25p	J13influx.xls
MOX0_1~1 ALL	30,633,378	07-27-98	6:48p	MOX0_15I.allin
MOX0_1~2 ALL	41,591,030	07-27-98	6:49p	MOX0_15I.alltab
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MOX0_15I sum	559,562	07-27-98	12:05p	MOX0_15I.sum
MOXcomp2.xls	142,848	07-24-98	9:08a	MOXcomp2.xls
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MOXPd0~2 ALL	20,773,350	07-27-98	1:05p	MOXpd0_15II.alltab
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MOXPdA~1 SUM	384,962	07-27-98	12:49p	MOXpda0_15II.sum
MOXpda1.xls	378,368	07-24-98	2:27p	MOXpda1.xls
MOXPdS~4 ALL	8,887,342	07-27-98	1:16p	MOXpdsw0_15II.allin
MO870F~1 ALL	48,829,470	07-27-98	1:18p	MOXpdsw0_15II.allout
MO86C5~1 ALL	7,646,600	07-27-98	1:18p	MOXpdsw0_15II.alltab
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MO2538~1 ALL	49,907,260	07-27-98	1:22p	MOXpdsw0_15III.alltab
MOXPdS~2 POS	4,935,831	07-27-98	1:22p	MOXpdsw0_15III.post
MOXPdswa.xls	534,016	07-24-98	2:26p	MOXPdswa.xls
MOXPdS~1 6I	42,673	07-03-98	2:34p	MOXPdswa0_015II.6i
MOXPdS~3 ALL	66,476,470	07-07-98	1:51a	MOXPdswa0_015II.allin
MOXPdS~2 ALL	9,938,536	07-07-98	1:51a	MOXPdswa0_015II.allpost
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MOF6C9~1 ALL	52,141,180	07-27-98	7:11p	MOXSF0_5II.alltab
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MOXSF0~3 POS	5,308,291	07-27-98	7:27p	MOXSF0_5III.post
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Name doc	22,528	07-29-98	9:58a	Name.doc
PWR015~1 SUM	14,083	03-09-98	10:32a	PWR0.15I.sum
PWR015~2 SUM	86,995	03-09-98	10:11a	PWR0.15II.sum
PWR015~3 SUM	114,512	03-09-98	10:11a	PWR0.15III.sum
PWR015~4 SUM	133,600	03-09-98	5:11p	PWR0.15IV.sum
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PW2F2A~1 ALL	35,791,729	07-28-98	10:05a	PWR0_15ahI.allout
PW8639~1 ALL	6,074,112	07-28-98	10:05a	PWR0_15ahI.alltab
PW50CF~1 ALL	7,167,349	07-28-98	10:05a	PWR0_15ahII.allin
PWC730~1 ALL	91,184,486	07-28-98	10:08a	PWR0_15ahII.allout
PWD6F6~1 ALL	10,455,892	07-28-98	10:08a	PWR0_15ahII.alltab
PW96AE~1 ALL	3,736,279	07-28-98	8:44a	PWR0_15I.allin
PW83CE~1 ALL	18,496,900	07-28-98	8:45a	PWR0_15I.allout
PWR0_1~1 ALL	135,457	07-24-98	4:12p	PWR0_15I.allpost
PWEACD~1 ALL	3,061,890	07-28-98	8:45a	PWR0_15I.alltab
PWC45C~1 ALL	27,154,839	07-28-98	8:46a	PWR0_15II.allin
PWR0_1~2 ALL	864,661	07-24-98	4:13p	PWR0_15II.allpost
PW3B83~1 ALL	20,945,340	07-28-98	8:47a	PWR0_15II.alltab
PWCF3D~1 ALL	35,005,754	07-28-98	8:48a	PWR0_15III.allin
PWR0_1~3 ALL	1,139,355	07-24-98	4:15p	PWR0_15III.allpost
PW7715~1 ALL	28,974,400	07-28-98	8:49a	PWR0_15III.alltab
PWCE6C~1 ALL	40,846,302	07-28-98	8:50a	PWR0_15IV.allin
PWR0_1~4 ALL	1,331,333	07-24-98	4:18p	PWR0_15IV.allpost
PW35A3~1 ALL	33,790,900	07-28-98	8:51a	PWR0_15IV.alltab
PWB6A4~1 ALL	26,702,616	07-28-98	8:52a	PWR0_15V.allin
PWFAC8~1 ALL	37,957,920	07-28-98	8:53a	PWR0_15V.alltab
PWR0_1~1 POS	5,163,595	07-28-98	8:54a	PWR0_15V.post
PWR0_15V sum	521,089	07-28-98	8:54a	PWR0_15V.sum
PWRSF0~2 XLS	617,984	08-06-98	3:39p	PWRSF0_15.xls
PWRSF0~2 ALL	3,377,685	07-28-98	9:27a	PWRSF0_15bII.allin
PWRSF0~3 ALL	27,046,348	07-28-98	9:28a	PWRSF0_15bII.allout
PWRSF0~4 ALL	3,476,070	07-28-98	9:28a	PWRSF0_15bII.alltab
PWRSF0~1 POS	198,701	07-24-98	5:28p	PWRSF0_15bII.post
PWRSF0~1 SUM	21,333	05-26-98	6:19p	PWRSF0_15bII.sum
PWRSF0~1 ALL	11,703,786	07-28-98	9:49a	PWRSF0_15bIII.allin
PW7B4F~1 ALL	11,653,200	07-28-98	9:49a	PWRSF0_15bIII.alltab
PWRSF0~2 POS	704,556	07-24-98	5:29p	PWRSF0_15bIII.post
PWRSF0~2 SUM	71,759	07-24-98	5:29p	PWRSF0_15bIII.sum
PW472C~1 ALL	75,958,315	07-28-98	9:51a	PWRSF0_15bIV.allin
PW3B84~1 ALL	70,347,030	07-28-98	9:54a	PWRSF0_15bIV.alltab
PWRSF0~3 POS	4,401,969	07-24-98	5:29p	PWRSF0_15bIV.post
PWRSF0~3 SUM	440,773	07-24-98	5:29p	PWRSF0_15bIV.sum

PW2C38~1 ALL 9,288,084 07-28-98 9:29a PWRSF0\_15cI.allin  
PW93B8~1 ALL 53,711,791 07-28-98 9:30a PWRSF0\_15cI.allout  
PW927F~1 ALL 7,645,820 07-28-98 9:31a PWRSF0\_15cI.alltab  
PWRSF0~4 POS 362,131 07-24-98 5:29p PWRSF0\_15cI.post  
PWRSF0~1 XLS 752,128 07-24-98 12:28p PWRSF0\_15nH.xls  
PWRSFN~3 ALL 9,384,305 07-28-98 4:04p PWRSFnHO\_15I.allin  
PWRSFN~4 ALL 45,671,501 07-28-98 4:06p PWRSFnHO\_15I.allout  
PWRSFN~1 POS 291,267 07-28-98 4:06p PWRSFnHO\_15I.post  
PWRSFN~1 SUM 34,584 07-28-98 4:06p PWRSFnHO\_15I.sum  
PW3019~1 ALL 5,625,673 07-28-98 4:06p PWRSFnHO\_15II.allin  
PWRSFN~2 ALL 328,845 07-28-98 4:06p PWRSFnHO\_15II.allpost  
PWA640~1 ALL 5,632,380 07-28-98 4:06p PWRSFnHO\_15II.alltab  
PWRSFN~2 SUM 38,896 07-28-98 4:06p PWRSFnHO\_15II.sum  
PW3BFD~1 ALL 11,235,778 07-28-98 4:14p PWRSFnHO\_15III.allin  
PWRSFN~1 ALL 669,949 07-28-98 4:14p PWRSFnHO\_15III.allpost  
PW357D~1 ALL 11,388,130 07-28-98 4:15p PWRSFnHO\_15III.alltab  
PWRSFN~3 SUM 72,454 07-28-98 4:15p PWRSFnHO\_15III.sum  
PW3A29~1 ALL 32,046,080 07-28-98 4:16p PWRSFnHO\_15IV.allin  
PWA060~1 ALL 30,743,050 07-28-98 4:17p PWRSFnHO\_15IV.alltab  
PWRSFN~2 POS 2,004,348 07-28-98 4:17p PWRSFnHO\_15IV.post  
PWRSFN~4 SUM 206,019 07-28-98 4:17p PWRSFnHO\_15IV.sum  
PWRSFpd xls 672,256 07-24-98 12:30p PWRSFpd.xls  
Rhdata xls 26,624 04-02-98 2:28p Rhdata.xls  
V5MOXV~1 XLS 14,848 07-23-98 5:26p V5moxvorig.xls  
VOLMAS~1 XLS 1,847,296 07-23-98 3:54p volmas21c.xls  
water xls 17,920 07-23-98 5:06p water.xls  
118 file(s) 1,775,450,619 bytes

## Attachment I Scripts and Programs to Perform Simulations

Several of the scripts include adjustable parameters that are changed to suitable values to start specific simulations, e.g. variables \$count and \$ocount in allpost.bat

bldinput.bat

```
echo "did not run bldinput" >sfile
count=1
bldinput
read status <sfile
if [ "$status" != "go" ]
then
    echo $status
    echo "job terminated"
    exit
fi
echo $count
while [ $count -lt 200 ]
do
    mv bldinput.out input
    eq6dR136.opt
    cat input >> allin
    cat pickup >> allpick
    cat output >> allout
    cat tab >> alltab
    ntxtinput
    read status <sfile
    if [ "$status" != "go" ]
    then
        echo $status
        echo "job terminated"
        exit
    fi
    count=`expr $count + 1`
    echo $count
done
exit
```

nxtinput.bat

```
count=1
while [ $count -lt 200 ]
do
    mv bldinput.out input
    eq6dR136.opt
    cat input >> allin
    cat pickup >> allpick
    cat output >> allout
    cat tab >> alltab
    ntxtinput
    read status <sfile
    if [ $status != "go" ]
    then
        exit
    fi
    count=`expr $count + 1`
```

```

    echo $count
done
rename
exit

bldinput.in

root      date      creator      delmaxtime
PWRSF0:15II 05/26/98  Automated    9.56e+08

```

```
allpost.bat
```

```
ocount=1
```

```
while [ $ocount -lt 5 ]
```

```
do
```

```
count=1
```

```
while [ $count -lt 200 ]
```

```
do
```

```
mv bldinput.out input
```

```
eq6dR136.opt
```

```
cat input >> allin
```

```
cat output >> allout
```

```
cat tab >> alltab
```

```
nxtinput
```

```
read status <sfile
```

```
if [ $status != "go" ]
```

```
then
```

```
exit
```

```
fi
```

```
count=`expr $count + 1`
```

```
echo $count
```

```
done
```

```
rm rootname
```

```
postprocC
```

```
cat postproc.out >> allpost
```

```
rm allout
```

```
ocount=`expr $ocount + 1`
```

```
done
```

```
exit
```

```
bldinput.c
```

```
#include <stdio.h>
```

```
#include <string.h>
```

```
#include <stdlib.h>
```

```
#include <math.h>
```

```
float getfloat(char*,int,int);
```

```
void setup(),bldpick(),infromstd(),infromlast(),
```

```
strinsert(char*,char*,int,int);
```

```
int locate0(char*,FILE*),locateall(char*,FILE*),tobar(char*,int);
```

```
float duration,delmaxtime;
```

```
char dummy[100],buffer[90],lookahead[90];
```

```
char froot[20],cname[20],fname[20];
```

```
FILE *fin,*fout,*fp,*ftemp,*fstd,*foutout,*finin,*fsfile;
```

```
void main()
```

```
{int i,j,k,flag;
```

```
fsfile=fopen("sfile","w");
```

```

fprintf(fsfile,"go\n");
flag=1;
fout=fopen("bldinput.out","w");/*file to be moved to input*/
if(flag==1) infromstd();
/*else infromlast();*/

void infromstd()
{int i,j,k;
char tempstr[20],datestr[10];
fstd=fopen("input","r");/*template for initial input file*/
fin=fopen("bldinput.in","r");/*filename,creator,duration*/
fgets(dummy,100,fin);/*readthrough labels of setup data*/
fscanf(fin,"%s %s %s %f",froot,datestr,cname,&delmaxtime);
strcpy(fname,froot);
strcat(fname,"1.6i      ");
locate0("|EQ",fstd);
strinsert(dummy,fname,22,strlen(fname));
fputs(dummy,fout);
locate0("|Created",fstd);
strcat(cname,"      ");
strinsert(dummy,datestr,9,8);
strinsert(dummy,cname,30,strlen(cname));
fputs(dummy,fout);
locate0("| starting time",fstd);
i=tobar(dummy,1);
if(i<0)
    {printf("couldn't find |");
    exit(0);}
i=tobar(dummy,i+1);
if(i<0)
    {printf("couldn't find |");
    exit(0);}
i=tobar(dummy,i+1);
if(i<0)
    {printf("couldn't find |");
    exit(0);}
sprintf(tempstr,"%12.5e",delmaxtime);
k=strlen(tempstr);
j=tobar(dummy,i+1);
if(j<0)
    {printf("couldn't find |");
    exit(0);}
strncat(tempstr,"      ",j-i-1-k);
strinsert(dummy,tempstr,i+1,j-i-1);
fputs(dummy,fout);
while(fgets(dummy,90,fstd)!=NULL)fputs(dummy,fout);}

void strinsert(char inline[90],char insert[90],int start,int len)
{int i;
for(i=0;i<len;i++) inline[start+i]=insert[i];}

int locate0(char sstring[50],FILE *fp)
{int i=0;
while(fgets(dummy,90,fp)!=NULL)
    {if(strncmp(dummy,sstring,strlen(sstring))==0)return i;
    i++;
    fputs(dummy,fout);}
return 0;}

int tobar(char line[100],int start)
{int i;
i=start;
while((i<strlen(line))&&(line[i]!='|'))i++;
if(line[i]=='|')return i;
else return -1;}

```

nxtinput.c

```
#include <stdio.h>
#include <string.h>
#include <stdlib.h>
#include <math.h>
double getfloat(char*,int,int),gettobar(char*,int);
void setup(),bldpick(),infromstd(),infromlast(),
    convert(double,double,FILE*,FILE*),
    strinsert(char*,char*,int,int);
int locaterw(char*,FILE*,FILE*),locatero(char*,FILE*),
    locate2(char*,char*,FILE*),tobar(char*,int),findinline(char*),
    puttobar(char*,char*,int),locatelof2(char*,char*,FILE*);
int finished=0;
double mash2oend,duration;
char dummy[100],tdummy[100];
char froot[20],cname[20],fname[20];
FILE *fout,*fpick,*fotemp,*fptemp,*fstd,*foutout,*finin,
    *fttemp,*fs,*fin;

void main()
{int i,j,k,flag;
fs=fopen("sfile","w");
fprintf(fs,"go\n");
flag=1;
fout=fopen("bldinput.out","w");/*file to be moved to input*/
infromlast();}

void infromlast()
{int i,j,k,dot;
char tempstr[30],carbstr[7],*cp,sstring[60],tempstr2[20];
double dmj13,msh2o,msh2ox,xx,yy,moles,dmoles,delmaxtime;
fin=fopen("bldinput.in","r");/*input parameters special to this case*/
fstd=fopen("input","r");/*template from last input file*/
fpick=fopen("pickup","r");/*old pickup file; extract section to bldinput.out*/
foutout=fopen("output","r");/*from last iteration to new input*/
finin=fopen("input","r");/*from last iteration to new input*/
fotemp=fopen("otemp","w");/*store intermediate segments from output*/
fptemp=fopen("ptemp","w");/*store intermediate segments from pickup*/
fgets(dummy,90,fin); /*readthrough labels*/
fscanf(fin,"%s %s %s %lf\n",
    tempstr,tempstr,tempstr,&delmaxtime);/*only 1 param used this prgrm*/
locatero("Moles of solvent H2O",foutout);
msh2ox=getfloat(dummy,44,12); /*optional parameter from the first block*/
foutout=freopen("output","r",foutout);
strcpy(sstring,"Reaction progress");
if(locatero(sstring,foutout)==-1) /*find output block of interest*/
    {printf("bad output file\n");
    exit(0);}
fputs(dummy,fotemp); /*and write it to temporary*/
while(fgets(dummy,90,foutout)!=NULL)
    {fputs(dummy,fotemp);
    if(strncmp(dummy,sstring,strlen(sstring))==0)
        {fotemp=freopen("otemp","w",fotemp);
        fputs(dummy,fotemp);}}
fotemp=freopen("otemp","r",fotemp);/* re-open to find water*/
strcpy(sstring,"Mass of solvent H2O");
if(locatero(sstring,fotemp)!=1)
    {printf("Can't find ending water\n");
    fs=fopen("sfile","w");
    fprintf(fs,"cant find ending water");
    exit(0);}/*ending water*/
mash2oend=getfloat(dummy,44,12);
fotemp=freopen("otemp","r",fotemp);/*now reopen for use*/
if(locatero("c pickup file",fpick)==-1) /*start copying here*/
    {printf("bad pickup file\n");
```

```

    exit(0);}
fputs(dummy, fptemp);
for(i=0;i<2;i++) /*readwrite through first "|EQ"*/
    {fgets(dummy, 90, fpick);
    fputs(dummy, fptemp);}
while(fgets(dummy, 90, fpick)!=NULL) /*pickup to ptemp*/
    {fputs(dummy, fptemp);
    if(strncmp(dummy, "|EQ", 3)==0) /*read through without copying*/
        while(fgets(dummy, 90, fpick)!=NULL)
            if(strncmp(dummy, "c pickup file", strlen("c pickup file"))==0)
                {fptemp=freopen("ptemp", "w", fptemp); /*start copying over again*/
                fputs(dummy, fptemp);
                for(i=0;i<2;i++)
                    {fgets(dummy, 90, fpick);
                    fputs(dummy, fptemp);}
                break;}}
fptemp=freopen("ptemp", "r", fptemp); /*now reopen for use*/
if(locaterw("|EQ", fstd, fout)==-1)
    {printf("bad input file\n");
    exit(0);}
i=0;
while((i<strlen(dummy))&&(dummy[i]!='.'))i++;
dot=i;
i=0;
while((dummy[dot-i-1]<='9')&&(dummy[dot-i-1]>='0'))i++;
for(j=0;j<i;j++) tempstr[j]=dummy[dot-i+j];
tempstr[i]='\0';
k=atoi(tempstr);
sprintf(tempstr, "%u%s", k+1, ".6i");
strinsert(dummy, tempstr, dot-i, strlen(tempstr));
fputs(dummy, fout);
fgets(dummy, 90, fotemp); /*get ending value of zi from first line*/
xx=getfloat(dummy, 48, 22);
if(locaterw("| starting value of zi", fstd, fout)==-1)
    {printf("can't find starting zi in input file\n");
    exit(0);}
sprintf(tempstr, "%15.81E", xx);
i=tobar(dummy, 1);
strinsert(dummy, tempstr, i+1, strlen(tempstr));
fputs(dummy, fout); /*and put into input*/
fgets(dummy, 90, fstd);
fputs(dummy, fout);
fgets(tdummy, 90, fstd); /*this takes us to entry for starting time*/
if(locatero("      Time increased from", fotemp)==-1)
    {printf("can't find last ending time in output\n");
    exit(0);}
fgets(dummy, 90, fotemp); /*this line will have end time of last run*/
xx=getfloat(dummy, 31, 12);
sprintf(tempstr, "%11.51E", xx);
i=tobar(tdummy, 1);
if(i==-1)
    {printf("cant find slot for starttime\n");
    exit(0);}
strinsert(tdummy, tempstr, i+1, strlen(tempstr));
i=tobar(tdummy, i+1);
i=tobar(tdummy, i+1);
if(i==-1)
    {fs=freopen("sfile", "w", fs);
    printf("cant find slot for maxtime\n");
    exit(0);}
/*yy=gettobar(tdummy, i+1); */
sprintf(tempstr, "%12.41E", xx+delmaxtime);
strinsert(tdummy, tempstr, i+1, strlen(tempstr));
fputs(tdummy, fout); /*and put into input*/
fotemp=freopen("otemp", "r", fotemp); /*last read was beyond current interest*/
if(locatero("      Reactant          Moles      Delta moles", fotemp)==-1)
    {printf("cant find values for reactants in the output file\n");

```

```

    exit(0);}
fgets(tdummy,90,fotemp);
fgets(tdummy,90,fotemp);/*get to first reactant in otemp*/
while((finished==0)&&(strncmp(tdummy,"\n",1)!=0))/*loop to do all reactants*/
    {moles=getfloat(tdummy,29,10);
    dmoles=getfloat(tdummy,42,10);
    locaterw("| moles remaining",fstd,fout);/*next reactant*/
    sprintf(tempstr,"%10.41E",moles);
    strinsert(dummy,tempstr,20,strlen(tempstr));
    if(strncmp(tdummy," J-13 water",12)!=0)
        {sprintf(tempstr2,"%10.41E",dmoles);
        strinsert(dummy,tempstr2,58,strlen(tempstr2));}
    else
        {dmj13=dmoles;
        finished=1;} /*Water is the last reactant*/
    fputs(dummy,fout);
    fgets(tdummy,90,fotemp);}
if(locatero(" Moles of solvent H2O",fotemp)==-1)
    {fprintf(fs,"cant find moles water in output\n");
    exit(0);}
msh2o=getfloat(dummy,44,12);
k=locatero(" --- The reaction path has terminated normally",fotemp);
if(k==-1)
    {fputs("abnormal reaction path termination\n",fs);
    exit(0);}
fotemp=freopen("otemp","r",fotemp);/*back to the top again*/
if((k=locate2(" CO3--"," HCO3-",fotemp))==1) strcpy(carbstr,"| CO3--");
else if (k==2) strcpy(carbstr,"| HCO3-");
fttemp=fopen("ttemp","w");/*will later attach to input*/
if(locate1of2("| CO3--","| HCO3-",fptemp)==-1)/*also copies ptemp to ttemp*/
    {fprintf(fs,"cant find line to insert carbonates in pickup\n");
    exit(0);}
strinsert(dummy,carbstr,0,strlen(carbstr));
fputs(dummy,fttemp);
while(fgets(dummy,90,fptemp)!=NULL)fputs(dummy,fttemp);/*rest of ptemp to ttemp*/
fttemp=freopen("ttemp","r",fttemp);
if(locaterw("c pickup file",fstd,fout)==-1)/*transfer the relevant remainder of the
template*/
    {fprintf(fs,"cant find start for pickup info\n");
    exit(0);}
convert(msh2o,dmj13/3,fstd,fttemp);}

int locate1of2(char sstring1[50],char sstring2[50],FILE *fp)
{int found1=0,found2=0;
while((found1==0)&&(found2==0))
    {if(fgets(dummy,90,fp)==NULL)return -1;
    if(found1==0)
        if(strncmp(dummy,sstring1,strlen(sstring1))==0)
            found1=1;
    if(found2==0)
        if(strncmp(dummy,sstring2,strlen(sstring2))==0)
            found2=1;
    if((found1==0)&&(found2==0))fputs(dummy,fttemp);}
if((found1==0)&&(found2==0))return -1;
else return 0;}

void strinsert(char inline[90],char insert[90],int start,int len)
{int i;
for(i=0;i<len;i++) inline[start+i]=insert[i];}

int locate2(char sstring1[50],char sstring2[50],FILE *fp)
{int i,found1=0,found2=0;
double x1=0,x2=0;
char buffer[100];
while((fgets(dummy,90,fp)!=NULL)&&((found1==0)|| (found2==0)))
    {strcpy(buffer,dummy);
    if(found1==0)

```

```

        if (strcmp(dummy, sstring1, strlen(sstring1)) == 0)
            {found1=1;
             x1=getfloat(dummy, 28, 12);}
    if (found2==0)
        if (strcmp(dummy, sstring2, strlen(sstring2)) == 0)
            {found2=1;
             x2=getfloat(dummy, 28, 12);}
    if (x1<x2) return 2;
    else return 1;}

int locatero(char sstring[60], FILE *fp) /*read only*/
{while (fgets(dummy, 90, fp) != NULL)
    if (findinline(sstring) == 1) return 1;
return -1;}

int locaterw(char sstring[60], FILE *fpin, FILE *fpout) /*read&write*/
{while (fgets(dummy, 90, fpin) != NULL)
    {if (strcmp(dummy, sstring, strlen(sstring)) == 0) return 1;
     fputs(dummy, fpout);}
return -1;}

void convert(double x, double z, FILE *fins, FILE *finp)
{int i, count=0;
 double u, v, w, r;
 char buffer[100], temp[50], temp2[50];
 r=x/(x+z);
 if (mash2oend*r>1)
     {r=1/mash2oend;
      printf("converted to %f\n", r);}
 if (locaterw("| elements, moles", finp, fout) == -1) /*readwrite to this point*/
     {printf("cant locate place to put new values of reagents in input\n");
      exit(0);}
 fputs(dummy, fout);
 fgets(buffer, 90, finp);
 fputs(buffer, fout);
 fgets(buffer, 98, finp);
 while (strcmp(buffer, "|-----", 8) != 0)
     {w=getfloat(buffer, 55, 21);
      v=w*r;
      u=getfloat(buffer, 30, 21) - w*(1-r);
      sprintf(temp, "%22.151E", u);
      strinsert(buffer, temp, 29, strlen(temp));
      sprintf(temp, "%22.151E", v);
      strinsert(buffer, temp, 54, strlen(temp));
      fputs(buffer, fout);
      fgets(buffer, 90, finp);
      count++;}
 fputs(buffer, fout);
 for (i=0; i<2; i++)
     {fgets(buffer, 100, finp); /*readthrough to species table*/
      fputs(buffer, fout);}
 for (i=0; i<count; i++)
     {fgets(buffer, 100, finp);
      w=getfloat(buffer, 56, 22);
      sprintf(temp, "%+20.151E", w+log10(r));
      strinsert(buffer, temp, 56, strlen(temp));
      fputs(buffer, fout);}
 while (fgets(buffer, 100, finp) != NULL) fputs(buffer, fout);}

double getfloat(string, start, len)
char string[100];
int start, len;
{char temp[30];
strncpy(temp, string+start, len);
temp[len]='\0';
return atof(temp);}

```

```

double gettoabar(char line[100],int start)
{int i;
char temp[30];
i=start;
while((i<strlen(line))&&(line[i]!='|'))
    {temp[i-start]=line[i];
    i++;}
temp[i]='\0';
if(line[i]!='|')return -1;
return atof(temp);}

int puttoabar(char line[100],char string[30],int start)
{int i,k;
i=start;
k=strlen(string);
while((i<strlen(line))&&(line[i]!='|')&&(i-start<k))
    {line[i]=string[i-start];
    i++;}
if(line[i]=='|')return i;
else return -1;}

int tobar(char line[100],int start)
{int i;
i=start;
while((i<strlen(line))&&(line[i]!='|'))i++;
if(line[i]=='|')return i;
else return -1;}

int findinline(char sstring[50])
{int i=0;
while(i<100)
    {if(strncmp(dummy+i,sstring,strlen(sstring))==0) return 1;
    else i++;}
return 0;}

```

postprocP.c

```

/* postprocJ.c expanded mineral set*/
#include <stdio.h>
#include <string.h>
#include <stdlib.h>
#include <math.h>
#include <malloc.h>

double getfloat(char*,int,int);
int locate(char*,char*),getreacts(),numreacts;
void msgerr(char*,int,int),getmrls(),trimb(char*),getelements();
int finished=0;
char dummy[150],reactstrs[20][20];
FILE *fout,*ferr,*fin,*fout,*fallyrs1,*fallyrs2,*fchgyrs1,
*fchgyrs2,*froot;
float ph,is,mos,mas,hpluss,time,b,gd,ps,pu,u,j13,reactvals[20],
puo2,npo2,amoh,sodd,haiw,rhabdo,gdpo4,ndpo4,smpo4,gdoh,ndoh,euoh,smco3,laf,
gdf,ndf,smf,agcl,rh2o3,ruo2,dias,hema,goet,trev,nisi,pyro,smec,nonca,nonk,
nonmg,nonna,cauo,uo3;
struct OUTREC
{struct OUTREC *next;
char data[1000];};

void main()
{int i,j,k,bcount=0,lcount=0,endblock,firstall=1,firstchg=1,
firsttime=1,newblock=1,fileflag=0;
struct OUTREC *pallyrs1,*pallyrs2,*pallyrs3,
*pchgyrs1,*pchgyrs2,*pchgyrs3,*p,
*pfallyrs1,*pfallyrs2,*pfallyrs3,
*pfchgyrs1,*pfchgyrs2,*pfchgyrs3;
char outs[4][1000],fstr[50],rootstr[50];

```

```

if((froot=fopen("rootname","r")!=NULL)
  {fscanf(froot,"%s",rootstr);
  fclose(froot);
  strcpy(fstr,rootstr);
  strcat(fstr,".allout");
  if((fin=fopen(fstr,"r")!=NULL)fileflag=1;}
if(fileflag==0)
  if((fin=fopen("allout","r")==NULL)
    {printf("Cant open input file\n");
    exit(0);}
if(fileflag==0)fout=fopen("postproc.out","w");
else
  {strcat(rootstr,".postproc");
  fout=fopen(rootstr,"w");}
printf("filename=%s fileflag=%d\n",fstr,fileflag);
while(finished==0)
  {if((k=locate("          Time = "," J-13 water"))==1)
    {fgets(dummy,100,fin);
    time=getfloat(dummy,29,11);}
  else if(k==0) msgerr("Missed time",bcount,lcount);
  else break; /*proper end of file */
  if((k=locate("          Reactant          Moles",
    "          --- Element Totals"))==1)
    {if(firsttime==1)
      {numreacts=getreacts(1);
      firsttime=0;}
    else getreacts(0);}
  else if(k==0) msgerr("Missed reactants",bcount,lcount);
  else msgerr("Unexpected end of file",bcount,lcount);
  getelements();
  if((k=locate("          modified NBS pH scale"," H+"))==1)
    ph=getfloat(dummy,37,8); /* pH */
  else if(k==0) msgerr("Missed pH",bcount,lcount);
  else msgerr("Unexpected end of file",bcount,lcount);
  if((k=locate("          Ionic strength"," H+"))==1)
    is=getfloat(dummy,38,13); /* Ionic strength */
  else if(k==0) msgerr("Missed ionic str",bcount,lcount);
  else msgerr("Unexpected end of file",bcount,lcount);
  if((k=locate("          Moles of solvent"," H+"))==1)
    mos=getfloat(dummy,44,13); /* Moles solvent water */
  else if(k==0) msgerr("Missed moles water",bcount,lcount);
  else msgerr("Unexpected end of file",bcount,lcount);
  if((k=locate("          Mass of solvent"," H+"))==1)
    mas=getfloat(dummy,44,13); /* Mass solvent water */
  else if(k==0) msgerr("Missed mass water",bcount,lcount);
  else msgerr("Unexpected end of file",bcount,lcount);
  if((k=locate(" H+","          --- Summary of Solid Product Phases---"))==1)
    hpluss=getfloat(dummy,68,9); /* H+ */
  else if(k==0) msgerr("Missed H+",bcount,lcount);
  else msgerr("Unexpected end of file",bcount,lcount);
  if(fabs(ph-hpluss)>1.e-4)
    {printf("%f %f\n",ph,hpluss);
    msgerr("pH mismatch",bcount,lcount);}
  getmrls();
  if((k=locate("          Time increased from",
    "          Reaction progress"))==1)
    {endblock=1;
    bcount++;}
  else if (k==0) endblock=0;
  else finished=1;
  lcount++;
  printf("%d %d\n",bcount,lcount);
  if ((endblock==0) || (finished==1))
  {sprintf(outs[0],"%11.3e%11.3e%11.3e%11.3e%11.3e%11.3e%11.3e%11.3e%11.3e\n",
    time/365.2486/1000,ph,b,gd,ps,pu,u,is,mos);
  sprintf(outs[1],

```





```

return atof(temp);}

void getmnrsls()
{int i,k,num=33,found[33]={0},finished=0,slens[33];
char mnrslstrs[33][20]={" AmOHCO3"," CaUO4"," Chlorargyrite"," Diaspore"," Eu(OH)CO3(s)",
" GdOHCO3"," Goethite"," Haiweeite"," Hematite"," NdOHCO3"," Ni2SiO4",
" NpO2"," PuO2"," Pyrolusite"," Rh2O3"," RuO2"," Sm2(CO3)3"," Soddyite",
" Trevorite"," UO3:2H2O"," Smectite-di"," Nontronite-Ca"," Nontronite-K",
" Nontronite-Mg"," Nontronite-Na"," Rhabdophane-ss"," NdPO4:H2O",
" GdPO4:H2O"," SmPO4:H2O"," LaF3:0.5H2O"," NdF3:0.5H2O",
" GdF3:0.5H2O"," SmF3:0.5H2O"},
ss[]=" --- Summary of Pure Mineral Saturation States ---";
for(i=0;i<num;i++) slens[i]=strlen(mnrslstrs[i]);
k=strlen(ss);
while((fgets(dummy,100,fin)!=NULL)&&(finished==0))
{if(strncmp(dummy,ss,k)==0)finished=1;
else
for(i=0;i<num;i++)
if(strncmp(dummy,mnrslstrs[i],slens[i])==0)
{found[i]=1;
switch(i)
{case 0: amoh=getfloat(dummy,40,12);break;
case 1: cauo=getfloat(dummy,40,12);break;
case 2: agcl=getfloat(dummy,40,12);break;
case 3: dias=getfloat(dummy,40,12);break;
case 4: euoh=getfloat(dummy,40,12);break;
case 5: gdoh=getfloat(dummy,40,12);break;
case 6: goet=getfloat(dummy,40,12);break;
case 7: haiw=getfloat(dummy,40,12);break;
case 8: hema=getfloat(dummy,40,12);break;
case 9: ndoh=getfloat(dummy,40,12);break;
case 10: nisi=getfloat(dummy,40,12);break;
case 11: npo2=getfloat(dummy,40,12);break; /* NpO2 */
case 12: puo2=getfloat(dummy,40,12);break; /* PuO2 */
case 13: pyro=getfloat(dummy,40,12);break;
case 14: rh2o3=getfloat(dummy,40,12);break;
case 15: ruo2=getfloat(dummy,40,12);break;
case 16: smco3=getfloat(dummy,40,12);break;
case 17: sodd=getfloat(dummy,40,12);break; /* Soddyite */
case 18: trev=getfloat(dummy,40,12);break;
case 19: uo3=getfloat(dummy,40,12);break;
case 20: smec=getfloat(dummy,40,12);break;
case 21: nonca=getfloat(dummy,40,12);break;
case 22: nonk=getfloat(dummy,40,12);break;
case 23: nonmg=getfloat(dummy,40,12);break;
case 24: nonna=getfloat(dummy,40,12);break;
case 25: rhabdo=getfloat(dummy,40,12);break;
case 26: ndpo4=getfloat(dummy,40,12);break;
case 27: gdpo4=getfloat(dummy,40,12);break;
case 28: smpo4=getfloat(dummy,40,12);break;
case 29: laf=getfloat(dummy,40,12);break;
case 30: ndf=getfloat(dummy,40,12);break;
case 31: gdf=getfloat(dummy,40,12);break;
case 32: smf=getfloat(dummy,40,12);}}}

for(i=0;i<num;i++)
if(found[i]==0)
switch(i)
{case 0: amoh=0;break;
case 1: cauo=0;break;
case 2: agcl=0;break;
case 3: dias=0;break;
case 4: euoh=0;break;
case 5: gdoh=0;break;
case 6: goet=0;break;
case 7: haiw=0;break;
case 8: hema=0;break;

```

```

    case 9: ndoh=0;break;
    case 10: nisi=0;break;
    case 11: npo2=0;break;
    case 12: puo2=0;break;
    case 13: pyro=0;break;
    case 14: rh2o3=0;break;
    case 15: ruo2=0;break;
    case 16: smco3=0;break;
    case 17: sodd=0;break;
    case 18: trev=0;break;
    case 19: uo3=0;break;
    case 20: smec=0;break;
    case 21: nonca=0;break;
    case 22: nonk=0;break;
    case 23: nonmg=0;break;
    case 24: nonna=0;break;
    case 25: rhabdo=0;break;
    case 26: ndpo4=0;break;
    case 27: gdpo4=0;break;
    case 28: smpo4=0;break;
    case 29: laf=0;break;
    case 30: ndf=0;break;
    case 31: gdf=0;break;
    case 32: smf=0;}}

void getelements()
{int i,k,num=5,founds[5]={0},finished=0,slens[10];
char elstrs[5][20]={" B "," Gd"," P "," Pu",
" U "},ss={" Single ion"};
for(i=0;i<num;i++) slens[i]=strlen(elstrs[i]);
k=strlen(ss);
while((fgets(dummy,100,fin)!=NULL)&&(finished==0))
{if(strncmp(dummy,ss,k)==0)finished=1;
else
for(i=0;i<num;i++)
if(strncmp(dummy,elstrs[i],slens[i])==0)
{founds[i]=1;
switch(i)
{case 0:b=getfloat(dummy,57,13);break;
case 1: gd=getfloat(dummy,57,13);break;
case 2: ps=getfloat(dummy,57,13);break;
case 3: pu=getfloat(dummy,57,13);break;
case 4: u=getfloat(dummy,57,13);break;}}}

for(i=0;i<num;i++)
if(founds[i]==0)
switch(i)
{case 0:b=0;break;
case 1: gd=0;break;
case 2: ps=0;break;
case 3: pu=0;break;
case 4: u=0;break;}}

int getreacts(int k)
{int i;
char temps[30];
fgets(dummy,100,fin); /*skip blank line*/
i=0;
fgets(dummy,100,fin); /*now read first line of reactants*/
while(dummy[0]!='\n')
{if(k==1)
{strncpy(temps,dummy,25);
temps[25]='\0';
trimb(temps);
strcpy(reactstrs[i],temps); /* name of reactant */
reactvals[i]=getfloat(dummy,29,11); /* moles of reactant */
i++;

```

```
fgets(dummy,100,fin);}
return(i);}

```

```
void trimb(char string[30])
{int i=0,j,k;
while(string[i]!=' ')i++;
j=strlen(string)-1;
while(string[j]!=' ')j--;
for(k=0;k<j-i+1;k++) string[k]=string[k+i];
if(j-i+1<9)string[j-i+1]='\0';
else string[9]='\0';} /*no reactant string name greater than 9chars*/

```

```
/*
Time =
= 3.329E+06 days
J-13 water 3.9080E+03 .0000E+00 2.3471E+04 .0000E+00
B 1.405415E-01 1.316626E-05 1.316629E-05
Gd 1.531378E-03 9.863147E-09 9.863168E-09
P 1.742931E-04 5.699148E-09 5.699160E-09
Pu 5.260290E-07 2.183452E-12 2.183456E-12
U 2.582874E-03 1.098999E-08 1.099001E-08
modified NBS pH scale 6.6651
Ionic strength = 2.596699E-01 molal
Moles of solvent H2O = 5.55085E+01
Mass of solvent H2O = 1.00000E+00 kg
H+ 2.7749E-07 -6.5567 -.1083 -6.6651
PuO2 -5.5313 2.9425E-06 8.1213E-04 7.0120E-05
Soddyite -1.5865 2.5912E-02 1.7314E+01 3.4015E+00
Rhabdophane-ss -2.1365 7.3031E-03 1.9141E+00 .0000E+00
GdPO4:H2O -2.6521 2.2280E-03 6.0208E-01 .0000E+00
*/

```

```
lastpost.c

```

```
/* lastpost.c processes a file named allpost, which is the result of
concatenating the results of a sequence of runs of postproc.c representing
consecutive timesteps which have been sliced into blocks so that the
output files do not grow too large to handle. The result of the concatenation
is a sequence of six table groups, with the groups representing sequential
timesteps. This program merges the individual tables accros all the groups,
resulting in a set of six tables, each covering the entire timespan.
The present version is also set to print only every tenth line to reduce
the size of the output file so that it can be easily graphed from a
spreadsheet.*/

```

```
#include <stdio.h>
#include <string.h>
#include <stdlib.h>
#include <malloc.h>

```

```
FILE *fin, *fout;

```

```
struct OUTREC /* for linked list of output records */
{struct OUTREC *next;
char data[400];};

```

```
void main()
{int i, j, count=0,finished=0;
struct OUTREC *pyrs[6],/*used for constructing one linked list for each table*/
*ppyrs[6],/*used for the start of each linked list*/
*p; /*used for traversing the linked list to write the output file*/
char outs[400], /*for output line*/
recstrs[6][100]={"DATA FOR EACH TIMESTEP Elements",
"DATA FOR EACH TIMESTEP Minerals","DATA FOR EACH TIMESTEP Reactants",
"DATA FOR CHANGING TIMESTEPS Elements","DATA FOR CHANGING TIMESTEPS Minerals",

```

```

"DATA FOR CHANGING TIMESTEPS Reactants"}, /*headings for input file tables*/
dummy[400], /*for reading a line of input data*/
headstrs[6][400]; /*will be used for column headings for each output table.*/
fin=fopen("allpost", "r"); /*input data file*/
fout=fopen("lastpost.out", "w"); /*output file*/
for(i=0; i<6; i++) /*allocate memory for start of each linked list*/
    {pfyrs[i]=malloc(sizeof(struct OUTREC));
    pyrs[i]=pfyrs[i];
    pyrs[i]->next=malloc(sizeof(struct OUTREC));} /*next rec for the first data*/
while((finished==0) && (fgets(dummy, 400, fin) != NULL)) /*outer loop to read all data*/
    for(i=0; i<6; i++) /*inner loop to read each group of six*/
        /*starting with the first line read in the above while statement, read through
        lines until the first table heading is reached. On subsequent passes, it
        will read through the blank lines before the next table*/
            {while((finished==0) && (strcmp(dummy, recstrs[i], strlen(recstrs[i])) != 0))
            if(fgets(dummy, 400, fin) == NULL) /*EOF if we run out of lines*/
                {finished=1;
                break;}
            fgets(dummy, 400, fin); /*readthrough a blank line following the table heading*/
            fgets(dummy, 400, fin);
            strcpy(headstrs[i], dummy); /*copy the column headings for use in the output*/
            fgets(dummy, 400, fin); /*now get the first data line*/
            /*the following test includes whether the input line is blank, which would
            indicate the end of the input table.*/
            while((finished==0) && (strcmp(dummy, " ", 6) != 0) && (dummy[0] != '\n'))
                {pyrs[i]=pyrs[i]->next;
                strcpy(pyrs[i]->data, dummy); /*if not blank, copy it to the linked list*/
                pyrs[i]->next=malloc(sizeof(struct OUTREC)); /*allocate for the next line*/
                if(i==0) count++;
                if(fgets(dummy, 400, fin) == NULL) finished=1;}} /*get the line for the next*/
                /*iteration and test for EOF*/
for(i=0; i<6; i++)
    {free(pyrs[i]->next); /*free the last allocation which won't be needed*/
    pyrs[i]->next=NULL; /*now tag the last link*/
for(i=0; i<6; i++)
    {count=0;
    fprintf(fout, "\n\n%s\n\n", recstrs[i]); /*print table heading*/
    fprintf(fout, "%s\n", headstrs[i]); /*print column headings*/
    p=pfyrs[i]; /*point to start of linked list*/
    while((p=p->next) != NULL) /*skip the first record which has no data*/
        {if (count%10==0) fprintf(fout, "%s", p->data); /*print every tenth line*/
        count++;}}

```

**Check of Flushing Routine for case Ua115mmr Stage 1 to 2**

End of Stage 1, mole solvent = 55.7212 = y  
mass solvent = 1.00383

Al moles aqueous = 4.053240E-07  
B moles aqueous = 7.355274E-02  
Ca moles aqueous = 1.376098E-08

Delta moles J-13 water (added)/3 = 1.144 = z  
Initial moles solvent = 55.5088 = x

$$x/(x+z) = 0.979812$$

Start of Stage 2, mass solvent = 0.983643,  
therefore, reduction factor should be  $x/(x+z)$

	<u>Element Hand calc. of new moles aqueous</u>	<u>Flushing routine calc.</u>
Al	3.971413E-07	3.9717878E-07
B	7.206786E-02	7.207341E-02
Ca	1.348317E-08	1.348421E-08

Attachment III Pro-Engineer Output  
MASS PROPERTIES OF THE PART OUTER\_BARRIER

VOLUME = 2.5323951e+09 MM<sup>3</sup>  
SURFACE AREA = 5.3536901e+07 MM<sup>2</sup>  
DENSITY = 7.8500000e-06 KILOGRAM / MM<sup>3</sup>  
MASS = 1.9879301e+04 KILOGRAM

CENTER OF GRAVITY with respect to \_OUTER\_BARRIER coordinate frame:  
X Y Z 0.0000000e+00 0.0000000e+00 2.6675000e+03 MM

INERTIA with respect to \_OUTER\_BARRIER coordinate frame: (KILOGRAM \* MM<sup>2</sup>)

INERTIA TENSOR:  
Ixx Ixy Ixz 1.9185547e-11 4.1852897e+06 0.0000000e+00  
Iyx Iyy Iyz 4.1852897e+06 1.9185769e+11 0.0000000e+00  
Izx Izy Izz 0.0000000e+00 0.0000000e+00 1.2229752e+10

INERTIA at CENTER OF GRAVITY with respect to \_OUTER\_BARRIER coordinate frame:  
(KILOGRAM \* MM<sup>2</sup>)

INERTIA TENSOR:  
Ixx Ixy Ixz 5.0403180e+10 4.1852897e+06 0.0000000e+00  
Iyx Iyy Iyz 4.1852897e+06 5.0405399e+10 0.0000000e+00  
Izx Izy Izz 0.0000000e+00 0.0000000e+00 1.2229752e+10

PRINCIPAL MOMENTS OF INERTIA: (KILOGRAM \* MM<sup>2</sup>)  
I1 I2 I3 1.2229752e+10 5.0399959e+10 5.0408619e+10

ROTATION MATRIX from \_OUTER\_BARRIER orientation to PRINCIPAL AXES:

0.00000	0.79254	0.60982
0.00000	-0.60982	0.79254
1.00000	0.00000	0.00000

ROTATION ANGLES from \_OUTER\_BARRIER orientation to PRINCIPAL AXES (degrees):  
angles about x y z -90.000 37.576 -90.000

RADII OF GYRATION with respect to PRINCIPAL AXES:  
R1 R2 R3 7.8434706e+02 1.5922620e+03 1.5923988e+03 MM

MASS PROPERTIES OF THE PART OUTER\_BARRIER\_LID

VOLUME = 1.8577509e+08 MM<sup>3</sup>  
 SURFACE AREA = 3.8844803e+06 MM<sup>2</sup>  
 DENSITY = 7.8500000e-06 KILOGRAM / MM<sup>3</sup>  
 MASS = 1.45833344e-03 KILOGRAM

CENTER OF GRAVITY with respect to \_OUTER\_BARRIER\_LI coordinate frame:  
 X Y Z 0.0000000e+00 0.0000000e+00 5.5000000e-01 MM

INERTIA with respect to \_OUTER\_BARRIER\_LI coordinate frame: (KILOGRAM \* MM<sup>2</sup>)

INERTIA TENSOR:  
 Ixx Ixy Ixz 2.0187822e+08 -7.9991014e+03 0.0000000e+00  
 Iyx Iyy Iyz -7.9991014e+03 2.0187302e+08 0.0000000e+00  
 Izx Izy Izz 0.0000000e+00 0.0000000e+00 3.9198734e+08

INERTIA at CENTER OF GRAVITY with respect to \_OUTER\_BARRIER\_LI coordinate frame:  
 (KILOGRAM \* MM<sup>2</sup>)

INERTIA TENSOR:  
 Ixx Ixy Ixz 1.9746676e+08 -7.9991014e+03 0.0000000e+00  
 Iyx Iyy Iyz -7.9991014e+03 1.9746156e+08 0.0000000e+00  
 Izx Izy Izz 0.0000000e+00 0.0000000e+00 3.9198734e+08

PRINCIPAL MOMENTS OF INERTIA: (KILOGRAM \* MM<sup>2</sup>)  
 I1 I2 I3 1.9745575e+08 1.9747257e+08 3.9198734e+08

ROTATION MATRIX from \_OUTER\_BARRIER\_LI orientation to PRINCIPAL AXES:  
 0.58778 -0.80902 0.00000  
 0.80902 0.58778 0.00000  
 0.00000 0.00000 1.00000

ROTATION ANGLES from \_OUTER\_BARRIER\_LI orientation to PRINCIPAL AXES (degrees):  
 angles about x y z 0.000 0.000 54.000

RADII OF GYRATION with respect to PRINCIPAL AXES:  
 R1 R2 R3 3.6796484e+02 3.6798052e+02 5.1845069e+02 MM

MASS PROPERTIES OF THE PART INNER\_BARRIER

VOLUME = 4.2001935e+08 MM<sup>3</sup>  
 SURFACE AREA = 4.2217363e+07 MM<sup>2</sup>  
 DENSITY = 8.6910000e-06 KILOGRAM / MM<sup>3</sup>  
 MASS = 3.6503882e+03 KILOGRAM

CENTER OF GRAVITY with respect to \_INNER\_BARRIER coordinate frame:  
 X Y Z 0.0000000e+00 0.0000000e+00 2.3175000e-03 MM

INERTIA with respect to \_INNER\_BARRIER coordinate frame: (KILOGRAM \* MM<sup>2</sup>)

INERTIA TENSOR:

Ixx Ixy Ixz 2.7081108e+10 5.8084992e+05 0.0000000e+00  
 Iyx Iyy Iyz 5.8084992e+05 2.7081453e+10 0.0000000e+00  
 Izx Izy Izz 0.0000000e+00 0.0000000e+00 1.9017120e+09

INERTIA at CENTER OF GRAVITY with respect to \_INNER\_BARRIER coordinate frame:  
 (KILOGRAM \* MM<sup>2</sup>)

INERTIA TENSOR:

Ixx Ixy Ixz 7.4755801e+09 5.8084992e+05 0.0000000e+00  
 Iyx Iyy Iyz 5.8084992e+05 7.4759255e+09 0.0000000e+00  
 Izx Izy Izz 0.0000000e+00 0.0000000e+00 1.9017120e+09

PRINCIPAL MOMENTS OF INERTIA: (KILOGRAM \* MM<sup>2</sup>)

I1 I2 I3 1.9017120e+09 7.4751468e+09 7.4763588e+09

ROTATION MATRIX from \_INNER\_BARRIER orientation to PRINCIPAL AXES:

0.00000 0.80155 0.59792  
 0.00000 -0.59792 0.80155  
 1.00000 0.00000 0.00000

ROTATION ANGLES from \_INNER\_BARRIER orientation to PRINCIPAL AXES (degrees):  
 angles about x y z -90.000 36.721 -90.000

RADII OF GYRATION with respect to PRINCIPAL AXES:

R1 R2 R3 7.2177668e+02 1.4310023e+03 1.4311183e+03 MM

MASS PROPERTIES OF THE PART INNER\_BARRIER\_LID

VOLUME = 3.9949611e+07 MM<sup>3</sup>  
 SURFACE AREA = 3.3079980e+06 MM<sup>2</sup>  
 DENSITY = 8.6910000e-06 KILOGRAM / MM<sup>3</sup>  
 MASS = 3.4720207e+02 KILOGRAM

CENTER OF GRAVITY with respect to \_INNER\_BARRIER\_LI coordinate frame:  
 X Y Z 0.0000000e+00 0.0000000e+00 1.2500000e+01 MM

INERTIA with respect to \_INNER\_BARRIER\_LI coordinate frame: (KILOGRAM \* MM<sup>2</sup>)

INERTIA TENSOR:

Ixx Ixy Ixz 4.4223831e+07 -1.4361281e+02 0.0000000e+00  
 Iyx Iyy Iyz -1.4361281e+02 4.4223738e+07 0.0000000e+00  
 Izx Izy Izz 0.0000000e+00 0.0000000e+00 8.8302901e+07

INERTIA at CENTER OF GRAVITY with respect to \_INNER\_BARRIER\_LI coordinate frame:  
 (KILOGRAM \* MM<sup>2</sup>)

INERTIA TENSOR:

Ixx Ixy Ixz 4.4169581e+07 -1.4361281e+02 0.0000000e+00  
 Iyx Iyy Iyz -1.4361281e+02 4.4169487e+07 0.0000000e+00  
 Izx Izy Izz 0.0000000e+00 0.0000000e+00 8.8302901e+07

PRINCIPAL MOMENTS OF INERTIA: (KILOGRAM \* MM<sup>2</sup>)

I1 I2 I3 4.4169383e+07 4.4169685e+07 8.8302901e+07

ROTATION MATRIX from \_INNER\_BARRIER\_LI orientation to PRINCIPAL AXES:

1.00000 0.00000 0.00000  
 0.00000 1.00000 0.00000  
 0.00000 0.00000 1.00000

ROTATION ANGLES from \_INNER\_BARRIER\_LI orientation to PRINCIPAL AXES (degrees):  
 angles about x y z 0.000 0.000 0.000

RADII OF GYRATION with respect to PRINCIPAL AXES:

R1 R2 R3 3.5667241e+02 3.5667363e+02 5.0430856e+02 MM

MASS PROPERTIES OF THE PART A\_GUIDE

VOLUME = 8.1003148e-06 MM<sup>3</sup>  
 SURFACE AREA = 1.6793636e-06 MM<sup>2</sup>  
 DENSITY = 7.8500000e-06 KILOGRAM / MM<sup>3</sup>  
 MASS = 6.3587471e-01 KILOGRAM

CENTER OF GRAVITY with respect to \_A\_GUIDE coordinate frame:  
 X Y Z 3.6560000e+02 4.9600063e+00 5.6555000e-02 MM

INERTIA with respect to \_A\_GUIDE coordinate frame: (KILOGRAM \* MM<sup>2</sup>)

INERTIA TENSOR:

Ixx	Ixy	Ixz	2.7129351e+07	-1.1562354e-05	-1.3185962e+07
Iyx	Iyy	Iyz	-1.1562354e+05	3.8391375e-07	-1.7840276e+05
Izx	Izy	Izz	-1.3185962e-07	-1.7840276e+05	1.1266213e+07

INERTIA at CENTER OF GRAVITY with respect to \_A\_GUIDE coordinate frame:  
 (KILOGRAM \* MM<sup>2</sup>)

INERTIA TENSOR:

Ixx	Ixy	Ixz	6.7823439e+06	0.0000000e+00	0.0000000e+00
Iyx	Iyy	Iyz	0.0000000e+00	9.5000587e+06	0.0000000e+00
Izx	Izy	Izz	0.0000000e+00	0.0000000e+00	2.7187744e+06

PRINCIPAL MOMENTS OF INERTIA: (KILOGRAM \* MM<sup>2</sup>)  
 I1 I2 I3 2.7187744e+06 6.7823439e+06 9.5000587e+06

ROTATION MATRIX from \_A\_GUIDE orientation to PRINCIPAL AXES:

0.00000	1.00000	0.00000
0.00000	0.00000	1.00000
1.00000	0.00000	0.00000

ROTATION ANGLES from \_A\_GUIDE orientation to PRINCIPAL AXES (degrees):  
 angles about x y z -90.000 0.000 -90.000

RADII OF GYRATION with respect to PRINCIPAL AXES:

R1 R2 R3 2.0677632e+02 3.2659094e+02 3.8652480e+02 MM

MASS PROPERTIES OF THE PART B\_GUIDE

VOLUME = 9.2015813e+05 MM<sup>3</sup>  
 SURFACE AREA = 2.0845188e+05 MM<sup>2</sup>  
 DENSITY = 7.8500000e-06 KILOGRAM / MM<sup>3</sup>  
 MASS = 7.2232413e+00 KILOGRAM

CENTER OF GRAVITY with respect to \_B\_GUIDE coordinate frame:  
 X Y Z -5.0176971e+00 -4.0669703e+01 5.6666000e-02 MM

INERTIA with respect to \_B\_GUIDE coordinate frame: (KILOGRAM \* MM<sup>2</sup>)

INERTIA TENSOR:

Ixx	Ixy	Ixz	3.0974608e+06	-1.4792327e+03	2.0501439e+04
Iyx	Iyy	Iyz	-1.4792327e+03	3.0817724e+06	1.6616935e+05
Izx	Izy	Izz	2.0501439e+04	1.6616935e+05	1.6172545e+04

INERTIA at CENTER OF GRAVITY with respect to \_B\_GUIDE coordinate frame:  
 (KILOGRAM \* MM<sup>2</sup>)

INERTIA TENSOR:

Ixx	Ixy	Ixz	7.7436565e+05	-5.1984314e+00	0.0000000e+00
Iyx	Iyy	Iyz	-5.1984314e+00	7.7044277e+05	0.0000000e+00
Izx	Izy	Izz	0.0000000e+00	0.0000000e+00	4.0432634e+03

PRINCIPAL MOMENTS OF INERTIA: (KILOGRAM \* MM<sup>2</sup>)  
 I1 I2 I3 4.0432634e+03 7.7044276e+05 7.7436565e+05

ROTATION MATRIX from \_B\_GUIDE orientation to PRINCIPAL AXES:

	0.00000	0.00133	-1.00000
	0.00000	1.00000	0.00133
	1.00000	0.00000	0.00000

ROTATION ANGLES from \_B\_GUIDE orientation to PRINCIPAL AXES (degrees):  
 angles about x y z -90.000 -89.924 -90.000

RADII OF GYRATION with respect to PRINCIPAL AXES:  
 R1 R2 R3 2.3659195e+01 3.2659094e+02 3.2742134e+02 MM

MASS PROPERTIES OF THE PART CORNER\_GUIDE

VOLUME = 5.3357510e+05 MM<sup>3</sup>  
 SURFACE AREA = 1.1033308e+06 MM<sup>2</sup>  
 DENSITY = 7.8500000e-06 KILOGRAM / MM<sup>3</sup>  
 MASS = 4.1893495e-01 KILOGRAM

CENTER OF GRAVITY with respect to CORNER\_GUIDE coordinate frame:  
 X Y Z 6.3802932e+01 6.3802932e+01 5.6690000e-02 MM

INERTIA with respect to CORNER\_GUIDE coordinate frame: (KILOGRAM \* MM<sup>2</sup>)

INERTIA TENSOR:

Ixx	Ixy	Ixz	1.8364056e+07	-2.5468842e+04	-1.5152828e+06
Iyx	Iyy	Iyz	-2.5468842e+04	1.8364056e+07	-1.5152828e+06
Izx	Izy	Izz	-1.5152828e+06	-1.5152828e+06	8.2531813e+05

INERTIA at CENTER OF GRAVITY with respect to CORNER\_GUIDE coordinate frame:  
 (KILOGRAM \* MM<sup>2</sup>)

INERTIA TENSOR:

Ixx	Ixy	Ixz	4.7299576e+06	1.4507179e+05	0.0000000e+00
Iyx	Iyy	Iyz	1.4507179e+05	4.7299576e+06	0.0000000e+00
Izx	Izy	Izz	0.0000000e+00	0.0000000e+00	4.8423687e+05

PRINCIPAL MOMENTS OF INERTIA: (KILOGRAM \* MM<sup>2</sup>)  
 I1 I2 I3 4.8423687e+05 4.5848958e+06 4.8750394e+06

ROTATION MATRIX from CORNER\_GUIDE orientation to PRINCIPAL AXES:

0.00000	0.70711	0.70711
0.00000	-0.70711	0.70711
1.00000	0.00000	0.00000

ROTATION ANGLES from CORNER\_GUIDE orientation to PRINCIPAL AXES (degrees):  
 angles about x y z -90.000 45.000 -90.000

RADII OF GYRATION with respect to PRINCIPAL AXES:  
 R1 R2 R3 1.0751168e+02 3.3081976e+02 3.4112674e+02 MM

MASS PROPERTIES OF THE PART CORNER\_STIFFENER

VOLUME = 2.9468916e+05 MM<sup>3</sup>  
 SURFACE AREA = 6.7354628e+04 MM<sup>2</sup>  
 DENSITY = 7.8500000e-06 KILOGRAM / MM<sup>3</sup>  
 MASS = 2.3133099e+00 KILOGRAM

CENTER OF GRAVITY with respect to \_CORNER\_STIFFENER coordinate frame:  
 X Y Z 5.7762779e-00 5.7762321e-00 5.0000000e-00 MM

INERTIA with respect to \_CORNER\_STIFFENER coordinate frame: (KILOGRAM \* MM<sup>2</sup>)

INERTIA TENSOR:

Ixx	Ixy	Ixz	7.2799223e+03	3.1343997e+03	-6.6811605e+01
Iyx	Iyy	Iyz	3.1343997e+03	7.2799238e+03	-6.6811075e+01
Izx	Izy	Izz	-6.6811605e+01	-6.6811075e+01	1.4405625e+04

INERTIA at CENTER OF GRAVITY with respect to \_CORNER\_STIFFENER coordinate frame:  
 (KILOGRAM \* MM<sup>2</sup>)

INERTIA TENSOR:

Ixx	Ixy	Ixz	7.1449063e+03	3.2115836e+03	0.0000000e+00
Iyx	Iyy	Iyz	3.2115836e+03	7.1449066e+03	0.0000000e+00
Izx	Izy	Izz	0.0000000e+00	0.0000000e+00	1.4251258e+04

PRINCIPAL MOMENTS OF INERTIA: (KILOGRAM \* MM<sup>2</sup>)

I1	I2	I3	3.9333229e+03	1.0356490e+04	1.4251258e+04
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ROTATION MATRIX from \_CORNER\_STIFFENER orientation to PRINCIPAL AXES:

	0.70711	0.70711	0.00000
	-0.70711	0.70711	0.00000
	0.00000	0.00000	1.00000

ROTATION ANGLES from \_CORNER\_STIFFENER orientation to PRINCIPAL AXES (degrees):  
 angles about x y z 0.000 0.000 -45.000

RADII OF GYRATION with respect to PRINCIPAL AXES:

R1	R2	R3	4.1234704e+01	6.6909747e+01	7.8489161e+01
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MASS PROPERTIES OF THE PART A-PLATE

VOLUME = 9.4683638e+06 MM<sup>3</sup>  
 SURFACE AREA = 2.7698904e+06 MM<sup>2</sup>  
 DENSITY = 7.7600000e-06 KILOGRAM / MM<sup>3</sup>  
 MASS = 7.3474503e+01 KILOGRAM

CENTER OF GRAVITY with respect to \_A-PLATE coordinate frame:  
 X Y Z 6.0800000e+02 5.7236467e+02 3.5000000e+00 MM

INERTIA with respect to \_A-PLATE coordinate frame: (KILOGRAM \* MM<sup>2</sup>)

INERTIA TENSOR:

Ixx	Ixy	Ixz	3.1940321e+07	-2.5568959e+07	-1.5635374e+05
Iyx	Iyy	Iyz	-2.5568959e+07	3.6301009e+07	-1.4718973e+05
Izx	Izy	Izz	-1.5635374e+05	-1.4718973e+05	6.8238930e+07

INERTIA at CENTER OF GRAVITY with respect to \_A-PLATE coordinate frame:  
 (KILOGRAM \* MM<sup>2</sup>)

INERTIA TENSOR:

Ixx	Ixy	Ixz	7.8690770e+06	0.0000000e+00	0.0000000e+00
Iyx	Iyy	Iyz	0.0000000e+00	9.1392304e+06	0.0000000e+00
Izx	Izy	Izz	0.0000000e+00	0.0000000e+00	1.7007707e+07

PRINCIPAL MOMENTS OF INERTIA: (KILOGRAM \* MM<sup>2</sup>)  
 I1 I2 I3 7.8690770e+06 9.1392304e+06 1.7007707e+07

ROTATION MATRIX from \_A-PLATE orientation to PRINCIPAL AXES:

1.00000	0.00000	0.00000
0.00000	1.00000	0.00000
0.00000	0.00000	1.00000

ROTATION ANGLES from \_A-PLATE orientation to PRINCIPAL AXES (degrees):  
 angles about x y z 0.000 0.000 0.000

RADII OF GYRATION with respect to PRINCIPAL AXES:

R1 R2 R3 3.2726048e+02 3.5268459e+02 4.8112127e+02 MM

MASS PROPERTIES OF THE PART B-PLATE

VOLUME = 9.4683638e+06 MM<sup>3</sup>  
 SURFACE AREA = 2.7698904e+06 MM<sup>2</sup>  
 DENSITY = 7.7600000e-06 KILOGRAM / MM<sup>3</sup>  
 MASS = 7.3474503e+01 KILOGRAM

CENTER OF GRAVITY with respect to \_B-PLATE coordinate frame:

X Y Z 6.0600000e+02 -3.5000000e+00 5.6808797e+02 MM

INERTIA with respect to \_B-PLATE coordinate frame: (KILOGRAM \* MM<sup>2</sup>)

INERTIA TENSOR:

Ixx	Ixy	Ixz	3.1584049e+07	1.5635374e+05	-2.5377909e+07
Iyx	Iyy	Iyz	1.5635374e+05	6.7882658e+07	1.4608993e+05
Izx	Izy	Izz	-2.5377909e+07	1.4608993e+05	3.6301009e+07

INERTIA at CENTER OF GRAVITY with respect to \_B-PLATE coordinate frame:

(KILOGRAM \* MM<sup>2</sup>)

INERTIA TENSOR:

Ixx	Ixy	Ixz	7.8711674e+06	0.0000000e+00	0.0000000e+00
Iyx	Iyy	Iyz	0.0000000e+00	1.7009798e+07	0.0000000e+00
Izx	Izy	Izz	0.0000000e+00	0.0000000e+00	9.1392304e+06

PRINCIPAL MOMENTS OF INERTIA: (KILOGRAM \* MM<sup>2</sup>)

I1 I2 I3 7.8711674e+06 9.1392304e+06 1.7009798e+07

ROTATION MATRIX from \_B-PLATE orientation to PRINCIPAL AXES:

1.00000	0.00000	0.00000
0.00000	0.00000	-1.00000
0.00000	1.00000	0.00000

ROTATION ANGLES from \_B-PLATE orientation to PRINCIPAL AXES (degrees):

angles about x y z 90.000 0.000 0.000

RADII OF GYRATION with respect to PRINCIPAL AXES:

1 R2 R3 3.2730395e+02 3.5268459e+02 4.8115084e+02 MM

MASS PROPERTIES OF THE PART C-PLATE

VOLUME = 5.6873676e+06 MM<sup>3</sup>  
 SURFACE AREA = 1.6669370e+06 MM<sup>2</sup>  
 DENSITY = 7.7600000e-06 KILOGRAM / MM<sup>3</sup>  
 MASS = 4.4133972e+01 KILOGRAM

CENTER OF GRAVITY with respect to \_C-PLATE coordinate frame:

X Y Z 3.6530000e+02 -3.5000000e+00 5.6136232e+02 MM

INERTIA with respect to \_C-PLATE coordinate frame: (KILOGRAM \* MM<sup>2</sup>)

INERTIA TENSOR:

Ixx Ixy Ixz 1.8635063e+07 5.6427490e+04 -9.0503620e+06  
 Iyx Iyy Iyz 5.6427490e+04 2.6511938e+07 8.6713022e+04  
 Izx Izy Izz -9.0503620e+06 8.6713022e+04 7.8783166e+06

INERTIA at CENTER OF GRAVITY with respect to \_C-PLATE coordinate frame:  
 (KILOGRAM \* MM<sup>2</sup>)

INERTIA TENSOR:

Ixx Ixy Ixz 4.7266876e+06 0.0000000e+00 0.0000000e+00  
 Iyx Iyy Iyz 0.0000000e+00 6.7146853e+06 0.0000000e+00  
 Izx Izy Izz 0.0000000e+00 0.0000000e+00 1.9883582e+06

PRINCIPAL MOMENTS OF INERTIA: (KILOGRAM \* MM<sup>2</sup>)

I1 I2 I3 1.9883582e+06 4.7266876e+06 6.7146853e+06

ROTATION MATRIX from \_C-PLATE orientation to PRINCIPAL AXES:

0.00000 1.00000 0.00000  
 0.00000 0.00000 1.00000  
 1.00000 0.00000 0.00000

ROTATION ANGLES from \_C-PLATE orientation to PRINCIPAL AXES (degrees):

angles about x y z -90.000 0.000 -90.000

RADII OF GYRATION with respect to PRINCIPAL AXES:

R1 R2 R3 2.1225640e+02 3.2725926e+02 3.9005543e+02 MM

MASS PROPERTIES OF THE PART D-PLATE

VOLUME = 6.7403340e+06 MM<sup>3</sup>  
 SURFACE AREA = 2.7422246e+06 MM<sup>2</sup>  
 DENSITY = 2.7130000e-06 KILOGRAM / MM<sup>3</sup>  
 MASS = 1.8286526e+01 KILOGRAM

CENTER OF GRAVITY with respect to \_D-PLATE coordinate frame:  
 X Y Z 6.0720000e-02 5.7121092e+02 2.5000000e+00 MM

INERTIA with respect to \_D-PLATE coordinate frame: (KILOGRAM \* MM<sup>2</sup>)

INERTIA TENSOR:

Ixx Ixy Ixz	7.9171812e+06	-6.3424854e+06	-2.7758947e+04
Iyx Iyy Iyz	-6.3424854e+06	9.0107564e+06	-2.6113658e+04
Izx Izy Izz	-2.7758947e+04	-2.6113658e+04	1.6927633e+07

INERTIA at CENTER OF GRAVITY with respect to \_D-PLATE coordinate frame:  
 (KILOGRAM \* MM<sup>2</sup>)

INERTIA TENSOR:

Ixx Ixy Ixz	1.9505042e+06	0.0000000e+00	0.0000000e+00
Iyx Iyy Iyz	0.0000000e+00	2.2685491e+06	0.0000000e+00
Izx Izy Izz	0.0000000e+00	0.0000000e+00	4.2189772e+06

PRINCIPAL MOMENTS OF INERTIA: (KILOGRAM \* MM<sup>2</sup>)

I1 I2 I3	1.9505042e+06	2.2685491e+06	4.2189772e+06
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ROTATION MATRIX from \_D-PLATE orientation to PRINCIPAL AXES:

	1.00000	0.00000	0.00000
	0.00000	1.00000	0.00000
	0.00000	0.00000	1.00000

ROTATION ANGLES from \_D-PLATE orientation to PRINCIPAL AXES (degrees):  
 angles about x y z 0.000 0.000 0.000

RADII OF GYRATION with respect to PRINCIPAL AXES:

R1 R2 R3	3.2659373e+02	3.5221552e+02	4.8032809e+02
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MASS PROPERTIES OF THE PART E-PLATE

VOLUME = 6.7403340e-06 MM<sup>3</sup>  
 SURFACE AREA = 2.7422246e-06 MM<sup>2</sup>  
 DENSITY = 2.7130000e-06 KILOGRAM / MM<sup>3</sup>  
 MASS = 1.8286526e+01 KILOGRAM

CENTER OF GRAVITY with respect to \_E-PLATE coordinate frame:  
 X Y Z 6.0720000e+02 -2.5000000e+00 5.6693716e+02 MM

INERTIA with respect to \_E-PLATE coordinate frame: (KILOGRAM \* MM<sup>2</sup>)

INERTIA TENSOR:

Ixx	Ixy	Ixz	7.8287520e+06	2.7758947e+04	-6.2950313e+06
Iyx	Iyy	Iyz	2.7758947e+04	1.6839204e+07	2.5918278e+04
Izx	Izy	Izz	-6.2950313e+06	2.5918278e+04	9.0107564e+06

INERTIA at CENTER OF GRAVITY with respect to \_E-PLATE coordinate frame:  
 (KILOGRAM \* MM<sup>2</sup>)

INERTIA TENSOR:

Ixx	Ixy	Ixz	1.9510238e+06	0.0000000e+00	0.0000000e+00
Iyx	Iyy	Iyz	0.0000000e+00	4.2194967e+06	0.0000000e+00
Izx	Izy	Izz	0.0000000e+00	0.0000000e+00	2.2685491e+06

PRINCIPAL MOMENTS OF INERTIA: (KILOGRAM \* MM<sup>2</sup>)

I1	I2	I3	1.9510238e+06	2.2685491e+06	4.2194967e+06
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ROTATION MATRIX from \_E-PLATE orientation to PRINCIPAL AXES:

1.00000	0.00000	0.00000
0.00000	0.00000	-1.00000
0.00000	1.00000	0.00000

ROTATION ANGLES from \_E-PLATE orientation to PRINCIPAL AXES (degrees):  
 angles about x y z 90.000 0.000 0.000

RADII OF GYRATION with respect to PRINCIPAL AXES:

R1	R2	R3	3.2663723e+02	3.5221552e+02	4.8035766e+02
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MASS PROPERTIES OF THE PART SIDE\_COVER

VOLUME = 5.0144801e+05 MM<sup>3</sup>  
 SURFACE AREA = 1.1595236e+05 MM<sup>2</sup>  
 DENSITY = 7.8500000e-06 KILOGRAM / MM<sup>3</sup>  
 MASS = 3.9363668e+00 KILOGRAM

CENTER OF GRAVITY with respect to \_SIDE\_COVER coordinate frame:  
 X Y Z 3.6660000e+02 4.0888533e+01 5.0000000e-00 MM

INERTIA with respect to \_SIDE\_COVER coordinate frame: (KILOGRAM \* MM<sup>2</sup>)

INERTIA TENSOR:

Ixx Ixy Ixz 9.5276543e+03 -5.9005088e+04 -7.2153605e+03  
 Iyx Iyy Iyz -5.9005088e+04 6.3752055e+05 -8.0476132e+02  
 Izx Izy Izz -7.2153605e+03 -8.0476132e+02 6.4678578e+05

INERTIA at CENTER OF GRAVITY with respect to \_SIDE\_COVER coordinate frame:  
 (KILOGRAM \* MM<sup>2</sup>)

INERTIA TENSOR:

Ixx Ixy Ixz 2.8481431e+03 1.3046996e-02 0.0000000e+00  
 Iyx Iyy Iyz 1.3046996e-02 1.0839191e+05 0.0000000e+00  
 Izx Izy Izz 0.0000000e+00 0.0000000e+00 1.1117445e+05

PRINCIPAL MOMENTS OF INERTIA: (KILOGRAM \* MM<sup>2</sup>)  
 I1 I2 I3 2.8481431e+03 1.0839191e+05 1.1117445e+05

ROTATION MATRIX from \_SIDE\_COVER orientation to PRINCIPAL AXES:

1.00000 0.00000 0.00000  
 0.00000 1.00000 0.00000  
 0.00000 0.00000 1.00000

ROTATION ANGLES from \_SIDE\_COVER orientation to PRINCIPAL AXES (degrees):  
 angles about x y z 0.000 0.000 0.000

RADII OF GYRATION with respect to PRINCIPAL AXES:  
 R1 R2 R3 2.6898814e+01 1.6593983e+02 1.6805626e+02 MM

MASS PROPERTIES OF THE PART TUBE

VOLUME = 2.0879658e+07 MM<sup>3</sup>  
 SURFACE AREA = 8.3616621e+06 MM<sup>2</sup>  
 DENSITY = 7.8500000e-06 KILOGRAM / MM<sup>3</sup>  
 MASS = 1.6390531e+02 KILOGRAM

CENTER OF GRAVITY with respect to \_TUBE coordinate frame:  
 X Y Z 1.1320000e+02 -1.1320001e+02 2.2976201e+03 MM

INERTIA with respect to \_TUBE coordinate frame: (KILOGRAM \* MM<sup>2</sup>)

INERTIA TENSOR:

Ixx	Ixy	Ixz	1.1472196e+09	2.1003221e+06	-4.2444685e+07
Iyx	Iyy	Iyz	2.1003221e+06	1.1472195e+09	4.2444692e+07
Izx	Izy	Izz	-4.2444685e+07	4.2444692e+07	7.1055817e+06

INERTIA at CENTER OF GRAVITY with respect to \_TUBE coordinate frame:  
 (KILOGRAM \* MM<sup>2</sup>)

INERTIA TENSOR:

Ixx	Ixy	Ixz	2.8736905e+08	0.0000000e+00	0.0000000e+00
Iyx	Iyy	Iyz	0.0000000e+00	2.8736905e+08	0.0000000e+00
Izx	Izy	Izz	0.0000000e+00	0.0000000e+00	2.9049375e+06

PRINCIPAL MOMENTS OF INERTIA: (KILOGRAM \* MM<sup>2</sup>)  
 I1 I2 I3 2.9049375e+06 2.8736905e+08 2.8736905e+08

ROTATION MATRIX from \_TUBE orientation to PRINCIPAL AXES:

	0.00000	1.00000	0.00000
	0.00000	0.00000	1.00000
	1.00000	0.00000	0.00000

ROTATION ANGLES from \_TUBE orientation to PRINCIPAL AXES (degrees):  
 angles about x y z -90.000 0.000 -90.000

RADII OF GYRATION with respect to PRINCIPAL AXES:  
 R1 R2 R3 1.3312876e+02 1.3241082e+03 1.3241082e+03 MM

CRWMS/M&O

Calculation Cover Sheet

Complete only applicable items.

1. QA: L

Page: 1

Of: 26

2. Calculation Title  
Frequency of SNF Misload for Uncanistered Fuel Waste Package **INFORMATION ONLY**

3. Document Identifier (including Revision Number)  
BBA000000-01717-0210-00011REV00

4. Total Pages  
26

5. Total Attachments  
8

6. Attachment Numbers - Number of pages in each  
I(14), II(4), III(6), IV(4), V(5), VI(3), VII(2), VIII(6)

	Print Name	Signature	Date
7. Originator	Stanley H. Levinson	<i>Stanley H. Levinson</i>	7/13/98
8. Checker	S.F. (Alex) Deng	<i>S.F. Deng</i>	7/17/98
9. Lead Design Engineer	John R. Massari	<i>John R. Massari</i>	7/30/98

10. Remarks  
Electronic copies of Attached spreadsheets can be found in MOL.19980814.0178  
Jul 8/17/98

Revision History

11. Revision No.	12. Date Approved	13. Description of Revision
REV 00	7/13/98	Initial issue

**Table of Contents**

<u>Item</u>	<u>Page</u>
1. Purpose .....	3
2. Method.....	3
3. Assumptions.....	3
4. Use of Computer Software .....	8
4.1 Software Approved for QA Work.....	8
4.2 Software Routines.....	8
5. Calculation.....	9
5.1 Introduction.....	9
5.2 Waste Package/Fuel Assembly Operational Process .....	10
5.3 Misload (Criticality) Analysis .....	11
5.3.1 Consequence Matrix.....	11
5.3.2 Misload Frequency Determination .....	13
5.3.3 Parameterization and Sensitivity Analysis .....	15
5.3.4 Selection of Waste Package HEP .....	17
6. Results.....	17
6.1 Results for Case PWR-A .....	17
6.2 Results for Case PWR-B .....	19
6.3 Results for Case PWR-C .....	20
6.4 Results for Case PWR-D .....	22
6.5 Results for Case BWR.....	23
6.6 Final Observations.....	24
7. References .....	25
8. Attachments.....	26

**Title:** Frequency of SNF Misload for Uncanistered Fuel Waste Packages**Document Identifier:** BBA000000-01717-0210-00011 REV 00**Page 3 of 26**

## 1. Purpose

The purpose of this engineering calculation is to estimate the frequency of misloading spent nuclear fuel (SNF) assemblies that would result in exceeding the criticality design basis of a waste package (WP). This type of misload -- a reactivity misload -- results from the incorrect placement of one or more fuel assemblies into a waste package such that the criticality controls do not match the required controls for the fuel assemblies. An actual criticality event can not occur in an WP unless a moderator (e.g., water) is present. While a thermal misload is possible (load fuel that exceeds the thermal limits of a WP), it is not addressed in this analysis.

## 2. Method

Decision trees with mutually exclusive branch points have been developed to estimate the probability that a particular WP will result in a reactivity (criticality) misload. For each branch point on the decision tree, a probability is developed or assumed. For each decision tree sequence, the probabilities at each branch point are multiplied together to estimate the probability for the entire sequence.

Headers for the decision tree reflect operator errors and the expected distribution of DCs and their associated fuel assemblies. A consequence matrix is developed to determine the consequence of different combinations of misloads (as represented by sequences/end states of the decision tree). For example, some misloads could result in only an economic, not criticality, consequence. The endstate probabilities for sequences resulting in a potential reactivity consequence are summed to determine the total probability of a fuel misload that results in exceeding the criticality loading limits or criteria for the WP.

The probability of a misload is multiplied by the expected number of WPs processed per year; this result is the frequency (per yr) of a fuel assembly misload that would result in exceeding the criticality design basis of a WP. Decision trees are developed for both pressurized water reactor (PWR) fuel assemblies and boiling water reactor (BWR) fuel assemblies. Because the criticality control mechanism for a high-criticality PWR fuel assembly is not contained in the WP, a variety of cases, with different assumptions have been developed.

## 3. Assumptions

3.1 The criticality misload analysis assumes that there are five different types of PWR waste packages available; these are type numbers 1 through 5, as delineated in the Preliminary List of Waste Package Designs for VA (Ref. 7.1). Further, this analysis assumes there are three types of BWR waste packages; these are type numbers 6 through 8, as delineated in Reference 7.1. These include:

- 21-PWR - No Absorber (1)
- 21-PWR - Absorber Plates (2)
- 21-PWR - Absorber Rods (no plates) (3)
- 12-PWR - No Absorber (4)
- 12-PWR - Absorber Plates/Long (South Texas) (5)
- 44-BWR - No Absorber (6)
- 44-BWR - Absorber Plates (7)
- 24-BWR - Thick Absorber Plates (8)

This assumption is used throughout the calculation.

- 3.2 It is assumed, that since the length of package types 1 through 4 are identical, that these waste packages are visually indistinguishable. Similarly, waste package types 6 through 8 are assumed to be visually indistinguishable. It should be noted that the 21-PWR waste packages are distinguishable from the 12-PWR waste packages by noting the difference in the number of cells, however, waste packages with a smaller number of cells were developed to handle thermal loads. Since the number of cells do not have an effect on exceeding the criticality design basis (see Assumption 3.4), waste package types 1 through 4 will be assumed to be identical. A similar argument can be applied to the BWR waste packages.

This assumption is used throughout the calculation and specifically in Section 5.3.2.

- 3.3 Because the criticality misload analysis for PWR and BWR fuel assemblies are separate and independent, it is assumed there are no potential consequences for loading (or trying to load) a PWR fuel assembly in a BWR waste package because the PWR assembly is larger than a BWR assembly. Any attempt to load a PWR assembly into a BWR waste package would be immediately detected and corrected. Similarly, there are no criticality concerns for the reverse operation -- loading a BWR fuel assembly into a PWR waste package. In addition to the smaller size of a BWR assembly being immediately discovered, the PWR waste packages are designed to store about one-half the number of assemblies as the BWR waste packages. Therefore, even if a PWR waste package was filled with BWR fuel assemblies, no criticality loading limits or criteria would be approached.

This assumption is used in Section 5.1.

- 3.4 It is assumed, in terms of the ability to control/limit reactivity consequences, that waste package types 1 and 4 are identical, and that package types 2 and 5 are identical. Therefore, fuel assemblies with comparable reactivity will be subject to the same criticality constraints, whether in package type 1 or 4.

This assumption used throughout the calculation.

- 3.5 It is assumed that the distribution of fuel assemblies (e.g., the waste stream mix expected to be delivered to the site over a 24-year period) will be proportional to the waste package types available.

This assumption is used throughout the calculation.

- 3.6 The use of a detector is assumed when the fuel assemblies are unloaded. The detector is used to characterize the thermal load and burnup of the removed fuel assembly. This is consistent with recommendations of Reg. Guide 3.58 (Ref. 7.3), which states that when burnup credit is taken, the amount of burnup needs to be confirmed by reactivity measurements. One detector device capable of performing this function is the Fork+ radiation measurement system discussed in Appendix B.2 of Reference 7.4.

This assumption is used in Sections 3.7(a) and 5.2.

- 3.7 The following human errors are assumed to occur during the fuel assembly unloading process from the transportation cask and the subsequent loading into the waste packages (Ref. 7.5, 7.6). These are actions are assumed to occur because there have not been any formal procedures for fuel assembly loading developed at this time.

- (a) During the cask unloading process, the operator will need to record the assembly identification, the associated heat rate and burnup from the licensing paperwork, and to perform a verification measurement with a detector (Ref. 7.3); see Assumption 3.6. It is assumed that the operator will fail to identify a discrepancy between the licensing paperwork and the detector reading with a human error probability (HEP) of 0.001 (Ref. 7.7, p. 20-26). The error may occur due to either faulty paperwork or a faulty detector. In either case, applying an HEP to the decision tree will generate a set of endstates three orders of magnitude lower (i.e., insignificant endstates) than the rest of the endstates, therefore this error will not be explicitly treated in the development of the decision trees.

This assumption is used throughout the calculation.

- (b) The Assembly Transfer System Line operator (Line operator) determines what type of waste package (disposal container, DC) is to be used, informs the Empty DC Preparation Area operator (DC Area operator), who selects the desired WP type (by methods unknown at this time), loads the WP on a WP cart and positions it under one of three transfer ports. This process can result in a variety of human errors, particularly with the required communications between the Line operator and the DC Area operator. It is therefore assumed that recovery is limited to correcting another operator's error (rather than an operator's own error).

The types of human errors possible include conceptual and selection error. A conceptual error would be if the Line operator decided on the wrong WP type and requested the wrong WP from the DC Area operator. The HEP (human error probability) is approximated by a rule-based action after a diagnosis of an event without recovery; taken from Reference 7.7 (p. 20-18), the HEP is 0.05 following an abnormal event. Since this occurs under normal operating conditions, assume the HEP is at its lower bounds (using an error factor of 10), 0.005. There is no unusual or stress conditions requiring an additional multiplier.

The other possible human error is a selection error for which the HEP is approximated by an error of commission in selecting the wrong control on a panel of similar looking controls that are arranged in well-defined functional group; the HEP is 0.001 (Reference 7.7, p. 20-25). This selection error is assumed to include either the selection of an incorrect WP (different than requested) or placement of the WP on the wrong WP cart (arrives at the wrong Assembly Transfer System Line). Consistent with the first paragraph of this Section, it is assumed that the Line operator can recover from the DC Area operator's error. It is assumed the DC Area operator can only make a selection error.

A human reliability analysis (see Attachment VII) shows that the conceptual error by the Line operator (endstate HEP-4 in Attachment VII) dominates over the selection error by the DC Area operator (endstate HEP-3 in Attachment VII) (due to recovery). Because HEP-4 dominates, the WP selection error (HEP-3) is not developed in the decision trees, and an incorrect WP is assumed to occur only due to a conceptual error on the part of the Line operator. Further, if a concept error occurs, the Line operator is assumed to be loading into the *original, intended* WP (i.e., ignoring the original conceptual error) **unless** the Line operator subsequently makes a conceptual error selecting the fuel assembly. (The assumption can be modified by applying a recovery factor.) Whenever this conceptual error (for fuel assemblies) occurs, *it is assumed that the Line operator behaves as if the WP is appropriate for the fuel assembly that was (erroneously) selected.*

These assumptions are used throughout the calculation.

- (c) The Line operator determines what type of fuel assembly is to be loaded into the WP, selects the desired fuel assembly basket from the Assembly Storage Rack (by methods unknown at this time), transfers the basket up the incline, into the Assembly Drying Stations, and finally positions it over a transfer port to be placed into the WP. This could result in a conceptual human error or selection human error. The concept error would be deciding on the wrong fuel assembly basket type. The HEPs are assumed to be the same as developed in item (b). Any recovery action is assumed to occur during the verification step (see item (d)).

This assumption is used throughout the calculation.

- (d) The physical verification occurs after the fuel assembly is loaded into the WP. This includes verifying the fuel assembly identity (e.g., via a remote camera), and confirming the fuel assembly's characteristics and the appropriateness of the WP into which it has been loaded. The HEP is estimated at 0.01 as failure to use written operating procedures under normal operating conditions (Ref. 7.7, p. 20-22).

In the instance of a conceptual error (versus a selection error), since the operator will be checking a WP completely misloaded (i.e., the effect of a conceptual error), the lower limit of the HEP is used, e.g., 0.001.

This assumption is used throughout the calculation.

- (e) As a sensitivity analysis, it is assumed that for each operator action (e.g., selection of a WP and selection of a fuel assembly) that there exists a specialized error recovery mechanism. This may be another operator shadowing the first operator or some sort of automated checking system. This value can vary from zero (0.0), i.e., no recovery possible, to one (1.0), i.e., recovery is always successful. Since the loading procedures and processes are unknown, a recovery factor of 0.9 was assumed to develop bounds on the results.

This assumption is used in Section 6.

- 3.8 Because the criticality control mechanism for high-criticality PWR fuel assemblies are contained within the fuel assembly itself, and not in the WP, four cases for PWR fuel assemblies were developed with the following assumptions, used throughout the calculation:

- (a) Case PWR-A: Treat the no absorber WP and the absorber rod WP as distinct and unique, as if the DC Area operator has a means to distinguish them from each other. Further, assume that the Line operator loads the absorber rods into the fuel assemblies only when the Line operator recognizes the use of an absorber rod WP or believes a high-criticality (HK) fuel assembly is being loaded into the WP. Failure to load the absorber rods is 100% dependent on operator failure to recognize the use of an absorber rod WP (and therefore is not explicitly modeled in the decision tree).
- (b) Case PWR-B: Treat the no absorber WP and the absorber rod WP as the same and indistinguishable; the DC Area operator will only be requested to load one of two types of WPs: no absorber or absorber plate. Further, assume that the Line operator loads the absorber rods into the fuel assemblies only when the Line operator recognizes the use of an absorber rod WP. Failure to load the absorber

**Title:** Frequency of SNF Misload for Uncanistered Fuel Waste Packages

**Document Identifier:** BBA000000-01717-0210-00011 REV 00

**Page 8 of 26**

rods is 100% dependent on operator failure to recognize the use of an absorber rod WP (and therefore is not explicitly modeled in the decision tree).

- (c) Case PWR-C: Assume another method of criticality control for the high-criticality fuel assemblies that is intrinsic to the WP. Assume this criticality control mechanism makes this WP distinct and unique from a no absorber WP. For convenience, this WP will continue to be referred to as an absorber rod WP. This is similar to the BWR case.
- (d) Case PWR-D: Assume that the absorber rods are properly inserted into the appropriate fuel assemblies at the nuclear power plant prior to transport, and that except for confirmation, repository personnel have no responsibility for loading absorber rods. Accordingly, it is assumed that the no absorber WP and the absorber rod WP are the same and indistinguishable. This case represents a non-conservative assumption.

- 3.9 It is assumed that the likelihood of selecting an incorrect fuel assembly to load into the WP is based on the percentage of fuel assemblies with specific characteristics from the total number of fuel assemblies to be delivered to the site over the 24-year period.

This assumption is used throughout the calculation.

- 3.10 In Section 5.1, each of the five cases was developed for only uncanistered fuel (UCF). It is assumed because canistered fuel (if any is shipped to the repository), in most cases, will be taken out of the canister and placed directly into the DC, there is no opportunity for misloading errors.

## **4. Use of Computer Software**

### **4.1 Software Approved for QA Work**

No software approved for QA work was used in this calculation.

### **4.2 Software Routines**

The only software used to support this engineering calculation is Microsoft's spreadsheet package Excel (Version: Microsoft Excel 97). The spreadsheet was executed on a personal computer (PC) under the Windows NT 4.0 operating system. The use of Excel in this calculation does not generate data. All calculations performed by the Excel spreadsheet are verified by visual inspection and/or hand calculations. The five decision trees were developed and quantified using Excel. Excel was also used to generate the regression analysis results.

**Title:** Frequency of SNF Misload for Uncanistered Fuel Waste Packages**Document Identifier:** BBA000000-01717-0210-00011 REV 00**Page 9 of 26**

## 5. Calculation

### 5.1 Introduction

The purpose of this section is to estimate the frequency of a fuel assembly misload that would result in exceeding the criticality design basis of a waste package. This analysis considers three items:

- a) the operational handling of the fuel assemblies from when they are removed from the transport casks to when they are placed (or loaded) into the disposal container (Section 5.2),
- b) the consequence of loading any one of the fuel assemblies into any one of the waste packages (Section 5.3.1), and
- c) estimating the probability/frequency for the consequences that are identified as being undesirable (Section 5.3.2).

Decision trees have been developed for five cases:

Case	Consequence	Comment
PWR-A	Exceed Criticality Design Basis	See Assumption 3.8 (a). Decision tree is in Attachment I.
PWR-B	Exceed Criticality Design Basis	See Assumption 3.8 (b). Decision tree is in Attachment II.
PWR-C	Exceed Criticality Design Basis	See Assumption 3.8 (c). Decision tree is in Attachment III.
PWR-D	Exceed Criticality Design Basis	See Assumption 3.8 (d). Decision tree is in Attachment IV.
BWR	Exceed Criticality Design Basis	Decision tree is in Attachment V.

There are four PWR cases to account for the assumptions related the fact that the criticality control mechanism for high-criticality PWR fuel assemblies is separate from the WP itself. The assumptions range from conservative to non-conservative.

The PWR and BWR fuel assembly evaluation are separate and independent. There are no consequences for loading (trying to load) a PWR fuel assemblies into a BWR WP because the PWR assemblies are larger than a BWR UCF assembly. Any attempt to load a PWR assembly into a BWR WP would be immediately detected and corrected. Similarly, there are no criticality concerns for the reverse -- loading a BWR fuel assembly into a WP. In addition to the smaller size of the BWR assemblies being immediately discovered, the PWR waste packages are designed to hold about one-half the number of assemblies as the BWR packages. Therefore, even if a PWR package was filled with BWR fuel assemblies, no criticality limits would be approached.

Based on the analysis in Reference 7.2, the waste package mix in case L1-T4-C1 is used to determine the nominal percentage of waste package types. From Reference 7.2, the nominal waste stream coverage for PWRs for scenario C1 is<sup>1</sup>:

21 PWR (no absorber) (1)	- 35.5%
21 PWR (absorber plates) (2)	- 55.5%
21 PWR (absorber rods) (3)	- 3.5%
12 PWR (no absorber) (4)	- 3.5%
12 PWR (ST, absorber plates) (5)	- 2.0%

Types 1 and 4, and types 2 and 5 are identical from a criticality point of view.

From Reference 7.2, the nominal waste stream coverage for BWRs for scenario C1 is:

44 BWR (no absorber) (6)	- 27.5%
44 BWR (absorber plates) (7)	- 71.5%
24 PWR (absorber rods) (8)	- 1.0%

There are no equivalent types for BWR waste packages, in terms of criticality control.

However, to enhance flexibility and permit the development of a regression expression for misload probability as a function of waste stream composition, the Excel spreadsheets (e.g., decision trees) were developed to permit the entry of a variety of WP allocations (e.g., different percentages for each type of WP).

## 5.2 Waste Package/Fuel Assembly Operational Process

At a minimum, the process in which the fuel assemblies are unloaded from the transportation casks and are readied for loading into a WP must be considered. As discussed in Reference 7.8, the transport casks are delivered to the repository by truck or rail. They are inspected, decontaminated, if necessary, and upended in the Carrier Washdown Station and the Carrier Bay. They are then delivered to the Assembly Transfer System, where in the Cask Preparation Area, the transport cask's lid is removed. The cask is placed in the Cask Unload Pool, where the Assembly Transfer Machine removes fuel assemblies and places them into Assembly Baskets (with capacities of either four PWR assemblies or eight BWR assemblies). The Assembly Baskets are moved through the Transfer Canal to the Assembly Cell, where an Assembly Transfer Machine places Assembly Baskets into an Assembly Drying Station and finally the individual assemblies into a waste package positioned under a transfer port. Assembly baskets continue through the

<sup>1</sup> The values presented here are the averages of the coverage ranges taken from a Check Copy of Ref. 7.2. The REV 00 version of Ref. 7.2 provides slightly different coverage ranges. However, since the values shown here are still within the ranges shown in Ref. 7.2, they will be used as the nominal coverage values for PWRs for this document.

**Title:** Frequency of SNF Misload for Uncanistered Fuel Waste Packages

**Document Identifier:** BBA000000-01717-0210-00011 REV 00

**Page 11 of 26**

Transfer Canal until there are sufficient fuel assemblies to fill the waste package. There are three independent Assembly Transfer System Lines.

The empty waste package is retrieved from the Empty DC Preparation Area. The Assembly Transfer System Line operator (Line operator) makes a request of the Empty DC Preparation Area operator (DC Area operator), who places the appropriate WP on a WP cart that conveys the WP to the appropriate transfer port.

During the unloading process, the Line operator will need to record the assembly identification and associated heat rate and burnup from the licensing paperwork and a detector (Ref. 7.3). In this way, the characteristics of each assembly in the Assembly Baskets will be known. Mis-identification of the fuel assembly's characteristics and/or location is the first opportunity for a human error that can contribute to a misload (reading the paperwork incorrectly or misreading the detector output). This error does not significantly contribute to the overall misload frequency (see Assumption 3.7 (a)). Based on the characterization of the fuel assemblies removed from the transport casks, the Line operator must decide what type of WP is to be used. The Line operator requests the desired WP type (by methods unknown at this time) from the DC Area operator, who places it on a WP cart and positions it under a transfer port. Deciding on an inappropriate WP type or selecting the wrong WP type is another opportunity for a human error.

Operator treatment of absorber rods is described in Assumptions 3.8 (a) through 3.8 (d) to reflect a range of actions, from conservative to non-conservative.

The selection of fuel assemblies (from the Assembly Storage Rack) to be placed in the WP is another opportunity for human error. The operator can select an incorrect assembly (conceptual error), or after selecting the correct assembly for the WP, make a manipulation error with the Assembly Transfer Machine and transfer the wrong assembly (selection error).

After placing the fuel assemblies into the WP, the Line operator will perform a physical verification (e.g., ensure that the fuel assembly that was intended to be loaded was correctly loaded). The physical verification process is an opportunity for human error recovery. The loaded WP is then moved to an area where an inner lid is seal-welded in place.

### **5.3 Misload (Criticality) Analysis**

#### **5.3.1 Consequence Matrix**

This section develops and discusses the PWR and BWR consequence matrices, which consider the placement of any of the possible transported fuel assemblies into any one of the designed WPs. The WP types, with the criticality ranges, were taken from Case L1-T4-C1 tabulated in Reference 7.2.

The following explains the cell designations in the PWR and BWR Consequence Matrices shown in Tables 5-1 and 5-2:

1. Those cells labeled *As Designed* indicate that a fuel assembly was placed into a WP appropriate for that fuel assembly's criticality characteristics.
2. Those cells labeled *Possible Criticality* indicate that some percentage of the fuel assemblies placed in the specified WP may exceed the criticality design basis of the WP. The reactivity level (i.e.,  $k_{\infty}$ ) is determined by curves attached to each licensed transport cask. Note further that transport casks are licensed for use employing no burn-up credit, i.e., as if the fuel were fresh fuel, and therefore the value of  $k_{\infty}$  is not a deciding parameter for the selection of a transport cask. The value of  $k_{\infty}$  becomes important when determining what WP is to be used because the waste package design takes credit for burnup. Therefore, for any WPs that do not required fuel assemblies with absorber rods as criticality control (e.g., use absorber plates or no absorber), it is possible, via human error, to place a fuel assembly into a WP and to exceed the criticality design basis.

Some combinations are not credible and will not be explicitly considered. If a South Texas (ST) fuel assembly is placed in any waste package except PWR 12 (absorber plates), it would be immediately discovered and detected due to the extra length of a ST fuel assembly. However, the converse is not true; if a fuel assembly requiring absorber rods is placed in a ST waste package, then there is the possibility of a criticality concern.

3. Those cells labeled *Possible Economic* indicate that some percentage of the fuel assemblies placed in the specified WP will exceed the economic considerations for the use of a WP. The WP does not contain absorber rods for criticality control; the absorber rods are placed directly into the fuel assemblies. Therefore, if a fuel assembly received absorber rods when not necessary, this is an appropriate use of resources, i.e., an economic concern. Similarly, if a fuel assembly with absorber rods (when required) is placed into an WP with absorber plates, then the WP usage is not economical.

Those cells labeled *Possible Criticality* represent potential misload situations, which would require the introduction of a moderator (e.g., water). The estimation of probability/frequency of misloads is discussed in Section 5.3.2.

**Table 5-1.**  
**Fuel Assembly to Waste Package (PWR) Consequence Matrix**

Type of Waste Package	Fuel Assembly Characterization		
	Low-criticality (LK)	Mid-criticality (MK)	High-criticality (HK)
21 PWR (no absorber)	As designed	<i>Possible Criticality</i>	<i>Possible Criticality</i>
21 PWR (absorber plate)	Possible Economic	As designed	<i>Possible Criticality</i>
21 PWR (absorber rod)	Possible Economic	Possible Economic	As designed
12 PWR (no absorber)	As designed	<i>Possible Criticality</i>	<i>Possible Criticality</i>
12 PWR (ST/absorber plate)	Possible Economic	As designed	<i>Possible Criticality</i>

**Table 5-2.**  
**Fuel Assembly to Waste Package (BWR) Consequence Matrix**

Type of Waste Package	Fuel Assembly Characterization		
	Low-criticality (LK)	Mid-criticality (MK)	High-criticality (HK)
44 BWR (no absorber)	As designed	<i>Possible Criticality</i>	<i>Possible Criticality</i>
44 BWR (absorber plate)	Possible Economic	As designed	<i>Possible Criticality</i>
24 BWR (thick absorber plate)	Possible Economic	Possible Economic	As designed

**5.3.2 Misload Frequency Determination**

Decision trees (Figures I through IV, located in Attachments I through IV, respectively) were developed to evaluate exceeding the criticality design basis due to misload errors for PWR fuel assemblies loaded into the available waste packages under a variety of assumptions for the treatment of absorber rods (see Assumption 3.8). A fifth decision tree (Figure V, Attachment V) was developed to similarly evaluate BWR fuel assemblies. Figures I through V show the nominal WP percentages.

The sequence development is not automatic and relies on a careful consideration of which fuel assemblies are being loaded into which waste packages, and what human errors are being committed. The consequence matrices are used to determine whether a sequence has a criticality consequence.

The following is some information used in the development of the decision trees:

- The likelihood of selecting an incorrect fuel assembly to load into the waste package is estimated based on the percentage of fuel assemblies with specific characteristics *from the total number of fuel assemblies to be delivered to the site over the 24-year period.*

- The South Texas-(ST) waste packages are approximately two feet longer than any of the other PWR waste packages to accommodate the long ST fuel assemblies. Accordingly, when a ST fuel assembly is misloaded into any other waste package, it is assumed to be immediately recoverable and corrected. Likewise, when any non-ST fuel assembly is misloaded into the ST disposal container, it is assumed to be immediately recoverable and corrected. This assumption implies a verification HEP equal to 1.0, and is so reflected in the decision tree.

The ST waste package is not explicitly represented on the PWR-C decision tree. PWR-C was based on the BWR decision tree, since for BWRs, the waste package designed for high-criticality fuel assemblies does indeed have the criticality controls designed into the WP. This omission is conservative in light of the assumption that all assemblies misloaded into a ST package are immediately detected and corrected.

- For cases PWR-B and PWR-D (see Attachments II and IV), there is no explicit mention of the absorber rod waste packages, since the assumptions for these cases state that the “no absorber” and “absorber rod” packages are of identical construction. The waste package in the decision tree, whether for low-criticality or high-criticality fuel assemblies, is referred to as “no absorber.”

The calculation performed on the decision tree to generate the endstate probability is simply the product of the probabilities on each node of the endstate sequence. For example, in Figure I (Attachment I), endstate PA-4’s probability is calculated as the product of:

<b>Decision Tree Header</b>	<b>Probability</b>
WP Usage (no absorber)	0.390
Select WP (intended WP)	0.995
Select FA (concept)	0.005
FA Type (MK)	0..951
Verification (failure)	0.001
<i>Endstate Probability (Product)</i>	$1.84 \times 10^{-6}$

This endstate also represents a possible criticality concern, e.g., possibility of exceeding a criticality design basis. The total probability of misload leading to exceeding criticality design basis per disposal container (shown at the bottom of the decision trees and in the summary tables in Sections 6.1 through 6.5) is computed by simply adding all the endstates denoted with *criticality*. These endstates are further highlighted on the decision tree with a double-lined border.

**Title:** Frequency of SNF Misload for Uncanistered Fuel Waste Packages**Document Identifier:** BBA000000-01717-0210-00011 REV 00**Page 15 of 26**

The only exception to the straight multiplication method to calculate an endstate probability is for those endstates derived from a **Select FA** state of (*selection*). In these cases, the product is multiplied by the number of assemblies in the waste package, since any of the individual assemblies could be misloaded. So if for  $n_a = 21$  PWR, the probability was  $p_1 = 2.25 \times 10^{-6}$ , then the probability of the endstate would be  $(2.25 \times 10^{-6})(21) = 4.73 \times 10^{-5}$  (see endstate PA-10 in Figure I, Attachment I). To determine the probability that two assemblies are misloaded, the calculation is:

$$(p_1)(n_a)(p_1)(n_a-1) = (p_1)^2(n_a)(n_a-1)$$

This calculation is used for all of the “selection (2)” sequences to compute the probability of a misload leading to a possible criticality concern with a mission success definition of two misloaded assemblies representing a possible consequence.

### 5.3.3 Parameterization and Sensitivity Analysis

The decision trees, within Excel, were structured to permit a parametric examination of the percentage of the types of waste packages that are available. These percentages are directly related to the expected percentage of types of fuel assemblies to be placed in the repository. For examples, if the percentages of WPs for PWR SNF are the nominal values given in Section 5.1, then the expected fuel assembly percentages would be:

LK (no absorber: WP 1, WP 4)	35% + 4% = 39%
MK (absorber plates: WP 2, WP 5)	56% + 2% = 58%
HK (absorber rods: WP 3)	3% = 3%

Therefore, as the percentages for WPs change in the spreadsheet, the fuel assembly percentages would vary accordingly. The regression expressions were developed as a function of the fuel assembly percentages.

The base development of the decision trees included a single verification/recovery action at the end of the event sequence. This single action was established due to the uncertainty concerning the procedures and processes to be established for WP loading. To explore a range of possibilities in the (to be developed) loading procedures and processes, an additional verification/recovery action was added for both the WP selection and the fuel assembly (FA) selection human error. This recovery may take the form of an additional operator or supervisor overseeing the process, or some sort of electronic/automated system to “look over the shoulder” of the operator. This recovery action can be varied from zero (0.0), i.e., no recovery, to one (1.0), i.e., error detection always occurs. Interactively, this value can be changed on the Excel “Data” tab (shown in Attachment VI) for both the PWR and BWR cases.

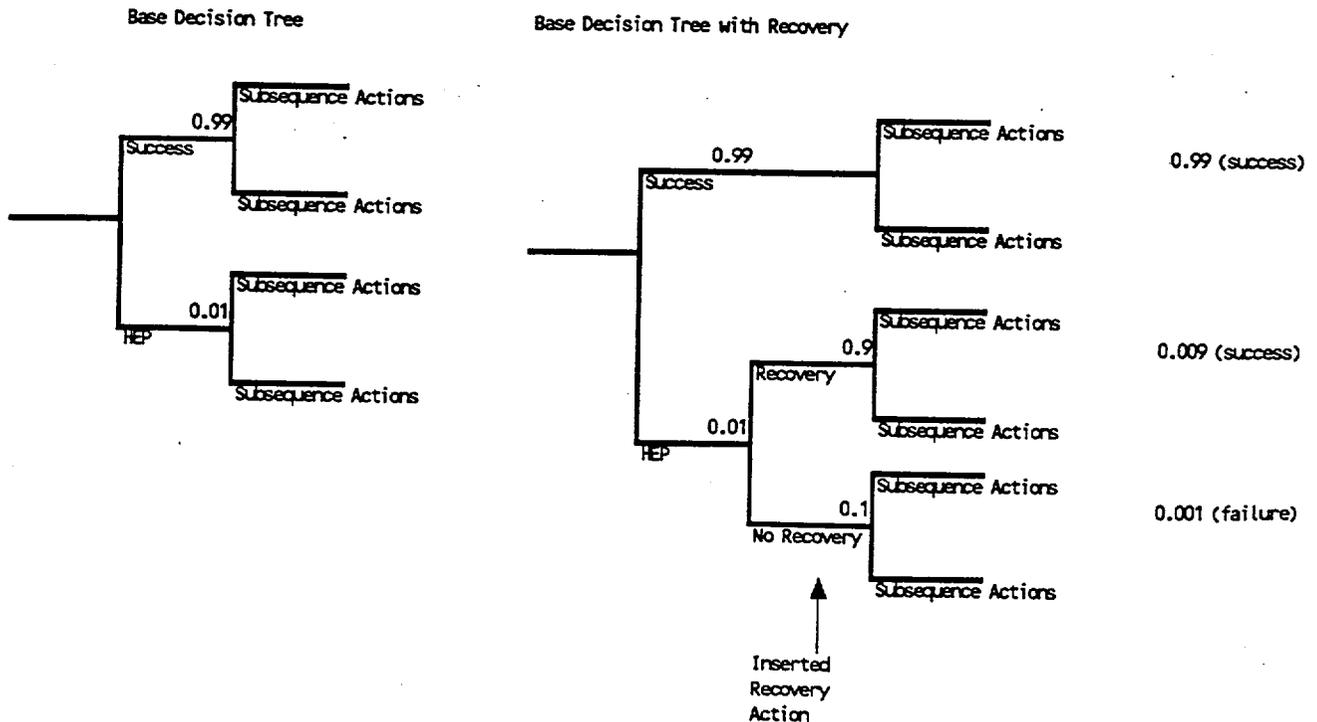
Typically, to model a recovery action, an additional branch point is added to the decision tree. To account for this sensitivity analysis, the HEP for the “recovered” action was modified as follows:

$$\text{HEP for "Select FA"} = \text{Base Failure Probability} * (1 - \text{Recovery Probability})$$

As the recovery probability varies from zero to one, the HEP will vary from the original failure probability to zero (i.e., absolute error detection and recovery). The modified HEP is used in the originally developed decision tree.

Modeling the recovery action in this way can be justified by looking at a small portion of a tree (see Figure 5-1 below), where a recovery action has been inserted. The failure probability with the recovery action is 0.001, while the total probability for the success sequences is 0.999. If the failure probability is calculated as the original HEP multiplied by (1 - recovery probability), and inserted in the original tree, then the probability of the failure sequences will be (0.01)(0.1) = 0.001, which is the same as the failure probability with the recovery action. Accordingly, if the success path for the HEP is (1 - HEP) = 1 - 0.001 = 0.999, the success sequences will be equivalent to the sum of the success sequences in the tree with the recovery actions. Accordingly, the HEPs are modified as indicated above to emulate the recovery action.

Figure 5-1.  
Decision Trees to Support Recovery Action Model



### 5.3.4 Selection of Waste Package HEP

The HEP for the selection of the WP is more complex than the selection error for fuel assemblies because there are two operators (Line operator and DC Area operator) involved. For this reason a separate human reliability analysis tree was developed to estimate the "Select WP" HEP. This tree is provided in Attachment VII. In the spreadsheet, the HEP calculated in this tree is automatically transferred to the "Data" tab (see Attachment VI). The relatively small value of the selection error versus the conceptual error is the basis for the assumptions developed in Section 3.7 (b).

## 6. Results

The total probability of misload is partitioned into different cases along two dimensions. The first dimension looks at the cause for the misload: conceptual versus selection error. The selection error is calculated for the resulting misload being one or two fuel assemblies ("selection (2)"). As the results show (see Sections 6.1, 6.3 and 6.5), the frequency of misloading two fuel assemblies (with a selection human error) is three to four orders of magnitude less than for one fuel assembly. Accordingly, the "selection (2)" frequencies are only provided for the PWR-A decision tree (Attachment I) for all selection sequences. For PWR-C and BWR decision trees (Attachments III and V), the "selection (2)" frequency are only given for the "criticality" sequences. Further, the "selection (2)" are not discussed below because of the insignificant contribution.

The second dimension examined is the waste package type into which the misloaded fuel assemblies were placed. Typically, the WP designed for the high-criticality (HK) fuel assemblies had few or no misloads; accordingly, the regression expressions were developed only for the WP designed to handle low-criticality (LK) and mid-criticality (MK) fuel assemblies.

### 6.1 Results for Case PWR-A

For the nominal values of the PWR-A case, the following table summarizes the results, i.e., the probability of a misload leading to exceeding criticality design basis:

	No Absorber	Absorber Plates	Absorber Rods	(Total)
Concept	4.41E-06	0.00E+00	1.33E-07	4.54E-06
Selection	5.50E-05	3.65E-06	3.77E-08	5.37E-05
Selection (2)	2.13E-09	1.26E-11	6.87E-07	2.15E-09
<b>Total</b>	<b>5.44E-05</b>	<b>3.65E-06</b>	<b>1.71E-07</b>	<b>5.83E-05</b>

**Title:** Frequency of SNF Misload for Uncanistered Fuel Waste Packages**Document Identifier:** BBA000000-01717-0210-00011 REV 00**Page 18 of 26**

As indicated above, the "Selection (2)" results (for misloading two fuel assemblies on selection errors) is orders of magnitude less than either the conceptual or selection errors. The selection error is approximately an order and half magnitude greater than the conceptual error. There can not be a conceptual error when loading an absorber plate package, since if the Line operator is aware of high-criticality (HK) fuel assembly that is being loaded, absorber rods will be placed into the fuel assembly. If the number of PWR WPs expected to be loaded in one year is 200 packages (from Key Assumption 3, Reference 7.9), then the frequency of a PWR waste package being misloaded such that the criticality design basis could be exceeded is  $(5.83 \times 10^{-5})(200) = 1.17 \times 10^{-2}/\text{yr}$ . (The expected number of PWR WPs to be loaded is estimated by summing the total number of the five types of PWR WPs shown in Table 3.9 of Ref. 7.9 and dividing by 24 years, the time required to load all of the fuel assemblies.)

When considering a recovery factor of 0.9 for both the WP selection and FA selection, the total probability of misload resulting in potentially exceeding the criticality design basis is  $5.82 \times 10^{-6}$ . This probability is estimated by changing the value of the recovery factor for WP-incorrect, FA-concept, and FA-select from 0.0 to 0.9 (see Attachment VI). This will change the appropriate values of the HEP with recovery for these three actions in the decision tree as per the discussion in Section 5.3.3. Since the HEPs are integrated in the decision tree logic, the result is not a straight multiplication of the probability with a 0.0 recovery factor. Accordingly, the frequency of a PWR waste package misload resulting in potentially exceeding the criticality design basis is  $(5.82 \times 10^{-6})(200) = 1.16 \times 10^{-3}/\text{yr}$ . Depending on the actual procedures and processes used to load the fuel assemblies into the waste packages, the expected frequency would be bounded by these values.

The results of the regression analysis for both the no absorber and the absorber plate cases for PWR-A are summarized below. The R-squared ( $R^2$ ) value shown below indicates the ability of the regression expression to predict the misload probability; the closer to 1.0, the better the predictive value. Other factors that can be examined to evaluate the regression fit are the *Significance F* for the regression and the *P-value* for the coefficients; the smaller these values, the better the regression fit. These parameters and other details of the regression analysis are available in Attachment VIII. Note the *P-value* for the intercept of the regression expression is relatively large, but the intercept is considered a necessary part of the model and retained regardless of the *P-value*. These observations are also applicable to the results in Sections 6.2 through 6.5.

**Title:** Frequency of SNF Misload for Uncanistered Fuel Waste Packages

**Document Identifier:** BBA000000-01717-0210-00011 REV 00

**Page 19 of 26**

PWR-A	No Absorber
R-squared	0.999300532
<i>Coefficients</i>	
Intercept	1.0639E-06
LK <sup>2</sup>	-0.00019831
MK <sup>2</sup>	7.90505E-06
LK*MK	2.68078E-05
LK	0.000201046
MK	-5.8763E-06

PWR-A	Absorber Plate
R-squared	0.9986142
<i>Coefficients</i>	
Intercept	5.96767E-06
MK <sup>2</sup>	-0.00020824
MK	0.000208447
LK*MK	-0.0002103

**6.2 Results for Case PWR-B**

For the nominal values of the PWR-B case, the following table summarizes the results, i.e., the probability of a misload leading to exceeding criticality design basis:

	No Absorber	Absorber Plates	(Total)
Concept	4.76E-06	0.00E+00	4.76E-06
Selection	5.35E-05	1.74E-07	5.37E-05
<b>Total</b>	<b>5.83E-05</b>	<b>1.74E-07</b>	<b>5.85E-05</b>

As indicated above, the “Selection (2)” results (for misloading two fuel assemblies on selection errors) is orders of magnitude less than either the conceptual or selection errors, and therefore was not evaluated for this case. The selection error is approximately an order and half magnitude greater than the conceptual error. There can not be a conceptual error when loading an absorber plate package, since if the Line operator is aware a high-criticality (HK) fuel assembly is being loaded, absorber rods will be placed into the fuel assembly. Since the no absorber package and the absorber rod package are identical, the “no absorber” label is used for both types. If the number of PWR WPs expected to be loaded in one year is 200 packages (from Key Assumption

**Title:** Frequency of SNF Misload for Uncanistered Fuel Waste Packages**Document Identifier:** BBA000000-01717-0210-00011 REV 00**Page 20 of 26**

3, reference 7.9), the frequency of a PWR waste package being misloaded such that the criticality design basis could be exceeded is  $(5.85 \times 10^{-5})(200) = 1.17 \times 10^{-2}/\text{yr}$ .

When considering a recovery factor of 0.9 for both the WP selection and FA selection, the total probability of misload resulting in potentially exceeding the criticality design basis is  $5.87 \times 10^{-6}$ . Thus the frequency of a PWR waste package misload resulting in potentially exceeding the criticality design basis is  $(5.87 \times 10^{-6})(200) = 1.17 \times 10^{-3}/\text{yr}$ . Depending on the actual procedures and processes used to load the fuel assemblies into the waste packages, the expected frequency would be bounded by these values.

The results of the regression analysis for both the no absorber and the absorber plate cases for PWR-B are summarized below. Details of the regression analysis are available in Attachment VIII.

PWR-B	No Absorber
<b>R-squared</b>	<b>0.998837064</b>
<i>Coefficients</i>	
Intercept	0.000209131
LK*MK	0.000209584
LK	-0.00020638
MK	-0.00020371

PWR-B	Absorber Plate
<b>R-squared</b>	<b>0.998523718</b>
<i>Coefficients</i>	
Intercept	5.96135E-09
MK <sup>2</sup>	-9.9905E-06
MK	909895E-06
LK*MK	-1.0087E-05

### 6.3 Results for Case PWR-C

For the nominal values of the PWR-C case, the following table summarizes the results, i.e., the probability of a misload leading to exceeding criticality loading criteria:

**Title:** Frequency of SNF Misload for Uncanistered Fuel Waste Packages

**Document Identifier:** BBA000000-01717-0210-00011 REV 00

**Page 21 of 26**

	No Absorber	Absorber Plates	Absorber Rods	(Total)
Concept	4.68E-06	2.96E-07	0.00E+00	4.98E-06
Selection	5.01E-05	3.65E-06	0.00E+00	5.37E-05
Selection (2)	2.13E-09	1.26E-11	0.00E+00	2.15E-09
<b>Total</b>	<b>5.47E-05</b>	<b>3.94E-06</b>	<b>0.00E+00</b>	<b>5.87E-05</b>

As indicated above, the "Selection (2)" results (for misloading two fuel assemblies on selection errors) is orders of magnitude less than either the conceptual or selection errors. The selection error is approximately an order and half magnitude greater than the conceptual error. There can be no misload into the "rod" packages, since the criticality control is assumed inherent in the package in this case. If the number of PWR WPs expected to be loaded in one year is 200 packages (from Key Assumption 3, Reference 7.9), then the frequency of a PWR waste package being misloaded such that the criticality design basis could be exceeded is  $(5.87 \times 10^{-5})(200) = 1.17 \times 10^{-2}/\text{yr}$ .

When considering a recovery factor of 0.9 for both the WP selection and FA selection, the total probability of misload resulting in potentially exceeding the criticality design basis is  $8.45 \times 10^{-6}$ . Thus the frequency of a PWR waste package misload resulting in potentially exceeding the criticality design basis is  $(8.45 \times 10^{-6})(200) = 1.69 \times 10^{-3}/\text{yr}$ . Depending on the actual procedures and processes used to load the fuel assemblies into the waste packages, the expected frequency would be bounded by these values.

The results of the regression analysis for both the no absorber and the absorber plate cases for PWR-C are summarized below. Details of the regression analysis are available in Attachment VIII.

PWR-C	No Absorber
<b>R-squared</b>	<b>0.999544201</b>
<i>Coefficients</i>	
Intercept	4.23477E-06
LK <sup>2</sup>	-0.00021378
MK <sup>2</sup>	1.91724E-05
LK*MK	1.72634E-05
LK	0.000214066
MK	-1.8396E-05

**Title:** Frequency of SNF Misload for Uncanistered Fuel Waste Packages

**Document Identifier:** BBA000000-01717-0210-00011 REV 00

**Page 22 of 26**

-PWR-C	Absorber Plate
<b>R-squared</b>	<b>0.997872071</b>
<i>Coefficients</i>	
Intercept	4.35403E-07
MK <sup>2</sup>	-0.00022734
MK	0.000227933
LK*MK	-0.00023353

**6.4 Results for Case PWR-D**

For the nominal values of the PWR-D case, the following table summarizes the results, i.e., the probability of a misload leading to exceeding criticality loading criteria:

	No Absorber	Absorber Plates	(Total)
Concept	4.86E-06	0.00E+00	4.86E-06
Selection	5.09E-05	0.00E+00	5.09E-05
<b>Total</b>	<b>5.58E-05</b>	<b>0.00E+00</b>	<b>5.58E-05</b>

As indicated above, the “Selection (2)” results (for misloading two fuel assemblies on selection errors) is orders of magnitude less than either the conceptual or selection errors, and therefore was not evaluated for this case. The selection error is approximately an order and half magnitude greater than the conceptual error. There can neither a conceptual nor selection error when loading an absorber plate package, since this case assumes the absorber rods are already loaded in the high-criticality (HK) fuel assemblies. Since the no absorber package and the absorber rod package are indistinguishable in this case, the “no absorber” label is used for both types. If the number of PWR WPs expected to be loaded in one year is 200 packages (from Key Assumption 3, Reference 7.9), then the frequency of a PWR waste package being misloaded such that the criticality design basis could be exceeded is  $(5.58 \times 10^{-5})(200) = 1.12 \times 10^{-2}/\text{yr}$ .

When considering a recovery factor of 0.9 for both the WP selection and FA selection, the total probability of misload resulting in potentially exceeding the criticality design basis is  $5.60 \times 10^{-6}$ . Thus the frequency of a PWR waste package misload resulting in potentially exceeding the criticality design basis is  $(5.60 \times 10^{-6})(200) = 1.12 \times 10^{-3}/\text{yr}$ . Depending on the actual procedures and processes used to load the fuel assemblies into the waste packages, the expected frequency would be bounded by these values.

The results of the regression analysis for the no absorber case for PWR-D are summarized below. For case PWR-D, no misloads into a WP with absorber plates is possible, since absorber rods are preloaded into the fuel assemblies. Details of the regression analysis are available in Attachment VIII.

**Title:** Frequency of SNF Misload for Uncanistered Fuel Waste Packages

**Document Identifier:** BBA000000-01717-0210-00011 REV 00

PWR-D	No Absorber
R-squared	0.999814996
<i>Coefficients</i>	
Intercept	4.85696E-06
MK <sup>2</sup>	-0.00021173
MK	0.000210616

**6.5 Results for Case BWR**

For the nominal values of the BWR case, the following table summarizes the results, i.e., the probability of a misload leading to exceeding criticality loading criteria:

	No Absorber	Plates	Thick Plates	(Total)
Concept	4.82E-06	1.61E-07	0.00E+00	4.98E-06
Selection	8.84E-05	3.14E-06	0.00E+00	9.15E-05
Selection (2)	7.24E-09	9.58E-12	0.00E+00	7.25E-09
<b>Total</b>	<b>9.32E-05</b>	<b>3.30E-06</b>	<b>0.00E+00</b>	<b>9.65E-05</b>

As indicated above, the "Selection (2)" results (for misloading two fuel assemblies on selection errors) is orders of magnitude less than either the conceptual or selection errors. The selection error is approximately an order and half magnitude greater than the conceptual error. There can not be a misload into the Thick Plate waste package. If the number of BWR WPs expected to be loaded in one year is 120 packages (from Key Assumption 3, reference 7.9), the frequency of a BWR waste package being misloaded such that the criticality design basis could be exceeded is  $(9.65 \times 10^{-5})(120) = 1.16 \times 10^{-2}/\text{yr}$ . The number of expected BWR waste packages to be loaded per years is calculated in a manner similar to PWRs described in Section 6.1.

When considering a recovery factor of 0.9 for both the WP selection and FA selection, the total probability of misload resulting in potentially exceeding the criticality design basis is  $9.59 \times 10^{-6}$ . Thus the frequency of a BWR waste package misload resulting in potentially exceeding the criticality design basis is  $(9.59 \times 10^{-6})(120) = 1.15 \times 10^{-3}/\text{yr}$ . Depending on the actual procedures and processes used to load the fuel assemblies into the waste packages, the expected frequency would be bounded by these values.

The results of the regression analysis for both the no absorber and the absorber plate cases for BWR are summarized below. Details of the regression analysis are available in Attachment VIII.

**Title:** Frequency of SNF Misload for Uncanistered Fuel Waste Packages**Document Identifier:** BBA000000-01717-0210-00011 REV 00**Page 24 of 26**

BWR	No absorber
<b>R-squared</b>	<b>0.999374599</b>
<i>Coefficients</i>	
Intercept	4.69836E-07
LK <sup>2</sup>	-0.000453153
LK	0.00045624

BWR	Absorber Plate
<b>R-squared</b>	<b>0.93357571</b>
<i>Coefficients</i>	
Intercept	5.17856E-06
MK <sup>2</sup>	-0.000350922
MK	0.000393047
LK*MK	-0.000475537

## 6.6 Final Observations

Despite the number of differing assumptions made to generate cases PWR-A, PWR-B, PWR-C, and PWR-D, the results do not substantially differ. The most non-conservative case (PWR-D) is only marginally better than the other cases. On the whole, the probability of a misload leading exceeding criticality design basis is approximately 0.01 package/year. This is true for both PWR and BWR fuel assemblies.

The expected number of PWR waste packages to be misloaded over the entire loading period (24 years) is approximately  $(0.01)(24) = 0.24$  waste packages. Similarly, the expected number of misloaded BWR waste packages is 0.24 waste packages. Therefore, it is expected that less than one waste package/waste form combination will be misloaded in the entire repository at the completion of the loading phase.

The tables following the decision trees in Attachments I through V show the results based on the waste package type (e.g., for PWRs, no absorber, absorber plate, and absorber rod). These results show that the no absorber waste package are more likely to be misloaded; this is expected since there is no additional criticality controls built into these waste packages. Without the no absorber waste packages available for loading (i.e., eliminate that waste package design), the frequency of misload would drop by approximately one order of magnitude.

**Title:** Frequency of SNF Misload for Uncanistered Fuel Waste Packages

**Document Identifier:** BBA000000-01717-0210-00011 REV 00

**Page 25 of 26**

The sensitivity analysis performed by including a recovery factor for the human error when they occurred (and not just at the end of the loading process), decreased the probability of a misload leading to exceeding criticality loading criteria by about an order of magnitude. This was driven by the choice of the recovery factor of 0.9. A more representative value can be used when there is a greater understanding of the loading process, and what checks and balances exist for confirming operator actions. However, when using a recovery factor of 0.9, the expected number of misloaded waste packages (either PWR or BWR) over the entire loading period (24 years) is approximately  $0.001 \times 24 = 0.024$  waste packages.

The R-squared values for each of the regression expressions is high, indicating the generated regression expressions will be good predictors of the probability of a misload leading to exceeding the criticality design basis as a function of fuel assembly percentages.

Relying on these results from a distinct criticality concern is conservative. Human errors will not be made on a strictly criticality basis (i.e., errors will result in a combination of criticality and thermal limit concerns). From examination of the decision trees, it is clear that they only approximate the large number of combinations in which a misload might occur. As an alternative to the methods presented here, a simulation (e.g., Monte Carlo simulation) could be performed that would accurately model the combination of errors leading to a waste package with a possible thermal and/or criticality consequence. Such a simulation could more comprehensively consider the arrangement of the storage area, the actual number of stored assemblies, the distribution of fuel assemblies as they arrive in the transport casks, the probability that the absorber rod is not present (when required), etc. These issues were too complex to handle within the decision tree framework.

This analysis should be revisited as the details are developed of how the fuel assemblies are handled from the time they are removed from the transport casks to the time they are placed into a waste package. Details concerning the procedures and operational practices can be used to further refine the human error probabilities used in this analysis.

## 7. References

- 7.1 *Preliminary List of Waste Package Designs for VA*, Document Identifier (DI) Number: BBA000000-01717-3300-00008 REV 02, Civilian Radioactive Waste Management System (CRWMS), Management & Operating Contractor (M&O).
- 7.2 *Determination of Waste Package Design Configurations*, DI Number: BBAA00000-01717-0200-00017 REV 00, CRWMS M&O.
- 7.3 *Criticality Safety for Handling, Sorting, and Transporting LWR Fuel at Fuels and Materials Facilities*, Regulatory Guide 3.58, NRC, October 1986.

**Title:** Frequency of SNF Misload for Uncanistered Fuel Waste Packages

**Document Identifier:** BBA000000-01717-0210-00011 REV 00

**Page 26 of 26**

- 7.4 *Topical Report on Actinide-Only Burnup Credit for PWR Spent Nuclear Fuel Packages, Draft Revision 1*, Office of Civilian Radioactive Waste Management (OCRWM), DOE/RW-0472 Rev. 1, April 1997.
- 7.5 *Reference Design Description for a Geologic Repository*, DI Number: B000000000-01717-5707-00002 REV 01, CRWMS, M&O.
- 7.6 *Assembly Transfer System Design Analysis (Draft)*, DI Number: BCBD00000-01717-0200-00007 REV 00A, CRWMS, M&O.
- 7.7 Swain, A. D. and Guttman, H. E., *Handbook of Human Reliability Analysis with Emphasis on Nuclear Power Plant Applications*, Sandia National Laboratories, prepared for the U.S. Nuclear Regulatory Commission, NUREG/CR-1278, August 1983.
- 7.8 *Mined Geological Disposal System Concept of Operations*, DI Number: B000000000-01717-00004 REV 01, CRWMS M&O.
- 7.9 *Controlled Design Assumptions Document*, DI Number: B000000000-01717-4600-00032 REV 04, ICN2, CRWMS M&O.

## **8. Attachments**

The following attachments are provided to support this engineering calculation:

Attachment I - PWR-A Exceeding Criticality Loading Criteria Decision Tree and Endstate Notes

Attachment II - PWR-B Exceeding Criticality Loading Criteria Decision Tree

Attachment III - PWR-C Exceeding Criticality Loading Criteria Decision Tree

Attachment IV - PWR-D Exceeding Criticality Loading Criteria Decision Tree

Attachment V - BWR Exceeding Criticality Loading Criteria Decision Tree

Attachment VI - Data "tab" for PWR and BWR Cases

Attachment VII - Select WP Human Reliability Analysis

Attachment VIII - Summary of PWR/BWR Regression Analysis Results

**ATTACHMENT I**

**PWR-A EXCEEDING CRITICALITY LOADING CRITERIA  
DECISION TREE AND ENDSTATE NOTES**

Figure I - PWR-A Exceeding Criticality Loading Criteria Decision Tree

WP Usage	Select WP	Select FA	FA Type	Verification		Endstate	
0.390	0.995	0.994		0.990	3.82E-01	PA-1	
(no absorber)	(intended WP)	(intended FA)	(LK)	(success)	(no consec.)		
				0.010	3.86E-03	PA-2	
				(failure)	(no consec.)		
		0.005	0.951	0.999	1.84E-03	PA-3	
		(concept)	(MK)	(success)	(no consec.)		
				0.001	1.84E-06	PA-4	
				(failure)	(criticality)		
			0.049	0.999	9.53E-05	PA-5	
			(HK)	(success)	(no consec.)		
				0.001	9.54E-08	PA-6	
				(failure)	(no consec.)		
		0.001	0.390	0.990	3.15E-03	PA-7	9.43E-06
		(selection)	(LK)	(success)	(no consec.)		
				0.010	3.18E-05	PA-8	9.62E-10
				(failure)	(no consec.)		
			0.580	0.990	4.68E-03	PA-9	2.09E-05
			(MK)	(success)	(no consec.)		
				0.010	4.73E-05	PA-10	2.13E-09
				(failure)	(criticality)		
			0.030	0.990	2.42E-04	PA-11	5.58E-08
			(HK)	(success)	(no consec.)		
				0.010	2.44E-06	PA-12	5.69E-12
				(failure)	(criticality)		
	0.005	0.918	0.994	0.999	1.78E-03	PA-13	
	(wrong WP)	(plate)	(intended FA)	(success)	(no consec.)		
				0.001	1.78E-06	PA-14	
				(failure)	(no consec.)		
			0.005	0.951	0.999	8.52E-06	PA-15
			(concept)	(MK)	(success)	(no consec.)	
				0.001	8.53E-09	PA-16	
				(failure)	(no consec.)		
			0.049	0.999	4.41E-07	PA-17	
			(HK)	(success)	(no consec.)		
				0.001	4.41E-10	PA-18	
				(failure)	(no consec.)		
		0.001	0.390	0.990	1.45E-05	PA-19	2.01E-10
		(selection)	(LK)	(success)	(no consec.)		
				0.010	1.47E-07	PA-20	2.06E-14
				(failure)	(no consec.)		
			0.580	0.990	2.16E-05	PA-21	4.46E-10
			(MK)	(success)	(no consec.)		
				0.010	2.18E-07	PA-22	4.55E-14
				(failure)	(no consec.)		
			0.030	0.990	1.12E-06	PA-23	1.19E-12
			(HK)	(success)	(no consec.)		
				0.010	1.13E-08	PA-24	1.22E-16
				(failure)	(criticality)		
		0.049	0.994	0.999	9.54E-05	PA-25	
		(rod)	(intended FA)	(success)	(no consec.)		
				0.001	9.55E-08	PA-26	

Figure I - PWR-A Exceeding Criticality Loading Criteria Decision Tree

				(failure)	(no conseq.)				
				0.005	0.951	0.999	4.56E-07	PA-27	
			(concept)	(MK)	(success)	(no conseq.)			
					0.001	4.57E-10	PA-28		
					(failure)	(criticality)			
				0.049	0.999	2.36E-08	PA-29		
				(HK)	(success)	(no conseq.)			
					0.001	2.36E-11	PA-30		
					(failure)	(no conseq.)			
				0.001	0.390	0.990	7.79E-07	PA-31	5.78E-13
			(selection)	(LK)	(success)	(no conseq.)			
					0.010	7.87E-09	PA-32	5.90E-17	
					(failure)	(no conseq.)			
				0.580	0.990	1.16E-06	PA-33	1.28E-12	
				(MK)	(success)	(no conseq.)			
					0.010	1.17E-08	PA-34	1.30E-16	
					(failure)	(criticality)			
				0.030	0.990	5.99E-08	PA-35	3.42E-15	
				(HK)	(success)	(no conseq.)			
					0.010	6.05E-10	PA-36	3.49E-19	
					(failure)	(criticality)			
				0.033	1.000	1.000	6.41E-05	PA-37	
			(ST)	(any FA)	(success)	(no conseq.)			
				0.580	0.995	0.994	0.990	5.68E-01	PA-38
	(plate/ST)	(intended WP)	(intended FA)	(MK)	(success)	(no conseq.)			
					0.010	5.74E-03	PA-39		
					(failure)	(no conseq.)			
				0.005	0.929	0.999	2.68E-03	PA-40	
			(concept)	(LK)	(success)	(no conseq.)			
					0.001	2.68E-06	PA-41		
					(failure)	(no conseq.)			
				0.071	0.999	2.06E-04	PA-42		
				(HK)	(success)	(no conseq.)			
					0.001	2.06E-07	PA-43		
					(failure)	(no conseq.)			
				0.001	0.390	0.990	4.68E-03	PA-44	2.09E-05
			(selection)	(LK)	(success)	(no conseq.)			
					0.010	4.73E-05	PA-45	2.13E-09	
					(failure)	(no conseq.)			
				0.580	0.990	6.96E-03	PA-46	4.61E-05	
				(MK)	(success)	(no conseq.)			
					0.010	7.03E-05	PA-47	4.71E-09	
					(failure)	(no conseq.)			
				0.030	0.990	3.60E-04	PA-48	1.23E-07	
				(HK)	(success)	(no conseq.)			
					0.010	3.64E-06	PA-49	1.26E-11	
					(failure)	(criticality)			
				0.005	0.886	0.994	0.999	2.56E-03	PA-50
	(wrong WP)	(no absorber)	(intended FA)	(success)	(no conseq.)				
					0.001	2.56E-06	PA-51		
					(failure)	(criticality)			
				0.005	0.929	0.999	1.19E-05	PA-52	

Figure I - PWR-A Exceeding Criticality Loading Criteria Decision Tree

			(concept)	(LK)	(success)	(no conseq.)			
					0.001	1.20E-08	PA-53		
					(failure)	(no conseq.)			
				0.071	0.999	9.19E-07	PA-54		
				(HK)	(success)	(no conseq.)			
					0.001	9.20E-10	PA-55		
					(failure)	(criticality)			
				0.001	0.390	0.990	2.09E-05	PA-56	4.15E-10
			(selection)	(LK)	(success)	(no conseq.)			
					0.010	2.11E-07	PA-57		4.24E-14
					(failure)	(no conseq.)			
				0.580	0.990	3.11E-05	PA-58		9.19E-10
				(MK)	(success)	(no conseq.)			
					0.010	3.14E-07	PA-59		9.37E-14
					(failure)	(criticality)			
				0.030	0.990	1.61E-06	PA-60		2.46E-12
				(HK)	(success)	(no conseq.)			
					0.010	1.62E-08	PA-61		2.51E-16
					(failure)	(criticality)			
		0.068	0.994	0.999	1.32E-04		PA-62		
		(rod)	(intended FA)	(success)	(no conseq.)				
				0.001	1.32E-07		PA-63		
				(failure)	(criticality)				
				0.005	0.929	0.999	6.18E-07	PA-64	
			(concept)	(LK)	(success)	(no conseq.)			
					0.001	6.19E-10	PA-65		
					(failure)	(criticality)			
				0.071	0.999	4.75E-08	PA-66		
				(HK)	(success)	(no conseq.)			
					0.001	4.76E-11	PA-67		
					(failure)	(no conseq.)			
				0.001	0.390	0.990	1.61E-06	PA-68	2.46E-12
			(selection)	(LK)	(success)	(no conseq.)			
					0.010	1.62E-08	PA-69		2.51E-16
					(failure)	(no conseq.)			
				0.580	0.990	2.39E-06	PA-70		5.44E-12
				(MK)	(success)	(no conseq.)			
					0.010	2.41E-08	PA-71		5.55E-16
					(failure)	(criticality)			
				0.030	0.990	1.24E-07	PA-72		1.45E-14
				(HK)	(success)	(no conseq.)			
					0.010	1.25E-09	PA-73		1.48E-18
					(failure)	(criticality)			
		0.045	1.000	1.000	1.32E-04		PA-74		
		(ST)	(any FA)	(success)	(no conseq.)				
	0.030	0.995	1.000	0.990	2.96E-02		PA-75		
	(rod)	(intended WP)	(any FA)	(success)	(no conseq.)				
				0.010	2.98E-04		PA-76		
				(failure)	(no conseq.)				
				0.005	0.402	0.994	0.999	6.00E-05	PA-77
		(wrong WP)	(no absorber)	(intended FA)	(success)	(no conseq.)			
				0.001	6.01E-08		PA-78		
				(failure)	(no conseq.)				

Figure I - PWR-A Exceeding Criticality Loading Criteria Decision Tree

		0.005	0.402	0.999	1.21E-07	PA-79	
		(concept)	(LK)	(success)	(no conseq.)		
				0.001	1.21E-10	PA-80	
				(failure)	(no conseq.)		
			0.598	0.999	1.80E-07	PA-81	
			(MK)	(success)	(no conseq.)		
				0.001	1.81E-10	PA-82	
				(failure)	(criticality)		
		0.001	1.000	0.990	1.26E-06	PA-83	1.50E-12
		(selection)	(any FA)	(success)	(no conseq.)		
				0.010	1.27E-08	PA-84	1.53E-16
				(failure)	(no conseq.)		
		0.577	0.994	0.990	8.54E-05	PA-85	
	(plate)	(intended FA)	(success)	(no conseq.)			
			0.010	8.62E-07		PA-86	
			(failure)	(no conseq.)			
		0.005	0.402	0.999	1.74E-07	PA-87	
		(concept)	(LK)	(success)	(no conseq.)		
				0.001	1.74E-10	PA-88	
				(failure)	(no conseq.)		
			0.598	0.999	2.59E-07	PA-89	
			(MK)	(success)	(no conseq.)		
				0.001	2.59E-10	PA-90	
				(failure)	(no conseq.)		
		0.001	1.000	0.990	8.59E-08	PA-91	
		(selection)	(any FA)	(success)	(no conseq.)		
				0.010	8.68E-10	PA-92	
				(failure)	(no conseq.)		
		0.021	1.000	1.000	3.10E-06	PA-93	
	(ST)	(any FA)	(success)	(no conseq.)			
		No Absorber	Plates	Rods		(Total)	
	Concept	4.41E-06	0.00E+00	1.33E-07		4.54E-06	
	Selection	5.00E-05	3.65E-06	3.77E-08		5.37E-05	
	Selection (2)	2.13E-09	1.26E-11	6.87E-16		2.15E-09	
	Total	5.44E-05	3.65E-06	1.71E-07		5.83E-05	
	Probability of Misload Leading to Exceeding Criticality Loading Criteria due to Concept Error per Waste Package		4.54E-06		Probability of Misload Leading to Exceeding Criticality Loading Criteria a No Absorber package		5.44E-05
	Probability of Misload Leading to Exceeding Criticality Loading Criteria due to Selection Error per Waste Package		5.37E-05		Probability of Misload Leading to Exceeding Criticality Loading Criteria an Absorber Plate package		3.65E-06
	Probability of Misload Leading to Exceeding Criticality Loading Criteria due to Selection (2) Error per Waste Package				Probability of Misload Leading to Exceeding Criticality Loading Criteria an Absorber Rod package		1.71E-07

Table I.  
PWR-A Decision Tree Endstate Notes

Endstate notes are provided for just the PWR-A decision tree. The other PWR cases and the BWR case decision trees are of a similar structure as PWR-A such that these endstate notes should serve as an illustrative example to permit the reader to follow and understand the decision tree event sequences for any of the decision trees in Attachments I – V.

Endstate	Endstate Notes for Case PWR-A Exceeding Criticality Loading Criteria Decision Tree
PA-1	For criticality concerns, the operator performed every task correctly. That is, one of the <i>no-absorber</i> waste packages was selected for a low reactivity fuel assembly.
PA-2	For criticality concerns, the operator performed every task correctly, except the final verification. Therefore, there is no criticality concern due to misloading, however, the fuel assembly records are likely to be corrupted.
PA-3	The operator made a conceptual error deciding which fuel assembly to load, so the decision tree is limited to only incorrect fuel assemblies (i.e., MK, HK). A mid-range criticality (MK) fuel assembly is loaded into a waste package with no absorber plates, but the error is identified and corrected through successful verification.
PA-4	The operator made a conceptual error deciding which fuel assembly to load, so the decision tree is limited to only incorrect fuel assemblies (i.e., MK, HK). A mid-range criticality (MK) fuel assembly is loaded into a waste package with no absorber plates, but the error is <b>not</b> identified or corrected through verification, creating a possible criticality concern due to misloading. No credit is given for recovery as fuel assemblies are continued to be loaded.
PA-5/PA-6	The operator made a conceptual error deciding which fuel assembly to load, so the decision tree is limited to only incorrect fuel assemblies (i.e., MK, HK). A high-range criticality (HK) fuel assembly is loaded into a waste package with no absorber plates, but since this is a conceptual selection error, the Line operator will load absorber rods into the fuel assembly prior to loading, therefore, there is no criticality concern, only an economic one, for using a waste package with absorber plates unnecessarily. If verification is not successful, the fuel assembly records are likely to be corrupted.
PA-7/PA-8	The operator makes a fuel assembly selection error. The operator can select from all of the available fuel assembly types, with any of the possible criticality ranges, including the type that was originally intended. The operator has selected a fuel assembly of the same type intended for this waste package. Therefore, with or without successful verification, there is no criticality concern due to misloading, however, without successful verification, the fuel assembly records are likely to be corrupted.
PA-9	The operator makes a fuel assembly selection error. The operator can select from all of the available fuel assembly types, with any of the possible criticality ranges, including the type that was originally intended. The operator has selected a mid-criticality (MK) fuel assembly, but the error is identified and corrected through successful verification.
PA-10	The operator makes a fuel assembly selection error. The operator can select from all of the available fuel assembly types, with any of the possible criticality ranges, including the type that was originally intended. The operator has selected a mid-criticality (MK) fuel assembly, but the error is <b>not</b> identified or corrected through verification, creating a possible criticality concern due to misloading.
PA-11	The operator makes a fuel assembly selection error. The operator can select from all of the available fuel assembly types, with any of the possible criticality ranges, including the type that was originally intended. The operator has selected a high-criticality (HK) fuel assembly, but the error is identified and corrected through successful verification.
PA-12	The operator makes a fuel assembly selection error. The operator can select from all of the available fuel assembly types, with any of the possible criticality ranges, including the type that was originally intended. The operator has selected a high-criticality (HK) fuel assembly, but the error is <b>not</b> identified or corrected through verification, creating a possible criticality concern due to misloading. Note: since this was a selection error, the operator will not place absorber rods in the fuel assembly.

Endstate	Endstate Notes for Case PWR-A Exceeding Criticality Loading Criteria Decision Tree
PA-13/PA-14	For criticality concerns, the operator has selected (via a conceptual error) the wrong waste package (a package with absorber plates). The operator selects the intended fuel assembly (low-criticality), and since this package can handle any fuel assembly in the low-criticality and mid-criticality range, there is no chance of a criticality concern. However, unless corrected through successful verification (i.e., PA-13), the fuel assembly records are likely to be corrupted and an economic impact may occur (i.e., PA-14).
PA-15/PA-16	For criticality concerns, the operator has selected (via a conceptual error) the wrong waste package (a package with absorber plates). The operator made a conceptual error deciding which fuel assembly to load, so the decision tree is limited to only incorrect fuel assemblies (i.e., MK, HK). A mid-range criticality (MK) fuel assembly is loaded into a waste package with absorber plates which would not lead to a criticality concern. However, unless corrected through successful verification (i.e., PA-15), the fuel assembly records are likely to be corrupted and an economic impact may occur (i.e., PA-16).
PA-17/PA-18	For criticality concerns, the operator has selected (via a conceptual error) the wrong waste package (a package with absorber plates). The operator made a conceptual error deciding which fuel assembly to load, so the decision tree is limited to only incorrect fuel assemblies (i.e., MK, HK). A high-range criticality (HK) fuel assembly is loaded into a waste package with absorber plates, but since this is a conceptual selection error, the Line operator will load absorber rods into the fuel assembly prior to loading, therefore, there is no criticality concern, only an economic one, for using a waste package with absorber plates unnecessarily. If verification is not successful, the fuel assembly records are likely to be corrupted.
PA-19/PA-20	For criticality concerns, the operator has selected (via a conceptual error) the wrong waste package (a package with absorber plates). The operator makes a fuel assembly selection error. The operator can select from all of the available fuel assembly types, with any of the possible criticality ranges, including the type that was originally intended (LK). The operator has selected a fuel assembly of the same type intended for this waste package. Therefore, with or without successful verification, there is no criticality concern due to misloading, however, without successful verification, the fuel assembly records are likely to be corrupted.
PA-21/PA-22	For criticality concerns, the operator has selected (via a conceptual error) the wrong waste package (a package with absorber plates). The operator makes a fuel assembly selection error. The operator can select from all of the available fuel assembly types, with any of the possible criticality ranges, including the type that was originally intended (LK). The operator has selected a fuel assembly in the mid-criticality range, for which this waste package with absorber plates is designed to handle. Therefore, with or without successful verification, there is no criticality concern due to misloading, however, without successful verification, the fuel assembly records are likely to be corrupted.
PA-23	For criticality concerns, the operator has selected (via a conceptual error) the wrong waste package (a package with absorber plates). The operator makes a fuel assembly selection error. The operator can select from all of the available fuel assembly types, with any of the possible criticality ranges, including the type that was originally intended (LK). The operator has selected a fuel assembly in the high-criticality range for an absorber plate package (possible criticality concern), but the error is identified and corrected through successful verification. Note: since this was a selection error, the operator will not place absorber rods in the fuel assembly.
PA-24	For criticality concerns, the operator has selected (via a conceptual error) the wrong waste package (a package with absorber plates). The operator makes a fuel assembly selection error. The operator can select from all of the available fuel assembly types, with any of the possible criticality ranges, including the type that was originally intended (LK). The operator has selected a fuel assembly in the high-criticality range for an absorber plate package (possible criticality concern), but the error is <b>not</b> identified or corrected through verification, creating a possible criticality concern due to misloading. Note: since this was a selection error, the operator will not place absorber rods in the fuel assembly.

Endstate	Endstate Notes for Case PWR-A Exceeding Criticality Loading Criteria Decision Tree
PA-25/PA-26	For criticality concerns, the operator has selected (via a conceptual error) the wrong waste package (a package intended for fuel assemblies with absorber rods). The operator selects the intended fuel assembly (low-criticality), and since this package can handle fuel assemblies in the low-criticality, there is no chance of a criticality concern. However, unless corrected through successful verification (i.e., PA-25), the fuel assembly records are likely to be corrupted and an economic impact may occur (i.e., PA-126).
PA-27	For criticality concerns, the operator has selected (via a conceptual error) the wrong waste package (a package intended for fuel assemblies with absorber rods). The operator made a conceptual error deciding which fuel assembly to load, so the decision tree is limited to only incorrect fuel assemblies (i.e., MK, HK). A mid-range criticality (MK) fuel assembly is loaded into a waste package with no absorber plates which could lead to a criticality concern, but the error is identified and corrected through successful verification.
PA-28	For criticality concerns, the operator has selected (via a conceptual error) the wrong waste package (a package intended for fuel assemblies with absorber rods). The operator made a conceptual error deciding which fuel assembly to load, so the decision tree is limited to only incorrect fuel assemblies (i.e., MK, HK). A mid-range criticality (MK) fuel assembly is loaded into a waste package with no absorber plates which could lead to a criticality concern, but the error is <b>not</b> identified or corrected through verification, creating a possible criticality concern due to misloading.
PA-29/PA-30	For criticality concerns, the operator has selected (via a conceptual error) the wrong waste package (a package intended for fuel assemblies with absorber rods). The operator made a conceptual error deciding which fuel assembly to load, so the decision tree is limited to only incorrect fuel assemblies (i.e., MK, HK). A high-range criticality (HK) fuel assembly is loaded into a no absorber waste package, but since this is a conceptual selection error, the Line operator will load absorber rods into the fuel assembly prior to loading, therefore, there is no criticality concern. If verification is not successful, the fuel assembly records are likely to be corrupted.
PA-31/PA-32	For criticality concerns, the operator has selected (via a conceptual error) the wrong waste package (a package intended for fuel assemblies with absorber rods). The operator makes a fuel assembly selection error. The operator can select from all of the available fuel assembly types, with any of the possible criticality ranges, including the type that was originally intended (LK). The operator has selected a fuel assembly of the same type intended for this waste package. Therefore, with or without successful verification, there is no criticality concern due to misloading, however, without successful verification, the fuel assembly records are likely to be corrupted.
PA-33	For criticality concerns, the operator has selected (via a conceptual error) the wrong waste package (a package intended for fuel assemblies with absorber rods). The operator makes a fuel assembly selection error. The operator can select from all of the available fuel assembly types, with any of the possible criticality ranges, including the type that was originally intended (LK). The operator has selected a mid-criticality (MK) fuel assembly, but the error is identified and corrected through successful verification.
PA-34	For criticality concerns, the operator has selected (via a conceptual error) the wrong waste package (a package intended for fuel assemblies with absorber rods). The operator makes a fuel assembly selection error. The operator can select from all of the available fuel assembly types, with any of the possible criticality ranges, including the type that was originally intended (LK). The operator has selected a mid-criticality (MK) fuel assembly, but the error is <b>not</b> identified or corrected through verification, creating a possible criticality concern due to misloading.
PA-35	For criticality concerns, the operator has selected (via a conceptual error) the wrong waste package (a package intended for fuel assemblies with absorber rods). The operator makes a fuel assembly selection error. The operator can select from all of the available fuel assembly types, with any of the possible criticality ranges, including the type that was originally intended (LK). The operator has selected a mid-criticality (HK) fuel assembly, but the error is identified and corrected through successful verification.

Endstate	Endstate Notes for Case PWR-A Exceeding Criticality Loading Criteria Decision Tree
PA-36	For criticality concerns, the operator has selected (via a conceptual error) the wrong waste package (a package intended for fuel assemblies with absorber rods). The operator makes a fuel assembly selection error. The operator can select from all of the available fuel assembly types, with any of the possible criticality ranges, including the type that was originally intended (LK). The operator has selected a high-criticality (HK) fuel assembly, but the error is <b>not</b> identified or corrected through verification, creating a possible criticality concern due to misloading. Note: since this was a selection error, the operator will not place absorber rods in the fuel assembly.
PA-37	For criticality concerns, the operator has selected the wrong waste package (an ST package). If anything but an ST fuel assembly is loaded into this package, the error will be always be corrected through verification. If an ST fuel assembly is loaded into this package, and verification is not successful (not shown on the decision tree), then there is still no criticality concern, however, the fuel assembly records are likely to be corrupted.
PA-38	For criticality concerns, the operator performed every task correctly. That is, one of the absorber plate waste packages was selected for a mid-range reactivity fuel assembly.
PA-39	For criticality concerns, the operator performed every task correctly, except the final verification. Therefore, there is no criticality concern due to misloading, however, the fuel assembly records are likely to be corrupted.
PA-40/PA-41	The operator made a conceptual error deciding which fuel assembly to load, so the decision tree is limited to only incorrect fuel assemblies (i.e., LK, HK). A low-range criticality (LK) fuel assembly is loaded into a waste package with absorber plates which would not lead to a criticality concern. However, unless corrected through successful verification (i.e., PA-40), the fuel assembly records are likely to be corrupted and an economic impact may occur (i.e., PA-41).
PA-42/PA-43	The operator made a conceptual error deciding which fuel assembly to load, so the decision tree is limited to only incorrect fuel assemblies (i.e., LK, HK). A high-range criticality (HK) fuel assembly is loaded into a waste package with absorber plates, but since this is a conceptual selection error, the Line operator will load absorber rods into the fuel assembly prior to loading, therefore, there is no criticality concern, only an economic one, for using a waste package with absorber plates unnecessarily. If verification is not successful, the fuel assembly records are likely to be corrupted.
PA-44/PA-45	The operator makes a fuel assembly selection error. The operator can select from all of the available fuel assembly types, with any of the possible criticality ranges, including the type that was originally intended. The operator has selected a low-criticality fuel assembly (LK). Therefore, with or without successful verification, there is no criticality concern due to misloading, however, without successful verification, the fuel assembly records are likely to be corrupted.
PA-46/PA-47	The operator makes a fuel assembly selection error. The operator can select from all of the available fuel assembly types, with any of the possible criticality ranges, including the type that was originally intended. The operator has selected a fuel assembly of the same type intended for this waste package (MK). Therefore, with or without successful verification, there is no criticality concern due to misloading, however, without successful verification, the fuel assembly records are likely to be corrupted.
PA-48	The operator makes a fuel assembly selection error. The operator can select from all of the available fuel assembly types, with any of the possible criticality ranges, including the type that was originally intended. The operator has selected a high-criticality (HK) fuel assembly, but the error is identified and corrected through successful verification.
PA-49	The operator makes a fuel assembly selection error. The operator can select from all of the available fuel assembly types, with any of the possible criticality ranges, including the type that was originally intended. The operator has selected a high-criticality (HK) fuel assembly, but the error is <b>not</b> identified or corrected through verification, creating a possible criticality concern due to misloading. Note: since this was a selection error, the operator will not place absorber rods in the fuel assembly.

Endstate	Endstate Notes for Case PWR-A Exceeding Criticality Loading Criteria Decision Tree
PA-50	For criticality concerns, the operator has selected (via a conceptual error) the wrong waste package (a package with no absorber). The operator selects the intended fuel assembly (mid-criticality) , and since this package can not handle the MK fuel assembly, there is a chance of a criticality concern, but the error is identified and corrected through successful verification.
PA-51	For criticality concerns, the operator has selected (via a conceptual error) the wrong waste package (a package with no absorber). The operator selects the intended fuel assembly (mid-criticality) , and since this package can not handle the MK fuel assembly, there is a chance of a criticality concern, but the error is <b>not</b> identified or corrected through verification, creating a possible criticality concern due to misloading.
PA-52/PA-53	For criticality concerns, the operator has selected (via a conceptual error) the wrong waste package (a package with no absorber). The operator made a conceptual error deciding which fuel assembly to load, so the decision tree is limited to only incorrect fuel assemblies (i.e., LK, HK). A low-range criticality (LK) fuel assembly is loaded into a waste package with no absorber which would not lead to a criticality concern. However, unless corrected through successful verification (i.e., PA-52), the fuel assembly records are likely to be corrupted and an economic impact may occur (i.e., PA-53).
PA-54/PA-55	For criticality concerns, the operator has selected (via a conceptual error) the wrong waste package (a package with no absorber). The operator made a conceptual error deciding which fuel assembly to load, so the decision tree is limited to only incorrect fuel assemblies (i.e., LK, HK). A high-range criticality (HK) fuel assembly is loaded into a waste package with no absorber, but since this is a conceptual selection error, the Line operator will load absorber rods into the fuel assembly prior to loading, therefore, there is no criticality concern. If verification is not successful, the fuel assembly records are likely to be corrupted.
PA-56/PA-57	For criticality concerns, the operator has selected (via a conceptual error) the wrong waste package (a package with no absorber). The operator makes a fuel assembly selection error. The operator can select from all of the available fuel assembly types, with any of the possible criticality ranges, including the type that was originally intended (MK). The operator has selected a low-criticality (LK) fuel assembly which will be place in a no absorber waste package with no criticality concerns. Therefore, with or without successful verification, there is no criticality concern due to misloading, however, without successful verification, the fuel assembly records are likely to be corrupted.
PA-58	For criticality concerns, the operator has selected (via a conceptual error) the wrong waste package (a package with no absorber). The operator makes a fuel assembly selection error. The operator can select from all of the available fuel assembly types, with any of the possible criticality ranges, including the type that was originally intended (MK). The operator has selected a mid-criticality (MK) fuel assembly, but the error is identified and corrected through successful verification.
PA-59	For criticality concerns, the operator has selected (via a conceptual error) the wrong waste package (a package with no absorber). The operator makes a fuel assembly selection error. The operator can select from all of the available fuel assembly types, with any of the possible criticality ranges, including the type that was originally intended (MK). The operator has selected a mid-criticality (MK) fuel assembly, but the error is <b>not</b> identified or corrected through verification, creating a possible criticality concern due to misloading.
PA-60	For criticality concerns, the operator has selected (via a conceptual error) the wrong waste package (a package with no absorber). The operator makes a fuel assembly selection error. The operator can select from all of the available fuel assembly types, with any of the possible criticality ranges, including the type that was originally intended (MK). The operator has selected a high-criticality (HK) fuel assembly, but the error is identified and corrected through successful verification.

Endstate	Endstate Notes for Case PWR-A Exceeding Criticality Loading Criteria Decision Tree
PA-61	For criticality concerns, the operator has selected (via a conceptual error) the wrong waste package (a package with no absorber). The operator makes a fuel assembly selection error. The operator can select from all of the available fuel assembly types, with any of the possible criticality ranges, including the type that was originally intended (MK). The operator has selected a high-criticality (HK) fuel assembly, but the error is <b>not</b> identified or corrected through verification, creating a possible criticality concern due to misloading. Note: since this was a selection error, the operator will not place absorber rods in the fuel assembly.
PA-62	For criticality concerns, the operator has selected (via a conceptual error) the wrong waste package (a package intended for fuel assemblies with absorber rods). The operator selects the intended fuel assembly (mid-criticality), and since this package can not handle the MK fuel assembly, there is a chance of a criticality concern, but the error is identified and corrected through successful verification.
PA-63	For criticality concerns, the operator has selected (via a conceptual error) the wrong waste package (a package intended for fuel assemblies with absorber rods). The operator selects the intended fuel assembly (mid-criticality), and since this package can not handle the MK fuel assembly, there is a chance of a criticality concern, but the error is <b>not</b> identified or corrected through verification, creating a possible criticality concern due to misloading.
PA-64/PA-65	For criticality concerns, the operator has selected (via a conceptual error) the wrong waste package (package intended for fuel assemblies with absorber rods). The operator made a conceptual error deciding which fuel assembly to load, so the decision tree is limited to only incorrect fuel assemblies (i.e., LK, HK). A low-range criticality (LK) fuel assembly is loaded into a waste package with no absorber which would not lead to a criticality concern. However, unless corrected through successful verification (i.e., PA-64), the fuel assembly records are likely to be corrupted and an economic impact may occur (i.e., PA-65).
PA-66/PA-67	For criticality concerns, the operator has selected (via a conceptual error) the wrong waste package (package intended for fuel assemblies with absorber rods). The operator made a conceptual error deciding which fuel assembly to load, so the decision tree is limited to only incorrect fuel assemblies (i.e., LK, HK). A high-range criticality (HK) fuel assembly is loaded into a waste package with no absorber, but since this is a conceptual selection error, the Line operator will load absorber rods into the fuel assembly prior to loading, therefore, there is no criticality concern. If verification is not successful, the fuel assembly records are likely to be corrupted.
PA-68/PA-69	For criticality concerns, the operator has selected (via a conceptual error) the wrong waste package (a package intended for fuel assemblies with absorber rods). The operator makes a fuel assembly selection error. The operator can select from all of the available fuel assembly types, with any of the possible criticality ranges, including the type that was originally intended (MK). The operator has selected a low-criticality (LK) fuel assembly which will be place in a no absorber waste package with no criticality concerns. Therefore, with or without successful verification, there is no criticality concern due to misloading, however, without successful verification, the fuel assembly records are likely to be corrupted.
PA-70	For criticality concerns, the operator has selected (via a conceptual error) the wrong waste package (package intended for fuel assemblies with absorber rods). The operator makes a fuel assembly selection error. The operator can select from all of the available fuel assembly types, with any of the possible criticality ranges, including the type that was originally intended (MK). The operator has selected a mid-criticality (MK) fuel assembly, but the error is identified and corrected through successful verification.
PA-71	For criticality concerns, the operator has selected (via a conceptual error) the wrong waste package (package intended for fuel assemblies with absorber rods). The operator makes a fuel assembly selection error. The operator can select from all of the available fuel assembly types, with any of the possible criticality ranges, including the type that was originally intended (MK). The operator has selected a mid-criticality (MK) fuel assembly, but the error is <b>not</b> identified or corrected through verification, creating a possible criticality concern due to misloading.

Endstate	Endstate Notes for Case PWR-A Exceeding Criticality Loading Criteria Decision Tree
PA-72	For criticality concerns, the operator has selected (via a conceptual error) the wrong waste package (package intended for fuel assemblies with absorber rods). The operator makes a fuel assembly selection error. The operator can select from all of the available fuel assembly types, with any of the possible criticality ranges, including the type that was originally intended (MK). The operator has selected a high-criticality (HK) fuel assembly, but the error is identified and corrected through successful verification.
PA-73	For criticality concerns, the operator has selected (via a conceptual error) the wrong waste package (package intended for fuel assemblies with absorber rods). The operator makes a fuel assembly selection error. The operator can select from all of the available fuel assembly types, with any of the possible criticality ranges, including the type that was originally intended (MK). The operator has selected a high-criticality (HK) fuel assembly, but the error is <b>not</b> identified or corrected through verification, creating a possible criticality concern due to misloading. Note: since this was a selection error, the operator will not place absorber rods in the fuel assembly.
PA-74	For criticality concerns, the operator has selected the wrong waste package (an ST package). If anything but an ST fuel assembly is loaded into this package, the error will be always be corrected through verification. If an ST fuel assembly is loaded into this package, and verification is not successful (not shown on the decision tree), then there is still no criticality concern, however, the fuel assembly records are likely to be corrupted.
PA-75	For criticality concerns, the operator performed every task correctly. That is, one of packages intended for fuel assemblies with absorber rods was selected for a high-range reactivity fuel assembly.
PA-76	For criticality concerns, the operator performed every task correctly, except the final verification. Therefore, there is no criticality concern due to misloading, however, the fuel assembly records are likely to be corrupted.
PA-77/PA-78	For criticality concerns, the operator has selected (via a conceptual error) the wrong waste package (a package with no absorber). The operator selects the intended fuel assembly (high-criticality) , and since the Line operator believes a "rod" package is being load, absorber rods will be placed into the fuel assembly. However, unless corrected through successful verification (i.e., PA-77), the fuel assembly records are likely to be corrupted (i.e., PA-78).
PA-79/PA-80	For criticality concerns, the operator has selected (via a conceptual error) the wrong waste package (a package with no absorber). The operator made a conceptual error deciding which fuel assembly to load, so the decision tree is limited to only incorrect fuel assemblies (i.e., LK, MK). A low-range criticality (LK) fuel assembly is loaded into a waste package with no absorber which would not lead to a criticality concern. However, unless corrected through successful verification (i.e., PA-78), the fuel assembly records are likely to be corrupted (i.e., PA-79).
PA-81	For criticality concerns, the operator has selected (via a conceptual error) the wrong waste package (a package with no absorber). The operator made a conceptual error deciding which fuel assembly to load, so the decision tree is limited to only incorrect fuel assemblies (i.e., LK, MK). A mid-range criticality (MK) fuel assembly is loaded into a waste package with no absorber which could lead to a criticality concern, but the error is identified and corrected through successful verification.
PA-82	For criticality concerns, the operator has selected (via a conceptual error) the wrong waste package (a package with no absorber). The operator made a conceptual error deciding which fuel assembly to load, so the decision tree is limited to only incorrect fuel assemblies (i.e., LK, MK). A mid-range criticality (MK) fuel assembly is loaded into a waste package with no absorber which could lead to a criticality concern, but the error is <b>not</b> identified or corrected through verification, creating a possible criticality concern due to misloading.

Endstate	Endstate Notes for Case PWR-A Exceeding Criticality Loading Criteria Decision Tree
PA-83/PA-84	For criticality concerns, the operator has selected (via a conceptual error) the wrong waste package (a package with no absorber). The operator makes a fuel assembly selection error. The operator can select from all of the available fuel assembly types, with any of the possible criticality ranges, including the type that was originally intended (HK). Since the Line operator believes a "rod" package is being load, absorber rods will be placed into the fuel assembly (no matter which is selected). However, unless corrected through successful verification (i.e., PA-83), the fuel assembly records are likely to be corrupted and an economic impact may occur (i.e., PA-84).
PA-85/PA-86	For criticality concerns, the operator has selected (via a conceptual error) the wrong waste package (a package with absorber plates). The operator selects the intended fuel assembly (high-criticality), and since the Line operator believes a "rod" package is being load, absorber rods will be placed into the fuel assembly. However, unless corrected through successful verification (i.e., PA-85), the fuel assembly records are likely to be corrupted (i.e., PA-86).
PA-87/PA-88	For criticality concerns, the operator has selected (via a conceptual error) the wrong waste package (a package with absorber plates). The operator made a conceptual error deciding which fuel assembly to load, so the decision tree is limited to only incorrect fuel assemblies (i.e., LK, MK). A low-range criticality (LK) fuel assembly is loaded into a waste package with absorber plates which would not lead to a criticality concern. However, unless corrected through successful verification (i.e., PA-87), the fuel assembly records are likely to be corrupted and an economic impact may occur (i.e., PA-88).
PA-89/PA-90	For criticality concerns, the operator has selected (via a conceptual error) the wrong waste package (a package with absorber plates). The operator made a conceptual error deciding which fuel assembly to load, so the decision tree is limited to only incorrect fuel assemblies (i.e., LK, MK). A mid-range criticality (MK) fuel assembly is loaded into a waste package with absorber plates which would not lead to a criticality concern. However, unless corrected through successful verification (i.e., PA-89), the fuel assembly records are likely to be corrupted and an economic impact may occur (i.e., PA-90).
PA-91/PA-92	For criticality concerns, the operator has selected (via a conceptual error) the wrong waste package (a package with absorber plates). The operator makes a fuel assembly selection error. The operator can select from all of the available fuel assembly types, with any of the possible criticality ranges, including the type that was originally intended (HK). Since the Line operator believes a "rod" package is being load, absorber rods will be placed into the fuel assembly (no matter which is selected). However, unless corrected through successful verification (i.e., PA-91), the fuel assembly records are likely to be corrupted and an economic impact may occur (i.e., PA-92).
PA-93	For criticality concerns, the operator has selected the wrong waste package (an ST package). If anything but an ST fuel assembly is loaded into this package, the error will be always be corrected through verification. If an ST fuel assembly is loaded into this package, and verification is not successful (not shown on the decision tree), then there is still no criticality concern, however, the fuel assembly records are likely to be corrupted.

ATTACHMENT II

PWR-B EXCEEDING CRITICALITY LOADING CRITERIA  
DECISION TREE

Figure II - PWR-B Exceeding Criticality Loading Criteria Decision Tree

WP Usage	Select WP	Select FA	FA Type	Verification		Endstate	
0.420	0.995	0.994		0.990	4.11E-01	PB-1	
(no absorber)	(intended WP)	(intended FA)	(LK)	(success)	(no consec.)		
				0.010	4.15E-03	PB-2	
				(failure)	(no consec.)		
		0.005	0.951	0.999	1.98E-03	PB-3	
		(concept)	(MK)	(success)	(no consec.)		
				0.001	1.99E-06	PB-4	
				(failure)	(criticality)		
			0.049	0.999	1.03E-04	PB-5	
			(HK)	(success)	(no consec.)		
				0.001	1.03E-07	PB-6	
				(failure)	(criticality)		
		0.001	0.390	0.990	3.39E-03	PB-7	
		(selection)	(LK)	(success)	(no consec.)		
				0.010	3.42E-05	PB-8	
				(failure)	(no consec.)		
			0.580	0.990	5.04E-03	PB-9	
			(MK)	(success)	(no consec.)		
				0.010	5.09E-05	PB-10	
				(failure)	(criticality)		
			0.030	0.990	2.61E-04	PB-11	
			(HK)	(success)	(no consec.)		
				0.010	2.63E-06	PB-12	
				(failure)	(criticality)		
	0.005	0.966	0.994	0.999	2.02E-03	PB-13	
	(wrong WP)	(plate)	(intended FA)	(success)	(no consec.)		
				0.001	2.02E-06	PB-14	
				(failure)	(no consec.)		
			0.005	0.951	0.999	9.65E-06	PB-15
			(concept)	(MK)	(success)	(no consec.)	
				0.001	9.66E-09	PB-16	
				(failure)	(no consec.)		
			0.049	0.999	4.99E-07	PB-17	
			(HK)	(success)	(no consec.)		
				0.001	5.00E-10	PB-18	
				(failure)	(no consec.)		
			0.001	0.390	0.990	7.84E-07	PB-19
			(selection)	(LK)	(success)	(no consec.)	
				0.010	7.92E-09	PB-20	

Figure II - PWR-B Exceeding Criticality Loading Criteria Decision Tree

						(failure)	(no conseq.)	
					0.580	0.990	1.17E-06	PB-21
					(MK)	(success)	(no conseq.)	
						0.010	1.18E-08	PB-22
						(failure)	(no conseq.)	
					0.030	0.990	6.03E-08	PB-23
					(HK)	(success)	(no conseq.)	
						0.010	6.09E-10	PB-24
						(failure)	(criticality)	
			0.034	1.000	1.000	7.26E-05		PB-25
			(ST)	(any FA)	(success)	(no conseq.)		
	0.580	0.995	0.994		0.990	5.68E-01		PB-26
	(plate)	(intended WP)	(intended FA)		(success)	(no conseq.)		
					0.010	5.74E-03		PB-27
					(failure)	(no conseq.)		
			0.005	0.929	0.999	2.68E-03		PB-28
			(concept)	(LK)	(success)	(no conseq.)		
					0.001	2.68E-06		PB-29
					(failure)	(no conseq.)		
				0.071	0.999	2.06E-04		PB-30
				(HK)	(success)	(no conseq.)		
					0.001	2.06E-07		PB-31
					(failure)	(no conseq.)		
			0.001	0.390	0.990	2.23E-04		PB-32
			(selection)	(LK)	(success)	(no conseq.)		
					0.010	2.25E-06		PB-33
					(failure)	(no conseq.)		
				0.580	0.990	3.31E-04		PB-34
				(MK)	(success)	(no conseq.)		
					0.010	3.35E-06		PB-35
					(failure)	(no conseq.)		
				0.030	0.990	1.71E-05		PB-36
				(HK)	(success)	(no conseq.)		
					0.010	1.73E-07		PB-37
					(failure)	(criticality)		
		0.005	0.955	0.994		0.999	2.77E-03	PB-38
		(wrong WP)	(no absorber)	(intended FA)	(success)	(no conseq.)		
					0.001	2.77E-06		PB-39
					(failure)	(criticality)		
				0.005	0.929	0.999	1.29E-05	PB-40
				(concept)	(LK)	(success)	(no conseq.)	
					0.001	1.29E-08		PB-41



ATTACHMENT III

PWR-C EXCEEDING CRITICALITY LOADING CRITERIA  
DECISION TREE

Figure III - PWR-C Exceeding Criticality Loading Criteria Decision Tree

WP Usage	Select WP	Select FA	FA Type	Verification		Endstate
0.390	0.995	0.994		0.990	3.82E-01	PC-1
(no absorber)	(intended WP)	(intended FA)	(LK)	(success)	(no consec.)	
				0.010	3.86E-03	PC-2
				(failure)	(no consec.)	
		0.005	0.951	0.999	1.84E-03	PC-3
		(concept)	(MK)	(success)	(no consec.)	
				0.001	1.84E-06	PC-4
				(failure)	(criticality)	
			0.049	0.999	9.53E-05	PC-5
			(HK)	(success)	(no consec.)	
				0.001	9.54E-08	PC-6
				(failure)	(criticality)	
		0.001	0.390	0.990	3.15E-03	PC-7
		(selection)	(LK)	(success)	(no consec.)	
				0.010	3.18E-05	PC-8
				(failure)	(no consec.)	
			0.580	0.990	4.68E-03	PC-9
			(MK)	(success)	(no consec.)	
				0.010	4.73E-05	PC-10
				(failure)	(criticality)	2.13E-09
			0.030	0.990	2.42E-04	PC-11
			(HK)	(success)	(no consec.)	
				0.010	2.44E-06	PC-12
				(failure)	(criticality)	5.69E-12
	0.005	0.951	0.994	0.999	1.84E-03	PC-13
	(wrong WP)	(plate)	(intended FA)	(success)	(no consec.)	
				0.001	1.85E-06	PC-14
				(failure)	(no consec.)	
		0.005	0.951	0.999	8.82E-06	PC-16
		(concept)	(MK)	(success)	(no consec.)	
				0.001	8.83E-09	PC-17
				(failure)	(no consec.)	
			0.049	0.999	4.56E-07	PC-18
			(HK)	(success)	(no consec.)	
				0.001	4.57E-10	PC-19
				(failure)	(criticality)	
		0.001	0.390	0.990	1.51E-05	PC-20
			(selection)	(LK)	(success)	(no consec.)

Figure III - PWR-C Exceeding Criticality Loading Criteria Decision Tree

					0.010	1.52E-07	PC-21	
					(failure)	(no conseq.)		
				0.580	0.990	2.24E-05	PC-22	
				(MK)	(success)	(no conseq.)		
					0.010	2.26E-07	PC-23	
					(failure)	(no conseq.)		
				0.030	0.990	1.16E-06	PC-24	
				(HK)	(success)	(no conseq.)		
					0.010	1.17E-08	PC-25	1.30E-16
					(failure)	(criticality)		
		0.049	1.000	0.990	9.51E-05		PC-26	
		(rod)	any FA	(success)	(no conseq.)			
				0.010	9.61E-07		PC-27	
					(failure)	(no conseq.)		
	0.580	0.995	0.994	0.990	5.68E-01		PC-28	
	(plate)	(intended WP)	(intended FA)	(MK)	(success)	(no conseq.)		
				0.010	5.74E-03		PC-29	
					(failure)	(no conseq.)		
			0.005	0.929	0.999	2.68E-03	PC-30	
			(concept)	(LK)	(success)	(no conseq.)		
				0.001	2.68E-06		PC-31	
					(failure)	(no. conseq.)		
				0.071	0.999	2.06E-04	PC-32	
				(HK)	(success)	(no conseq.)		
				0.001	2.06E-07		PC-33	
					(failure)	(criticality)		
		0.001	0.390	0.990	4.68E-03		PC-34	
			(selection)	(LK)	(success)	(no conseq.)		
				0.010	4.73E-05		PC-35	
					(failure)	(no conseq.)		
				0.580	0.990	6.96E-03	PC-36	
				(MK)	(success)	(no conseq.)		
				0.010	7.03E-05		PC-37	
					(failure)	(no conseq.)		
				0.030	0.990	3.60E-04	PC-38	
				(HK)	(success)	(no conseq.)		
				0.010	3.64E-06		PC-39	1.26E-11
					(failure)	(criticality)		
		0.005	0.929	0.994	0.999	2.68E-03	PC-40	
		(wrong WP)	(no absorber)	(intended FA)	(success)	(no conseq.)		
				0.001	2.68E-06		PC-41	
					(failure)	(criticality)		

Figure III - PWR-C Exceeding Criticality Loading Criteria Decision Tree

				0.005	0.929	0.999	1.25E-05	PC-42	
			(concept)	(LK)	(success)	(no conseq.)			
					0.001	1.25E-08	PC-43		
					(failure)	(no conseq.)			
				0.071	0.999	9.63E-07	PC-44		
				(HK)	(success)	(no conseq.)			
					0.001	9.64E-10	PC-45		
					(failure)	(criticality)			
				0.001	0.390	0.990	2.19E-05	PC-46	
			(selection)	(LK)	(success)	(no conseq.)			
					0.010	2.21E-07	PC-47		
					(failure)	(no conseq.)			
				0.580	0.990	3.25E-05	PC-48		
				(MK)	(success)	(no conseq.)			
					0.010	3.29E-07	PC-49	1.03E-13	
					(failure)	(criticality)			
				0.030	0.990	1.68E-06	PC-50		
				(HK)	(success)	(no conseq.)			
					0.010	1.70E-08	PC-51	2.75E-16	
					(failure)	(criticality)			
				0.071	1.000	0.990	2.05E-04	PC-52	
			(rod)	(any FA)	(success)	(no conseq.)			
					0.010	2.08E-06	PC-53		
					(failure)	(no conseq.)			
	0.030	0.995	0.994		0.990	2.94E-02	PC-54		
	(rod)	(intended WP)	(any FA)		(success)	(no conseq.)			
					0.010	2.97E-04	PC-55		
					(failure)	(no conseq.)			
		0.005	0.402	0.994	0.999	6.00E-05	PC-56		
		(wrong WP)	(no absorber)	(intended FA)	(success)	(no conseq.)			
					0.001	6.01E-08	PC-57		
					(failure)	(criticality)			
				0.005	0.402	0.999	1.21E-07	PC-58	
			(concept)	(LK)	(success)	(no conseq.)			
					0.001	1.21E-10	PC-59		
					(failure)	(no conseq.)			
				0.598	0.999	1.80E-07	PC-60		
				(MK)	(success)	(no conseq.)			
					0.001	1.81E-10	PC-61		
					(failure)	(criticality)			

Figure III - PWR-C Exceeding Criticality Loading Criteria Decision Tree

			0.001	0.390	0.990	4.90E-07	PC-62	
			(selection)	(LK)	(success)	(no conseq.)		
					0.010	4.95E-09	PC-63	
					(failure)	(no conseq.)		
				0.580	0.990	7.29E-07	PC-64	
				(MK)	(success)	(no conseq.)		
					0.010	7.36E-09	PC-65	5.16E-17
					(failure)	(criticality)		
				0.030	0.990	3.77E-08	PC-66	
				(HK)	(success)	(no conseq.)		
					0.010	3.81E-10	PC-67	1.38E-19
					(failure)	(criticality)		
		0.598	0.994	0.999	8.92E-05		PC-68	
		(plate)	(intended FA)	(success)	(no conseq.)			
				0.001	8.93E-08		PC-69	
				(failure)	(criticality)			
			0.005	0.402	0.999	1.80E-07	PC-70	
			(concept)	LK	(success)	(no conseq.)		
					0.001	1.81E-10	PC-71	
					(failure)	(no conseq.)		
				0.598	0.999	2.68E-07	PC-72	
				(MK)	(success)	(no conseq.)		
					0.001	2.69E-10	PC-73	
					(failure)	(no conseq.)		
			0.001	0.390	0.990	7.29E-07	PC-74	
			(selection)	LK	(success)	(no conseq.)		
					0.010	7.36E-09	PC-75	
					(failure)	(no conseq.)		
				0.580	0.990	1.08E-06	PC-76	
				(MK)	(success)	(no conseq.)		
					0.010	1.09E-08	PC-77	
					(failure)	(no conseq.)		
				0.030	0.990	5.61E-08	PC-78	
				(HK)	(success)	(no conseq.)		
					0.010	5.66E-10	PC-79	3.05E-19
					(failure)	(criticality)		

Figure III - PWR-C Exceeding Criticality Loading Criteria Decision Tree

	No Absorber	Plates	Rods	(Total)
Concept	4.68E-06	2.96E-07	0.00E+00	4.98E-06
Selection	5.01E-05	3.65E-06	0.00E+00	5.37E-05
Selection (2)	2.13E-09	1.26E-11	0.00E+00	2.15E-09
<b>Total</b>	<b>5.47E-05</b>	<b>3.94E-06</b>	<b>0.00E+00</b>	<b>5.87E-05</b>
Probability of Misload Leading to Exceeding Criticality Loading Criteria due to <b>Concept</b> Error per Waste Package		4.98E-06	Probability of Misload Leading to Exceeding Criticality Loading Criteria a <b>No Absorber</b> package	
Probability of Misload Leading to Exceeding Criticality Loading Criteria due to <b>Selection</b> Error per Waste Package		5.37E-05	Probability of Misload Leading to Exceeding Criticality Loading Criteria an <b>Absorber Plate</b> package	
Probability of Misload Leading to Exceeding Criticality Loading Criteria due to <b>Selection (2)</b> Error per Waste Package		2.15E-09	Probability of Misload Leading to Exceeding Criticality Loading Criteria a <b>Absorber Rod</b> package	
			0.00E+00	

ATTACHMENT IV

PWR-D EXCEEDING CRITICALITY LOADING CRITERIA  
DECISION TREE

Figure IV - PWR-D Exceeding Criticality Loading Criteria Decision Tree

WP Usage	Select WP	Select FA	FA Type	Verification		Endstate
0.420	0.995	0.994		0.990	4.11E-01	PD-1
(no absorber)	(intended WP)	(intended FA)		(success)	(no consec.)	
				0.010	4.15E-03	PD-2
				(failure)	(no consec.)	
		0.005	1.000	0.999	2.09E-03	PD-3
		(concept)	(MK)	(success)	(no consec.)	
				0.001	2.09E-06	PD-4
				(failure)	(criticality)	
		0.001	0.420	0.990	3.65E-03	PD-5
		(selection)	(LK/HK)	(success)	(no consec.)	
				0.010	3.69E-05	PD-6
				(failure)	(no consec.)	
			0.580	0.990	5.04E-03	PD-7
			(MK)	(success)	(no consec.)	
				0.010	5.09E-05	PD-8
				(failure)	(criticality)	
	0.005	0.966	0.994	0.999	2.02E-03	PD-9
	(wrong WP)	(plate)	(intended FA)	(success)	(no consec.)	
				0.001	2.02E-06	PD-10
				(failure)	(no consec.)	
		0.005	1.000	0.999	1.01E-05	PD-11
		(concept)	(MK)	(success)	(no consec.)	
				0.001	1.02E-08	PD-12
				(failure)	(no consec.)	
		0.001	0.420	0.990	8.45E-07	PD-13
		(selection)	(LK/HK)	(success)	(no consec.)	
				0.010	8.53E-09	PD-14
				(failure)	(no consec.)	
			0.580	0.990	1.17E-06	PD-15
			(MK)	(success)	(no consec.)	
				0.010	1.18E-08	PD-16
				(failure)	(no consec.)	
		0.034	1.000	1.000	7.26E-05	PD-17
		(ST)	(any FA)	(success)	(no consec.)	
0.580	0.995	0.994		0.990	5.68E-01	PD-18
(plate)	(intended WP)	(intended FA)		(success)	(no consec.)	
				0.010	5.74E-03	PD-19
				(failure)	(no consec.)	

Figure IV - PWR-D Exceeding Criticality Loading Criteria Decsion Tree

			0.005	1.000	0.999	2.88E-03		PD-20
		(concept)	(LK/HK)	(success)	(no conseq.)			
				0.001	2.89E-06			PD-21
				(failure)	(no conseq.)			
			0.001	0.580	0.990	3.31E-04		PD-22
		(selection)	(MK)	(success)	(no conseq.)			
				0.010	3.35E-06			PD-23
				(failure)	(no conseq.)			
				0.420	0.990	2.40E-04		PD-24
			(LK/HK)	(success)	(no conseq.)			
				0.010	2.42E-06			PD-25
				(failure)	(no conseq.)			
			0.005	0.955	0.994	0.999	2.77E-03	PD-26
	(wrong WP)	(no absorber)	(intended FA)	(success)	(no conseq.)			
				0.001	2.77E-06			PD-27
				(failure)	(criticality)			
				0.005	1.000	0.999	1.39E-05	PD-28
			(concept)	(LK/HK)	(success)	(no conseq.)		
				0.001	1.39E-08			PD-29
				(failure)	(no conseq.)			
				0.001	0.580	0.990	1.59E-06	PD-30
		(selection)	(MK)	(success)	(no conseq.)			
				0.010	1.61E-08			PD-31
				(failure)	(criticality)			
				0.420	0.990	1.15E-06		PD-32
			(LK/HK)	(success)	(no conseq.)			
				0.010	1.16E-08			PD-33
				(failure)	(no conseq.)			
			0.045	1.000	1.000	1.32E-04		PD-34
		(ST)	(any FA)	(success)	(no conseq.)			

Figure IV - PWR-D Exceeding Criticality Loading Criteria Decision Tree

	No Absorber	Plates	(Total)	
Concept	4.86E-06	0.00E+00	4.86E-06	(Total Concept)
Selection	5.09E-05	0.00E+00	5.09E-05	(Total Selection)
<b>Total</b>	<b>5.58E-05</b>	<b>0.00E+00</b>	<b>5.58E-05</b>	
Probability of Misload Leading to Exceeding Criticality Loading Criteria due to <b>Concept</b> Error per Waste Package		4.86E-06	Probability of Misload Leading to Exceeding Criticality Loading Criteria a <b>No Absorber</b> package 5.58E-05	
Probability of Misload Leading to Exceeding Criticality Loading Criteria due to <b>Selection</b> Error per Waste Package		5.09E-05	Probability of Misload Leading to Exceeding Criticality Loading Criteria an <b>Absorber Plate</b> package 0.00E+00	

ATTACHMENT V

BWR EXCEEDING CRITICALITY LOADING CRITERIA  
DECISION TREE

Figure V - BWR Exceeding Criticality Loading Criteria Decision Tree

WP Usage	Select WP	Select FA	FA Type	Verification		Endstate	
	0.275	0.995	0.994	0.990	2.69E-01	B-1	
(no absorber)	(intended WP)	(intended FA)	(LK)	(success)	(no conseq.)		
				0.010	2.72E-03	B-2	
				(failure)	(no conseq.)		
		0.005	0.986	0.999	1.35E-03	B-3	
		(concept)	(MK)	(success)	(no conseq.)		
				0.001	1.35E-06	B-4	
				(failure)	(criticality)		
			0.014	0.999	1.89E-05	B-5	
			(HK)	(success)	(no conseq.)		
				0.001	1.89E-08	B-6	
				(failure)	(criticality)		
		0.001	0.275	0.990	3.28E-03	B-7	
		(selection)	(LK)	(success)	(no conseq.)		
				0.010	3.31E-05	B-8	
				(failure)	(no conseq.)		
			0.715	0.990	8.52E-03	B-9	
			(MK)	(success)	(no conseq.)		
				0.010	8.61E-05	B-10	7.24E-09
				(failure)	(criticality)		
			0.010	0.990	1.19E-04	B-11	
			(HK)	(success)	(no conseq.)		
				0.010	1.20E-06	B-12	1.42E-12
				(failure)	(criticality)		
	0.005	0.986	0.994	0.999	1.35E-03	B-13	
	(wrong WP)	(plate)	(intended FA)	(success)	(no conseq.)		
				0.001	1.35E-06	B-14	
				(failure)	(no conseq.)		
		0.005	0.986	0.999	6.69E-06	B-16	
		(concept)	(MK)	(success)	(no conseq.)		
				0.001	6.70E-09	B-17	
				(failure)	(no conseq.)		
			0.014	0.999	9.36E-08	B-18	
			(HK)	(success)	(no conseq.)		
				0.001	9.37E-11	B-19	
				(failure)	(criticality)		
		0.001	0.275	0.990	1.63E-05	B-20	
		(selection)	(LK)	(success)	(no conseq.)		
				0.010	1.64E-07	B-21	
				(failure)	(no conseq.)		
			0.715	0.990	4.23E-05	B-22	
			(MK)	(success)	(no conseq.)		
				0.010	4.27E-07	B-23	
				(failure)	(no conseq.)		

Figure V - BWR Exceeding Criticality Loading Criteria Decision Tree

					0.010	0.990	5.92E-07	B-24	
					(HK)	(success)	(no conseq.)		
						0.010	5.98E-09	B-25	3.49E-17
						(failure)	(criticality)		
		0.014	1.000		0.990	1.88E-05		B-26	
		(thick plate)	any FA		(success)	(no conseq.)			
					0.010	1.90E-07		B-27	
					(failure)	(no conseq.)			
	0.715	0.995	0.994		0.990	7.00E-01		B-28	
	(plate)	(intended WP)	(intended FA)	(MK)	(success)	(no conseq.)			
					0.010	7.07E-03		B-29	
					(failure)	(no conseq.)			
			0.005	0.965	0.999	3.43E-03		B-30	
			(concept)	(LK)	(success)	(no conseq.)			
					0.001	3.43E-06		B-31	
					(failure)	(no conseq.)			
				0.035	0.999	1.25E-04		B-32	
				(HK)	(success)	(no conseq.)			
					0.001	1.25E-07		B-33	
					(failure)	(criticality)			
			0.001	0.275	0.990	8.52E-03		B-34	
			(selection)	(LK)	(success)	(no conseq.)			
					0.010	8.61E-05		B-35	
					(failure)	(no conseq.)			
				0.715	0.990	2.22E-02		B-36	
				(MK)	(success)	(no conseq.)			
					0.010	2.24E-04		B-37	
					(failure)	(no conseq.)			
				0.010	0.990	3.10E-04		B-38	
				(HK)	(success)	(no conseq.)			
					0.010	3.13E-06		B-39	9.58E-12
					(failure)	(criticality)			
		0.005	0.965	0.994	0.999	3.43E-03		B-40	
		(wrong WP)	(no absorber)	(intended FA)	(success)	(no conseq.)			
					0.001	3.44E-06		B-41	
					(failure)	(criticality)			
				0.005	0.965	0.999	1.67E-05	B-42	
			(concept)	(LK)	(success)	(no conseq.)			
					0.001	1.67E-08		B-43	
					(failure)	(no conseq.)			
				0.035	0.999	6.06E-07		B-44	
				(HK)	(success)	(no conseq.)			
					0.001	6.06E-10		B-45	
					(failure)	(criticality)			
				0.001	0.275	0.990	4.14E-05	B-46	
			(selection)	(LK)	(success)	(no conseq.)			
					0.010	4.18E-07		B-47	

Figure V - BWR Exceeding Criticality Loading Criteria Decision Tree

					(failure)	(no consec.)		
				0.715	0.990	1.08E-04	B-48	
				(MK)	(success)	(no consec.)		
					0.010	1.09E-06	B-49	1.16E-12
					(failure)	(criticality)		
				0.010	0.990	1.51E-06	B-50	
				(HK)	(success)	(no consec.)		
					0.010	1.52E-08	B-51	2.26E-16
					(failure)	(criticality)		
			0.035	1.000	0.990	1.24E-04	B-52	
		(thick plate)	(any FA)	(success)	(no consec.)			
				0.010	1.26E-06		B-53	
				(failure)	(no consec.)			
	0.010	0.995	0.994	0.990	9.79E-03		B-54	
	(thick plate)	(intended WP)	(any FA)	(success)	(no consec.)			
				0.010	9.89E-05		B-55	
				(failure)	(no consec.)			
		0.005	0.278	0.994	0.999	1.38E-05	B-56	
	(wrong WP)	(no absorber)	(intended FA)	(success)	(no consec.)			
				0.001	1.38E-08		B-57	
				(failure)	(criticality)			
			0.005	0.278	0.999	1.93E-08	B-58	
			(concept)	(LK)	(success)	(no consec.)		
					0.001	1.93E-11	B-59	
				(failure)	(no consec.)			
				0.722	0.999	5.02E-08	B-60	
				(MK)	(success)	(no consec.)		
					0.001	5.03E-11	B-61	
				(failure)	(criticality)			
			0.001	0.275	0.990	1.67E-07	B-62	
			(selection)	(LK)	(success)	(no consec.)		
					0.010	1.68E-09	B-63	
				(failure)	(no consec.)			
				0.715	0.990	4.33E-07	B-64	
				(MK)	(success)	(no consec.)		
					0.010	4.38E-09	B-65	1.87E-17
				(failure)	(criticality)			
				0.010	0.990	6.06E-09	B-66	
				(HK)	(success)	(no consec.)		
					0.010	6.12E-11	B-67	3.66E-21
				(failure)	(criticality)			
			0.722	0.994	0.999	3.59E-05	B-68	
		(plate)	(intended FA)	(success)	(no consec.)			
				0.001	3.60E-08		B-69	
				(failure)	(criticality)			



ATTACHMENT VI

DATA "TAB" FOR PWR AND BWR CASES



Table VI-2 - Input Data Used to Quantify the BWR Decision Tree

				MK & HK Only		LK & HK Only		LK & MK Only		
				Fraction	Percent	Fraction	Percent	Fraction	Percent	
Fraction of BWR fuel assemblies with low-range criticality				(LK)	0.28		0.28	96.49%	0.28	27.78%
Fraction of BWR fuel assemblies with mid-range criticality				(MK)	0.72	0.72	98.62%		0.72	72.22%
Fraction of BWR fuel assemblies with high range criticality				(HK)	0.01	0.01	1.38%		0.01	3.51%
					1.00	0.73			0.29	0.99
Fraction of BWR fuel assemblies with low- and mid-range criticality					0.99					
Fraction of BWR fuel assemblies with high-range criticality					0.01					
<b>HEPs</b>										
	HEP	Recovery	HEP w/rec.		HEP	Recovery	HEP w/rec.			
WP-correct	0.9950	—	0.9950	FA-concept	0.005	0	0.005			
WP-incorrect	0.0050	0.000	0.0050	FA-select	0.001	0	0.001			
				Total Wrong FA	0.006		0.006			
				Verification/Match	0.01					
				Verification/Match following <i>Concept</i> error	0.001					
<b>Average Coverage for Scenario C1</b>										
		Fraction	Comments			Input to spreadsheet				
44 BWR (no absorber)		0.275	LK			0.275				
44 BWR (absorber plates)		0.715	MK			0.715				
24 BWR (thick absorber plates)		0.010	HK			0.010				

ATTACHMENT VII

SELECT WP HUMAN RELIABILITY ANALYSIS

Figure VII - Human Reliability Analysis for Incorrect WP

HEP Tree to determine the probability that the incorrect WP is selected (and place below the transport port).					
<b>Human Error Probabilities</b>					
	HEP				
	WP-concept	0.005			
	WP-select	0.001			
	Verification/Match (Recovery)	0.01			
					Endstate
		0.999		9.940E-01	HEP-1
					Success
	0.995				
	Requested correct Wp		0.990	9.851E-04	HEP-2
					Success
		0.001			
Line operator requests WP	DC operator loads incorrect WP (selection error)				
			0.010	9.950E-06	HEP-3
					No recovery
					Failure
	0.005	1.000		5.000E-03	HEP-4
	Requested incorrect WP (concept error)	DC operator loads requested WP (No recovery)			Failure
				1.000000	
	Success Endstates	0.994990			
	Failure Endstates	0.005010			

## ATTACHMENT VIII

### SUMMARY OF PWR/BWR REGRESSION ANALYSIS RESULTS

Regression Analysis Summary

PWR-A					
SUMMARY OUTPUT (PWR-A No Absorber)					
<i>Regression Statistics</i>					
Multiple R	0.999650205				
R Square	0.999300532				
Adjusted R Square	0.999166019				
Standard Error	5.10145E-07				
Observations	32				
ANOVA					
	<i>df</i>	<i>SS</i>	<i>MS</i>	<i>F</i>	<i>Significance F</i>
Regression	5	9.66696E-09	1.93339E-09	7429.02623	3.87681E-40
Residual	26	6.76645E-12	2.60248E-13		
Total	31	9.67372E-09			
	<i>Coefficients</i>	<i>Standard Error</i>	<i>t Stat</i>	<i>P-value</i>	
Intercept	1.0639E-06	4.6163E-07	2.304655213	0.029426914	
LK^2	-0.00019831	1.88599E-06	-105.148964	1.01208E-35	
MK^2	7.90505E-06	1.6361E-06	4.831627975	5.24115E-05	
LK*MK	2.68078E-05	2.89161E-06	9.270895388	1.00104E-09	
LK	0.000201046	2.02907E-06	99.08300338	4.72666E-35	
MK	-5.8763E-06	1.76733E-06	-3.324958057	0.002638449	
SUMMARY OUTPUT (PWR-A Absorber Plate)					
<i>Regression Statistics</i>					
Multiple R	0.99930686				
R Square	0.9986142				
Adjusted R Square	0.998465721				
Standard Error	6.35133E-07				
Observations	32				
ANOVA					
	<i>df</i>	<i>SS</i>	<i>MS</i>	<i>F</i>	<i>Significance F</i>
Regression	3	8.13924E-09	2.71308E-09	6725.64327	4.17264E-40
Residual	28	1.1295E-11	4.03393E-13		
Total	31	8.15053E-09			
	<i>Coefficients</i>	<i>Standard Error</i>	<i>t Stat</i>	<i>P-value</i>	
Intercept	5.96767E-08	2.57934E-07	0.231364406	0.818714149	
MK^2	-0.00020824	1.75793E-06	-118.4562231	2.30866E-39	
LK*MK	-0.0002103	1.84061E-06	-114.2530158	6.3359E-39	
MK	0.000208447	1.5945E-06	130.7286647	1.46788E-40	

Regression Analysis Summary

PWR-B					
SUMMARY OUTPUT (PWR-B No Absorber)					
<i>Regression Statistics</i>					
Multiple R	0.999418363				
R Square	0.998837064				
Adjusted R Square	0.998712463				
Standard Error	1.59918E-06				
Observations	32				
ANOVA					
	<i>df</i>	<i>SS</i>	<i>MS</i>	<i>F</i>	<i>Significance F</i>
Regression	3	6.15025E-08	2.05008E-08	8016.327364	3.58451E-41
Residual	28	7.16068E-11	2.55738E-12		
Total	31	6.15741E-08			
	<i>Coefficients</i>	<i>Standard Error</i>	<i>t Stat</i>	<i>P-value</i>	
Intercept	0.000209131	8.42967E-07	248.089198	2.41548E-48	
LK*MK	0.000209584	5.27075E-06	39.76365323	3.51486E-26	
LK	-0.00020638	1.62944E-06	-126.6563106	3.55546E-40	
MK	-0.00020371	1.62043E-06	-125.7131137	4.38164E-40	
SUMMARY OUTPUT (PWR-B Absorber Plates)					
<i>Regression Statistics</i>					
Multiple R	0.999261587				
R Square	0.998523718				
Adjusted R Square	0.998365545				
Standard Error	3.1418E-08				
Observations	32				
ANOVA					
	<i>df</i>	<i>SS</i>	<i>MS</i>	<i>F</i>	<i>Significance F</i>
Regression	3	1.86941E-11	6.23136E-12	6312.856505	1.01147E-39
Residual	28	2.76385E-14	9.8709E-16		
Total	31	1.87217E-11			
	<i>Coefficients</i>	<i>Standard Error</i>	<i>t Stat</i>	<i>P-value</i>	
Intercept	5.96135E-09	1.27592E-08	0.467221202	0.643957274	
MK^2	-9.9905E-06	8.69595E-08	-114.8867762	5.42851E-39	
LK*MK	-1.0087E-05	9.10492E-08	-110.7818183	1.50032E-38	
MK	9.9895E-06	7.8875E-08	126.6496532	3.56069E-40	

Regression Analysis Summary

PWR-C					
SUMMARY OUTPUT (PWR-C No Absorber)					
<i>Regression Statistics</i>					
Multiple R	0.999772074				
R Square	0.999544201				
Adjusted R Square	0.999456547				
Standard Error	4.2079E-07				
Observations	32				
ANOVA					
	<i>df</i>	<i>SS</i>	<i>MS</i>	<i>F</i>	<i>Significance F</i>
Regression	5	1.00956E-08	2.01912E-09	11403.32856	1.4815E-42
Residual	26	4.60366E-12	1.77064E-13		
Total	31	1.01002E-08			
	<i>Coefficients</i>	<i>Standard Error</i>	<i>t Stat</i>	<i>P-value</i>	
Intercept	4.23477E-06	3.80772E-07	11.12152987	2.21671E-11	
LK^2	-0.00021378	1.55564E-06	-137.4216173	9.7277E-39	
MK^2	1.91724E-05	1.34953E-06	14.20670992	9.12663E-14	
LK*MK	1.72634E-05	2.38512E-06	7.237959439	1.09594E-07	
LK	0.000214066	1.67366E-06	127.903008	6.27172E-38	
MK	-1.8396E-05	1.45777E-06	-12.61915378	1.36342E-12	
SUMMARY OUTPUT (PWR-C Absorber Plates)					
<i>Regression Statistics</i>					
Multiple R	0.998935469				
R Square	0.997872071				
Adjusted R Square	0.997644078				
Standard Error	8.65941E-07				
Observations	32				
ANOVA					
	<i>df</i>	<i>SS</i>	<i>MS</i>	<i>F</i>	<i>Significance F</i>
Regression	3	9.84583E-09	3.28194E-09	4376.777038	1.68986E-37
Residual	28	2.09959E-11	7.49854E-13		
Total	31	9.86683E-09			
	<i>Coefficients</i>	<i>Standard Error</i>	<i>t Stat</i>	<i>P-value</i>	
Intercept	4.35403E-07	3.51667E-07	1.238111409	0.225955783	
MK^2	-0.00022734	2.39677E-06	-94.85225996	1.14577E-36	
LK*MK	-0.00023353	2.50949E-06	-93.05982373	1.95156E-36	
MK	0.000227933	2.17395E-06	104.847212	6.98478E-38	



## Regression Analysis Summary

SUMMARY OUTPUT (BWR - Absorber Plate)					
<i>Regression Statistics</i>					
Multiple R	0.966217217				
R Square	0.93357571				
Adjusted R Square	0.922504995				
Standard Error	1.0773E-05				
Observations	22				
<i>ANOVA</i>					
	<i>df</i>	<i>SS</i>	<i>MS</i>	<i>F</i>	<i>Significance F</i>
Regression	3	2.93608E-08	9.78695E-09	84.32840247	8.60167E-11
Residual	18	2.08904E-09	1.16058E-10		
Total	21	3.14499E-08			
<i>Coefficients</i>					
	<i>Coefficients</i>	<i>Standard Error</i>	<i>t Stat</i>	<i>P-value</i>	
Intercept	5.17856E-06	4.16906E-06	1.242141436	0.230125339	
MK^2	-0.000350922	3.21615E-05	-10.91126168	2.29615E-09	
MK	0.000393047	2.99991E-05	13.1019297	1.21154E-10	
LK*MK	-0.000475537	3.44806E-05	-13.79144363	5.21109E-11	