OFFICE OF CIVILIAN RADIOACTIVE WASTE MANAGEMENT
CALCULATION COVER SHEET

2. Calculation Title Enrico Fermi Fast Reactor Spent Nuclear Fuel Criticality Calculations: Degraded Mode			
3. Document Identifier (including Revision Number) CAL-EDC-NU-000001 REV 00			
4. Total Attachments 5	5. Attachment Numbers – Number of pages in each I-1, II-1, III-1, IV-18, V-Compact Disk		
	Print Name	Signature	Date
6. Originator	Dionisie R. Moscalu (except Sections 5.3.1.3, 5.3.2, 6.1.3 and 6.2)	Dionisie R. Moscalu	07/19/00
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9. Remarks			

Revision History

10. Revision No.	11. Description of Revision
00	Initial issue

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1. PURPOSE

The objective of this calculation is to characterize the nuclear criticality safety concerns associated with the codisposal of the Department of Energy's (DOE) Enrico Fermi (EF) Spent Nuclear Fuel (SNF) in a 5-Defense High-Level Waste (5-DHLW) Waste Package (WP) and placed in a Monitored Geologic Repository (MGR). The scope of this calculation is limited to the determination of the effective neutron multiplication factor (k_{eff}) for the degraded mode internal configurations of the codisposal WP. The results of this calculation and those of Ref. 8 will be used to evaluate criticality issues and support the analysis that will be performed to demonstrate the viability of the codisposal concept for the Monitored Geologic Repository.

This calculation is associated with the waste package design and was performed in accordance with the *DOE SNF Analysis Plan for FY 2000* (See Ref. 22). The document has been prepared in accordance with the Administrative Procedure AP-3.12Q, Revision 0, ICN 2, *Calculations* (Ref. 26).

2. METHOD

The calculation method uses MCNP Version 4B2 computer code (Ref. 4) to calculate the effective neutron multiplication factor for various configurations of the degraded internal components of WP. With regard to the development of this calculation, the control of the electronic management of data was evaluated in accordance with AP-SV.1Q, *Control of the Electronic Management of Data* (Ref. 27). The evaluation (Ref. 32) determined that current work process and procedures are adequate for the control of the electronic management of data for this activity.

3. ASSUMPTIONS

3.1 It is assumed that the intact fuel pin is a right cylinder. The rationale for this assumption is that swaging the ends of a fuel pin does not change the mass of the fuel or its cladding (Ref. 6, Section 3.3). This assumption is used in Section 5.1.2 and 5.3.

3.2 It is assumed that the impurities in the fuel matrix (B, C, Cr, Fe, Ni, O, Zr, Cu, and other), Ref. 6, Section 3.3.4), are replaced with molybdenum (Mo) in the intact pin scenarios. The rationale for this assumption is that the replacement makes the calculations more conservative (resulting in higher k_{eff} values), as the majority of the elements present in the impurities have higher thermal absorption cross sections than Mo. This assumption is used in Section 5.1.2 and 5.3.

3.3 It is assumed that, for the intact pin arrays, the pins are modeled as a fuel matrix that is 61.0 in. (154.94 cm) in length, which is twice the length of a single fuel matrix. The rationale for this assumption is that the pins are stored as two axial matrices, thus evaluating these pins as a matrix that is twice as long as a single matrix is conservative and causes the greatest neutronic interaction. This assumption is used in Section 5.3.

3.4 Components resulting from the degradation of the DOE SNF canister shell and DOE SNF canister internals other than the fuel pins, the pin cladding, the iron shot, the aluminum, and the gadolinium are neglected. The rationale for this assumption is that is it conservative since these components are neutron absorbers, and, hence, their absence provides a conservative (higher) value for the k_{eff} of the system. This assumption is used in Section 5.3.

3.5 For the degraded configuration with intact pins surrounded by WP internals, the fuel pins are assumed to be stacked at the bottom of the waste package in a regular array rather than randomly. The rationale for this assumption is that it is conservative since it allows the moderation to be optimal. This assumption is used in Section 5.3.

3.6 It is assumed that waste package is surrounded by a water reflector with a thickness of 30 cm. This is based on the established fact among the nuclear criticality safety community that 30 cm is an effectively infinite thickness for water reflectors (Ref. 12, p. 27). This assumption is used in Section 5.3.

3.7 It is assumed that iron shot (Fe) and the aluminum present in the DOE SNF 18-inch canister degrade (oxidize) and produce FeOOH (goethite) and AlOOH (diaspore), respectively. The rationale for this assumption is that the choice of FeOOH, as the oxidation product of Fe, over Fe_2O_3 (hematite) makes the calculations more conservative (resulting in higher k_{eff} values), as the hydrogen present in FeOOH acts as neutron moderator. This assumption is used in Section 5.3.

3.8 It is assumed that the Mo can be ignored as a fuel component in the configurations with fully degraded pins. The rationale for this assumption is that Mo has a small neutronic absorption cross section (2.5 barn, Ref. 17), and it is therefore conservative to ignore this constituent when is replaced with moderator. This assumption is used in Section 5 for all scenarios evaluating degraded fuel matrices.

3.9 The fissile plutonium isotopes present in the pre-breach clay are neglected in the moderation ratio calculation. The rationale for this assumption is that the fissioning and moderation in the pre-breach clay have little influence on the k_{eff}. It acts as a reflector. This assumption is used in Section 5.3.

3.10 Beginning-of-life (BOL) pre-irradiation fuel composition is used for all calculations. The rationale for this assumption is that it is conservative to assume unirradiated fuel since it is more neutronically reactive than spent fuel. This assumption is used in Section 5.3.

3.11 Ba-138 cross section is used instead of Ba-137 cross section in the MCNP input since the cross section of Ba-137 is not available in either ENDF/B-V or ENDF/B-VI cross section libraries. The rationale for this assumption is that it is conservative since the thermal neutron capture cross section and the resonance integral of Ba-137 (5.1 and 4.0 barn, respectively, Ref. 17) are greater than the thermal neutron capture cross section and the resonance integral of Ba-138 (0.48 and 0.3 barn, respectively, Ref. 17). This assumption is used in Section 5.3.

3.12 Aluminum cross section is used instead of zinc cross section in the MCNP input since the cross section of zinc is not available in either ENDF/B-V or ENDF/B-VI cross section libraries. The rationale for this assumption is that it is conservative since the thermal neutron capture cross section and the resonance integral of zinc (1.1 and 2.8 barn, respectively, Ref. 17) are greater than the thermal neutron capture cross section and the resonance integral of aluminum (0.23 and 0.17 barn, respectively, Ref. 17). This assumption is used in Section 5.3.

3.13 The technical information related to spent nuclear fuel (Refs. 6, 7, and 21) is only used to determine the bounding values and identify items that are important to criticality control for this fuel group by establishing the limits based on the representative fuel type (Enrico Fermi) for this group (U-Zr and U-Mo [HEU] fuel). The technical information used establishes the bounds for acceptance. The rationale for this assumption is that it was designated by the DOE SNF grouping in support of criticality calculations (Refs. 31 and 6). The burden is placed on the custodian of the SNF to demonstrate that SNF characteristics identified as important to criticality control in this calculation are not exceeded before acceptance of SNF at the repository. This assumption is used in Section 5.

4. USE OF COMPUTER SOFTWARE AND MODELS

4.1 SOFTWARE

4.1.1 MCNP4B2

The MCNP code was used to calculate k_{eff} values. The software specifications are as follow:

- Software name: MCNP
- Software version/revision number: Version 4B2
- Software tracking number: 30033 V4B2LV
- Computer type: Hewlett Packard (HP) 9000 Series Workstations
- Computer processing unit number: Software is installed on the Civilian Radioactive Waste Management System (CRWMS) Management and Operating (M&O) workstation “bloom” whose CRWMS M&O Tag number is 700887

The input and output files for the various MCNP calculations are documented in Section 8, Attachments IV and V. The calculation files described in Sections 5 and 6 are such that an independent repetition of the software use may be performed. The MCNP software used was: (a) appropriate for the application of commercial SNF k_{eff} calculations, (b) used only within the range of validation as documented in Ref. 4, and (c) obtained from the Software Configuration Manager in accordance with appropriate procedures.

4.2 SOFTWARE ROUTINES

4.2.1 Excel

The commercially acquired Excel 97 spreadsheet program was used to generate some of the input data for the MCNP computer code. The software specifications are as follows:

- Software name: Excel
- Software version/revision number: 97
- Computer type: Personal Computer (PC), CRWMS M&O Tag number: 112369

Files containing the spreadsheets and graphical representations are included as part of the electronic data on a compact disk (CD) (Attachment V). The names and locations of the electronic copies of the spreadsheet files are provided in Section 8, Attachment IV. The information provided on the CD (Attachment V) meets the requirements of Sections 5.1 and 5.1.1.2 of AP-SI.1Q, *Software Management* (Ref. 28).

4.3 MODELS

None used.

5. CALCULATION

This section describes the calculations performed to evaluate k_{eff} of the 5-DHLW/DOE SNF codisposal waste package assembly containing Enrico Fermi SNF. The criticality evaluations are performed for the WP internal degraded configurations that can result during degradation process.

The description of the Enrico Fermi SNF is from Ref. 6. All fuel-related information is from this reference unless otherwise noted.

Compositions for structural and other non-fuel-related materials are from standard handbooks, and, due to the nature of these sources, these data are established facts and are therefore considered as accepted data.

The Savannah River Site (SRS) HLW glass composition is from Ref. 2, and the glass density is from Ref. 3. These data are unqualified.

Avogadro's number is from Ref. 17 and atomic weights are from Ref. 17 and Ref. 18; these data are established facts and are therefore considered as accepted data due to the nature of the references cited therein.

This calculation is based in part on unqualified data. The unqualified data related to spent nuclear fuel is only used to determine the bounding values and identify items that are important to criticality control for this fuel group by establishing the limits based on the representative fuel type (Enrico Fermi) for this group (U-Zr and U-Mo [HEU] fuel). Hence, the input values used for evaluation of codisposal viability of the U-Zr and U-Mo (Enrico Fermi) SNF do not constitute data that have to be qualified in this application. They only establish the bounds for acceptance. Since the input values are not relied upon directly to address safety and waste isolation issues and since the design inputs do not affect a system characteristic that is critical for satisfactory performance, according to the governing procedure (AP-3.15Q, *Managing Technical Product Inputs*, Ref. 29), the data do not need to be controlled as TBV (to be verified). The SRS HLW glass composition has not been finalized and are therefore controlled with TBV. Although the geochemical results have been shown to be relatively insensitive to the range of probable compositions (Ref. 25), the glass compositions and calculated degraded compositions must be demonstrated bounding in the future.

The number of digits in the values cited herein may include rounding or may reflect the input from another source; consequently, the number of digits should not be interpreted as an indication of accuracy.

Figure 5-1 shows the main components of a typical 5-DHLW/DOE SNF WP configuration. Attachment II provides a sketch of the 5-DHLW/DOE SNF disposal container utilized for the codisposal of the EF SNF. For the criticality evaluations within this calculation, the DOE SNF canister (the canister at the center of the WP [Figure 5-1]) contains Enrico Fermi SNF and the surrounding 5 canisters contain SRS HLW glass.

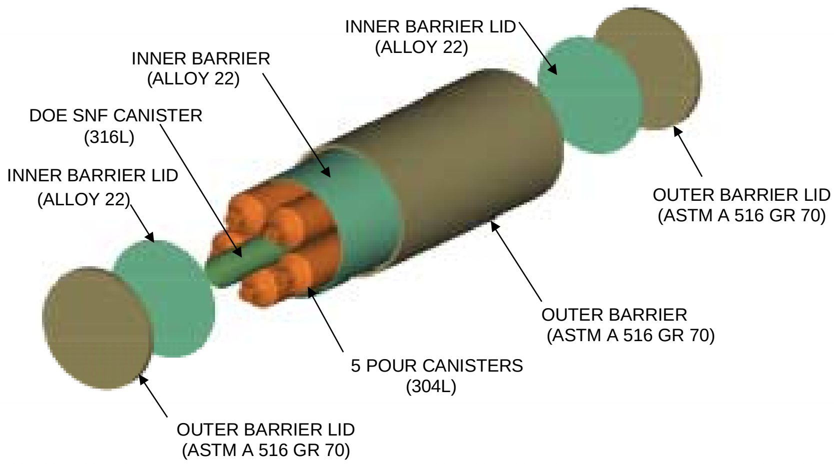

Figure 5-1. 5-DHLW/DOE SNF WP Design

Attachment III provides a sketch of the 18-inch-outer-diameter (OD) DOE standardized SNF canister, referred to as the DOE SNF 18-inch canisters. The short DOE SNF canister, with an internal length of 2575 mm and an external length of 2999 mm, is used for the codisposal of EF SNF.

The DOE SNF 18-inch canister (Attachment III) accommodates a stack of two sets of 4-inch-OD pipes. Twelve pipes, welded to a base plate, comprise each set. A spacer at the end of the second pipe set holds the stacked set of pipes in place. A shipping canister made of aluminum and referred to as the –01 canister (Ref. 6, p. 6) is contained in each pipe. Each –01 canister contains a second aluminum canister, referred to as the –04 canister (Ref. 6, p. 6). The –04 canister contains 140 SNF pins from the Enrico Fermi fast reactor core. The fuel pins have zirconium cladding and are derodded. The void space outside the pipes is filled with a mixture of iron shot and gadolinium phosphate (Fe-$GdPO_4$). One percent, by volume, of the Fe-$GdPO_4$ mixture is $GdPO_4$. The void space inside each pipe, but outside the –01 canister, is filled with the same mixture of Fe-$GdPO_4$.

5.1 ENRICO FERMI FAST REACTOR FUEL CHARACTERISTICS

The dimensions and composition of a typical fuel pin and its cladding are provided in this section, as given in Ref. 6. The weight percent of each element or isotope in the fuel and the density of the fuel are calculated in Ref. 6.

5.1.1 Fuel Pin Dimensions

The zirconium-clad fuel pins are 30.5 in. (77.47 cm) long (fuel matrix length). The diameter of the fuel matrix is 0.148 in. (0.37592 cm), and the outer diameter of the cladding is 0.158 in. (0.40132 cm). There is no gap between the fuel and the cladding.

5.1.2 Fuel Pin Composition and Density

Table 5-1 shows the composition of an Enrico Fermi fast reactor fuel pin. The composition of the fuel (U-Mo alloy) is that of fresh (non-irradiated) fuel.

Table 5-1. Composition of an Enrico Fermi Fast Reactor Fuel Pin (fresh fuel)

Element/Isotope/Impurities	Mass (g)	Weight Percent in Fuel Pin (no cladding)	Note
U (U-238 & U-235)	133.9		25.69% U-235 enriched
U-235	34.4	22.96	
U-238	99.5	66.41	
Mo	15.31	10.63	Impurities were added to Mo mass for conservatism
Impurities	0.609		
Total (U+Mo +Impurities)	149.819		
Zr Cladding	9.2		

Source: Ref. 6.

The following calculations provide the density of a fuel pin (with no cladding):

Fuel pin radius: $R = (0.148 \text{ in.}) \cdot (2.54 \text{ cm/1 in.})/2 = 0.18796 \text{ cm}$
Fuel pin length: $H = (30.5 \text{ in.}) \cdot (2.54 \text{ cm/1 in.}) = 77.47 \text{ cm}$
Fuel pin volume: $V = \pi R^2 H = \pi \cdot (0.18796 \text{ cm})^2 \cdot (77.47 \text{ cm}) = 8.598 \text{ cm}^3$
Fuel pin density: $\rho = (\text{fuel pin mass})/(\text{fuel pin volume})$
$= (149.819 \text{ g})/(8.598 \text{ cm}^3) = 17.424 \text{ g/cm}^3$

5.2 COMPOSITIONS AND DENSITIES OF NON-FUEL MATERIALS

Tables 5-2 through 5-7 show the composition of the non-fuel materials present in the 5-DHLW WP used for the codisposal of Enrico Fermi SNF. A value of 6.5 g/cm^3 was used as the density of zirconium (the fuel cladding material) (Ref. 6).

Table 5-2. Chemical Composition of Aluminum 6061

Element	Weight Percent	Value Used
Si	0.4 - 0.8	0.6
Fe	0.7	0.7
Cu	0.15 - 0.4	0.275
Mn	0.15	0.15
Mg	0.8 - 1.2	1.0
Cr	0.04 - 0.35	0.195
Zn[a]	0.25	0.25[a]
Ti	0.15	0.15
Others[b]	0.15	0.15[b]
Al	Balance	96.93[c]
Density = 2.70 g/cm^3 (Ref. 14, p. 945 and Ref. 5, p. 7)		

Source: Ref. 15, p. 373, Table 1.

NOTES: [a] Replaced by Al in the input for the MCNP computer code (MCNP cross-section library does not contain Zn).
[b] Replaced by Al.
[c] Value includes Zn and others.

Table 5-3. Chemical Composition of Type 316L Stainless Steel

Element	Weight Percent	Value Used
C	0.03 (max)	0.03
Mn	2.00 (max)	2.00
P	0.045 (max)	0.045
S	0.03 (max)	0.03
Si	1.00 (max)	1.00
Cr	16.00 - 18.00	17.00
Ni	10.00 - 14.00	12.00
Mo	2.00 - 3.00	2.50
N	0.10 (max)	0.10
Fe	Balance	65.295
Density = 7.98 g/cm^3 (Ref. 5, p. 7)		

Source: Ref. 9, p. 2, Table 1 and Ref. 10, p. 2, Table 1.

Table 5-4. Chemical Composition of Type 304L Stainless Steel

Element	Weight Percent	Value Used
C	0.03 (max)	0.03
Mn	2.00 (max)	2.00
P	0.045 (max)	0.045
S	0.03 (max)	0.03
Si	0.75 (max)	0.75
Cr	18.00 - 20.00	19.00
Ni	8.00 - 12.00	10.00
N	0.10 (max)	0.10
Fe	Balance	68.045
Density = 7.94 g/cm^3 (Ref. 5, p. 7)		

Source: Ref. 10, p. 2, Table 1.

Table 5-5. Chemical Composition of HLW Glass

Element/Isotope	Weight Percent	Element/Isotope	Weight Percent
Li-6	9.5955E-02	Li-7	1.3804E+00
B-10	5.9176E-01	B-11	2.6189E+00
O	4.4770E+01	F	3.1852E-02
Na	8.6284E+00	Mg	8.2475E-01
Al	2.3318E+00	Si	2.1888E+01
S	1.2945E-01	K	2.9887E+00
Ca	6.6188E-01	Ti	5.9676E-01
Mn	1.5577E+00	Fe	7.3907E+00
Ni	7.3490E-01	P	1.4059E-02
Cr	8.2567E-02	Cu	1.5264E-01
Ag	5.0282E-02	Ba-137[a]	1.1267E-01
Pb	6.0961E-02	Cl	1.1591E-01
Th-232	1.8559E-01	Cs-133	4.0948E-02
Cs-135	5.1615E-03	U-234	3.2794E-04
U-236	1.0415E-03	Zn[b]	6.4636E-02[b]
U-235	4.3514E-03	U-238	1.8666E+00
Pu-238	5.1819E-03	Pu-239	1.2412E-02
Pu-240	2.2773E-03	Pu-241	9.6857E-04
Pu-242	1.9168E-04		
Density at 25°C = 2.85 g/cm^3 (Ref. 3, p. 2.2.1.1-4)			

Source: Ref. 2, p. 7.

NOTES: [a] Ba-138 was used in the input data for the MCNP computer code (MCNP cross-section library does not contain Ba-137).
[b] Replaced by Al in the input data for the MCNP computer code (MCNP cross-section library does not contain Zn).

Table 5-6. Chemical Composition of Alloy 22

Element	Weight Percent	Value Used
C	0.015 (max)	0.015
Mn	0.50 (max)	0.50
Si	0.08 (max)	0.08
Cr	20.0 - 22.5	21.25
Mo	12.5 - 14.5	13.50
Co	2.50 (max)	2.50
W	2.5 - 3.5	3.00
V	0.35 (max)	0.35
Fe	2.0 - 6.0	4.00
P	0.02 (max)	0.02
S	0.02 (max)	0.020
Ni	Balance	54.765
Density = 8.69 g/cm^3		

Source: Ref. 1, p. 2.

Table 5-7. Chemical Composition of ASTM A 516 Grade 70

Element	Weight Percent Range	Value Used
C	0.30 (max)	0.30
Mn	0.85 - 1.20	1.025
P	0.035 (max)	0.035
S	0.035 (max)	0.035
Si	0.15 - 0.40	0.275
Fe	Balance	98.33
Density = 7.85 g/cm^3 (Ref. 11, p. 8)		

Source: Ref. 16, p. 2, Table 1.

Table 5-8 lists the chemical composition of the clayey material resulting after the degradation of all materials outside the DOE SNF canister. It is based on geochemistry calculations (Ref. 7 and corresponding EQ3/6 output files in Ref. 24) and will be simply referred to as clay throughout this document.

Table 5-8. Chemical Composition of Clayey Material, Everything Outside of DOE SNF Canister Degraded[a]

Element/Isotope	Weight Percent	Element/Isotope	Weight Percent
Ag	2.8009E-02	Na	4.4492E-02
Al	1.4213E+00	Ni	1.6971E+00
Ba-137	6.8590E-02	O	3.8704E+01
Ca	3.9011E-01	P	1.6405E-02
Cl	9.2057E-03	Pb	3.7193E-02
Cr	3.5428E-02	Pu-238	1.8638E-03
Cu	7.8954E-02	Pu-239	4.4832E-03
F	3.3558E-03	Pu-240	8.2600E-04
Fe	4.1248E+01	Pu-241	3.5278E-04
H	2.6893E-01	Pu-242	7.0105E-05
K	7.2980E-02	Si	1.3588E+01
Mg	2.5328E-01	Th-232	1.1293E-01
Mn	1.5492E+00	Ti	3.6452E-01

Source: Attachment V, spreadsheet: “clayey material pre breach.xls”.

NOTE: [a] Degraded material at 5000 years just prior to breach of DOE SNF Canister – minerals only.

Degradation of the DOE canister internals (iron shot, 4-inch pipes and aluminum canisters) will produce goethite (FeOOH) and diaspore (AlOOH). The density of goethite used in calculations is 4.264 g/cm^3 (Ref. 13, p. 240) and the density of diaspore is 3.38 g/cm^3 (Ref. 13, p. 172).

5.3 NUCLEAR CRITICALITY CALCULATIONS

Nuclear criticality evaluations of the Enrico Fermi SNF, codisposed in a 5-DHLW/DOE SNF WP, are performed for degraded “mode” of the DOE SNF 18-inch canister contained in the WP. The Enrico Fermi fuel pins contained within and the WP contents outside of the DOE SNF 18-inch SNF canister are considered to be either intact or degraded in some combination in all cases considered in this calculation. As part of the analysis for degraded mode configurations, parametric studies have been performed to determine the optimum moderation and configurations. The cases considered for the degraded mode configurations and their associated MCNP computer code representations are discussed in Sections 5.3.1 and 5.3.2. Ref. 17 and 18 were used as a source for the nuclear data required to calculate number densities of the materials present in each configuration. The number densities used throughout Section 5 and 6 are calculated using the following equation:

$$N = (m/V) \cdot N_A / M$$

where

N = the number density in atoms/cm^3
m = mass in grams
V = the volume in cm^3
N_A = the Avogadro’s number (0.6022 E+24 atoms/mole, Ref. 17, p. 59)
M = the atomic mass in grams per mole

The volumes of cylinder segments (volume = area of the segment of a circle x length of the cylinder) are also calculated throughout the spreadsheets in Attachment V. The equation for the area of the segment of a circle is shown below:

$$A = \left(R^2 \cdot \cos^{-1}\left(\frac{R-h}{R}\right) - (R-h)\sqrt{2Rh - h^2} \right)$$

where

A = area of the segment of a circle
R = the radius of the circle
h = the height of the segment of a circle

The developed spreadsheets containing all supporting calculations are included in electronic format in Attachment V.

5.3.1 Degraded Mode Configurations with Fissile Material Retained in the DOE SNF Canister

For the degraded mode, the contents of the DOE SNF 18-inch canister are evaluated in a combination of various intact and degraded configurations. Simplifying assumptions were made in the scenario development of the cases, in an attempt to envelop the most reactive scenarios in the most efficient manner. Guidelines taken from Ref. 20 have been directly used in constructing the degraded mode configurations that have potential for criticality.

5.3.1.1 DOE SNF Canister Containing Intact Fuel Pins Dispersed in the Degradation Products from Canister Internals

A degradation scenario that assumes the degradation of DOE SNF canister internal constituents before the fuel pins will result in a group of configurations that are similar to those included in class 1 from (Ref. 30, p. 3-8) or more precisely to refinement IP-3-A described in Ref. 20, p. 31. The configurations are characterized by the presence of the intact fuel pins dispersed in a mixture of corrosion products resulting from degradation of the 4-inch pipes, aluminum canisters, and iron shot contained in the DOE SNF canister.

For the purpose of the present evaluation, a set of possible variations of the above class of configurations has been investigated. The set comprises the fuel pins dispersed in a mass of goethite and diaspore. The pins are conservatively assumed arranged in a square lattice with constant pitch (distance between the center of two adjacent pins). The shape of the array of pins considered was rectangular or cylindrical. The DOE SNF canister shell is assumed intact and the degradation products are interspersed with the fuel pins within DOE SNF canister. The DOE SNF canister shell is placed at the bottom of a layer of pre-breach clay. Figure 5-2 presents a typical transversal cross-sectional view of the WP and Figure 5-3 includes the corresponding longitudinal cross section.

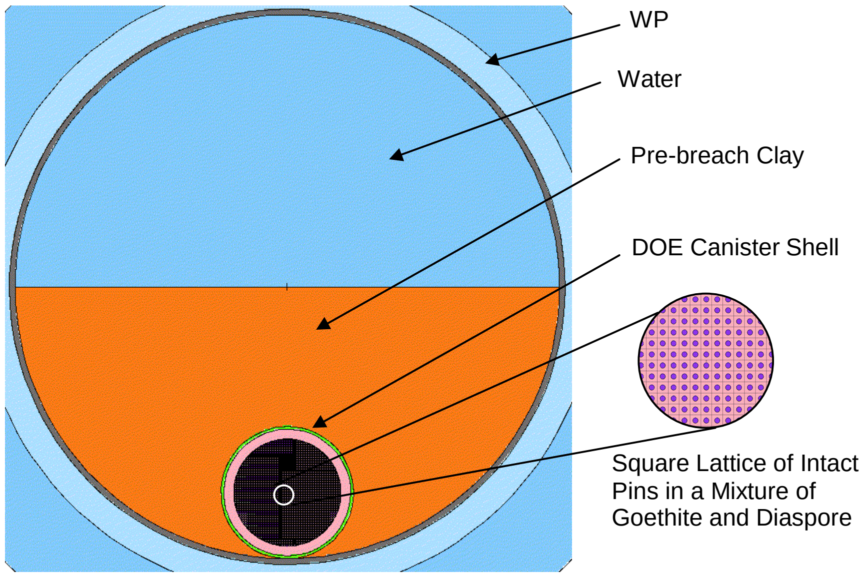

Figure 5-2. Transverse Cross-sectional View of the Degraded WP Configuration with Intact Fuel Pins Dispersed in the DOE SNF Canister Shell

The first MCNP representation considers a uniform mixture of goethite and diaspore distributed in the DOE SNF canister shell. Subsequent calculations proved that the cases, which include the diaspore only in the fuel region, are more conservative than others because the aluminum displaces the iron, which has a higher absorption cross section.

The influence of the lattice pitch variation has been assessed, and the most reactive configurations were used for calculating the necessary amount of neutron absorber to keep k_{eff} below the criticality limit of 0.93. The neutron absorber (gadolinium phosphate) was dispersed uniformly in the mixture that fills the entire volume of the DOE SNF canister shell.

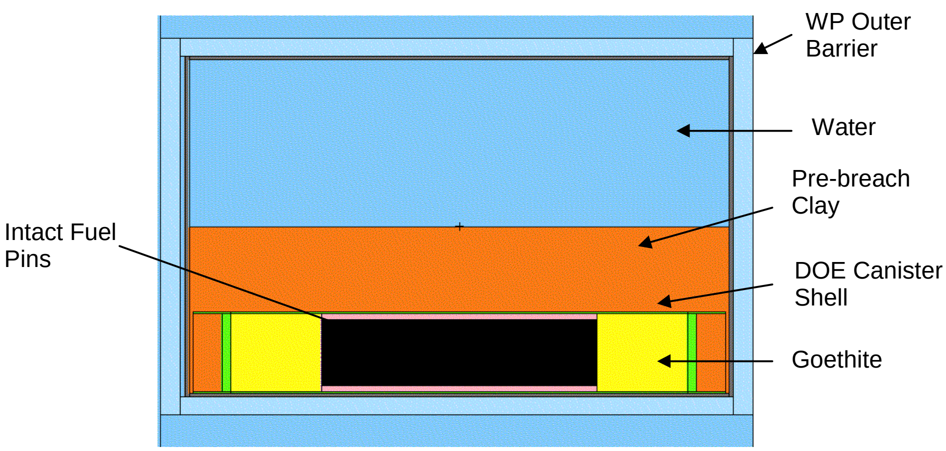

Figure 5-3. Longitudinal Cross-sectional View of the Degraded WP Configuration with Intact Fuel Pins Dispersed in the DOE SNF Canister Shell

Variations of the base configuration, including various positions of DOE SNF canister inside WP and various degrees of degradation of the WP, have been considered. Finally, the role of the fissile loading and of the reflective boundary condition have also been investigated for the representative cases. The quantity of neutron absorber necessary to keep these bounding configurations below the criticality limit was also evaluated. The supporting calculations for the input data used for constructing the MCNP input files are described in the spreadsheet “Intact fuel pins in degraded DOE SNF canister.xls” (Attachment V).

5.3.1.2 Degraded Fuel in the Intact WP

A rapid degradation of the metallic fuel (possible only if the fuel pins have initial penetration of the Zr cladding due to mechanical actions) can result in a class of configurations characterized by the presence of a degraded fuel mixture inside the 4-inch pipes. The rest of the waste package internals are considered non-degraded. This configuration is described by class 6 of degraded configurations in Ref. 30, p. 3-10 and is a result of a type IP-1 scenario (Ref. 30). The configuration is also represented by refinement IP-1-A from Ref. 20, p. 27.

The typical configuration is depicted in Figures 5-4 and 5-5. The fuel is completely degraded to uranium dioxide (other fuel constituents are neglected) and is mixed with the degraded constituents that were present inside the 4-inch pipes. The rest of the waste package internals are considered intact. The first MCNP model of the configuration is very conservative with respect to the calculation of the effective neutron multiplication factor.

For an initial set of cases, the presence of the goethite inside the 4-inch pipes was neglected. The aluminum was fully degraded to diaspore, and the remaining space in the 4-inch pipe filled with water.

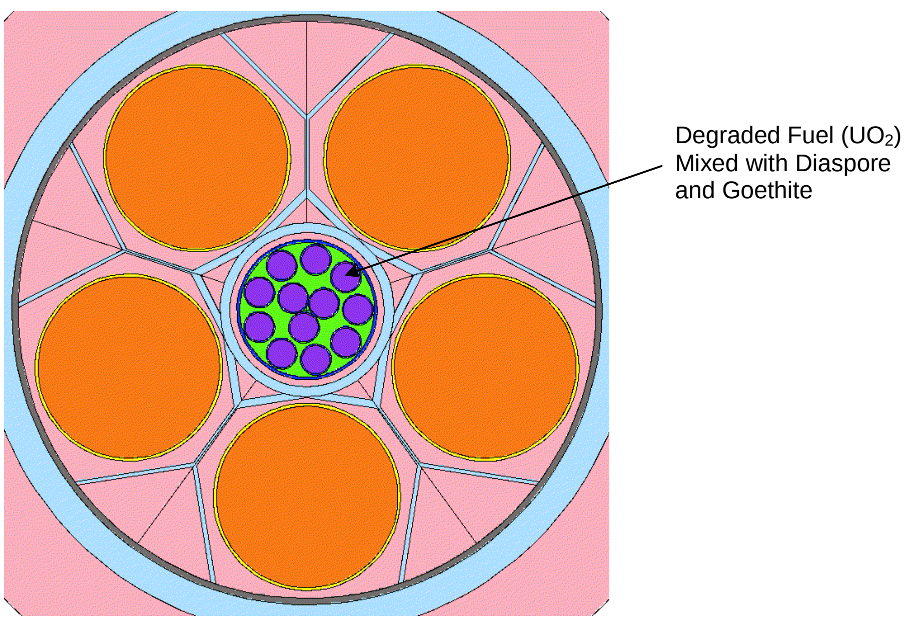

Figure 5-4. Transverse Cross Section of a WP Configuration with Degraded Fuel in Intact Pipes (initial position)

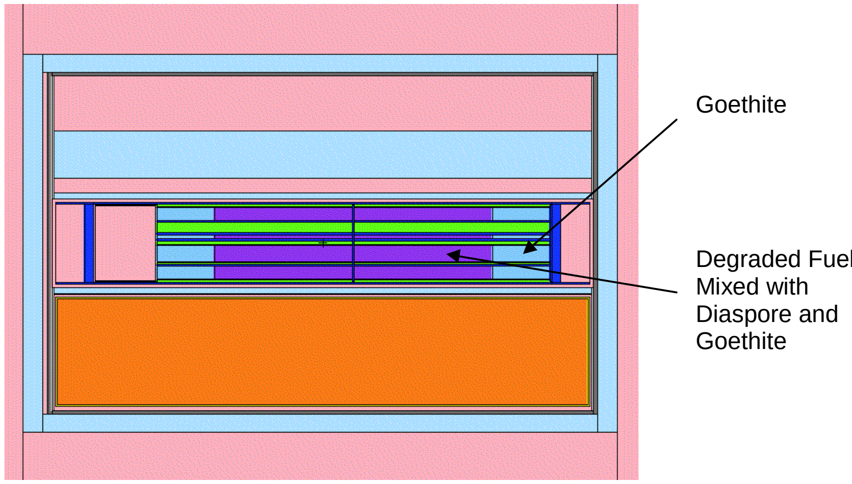

Figure 5-5. Longitudinal Cross Section of a WP Configuration with Degraded Fuel in Intact Pipes (initial position)

The conservative simplification of the model produced some unrealistic results. A subsequent set of calculations was performed with a model that took into account the presence of the goethite inside the 4-inch pipes. The amount considered was less than the amount that can result from iron shot degradation due to limited space available for accommodating these products. The minimum concentration of the neutron absorber to keep the system below criticality limit was identified. The calculations were performed for a range of lengths of the fuel column.

Finally, a number of variations that included changes in the geometry (settled 4-inch pipes inside the DOE SNF canister) and investigations of the effect of replacing U-238 with void were analyzed. The supporting calculations for the input data used for constructing the MCNP input files are described in the spreadsheet “new_intact_pipes.xls” (Attachment V).

5.3.1.3 Degraded Fuel and DOE SNF Internals Dispersed Inside the Intact DOE SNF Canister Shell

Another scenario considered the DOE SNF canister with its shell intact but with the contents of the canister totally degraded. As shown in the intact mode calculations, as the Fe shot degraded (Ref. 8, p. 27), degradation products occupy the void volume, thus, excluding water. There is actually not enough volumetric space available in the DOE SNF canister to degrade the entire amount of proposed filler material. The DOE SNF canister was evaluated in three locations:

- At the bottom of the waste package, such that the intact DOE SNF canister is fully reflected by the WP degraded components.
- Fully submerged into the degraded components and placed under and tangential to the top surface of degraded components.
- Sitting on top surface of the degraded components.

Examples of these configurations are shown in Figures 5-6 through 5-8. The most reactive configuration exists when uranium dioxide (UO_2) and goethite (FeOOH) and/or diaspore (AlOOH) are combined, and all of the other constituents from the degradation process ignored. A parametric study evaluated various combinations of UO_2, FeOOH, and AlOOH. In these cases, the UO_2 was modeled at various densities with the volume fractions occupied by FeOOH alone or a combination of FeOOH and AlOOH. The rest of the WP is filled with a layer of clay surrounding the DOE SNF canister and a layer of water. The supporting calculations for the input data used for constructing the MCNP input files are described in the spreadsheet "Degrade DOE SNF canister contents.xls" (Attachment V).

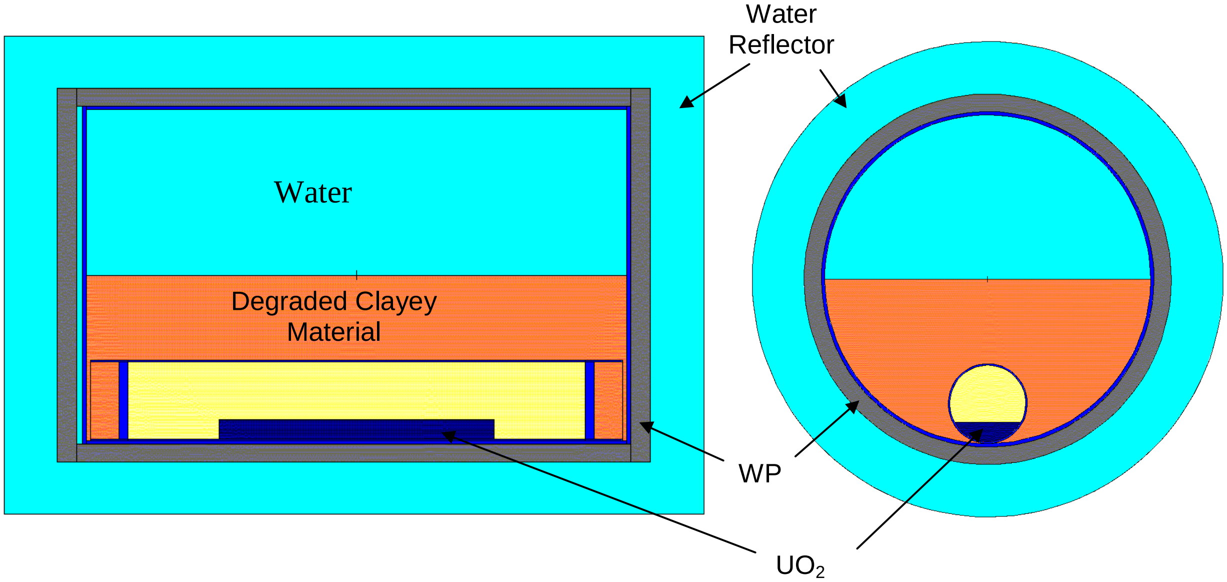

Figure 5-6. A Cross-sectional View of the Intact DOE SNF Canister in Clayey Material in the WP

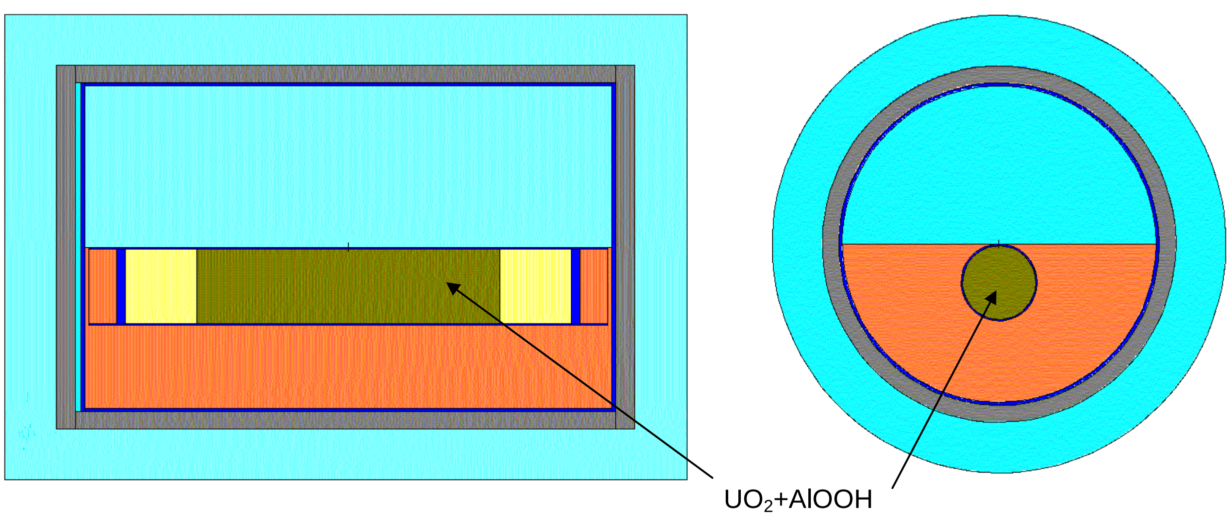

Figure 5-7. Intact DOE SNF Canister Located Below the Surface of Clayey Material in the WP

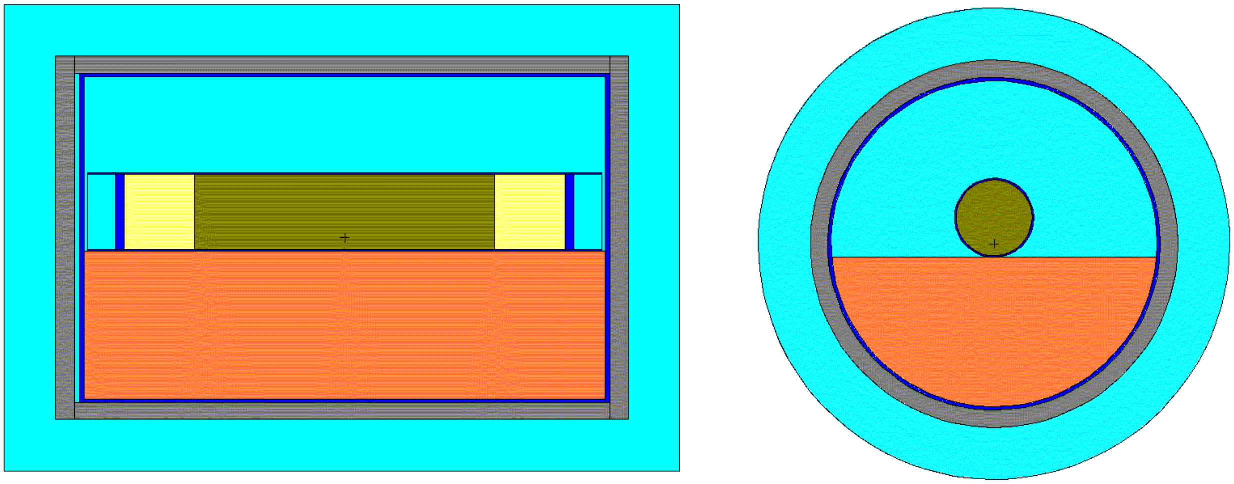

Figure 5-8. Intact DOE SNF Canister Located Above the Surface of Clayey Material in the WP

5.3.2 Degraded Mode Configurations with the Fissile Material Distributed in the WP

In this set of scenarios, the DOE SNF canister is evaluated as fully degraded, i.e., it has no structural integrity. The contents of the DOE SNF canister are evaluated in various states of degradation, configurations, and combinations of materials. The materials outside of the DOE SNF canister are also evaluated in various forms and configurations in combination with the contents of the degraded DOE SNF canister. The various scenarios evaluated are outlined in the following sections.

In the cases addressed in the next two sections, the fuel pins and the Zr cladding are intact while the other internal components of the waste package (HLW glass, DOE SNF canister, WP internal supporting structure, and internal components of the DOE SNF canister) are fully degraded. This configuration is described in detail on pages 31 through 34 of Ref. 20 and corresponds to the scenario IP-3 from Ref. 30, p. 3-3.

5.3.2.1 Intact SNF Pins Arrayed in Degraded Clayey Material

In this section, the corrosion products resulting from the degradation of the DOE SNF canister (FeOOH, AlOOH and Gd [Assumption 3.4]) and the pre-breach clay (Ref. 7) are mixed and surround the intact fuel pins. The amount of water in the clay varies from 0 vol.% of water to 48.64 vol.% of water as indicated in Attachment V (spreadsheet "part3final.xls"). The fuel pins sit at the bottom of the waste package (see Figure 5-9) or stacked as shown in Figure 5-10. The spacing between the fuel pins (pitch) varies. However, the height of the portion of the waste package containing the fuel pin can not be greater than the DOE SNF canister diameter. All MCNP representations listed in Tables 5.9 and 5.10 preserve the volume of the fuel. Table 5-9 lists the all the cases investigated and the main parameters varied. The loss of Gd is also investigated.

Table 5-9. List of the Cases Investigated when the Intact Fuel Pins are Surrounded by Pre-breach Clay and the Degraded Components of the DOE SNF Canister

File Name	Pitch (cm)	Height of the Fuel Layer (cm)	Volume Percent of Water in the Clay	Mass of Gd in the Clay (g)	Configuration
wif1d1	0.40132	6.07	0.00	0	See Figure 5-9
wif1d2	0.40132	6.07	16.67	0	See Figure 5-9
wif1d3	0.40132	6.07	28.57	0	See Figure 5-9
wif1d4	0.40132	6.07	37.50	0	See Figure 5-9
wif1d5	0.40132	6.07	48.64	0	See Figure 5-9
wif2d1	0.90132	18.09	0.00	0	See Figure 5-9
wif2d2	0.90132	18.09	16.67	0	See Figure 5-9
wif2d3	0.90132	18.09	28.57	0	See Figure 5-9
23g4k	0.90132	18.09	28.57	4000	See Figure 5-9
wif2d4	0.90132	18.09	37.50	0	See Figure 5-9
24g9k	0.90132	18.09	37.50	9000	See Figure 5-9
wif2d5	0.90132	18.09	48.64	0	See Figure 5-9
25g10	0.90132	18.09	48.64	10000	See Figure 5-9
25g18	0.90132	18.09	48.64	18000	See Figure 5-9
wif8d1	1.15132	25.27	0.00	0	See Figure 5-9
wif8d2	1.15132	25.27	16.67	0	See Figure 5-9
82g3k	1.15132	25.27	16.67	3000	See Figure 5-9
wif8d3	1.15132	25.27	28.57	0	See Figure 5-9
83g5k	1.15132	25.27	28.57	5000	See Figure 5-9
83g10	1.15132	25.27	28.57	10000	See Figure 5-9
wif8d4	1.15132	25.27	37.50	0	See Figure 5-9
84g10	1.15132	25.27	37.50	10000	See Figure 5-9
wif8d5	1.15132	25.27	48.64	0	See Figure 5-9
85g10	1.15132	25.27	48.64	10000	See Figure 5-9
85g18	1.15132	25.27	48.64	18000	See Figure 5-9
wif3d1	1.40132	33.15	0.00	0	See Figure 5-9
wif3d2	1.40132	33.15	16.67	0	See Figure 5-9
32g4k	1.40132	33.15	16.67	4000	See Figure 5-9
wif3d3	1.40132	33.15	28.57	0	See Figure 5-9
33g3k	1.40132	33.15	28.57	3000	See Figure 5-9
33g6k	1.40132	33.15	28.57	6000	See Figure 5-9
wif3d4	1.40132	33.15	37.50	0	See Figure 5-9
34g3k	1.40132	33.15	37.50	3000	See Figure 5-9
34g7k	1.40132	33.15	37.50	7000	See Figure 5-9
wif3d5	1.40132	33.15	48.64	0	See Figure 5-9
35g9k	1.40132	33.15	48.64	9000	See Figure 5-9
wif7d1	1.65132	41.70	0.00	0	See Figure 5-9
wif7d2	1.65132	41.70	16.67	0	See Figure 5-9
72g3k	1.65132	41.70	16.67	3000	See Figure 5-9

File Name	Pitch (cm)	Height of the Fuel Layer (cm)	Volume Percent of Water in the Clay	Mass of Gd in the Clay (g)	Configuration
wif7d3	1.65132	41.70	28.57	0	See Figure 5-9
73g3k	1.65132	41.70	28.57	3000	See Figure 5-9
wif7d4	1.65132	41.70	37.50	0	See Figure 5-9
74g35k	1.65132	41.70	37.50	3500	See Figure 5-9
wif7d5	1.65132	41.70	48.64	0	See Figure 5-9
75g3k	1.65132	41.70	48.64	3000	See Figure 5-9
75g5k	1.65132	41.70	48.64	5000	See Figure 5-9
tif1d1	0.40132	16.90	0.00	0	See Figure 5-10
tif1d2	0.40132	16.90	16.67	0	See Figure 5-10
tif1d3	0.40132	16.90	28.57	0	See Figure 5-10
tif1d4	0.40132	16.90	37.50	0	See Figure 5-10
tif1d5	0.40132	16.90	48.64	0	See Figure 5-10
tif2d1	0.90132	39.15	0.00	0	See Figure 5-10
tif2d2	0.90132	39.15	16.67	0	See Figure 5-10
t22g10	0.90132	39.15	16.67	10000	See Figure 5-10
t22g12	0.90132	39.15	16.67	12000	See Figure 5-10
tif2d3	0.90132	39.15	28.57	0	See Figure 5-10
t23g12	0.90132	39.15	28.57	12000	See Figure 5-10
tif2d4	0.90132	39.15	37.50	0	See Figure 5-10
t24g12	0.90132	39.15	37.50	12000	See Figure 5-10
tif2d5	0.90132	39.15	48.64	0	See Figure 5-10
t25g12	0.90132	39.15	48.64	12000	See Figure 5-10
t25g18	0.90132	39.15	48.64	18000	See Figure 5-10
t25g30	0.90132	39.15	48.64	30000	See Figure 5-10

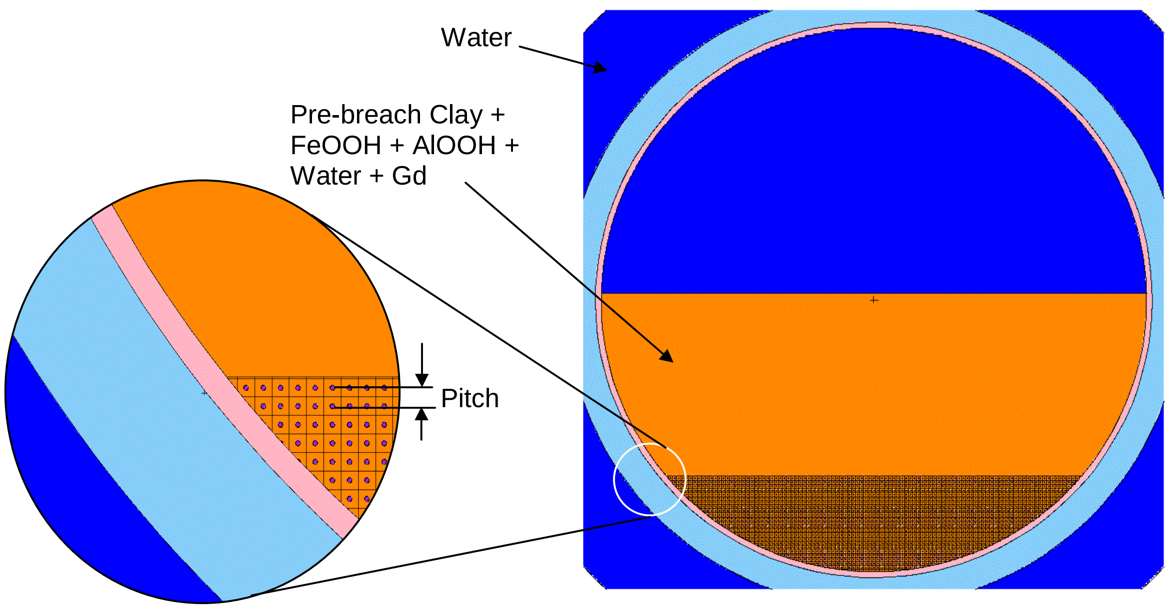

Figure 5-9. Fuel Pins Sitting at the Bottom of the WP

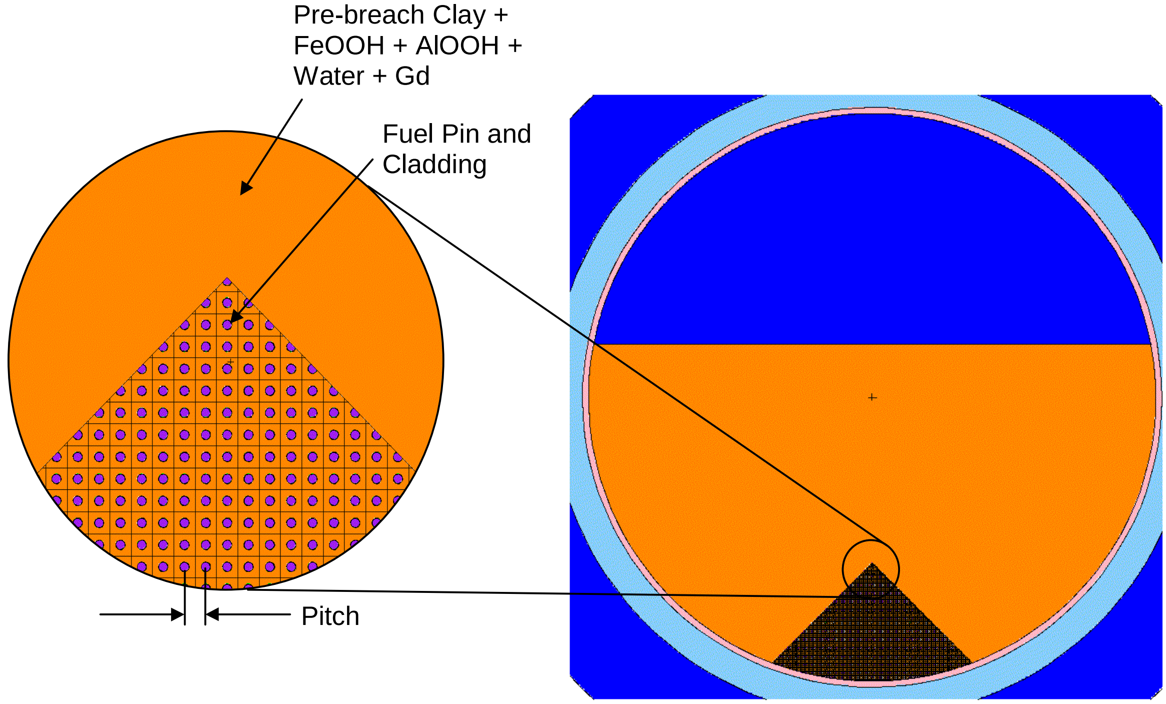

Figure 5-10. Fuel Pins Stacked at the Bottom of the WP

5.3.2.2 The Products Resulting from the Degradation of the DOE SNF Canister Form a Layer at the Bottom of the WP (SNF intact)

In the previous scenarios, the pre-breach clay and the degraded internals of the DOE SNF are mixed. This scenario is highly unrealistic since the degradation of the DOE SNF will not occur simultaneously with the degradation of the other internals of the waste package. The DOE SNF canister will sit intact at the bottom of the waste package surrounded by the pre-breach clay (as shown in Figure 5-6) and then degrade. The degraded iron and aluminum will form a layer at the bottom of the waste package with the clay above since the density of the goethite and aluminum mixture (4.18 g/cm^3, spreadsheet "part3final.xls", Attachment V) is higher than the density of the pre-breach clay (3.91 g/cm^3 [spreadsheet "clayey material pre breach.xls" in Attachment V]). Fuel pins are surrounded by the degraded components of the DOE SNF canister (FeOOH, AlOOH, Gd) as shown in Figures 5-11 and 5-12. The amount of water in the goethite-diaspore layer varies from 28.57 vol.% to 50 vol.%. The pre-breach clay has 37.5 vol.% of water. Table 5-10 lists the cases investigated for this scenario. The simplified geometry used in constructing the input files is a result of code internal modeling of the regular lattices.

Table 5-10. List of the Cases Investigated when the Intact Fuel Pins are Surrounded by the Degraded Components of the DOE SNF Canister Only

File Name	Pitch (cm)	Vol.% of Water in Goethite-Diaspore Layer	Height of the Fuel (cm)	Height of the Degraded Components of the DOE SNF Canister (cm)	Mass of Gd in the Goethite-Diaspore Layer (g)	Configuration
l15-4	0.40132	28.57	6.07	27.50	0	See Figure 5-11
l25-4	0.90132	28.57	18.09	27.50	0	See Figure 5-11
25-4g3k	0.90132	28.57	18.09	27.50	3000	See Figure 5-11
l85-4	1.15132	28.57	25.27	27.50	0	See Figure 5-11
85-4g3	1.15132	28.57	25.27	27.50	3000	See Figure 5-11
l15-6	0.40132	37.50	6.07	30.00	0	See Figure 5-11
l25-6	0.90132	37.50	18.09	30.00	0	See Figure 5-11
25-6g3k	0.90132	37.50	18.09	30.00	3000	See Figure 5-11
l85-6	1.15132	37.50	25.27	30.00	0	See Figure 5-11
85-6g3	1.15132	37.50	25.27	30.00	3000	See Figure 5-11
l15-10	0.40132	50.00	6.07	35.00	0	See Figure 5-11
l25-10	0.90132	50.00	18.09	35.00	0	See Figure 5-11
25-1035	0.90132	50.00	18.09	35.00	3500	See Figure 5-11
25-10g3	0.90132	50.00	18.09	35.00	3000	See Figure 5-11
l85-10	1.15132	50.00	25.27	35.00	0	See Figure 5-11
85-10g3	1.15132	50.00	25.27	35.00	3000	See Figure 5-11
l35-10	1.40132	50.00	33.15	35.00	0	See Figure 5-11
35-10g3	1.40132	50.00	33.15	35.00	3000	See Figure 5-11
tl14-4	0.40132	28.57	16.91	27.50	0	See Figure 5-12
tl14-6	0.40132	37.50	16.91	30.00	0	See Figure 5-12
tl14-10	0.40132	50.00	16.91	35.00	0	See Figure 5-12
tl24-10	0.90132	50.00	39.15	35.00	0	See Figure 5-12
tl20g7k	0.90132	50.00	39.15	35.00	7000	See Figure 5-12
tl20g8k	0.90132	50.00	39.15	35.00	8000	See Figure 5-12
tl208rs	0.90132	50.00	39.15	35.00	8000	See Figure 5-12 and Tuff as Reflector
tl208rw	0.90132	50.00	39.15	35.00	8000	See Figure 5-12 and Water-saturated Tuff as Reflector
tl20g9k	0.90132	50.00	39.15	35.00	9000	See Figure 5-12
tl209r	0.90132	50.00	39.15	35.00	9000	See Figure 5-12 Fully Reflected

The supporting calculations for the input data used for constructing the MCNP input files are described in the spreadsheet “part3final.xls” (Attachment V).

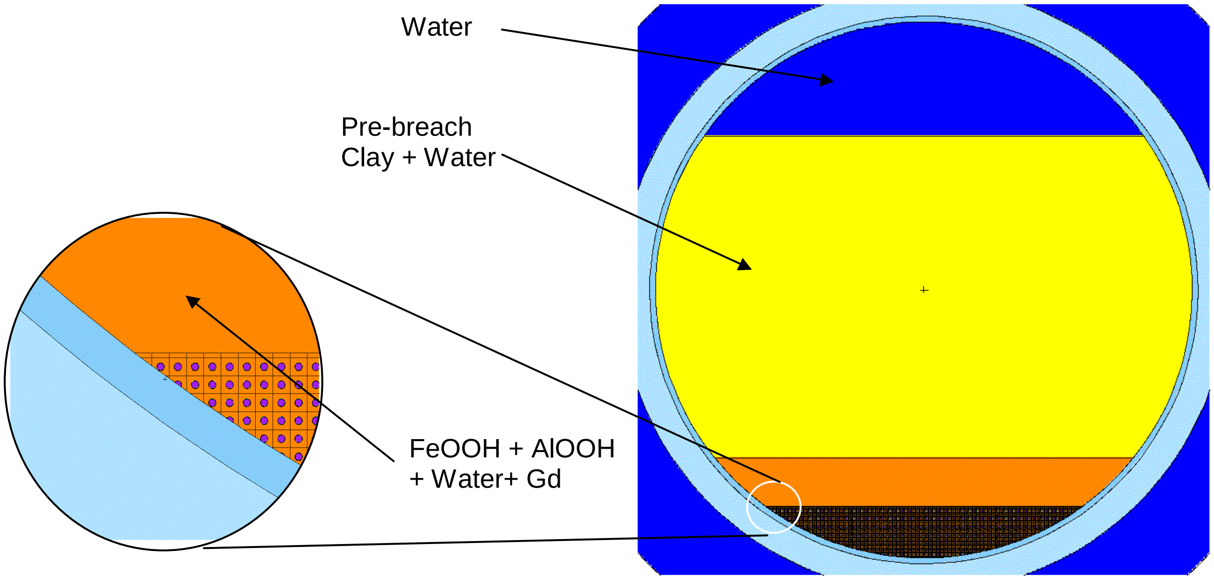

Figure 5-11. Degraded DOE SNF Canister Components Surround the Fuel Settled at the Bottom of the WP

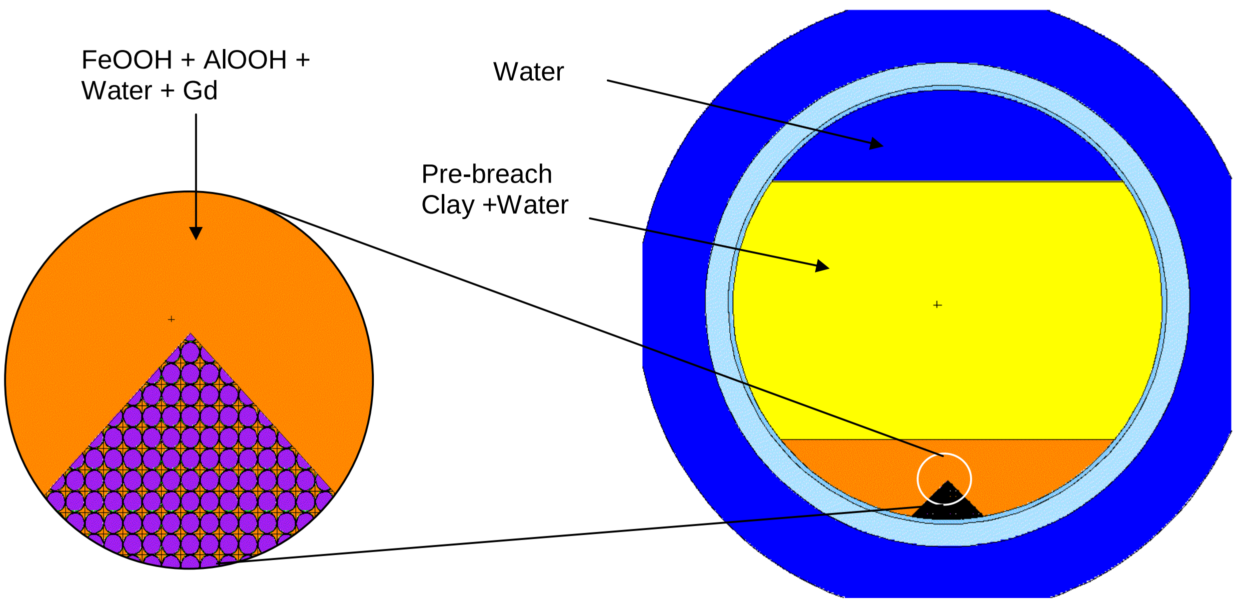

Figure 5-12. Degraded DOE SNF Canister Components Surround the Fuel Stacked at the Bottom of the WP

5.3.2.3 Fully Degraded DOE SNF Canister and WP Internal Structures

After the complete degradation of the WP internal constituents, the resultant configurations can include the degradation products as layers or complex mixtures settled in the WP. These configurations belong to class 2 (Ref. 30) and can be reached by any of the standard scenario IP-1, 2 or 3 (Ref. 30, p. 3-3). Specific arrangements for the codisposal WP are described in Ref. 20 under refinements IP-1-C, IP-2-A and IP-3-C. The degraded components are the waste package basket, HLW glass canisters, the DOE SNF canister and its internal structure, and the fissile material. The degradation products can settle in separate layers. As shown in Figure 5-13, the degraded fuel mixed with AlOOH (called here "mix-fuel") can be located at the bottom of the waste package. A layer of goethite is placed on the top of the fuel followed by a layer of clay and a layer of water.

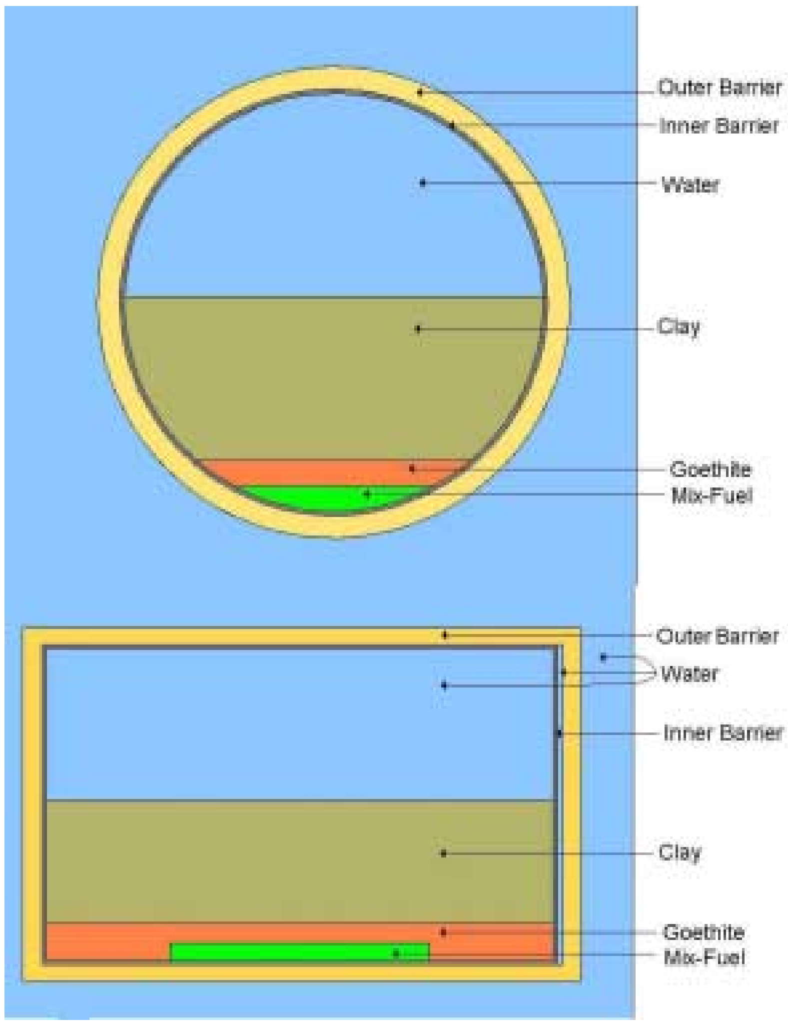

Figure 5-13. Fully Degraded DOE SNF Canister and WP Internal Structures

The first part of the analysis was performed considering the pre-breach clay and the explicit presence of the DOE SNF canister degradation products. The configurations can be regarded as the result of a subsequent step in the degradation of the configuration presented in Section 5.3.1.3 (intact DOE SNF canister shell). The pre-breach clay together with the degradation products from fuel, goethite (FeOOH), diaspore (AlOOH) and water are settled in layers in the WP. The fuel and diaspore are assumed fully mixed, due to their initial positions in the 4-inch pipes. Variations of the initial configuration were performed, using as parameters the mixing fractions of the constituents. The effects of various percentages of water in all layers inside the waste package have also been considered. In addition, different placements of the layers have been investigated, such as the fuel mixed with AlOOH ("mix-fuel") and FeOOH placed on top of the clay layer. (Figure 5-14).

The second part of the analysis was performed considering the post-breach clay, which results after 250,000 years of degradation. The composition of the post-breach clay was calculated using the most conservative geochemistry results (Ref. 7; see also spreadsheet "Book2.xls" in Attachment V).

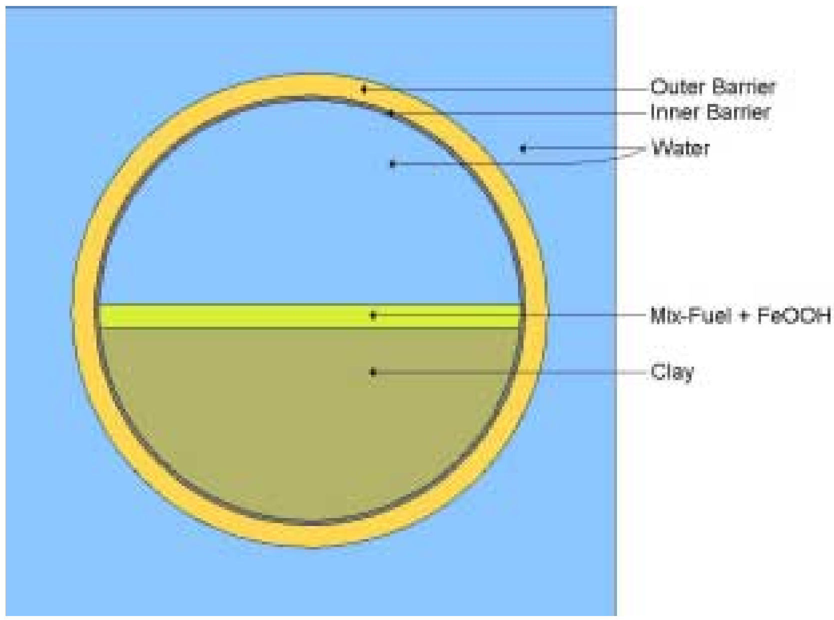

Figure 5-14. Clay on the Bottom of the WP Package; Fuel Mixture Plus FeOOH on Top of the Clay Layer

Finally, the roles of the fissile loading and the reflective boundary condition have been evaluated for the most reactive cases. The supporting calculations for the input data used for constructing the MCNP input files are described in the spreadsheet "Book2.xls" (Attachment V).

6. RESULTS

This document may be affected by technical product input information that requires confirmation. Any changes to the document that may occur as a result of completing the confirmation activities will be reflected in subsequent revisions. The status of the input information quality may be confirmed by review of the Document Input Reference System database.

MCNP results for the degraded mode configurations presented in Section 5.3 are provided in this section (Tables 6-1 through 6-34). Values of k_{eff}, H/X ratio and the average energy of a neutron causing fission (AENCF) are provided. The k_{eff} value represents the average collision, absorption, and track length estimator from the MCNP calculations. The standard deviation (σ) represents the standard deviation of k_{eff} about the average combined collision, absorption, and track length estimate due to Monte Carlo calculation statistics. The H/X ratio is the number density for hydrogen divided by that for U-235 in the region containing U-235. For the fully degraded cases, the H/X atom ratio is calculated over the volume that contains the degraded fuel. The AENCF is the energy per source particle lost to fission divided by the weight per source neutron lost to fission from the "problem summary section" of the MCNP output. The MCNP input and output files developed for this calculation are included in ASCII format in Attachment V.

6.1 RESULTS FOR DEGRADED MODE CONFIGURATIONS WITH FISSILE MATERIAL RETAINED IN THE DOE SNF CANISTER

Three postulated scenarios were discussed in Section 5.3.1 to evaluate the DOE SNF canister configurations with the fissile material retained inside. The configurations include the intact DOE SNF canister shell and the canister contents either fully or partially degraded.

6.1.1 DOE SNF Canister Containing Intact Fuel Pins Dispersed in the Degradation Products from Canister Internals

Preliminary MCNP cases have investigated the role of the shape of the array of pins on the k_{eff} and the influence of distribution of diaspore among fuel pins. These cases were run with the WP filled completely with clay. No gadolinium was considered in these cases. The supporting calculations for the input data used for constructing the MCNP input files are described in the spreadsheet "Intact fuel pins in degraded DOE SNF canister.xls" (Attachment V). The MCNP results are summarized in the following tables. Table 6-1 lists the results for a square array of pins placed in a mixture of goethite and diaspore with no neutron absorber. Table 6-2 presents similar results for a cylindrical array of pins. Table 6-3 includes cases in which the diaspore is distributed only in the region with the fuel pins.

Table 6-1. Results for a Square Array of Pins Inside the DOE SNF Canister (mixture with no Gd)

Case Name	Pitch (cm)	H/X	AENCF (MeV)	$k_{eff} \pm \sigma$	$k_{eff}+2\sigma$
icpa00n	0.40132	0.9035	0.7092	0.8646±0.0011	0.8668
icpa02n	0.60132	6.1456	0.3435	0.9919±0.0012	0.9943
icpa03n	0.70132	9.5509	0.2579	1.0589±0.0013	1.0615
icpa04n	0.80132	13.4790	0.2025	1.1186±0.0012	1.1210

Table 6-2. Results for a Cylindrical Array of Pins Inside DOE SNF Canister (mixture with no Gd)

Case Name	Pitch (cm)	H/X	AENCF (MeV)	$k_{eff} \pm \sigma$	$k_{eff}+2\sigma$
circ00n	0.40132	0.9035	0.7236	0.8615±0.0012	0.8639
circ02n	0.60132	6.1456	0.3490	0.9945±0.0011	0.9966
circ04n	0.80132	9.5509	0.2005	1.1290±0.0012	1.1314
circ05n	0.94132	13.4790	0.1529	1.1902±0.0012	1.1926

Table 6-3. Results for a Cylindrical Array of Pins with Diaspore Distributed only Among Fuel Pins Inside the DOE SNF Canister (mixture with no Gd)

Case Name	Pitch (cm)	H/X	AENCF (MeV)	$k_{eff} \pm \sigma$	$k_{eff}+2\sigma$
cial00n	0.40132	0.9223	0.7124	0.8722±0.0011	0.8744
cial02n	0.60132	6.2730	0.3420	1.0075±0.0010	1.0095
cial04n	0.80132	9.7489	0.1966	1.1449±0.0012	1.1473
cial05n	0.94132	13.7584	0.1500	1.2044±0.0010	1.2064

The results shown above indicate that the most reactive configuration is obtained when the fuel pins are dispersed in a cylindrical array, and the goethite is mixed with diaspore within the region of the fuel pins.

Figure 5-2 depicts a more realistic configuration that includes the exact amount of pre-breach clay obtained from the degradation of the HLW glass and WP internal supporting structure. The results obtained by investigating the influence of lattice pitch on a configuration similar to that described in Figure 5-2 are given in Table 6-4. The rest of the WP is filled with water. The fuel pins are dispersed in a cylindrical array, and the goethite is mixed with diaspore within the region of the fuel pins. There is no Gd in the mixture.

Table 6-4. Results for Degraded Configurations with Water Above Clay

Case Name	Pitch (cm)	H/X	AENCF (MeV)	$k_{eff} \pm \sigma$	$k_{eff}+2\sigma$
cial00z	0.40132	0.9223	0.7135	0.8725±0.0011	0.8747
cial02z	0.60132	6.2730	0.3411	1.0069±0.0009	1.0087
cial04z	0.80132	9.7489	0.1965	1.1469±0.0013	1.1495
cial05z	0.94132	13.7584	0.1498	1.2037±0.0013	1.2063

The calculation continued by evaluating the amount of neutron absorber necessary to keep the system described above below the criticality limit (0.93). Since the introduction of the neutron absorber has an effectiveness that is dependent on the state of the initial system, complete calculations for all the pitches have been performed with representative quantities of gadolinium. Based on the calculation described in the spreadsheet: “new_intact_pipes.xls”, the amount of Gd available in the current design (gadolinium phosphate is 1 vol.% of the filler material [Fe-$GdPO_4$]) is approximately 3 kg (see also Ref. 21, and Attachment V). Calculations with variations of the Gd have been performed for each lattice pitch investigated in Table 6-4. The results are listed in Table 6-5.

Table 6-5. Effect of Neutron Absorber on k_{eff}

Case Name	Pitch (cm)	Gd Content (g)	H/X	AENCF (MeV)	$k_{eff}±σ$	$k_{eff}+2σ$
gd02-3z	0.60132	3021	6.2730	0.3823	0.9304±0.0010	0.9324
gd02-4z	0.60132	4000	6.2730	0.3868	0.9212±0.0009	0.9230
gd02-5z	0.60132	5000	6.2730	0.3903	0.9149±0.0009	0.9167
gd02-9z	0.60132	9000	6.2730	0.3982	0.8961±0.0009	0.8979
gd04-2z	0.80132	2000	9.7489	0.2341	0.9892±0.0012	0.9915
gd04-3z	0.80132	3021	9.7489	0.2394	0.9635±0.0012	0.9659
gd04-4z	0.80132	4000	9.7489	0.2447	0.9422±0.0012	0.9446
gd04-5z	0.80132	5000	9.7489	0.2497	0.9227±0.0009	0.9249
gd04-9z	0.80132	9000	9.7489	0.2606	0.8798±0.0011	0.8820
gd05-1z	0.94132	1000	13.7584	0.1748	1.0041±0.0012	1.0065
gd05-2z	0.94132	2000	13.7584	0.1859	0.9717±0.0011	0.9739
gd05-3z	0.94132	3021	13.7584	0.1965	0.9325±0.0011	0.9347
gd05-4z	0.94132	4000	13.7584	0.2020	0.9043±0.0011	0.9065
gd05-5z	0.94132	5000	13.7584	0.2080	0.8791±0.0011	0.8813
gd05-9z	0.94132	9000	13.7584	0.2199	0.8264±0.0010	0.8284

Another set of calculations was done to investigate the effect of the position of the DOE SNF canister inside WP, and also of the condition of the rest of the WP. For a number of cases, the effect of adding a small amount of water in the mixture distributed among fuel pins was also investigated. The results are listed in Table 6-6.

Table 6-6. Results for the Influence of DOE SNF Canister Position on k_{eff}

Case Name	Description of the Case	H/X	AENCF (MeV)	$k_{eff}±σ$	$k_{eff}+2σ$
gd05-3z	See Table 6-5. DOE SNF canister at the bottom of WP	13.7584	0.1965	0.9325±0.0011	0.9347
gd05-3a	DOE SNF canister in the middle of the clay	13.7584	0.1959	0.9223±0.0012	0.9246
gd05-3w	DOE SNF canister at the bottom of WP surrounded by a mixture of clay + water (water 10 vol.%)	13.7584	0.1959	0.9218±0.0011	0.9240
gd05-3i	DOE SNF canister in non-degraded flooded WP	13.7584	0.2027	0.8985±0.0007	0.8999
gd05-3j	DOE SNF canister in non-degraded dry WP	13.7584	0.1972	0.9245±0.0007	0.9264
gd02-95	Similar with case gd02-9z from Table 6-5; 5 vol.% of water is added in the degraded mixture inside DOE SNF canister	6.2730	0.3935	0.8967±0.0010	0.8987
gd04-95	Similar with case gd04-9z from Table 6-5; 5 vol.% of water is added in the degraded mixture inside DOE SNF canister	9.7489	0.2618	0.8754±0.0010	0.8774
gd05-95	Similar with case gd05-9z from Table 6-5; 5 vol.% of water is added in the degraded mixture inside DOE SNF canister	13.7584	0.2190	0.8203±0.0009	0.8221

It can be seen that the most reactive configuration (DOE SNF canister at the bottom of pre-breach clay) is the one considered in the previous runs. Mixing the clay with water in the WP results in a decrease of k_{eff} of the system. Addition of water to the mixture of hydrated degradation products with neutron absorber does not result in an increase in $k_{eff,}$. The neutron absorber proves to be extremely effective for this class of configurations.

The influence of a WP reflective boundary on the most reactive configurations was also investigated. The results are listed in Table 6-7.

Table 6-7. Influence of a Reflective Boundary on k_{eff}

Case Name	Description of the Case	H/X	AENCF (MeV)	$k_{eff}\pm\sigma$	$k_{eff}+2\sigma$
gd05-4s	Similar to gd05-4z from Table 6-5 but with reflective boundary at outer WP surface	13.7584	0.1982	0.9130±0.0010	0.9150
gd04-5s	Similar to gd04-5z from Table 6-5 but with reflective boundary at outer WP surface	9.7489	0.2481	0.9263±0.0011	0.9285

Finally, the effect of replacing U-238 from the fuel with void was evaluated for the most reactive configuration with neutron absorber. The results are presented in Table 6-8.

Table 6-8. Effect of Replacing U-238 with Void for the Most Reactive Cases

Case Name	Description of the Case	H/X	AENCF (MeV)	$k_{eff}\pm\sigma$	$k_{eff}+2\sigma$
gd05-3v	Similar to gd05-3z from Table 6-5 but with U238 replaced with void. Contains 3000 g Gd	13.7584	0.1016	0.9977±0.0014	1.0005
gd05-4v	Similar to gd05-4z from Table 6-5 but with U-238 replaced with void. Contains 4000 g Gd	13.7584	0.1055	0.9617±0.0012	0.9641
gd05-5v	Similar to gd05-5z from Table 6-5 but with U-238 replaced with void. Contains 5000 g Gd	13.7584	0.1081	0.9404±0.0011	0.9426
gd05-6v	Similar to gd05-6z from Table 6-5 but with U-238 replaced with void. Contains 6000 g Gd	13.7584	0.1114	0.9178±0.0012	0.9203
gd04-5v	Similar to gd04-5z from Table 6-5 but with U-238 replaced with void. Contains 5000 g Gd	9.7489	0.1335	0.9856±0.0013	0.9881
gd04-9v	Geometry similar to above case. U-238 replaced with void. Contains 9000 g Gd	9.7489	0.1411	0.9338±0.0013	0.9364
gd0410v	Geometry similar to above case. U-238 replaced with void. Contains 10000 g Gd	9.7489	0.1426	0.9212±0.0011	0.9235

6.1.2 Degraded Fuel in the Intact WP

The calculations cover the configurations belonging to class 6 from Ref. 30. The base configuration is depicted in Figures 5-4 and 5-5. A very conservative arrangement that considers only a mixture of UO_2, diaspore, and water inside 4-inch pipes was first evaluated for the DOE SNF canister iron shot with various Gd content. The WP and the DOE SNF canister were fully flooded. The water fraction inside the fuel mixture was varied, and the volume of the mixture was correspondingly increased by modifying the level and/or fuel length. The results for these cases are summarized in Table 6-9.

Table 6-9. Results for a Degraded Configuration without Goethite and Neutron Absorber Inside the 4-inch Pipes

Case Name	Height of Fuel Mixture in the 4-inch Pipes (cm)	Gd Content in the Filler Material (g)	Length of Fuel Section per 4-inch Pipe (cm)	Water Volume Fraction in Fuel Mixture	H/X	AENCF (MeV)	$k_{eff}\pm\sigma$	$k_{eff}+2\sigma$
p-3a	7.180	3021	77.47	0	6.527	0.2611	0.8424±0.0008	0.8440
p-3b	Full cyl.[a]	3021	77.47	0.163	11.083	0.2277	0.9025±0.0008	0.9041
p-3c	Full cyl.	3021	80	0.189	11.995	0.2191	0.9065±0.0008	0.9081
p-3d	Full cyl.	3021	90	0.280	15.601	0.1862	0.9268±0.0008	0.9284
p-3e	Full cyl.	3021	100	0.352	19.207	0.1636	0.9391±0.0008	0.9407
p-3f	Full cyl.	3021	110	0.411	22.813	0.1465	0.9488±0.0009	0.9506
p-4a	7.180	4000	77.47	0	6.527	0.2642	0.8347±0.0008	0.8363
p-4b	Full cyl.	4000	77.47	0.163	11.083	0.2287	0.8951±0.0007	0.8965
p-4c	Full cyl.	4000	80	0.189	11.995	0.2195	0.9000±0.0007	0.9014
p-4d	Full cyl.	4000	90	0.280	15.601	0.1893	0.9191±0.0008	0.9207
p-4e	Full cyl.	4000	100	0.352	19.207	0.1656	0.9298±0.0008	0.9314
p-4f	Full cyl.	4000	110	0.411	22.813	0.1474	0.9402±0.0008	0.9418
p-6a	7.180	6000	77.47	0	6.527	0.2678	0.8259±0.0007	0.8273
p-6b	Full cyl.	6000	77.47	0.163	11.083	0.2309	0.8858±0.0008	0.8874
p-6c	Full cyl.	6000	80	0.189	11.995	0.2222	0.8899±0.0007	0.8913
p-6d	Full cyl.	6000	90	0.280	15.601	0.1912	0.9075±0.0007	0.9089
p-6e	Full cyl.	6000	100	0.352	19.207	0.1684	0.9205±0.0008	0.9221
p-6f	Full cyl.	6000	110	0.411	22.813	0.1489	0.9293±0.0008	0.9309

NOTE: [a] Cross-sectional area of the mixture containing fuel is equal to the area of the pipe.

A separate set of calculations for this configuration was done to investigate the influence of U-238 replacement with void and also of the outer reflective boundary. For this purpose the file “p-6f” from Table 6-9 was used as a base case. The results for the variations are listed in Table 6-10.

Table 6-10. Results for Variations of a Base Configuration (reflective WP boundary and removal of U-238)

Case Name	Height of Fuel Mixture in the 4-inch Pipes (cm)	Gd Content in the Filler Material (g)	Description	H/X	AENCF (MeV)	$k_{eff}\pm\sigma$	$k_{eff}+2\sigma$
p-6f	Full cyl.	6000	Base case	22.813	0.1481	0.9293±0.0008	0.9309
p-6fs	Full cyl.	6000	Reflective WP boundary	22.813	0.1481	0.9293±0.0008	0.9309
p-6fv	Full cyl.	6000	No U-238	22.813	0.0712	1.0275±0.0009	1.0293
p-9fv	Full cyl.	9000	No U-238	22.813	0.0731	1.0126±0.0009	1.0144

The results show that the configuration is extremely reactive when U-238 is replaced with void, and the addition of Gd seems to be less effective. This was the main reason for extending the present calculation to a more realistic degraded configuration that includes the degradation products from the iron shot present in the 4-inch pipes. Table 6-11 includes similar runs as above for the cases with 6 kg of Gd, the exception being the presence of goethite inside 4-inch pipes. The amount included is limited by the available space and accounts for almost 80% of the initial iron shot. The rest of the iron is conservatively neglected from the analysis. A proportional amount of gadolinium phosphate is also dispersed with the goethite inside the pipes. The calculated number densities (spreadsheet: "new_intact_pipes.xls", Attachment V) take into account the expansion in volume of the iron when degraded to goethite.

Table 6-11. Results for a Degraded Configuration with Goethite and Neutron Absorber Inside the 4-inch Pipes

Case Name	Height of Fuel Mixture in the 4-inch Pipes (cm)	Gd Content in the Filler Material (g)	Length of Fuel Section per 4-inch Pipe (cm)	Volume Fraction of Goethite in the Fuel Mixture	H/X	AENCF (MeV)	k_{eff}±σ	k_{eff}+2σ
r-6a	7.180	6000	77.47	0	6.527	0.2845	0.7994±0.0008	0.8010
r-6b	Full cyl.	6000	77.47	0.163	8.479	0.2647	0.8076±0.0007	0.8090
r-6d	Full cyl.	6000	90	0.280	10.414	0.2402	0.7657±0.0007	0.7671
r-6e	Full cyl.	6000	100	0.352	11.959	0.2266	0.7331±0.0007	0.7345
r-6f	Full cyl.	6000	110	0.411	13.503	0.2131	0.7046±0.0006	0.7058
r-9a	7.180	9000	77.47	0	6.527	0.2906	0.7857±0.0007	0.7871
r-9b	Full cyl.	9000	77.47	0.163	8.479	0.2709	0.7869±0.0007	0.7883
r-9d	Full cyl.	9000	90	0.280	10.414	0.2501	0.7397±0.0007	0.7411
r-9e	Full cyl.	9000	100	0.352	11.959	0.2341	0.6830±0.0006	0.6842
r-9f	Full cyl.	9000	110	0.411	13.503	0.2230	0.6730±0.0007	0.6744

Variations of the most reactive cases ("r-6b" and "r-9b") have been performed separately and are included in Table 6-12.

Table 6-12. Results for Variations of the Most Reactive Configurations from Table 6-11

Case Name	Length of Fuel Section per 4-inch Pipe (cm)	Gd Content in the Filler Material (g)	Description	H/X	AENCF (MeV)	k_{eff}±σ	k_{eff}+2σ
r-6b	77.47	6000	Base case with 6 kg of Gd	8.479	0.2647	0.8076±0.0007	0.8090
r-6bsh	64.83	6000	Shorter fuel section - no goethite mixed with fuel	6.527	0.2995	0.8575±0.0008	0.8591
r-6bt	77.47	6000	Settled pipes - geometrically stable geometry	8.479	0.2667	0.8829±0.0007	0.8843
r-6bv	77.47	6000	No U-238	8.479	0.1387	0.8774±0.0008	0.8790
r-6brf	77.47	6000	Reflective boundary at WP outer surface	8.479	0.2647	0.8076±0.0007	0.8090
r-6bnw	77.47	6000	Dry waste package outside DOE SNF canister	8.479	0.2533	0.8439±0.0007	0.8453
r-9b	Full cyl.	9000	Base case with 9 kg of Gd	8.479	0.2709	0.7869±0.0007	0.7883
r-9bt	77.47	9000	Settled pipes - geometrically stable geometry	8.479	0.2666	0.8631±0.0007	0.8645
r-9bv	77.47	9000	No U-238	8.479	0.1387	0.8516±0.0008	0.8532

The results are well below the criticality limit for each variation. The most important influence is due to resettlement of the fuel pipes inside DOE SNF canister. Removal of U-238 and a dry WP have also a major influence on the k_{eff}.

A final set of calculations with a configuration containing 9 kg of Gd (approximately 3 vol.% of $GdPO_4$ in the initial filler material [Fe-$GdPO_4$]) has been investigated. The results are also included in Table 6-12.

6.1.3 Degraded Fuel and DOE SNF Internals Dispersed Inside the Intact DOE SNF Canister Shell

The scenario consisted of the contents of the DOE SNF canister fully degraded and evaluated as a combination of UO_2 and FeOOH at various densities. The UO_2 was dispersed throughout the FeOOH as described in Section 5.3.1.3 with the length equal to the initial footprint length (154.94 cm). The results of these cases are given in Table 6-13.

Table 6-13. Results for Intact DOE SNF Canister, Contents Fully Degraded, UO_2 and FeOOH

Case Name	UO_2 Density (g/cm^3)	FeOOH Density (g/cm^3)	H/X	AENCF (MeV)	$k_{eff}\pm\sigma$	$k_{eff}+2\sigma$
df1	10.96	0	0	0.8400	0.7635±0.0009	0.7653
df2	5.11	2.28	5.22	0.3651	0.9510±0.0010	0.9530
df3	3.40	2.94	10.11	0.2388	1.0445±0.0010	1.0465
df4	2.55	3.28	14.99	0.1750	1.1107±0.0011	1.1129
df5	2.19	3.42	18.28	0.1488	1.1446±0.0012	1.1470
df51[a]	1.93	3.52	27.86	0.1314	1.1470±0.0011	1.1492
df52[a]	1.69	3.61	31.55	0.1158	1.1476±0.0011	1.1498
df53[a]	1.35	3.74	38.92	0.0922	1.1385±0.0011	1.1407
df54[a]	1.32	3.76	40.02	0.0897	1.1386±0.0011	1.1408

NOTE: [a] These cases were obtained from case "df5" by expanding the length of the fuel cylinder to 175, 200, 250, and 257.5 cm (canister internal full length), respectively.

As shown in Table 6-13, the most reactive case is the one where the UO_2 is dispersed in the FeOOH throughout the volume of a 200-cm-long cylinder filling the entire cross section of the DOE SNF canister.

Addition of the diaspore resulting from the degradation of –01 and –04 canisters to the configurations used in Table 6-13 resulted in a new set of configurations that is presented in Table 6-14. In all configurations, the diaspore and the UO_2 are mixed together. The DOE SNF canister is placed at the bottom of WP, as shown in Figure 5-6.

Table 6-14. Results of Intact DOE SNF Canister, Contents Fully Degraded, UO_2, FeOOH and AlOOH

Case Name	UO_2 Density (g/cm^3)	FeOOH Density (g/cm^3)	AlOOH Density (g/cm^3)	H/X	AENCF (MeV)	$k_{eff}\pm\sigma$	$k_{eff}+2\sigma$
dfa1	3.40	1.32	1.28	11.07	0.2248	1.0872±0.0012	1.0896
dfa2	2.55	2.06	0.96	15.95	0.1674	1.1482±0.0012	1.1496
dfa3	2.22	2.35	0.84	18.89	0.1451	1.1811±0.0012	1.1835
dfa4	2.19	2.38	0.82	19.24	0.1440	1.1801±0.0011	1.1823
dfa31[a]	1.97	2.57	0.74	21.80	0.1291	1.1769±0.0010	1.1789
dfa32[a]	1.72	2.78	0.65	25.42	0.1129	1.1762±0.0012	1.1786
dfa33[a]	1.38	3.08	0.52	32.68	0.0919	1.1653±0.0010	1.1673
dfa34[a]	1.34	3.11	0.50	33.76	0.0889	1.1644±0.0010	1.1664
dfa41[b]	1.93	2.59	0.73	22.19	0.1261	1.1819±0.0011	1.1841
dfa42[b]	1.69	2.80	0.64	25.88	0.1145	1.1650±0.0012	1.1674
dfa43[b]	1.35	3.10	0.51	33.25	0.0919	1.1608±0.0010	1.1628
dfa44[b]	1.32	3.13	0.50	34.35	0.0900	1.1577±0.0011	1.1599

NOTES: [a] These cases were obtained from cases "dfa3" by expanding the length of the fuel cylinder to 175, 200, 250, and 257.5 cm (canister internal full length), respectively.
[b] These cases were obtained from cases "dfa4" by expanding the length of the fuel cylinder to 175, 200, 250, and 257.5 cm (canister internal full length), respectively.

As described in Section 5, an amount of 1 vol.% of $GdPO_4$ was added to the filler material mixture (iron shot-$GdPO_4$) to maintain subcriticality. For the case with the highest k_{eff} in Table 6-14 (case "dfa41"), the corresponding case with 1 vol.% $GdPO_4$ in Table 6-15 is "dfab1gd". The DOE SNF canister was evaluated at the bottom of a horizontally emplaced WP. Two more configurations were evaluated: one with the canister placed below (Figure 5-7) and one with the canister placed above the pre-breach clay surface (Figure 5-8). The remainder of the WP was filled with water. The results for all three cases are given in Table 6-15.

Table 6-15. Results of Gd as Neutron Absorber, Canister Contents Fully Degraded

Case Name	Location of Intact Canister	Reflector	H/X	AENCF (MeV)	$k_{eff}\pm\sigma$	$k_{eff}+2\sigma$
dfab1gd	Bottom of WP	Full reflection with clayey material	22.19	0.1603	0.9401±0.0008	0.9417
dfam1gd	Below the surface of clayey material	Bottom reflection clayey material – top water	22.19	0.1602	0.9311±0.0009	0.9329
dfat1gd	Above the surface of clayey material	Effectively full reflection water	22.19	0.1656	0.9006±0.0009	0.9024

The most reactive configuration from Table 6-15 (case "dfab1gd") has been varied by adding features like 10 vol.% of water mixed with the pre-breach clay inside the WP, fully reflective outer WP boundary, total loss of U-238, and replacement of goethite with hematite. The results are listed in Table 6-16.

Table 6-16. Results of Gd as Neutron Absorber, Canister Contents Fully Degraded (variations)

Case Name	Characteristics	H/X	AENCF (MeV)	$k_{eff} \pm \sigma$	$k_{eff} + 2\sigma$
dfab1gd10w	10 vol.% water added to the clay outside canister	22.19	0.1608	0.9306±0.0009	0.9324
dfabr1gd	Fully reflected WP outer boundary	22.19	0.1580	0.9532±0.0009	0.9550
dfab81gd	All U-238 removed from UO_2	22.19	0.0795	1.0579±0.0009	1.0597
dfabh1gd	Goethite (FeOOH) is replaced with hematite (Fe_2O_3)	6.53	0.2797	0.8159±0.0008	0.8175

As shown in Tables 6-15 and 6-16, 1 vol.% of $GdPO_4$ in the initial $GdPO_4$-iron shot mix is not sufficient to keep all possible configurations subcritical and within the acceptance criterion. Therefore, the amount of $GdPO_4$ in the initial filler material (Fe-$GdPO_4$) was increased to 3 vol.% of the filler mixture (approximately 14.4 kg $GdPO_4$). A new set of calculations was performed for the configurations listed in Tables 6-14, 6-15, and 6-16. The results are shown in Tables 6-17, 6-18, and 6-19.

Table 6-17. Results of Intact DOE SNF Canister, Contents Fully Degraded, UO_2, FeOOH, and AlOOH (the cases from Table 6-14 with 3 vol.% $GdPO_4$)

Case Name	UO_2 Density (g/cm^3)	FeOOH Density (g/cm^3)	AlOOH Density (g/cm^3)	H/X	AENCF (MeV)	$k_{eff} \pm \sigma$	$k_{eff}+2\sigma$
da13gd	4.93	0	1.86	6.53	0.4035	0.8545±0.0009	0.8563
dfa13gd	3.40	1.32	1.28	11.07	0.2694	0.9178±0.0009	0.9196
dfa23gd	2.55	2.06	0.96	15.95	0.2179	0.8893±0.0009	0.8911
d03gd[a]	2.56	2.06	0.96	15.95	0.1687	0.8182±0.0008	0.8198
dfa33gd	2.22	2.35	0.84	18.89	0.1991	0.8691±0.0008	0.8707
dfa43gd	2.19	2.38	0.82	19.24	0.1956	0.8658±0.0008	0.8674
dfa413gd	1.93	2.59	0.73	22.19	0.1832	0.8210±0.0008	0.8226
dfa423gd	1.69	2.80	0.64	25.88	0.1756	0.7671±0.0007	0.7685
dfa433gd	1.35	3.10	0.51	33.25	0.1585	0.6795±0.0007	0.6809
dfa443gd	1.32	3.13	0.50	34.35	0.1548	0.6705±0.0006	0.6717

NOTE: [a] For this case the length of UO_2, FeOOH and AlOOH mixture is 132.34 cm.

Case “dfa23gd” in Table 6-17 has been selected as the most reactive case and base case for Table 6-18. Case “dfa13gd” has a higher k_{eff}, but the amount of FeOOH mixed with UO_2 is lower than the amount that is resulting from the degradation of the initial iron shot present in each 4-inch pipe.

Table 6-18. Results of Gd as Neutron Absorber, DOE SNF Canister Contents Fully Degraded (with 3 vol.% $GdPO_4$)

Case Name	Location of Intact Canister	Reflector	H/X	AENCF (MeV)	$k_{eff} \pm \sigma$	$k_{eff}+2\sigma$
dfab3gd	Bottom of WP	Full reflection with clayey material	15.95	0.2179	0.8893±0.0009	0.8911
dfam3gd	Below the surface of clayey material	Bottom reflection clayey material – top water	15.95	0.2187	0.8885±0.0009	0.8903
dfat3gd	Above the surface of clayey material	Effectively full reflection water	15.95	0.2249	0.8554±0.0009	0.8572

The most reactive configuration from Table 6-18 (case “dfab3gd”) has been varied by adding features like 1 or 10 vol.% water mixed with the goethite inside the DOE SNF canister, fully reflective outer WP boundary, replacement of U-238 with void, and replacement of goethite with hematite. The last case has also been analyzed with all water removed from inside and outside WP. The results are listed in Table 6-19.

Table 6-19. Results of Gd as Neutron Absorber, DOE SNF Canister Contents Fully Degraded

Case Name	Location of Intact Canister	H/X	AENCF (MeV)	$k_{eff}\pm\sigma$	$k_{eff}+2\sigma$
dfab3gd1w	0.48 vol.% water in the DOE SNF canister	16.08	0.2172	0.8879±0.0009	0.8897
dfab3gd10w	4.82 vol.% water in the DOE SNF canister	17.19	0.2152	0.8879±0.0009	0.8897
dfabr3gd	Fully reflected WP outer boundary	15.95	0.2141	0.9037±0.0008	0.9053
dfab83gd	U-238 removed from UO_2 (3 vol.% $GdPO_4$)	15.95	0.1142	0.9812±0.0009	0.9830
dfab85gd	U-238 removed from UO_2 (5 vol.% $GdPO_4$)	15.95	0.1195	0.9236±0.0008	0.9252
dfabh3gd	Goethite (FeOOH) is replaced with hematite (Fe_2O_3)	6.53	0.3112	0.8792±0.0009	0.8810
dfabhw3gd	Same configuration as above, with all water removed	6.53	0.3100	0.8775±0.0009	0.8793

For a system that has an isotopic composition within the limits of the initial fresh fuel, k_{eff} will remain below 0.93 with the addition of minimum 9 kg of Gd (14.4 kg of $GdPO_4$) for all configurations belonging to this class.

6.2 RESULTS FOR DEGRADED MODE CONFIGURATIONS WITH THE FISSILE MATERIAL DISTRIBUTED IN THE WP

Various scenarios were developed to evaluate the entire DOE SNF canister as degraded. The results from these scenarios are given in the following sections.

6.2.1 Intact SNF Pins Arrayed in Clayey Material

As described in Section 5.3.2, this set of configurations comprises the intact fuel pins settled at the bottom of the WP. The pins are dispersed in a mass of clayey material obtained by mixing the HLW glass degradation products with the rest of the degraded materials from WP internals and DOE SNF canister. The calculations investigated the influence of water content in the clayey material on k_{eff}. The results for various lattice pitch values, water content, and Gd content are listed in Table 6-21. H/X ratios are calculated in spreadsheet: “part3final.xls”, attachment V, and summarized in Table 6-20.

Table 6-20. Moderation Ratio for the Cases where the Intact Fuel Pins are Surrounded by Pre-breach Clay and the Degraded Components of the DOE SNF Canister

Pitch (cm)	H/X for Dry Clay	H/X for Clay with 16.67 vol.% of Water	H/X for Clay with 28.57 vol.% of Water	H/X for Clay with 37.50 vol.% of Water	H/X for Clay with 48.64 vol.% of Water
0.40132	2.46E-01	5.02E-01	6.85E-01	8.22E-01	9.93E-01
0.90132	4.87E+00	9.95E+00	1.36E+01	1.63E+01	1.97E+01
1.15132	8.52E+00	1.74E+01	2.37E+01	2.85E+01	3.44E+01
1.40132	1.31E+01	2.67E+01	3.64E+01	4.37E+01	5.28E+01
1.65132	1.85E+01	3.77E+01	5.15E+01	6.18E+01	7.47E+01

Table 6-21. k_{eff} for the Cases where the Intact Fuel Pins are Surrounded by Pre-breach Clay and the Degraded Components of the DOE SNF Canister

File Name	Pitch (cm)	Vol.% of Water in the Clay	Mass of Gd in the Clay (g)	$k_{eff}±σ$	$k_{eff}+2σ$	AENCF (MeV)
wif1d1	0.40132	0.00	0	0.6717±0.0010	0.6736	0.7970
wif1d2	0.40132	16.67	0	0.6849±0.0006	0.6860	0.7464
wif1d3	0.40132	28.57	0	0.6961±0.0011	0.6984	0.7115
wif1d4	0.40132	37.50	0	0.7030±0.0010	0.7050	0.6875
wif1d5	0.40132	48.64	0	0.7175±0.0011	0.7197	0.6645
wif2d1	0.90132	0.00	0	0.7578±0.0011	0.7601	0.2949
wif2d2	0.90132	16.67	0	0.8909±0.0014	0.8936	0.2292
wif2d3	0.90132	28.57	0	0.9707±0.0013	0.9732	0.1967
23g4k	0.90132	28.57	4000	0.9207±0.0013	0.9232	0.2105
wif2d4	0.90132	37.50	0	1.0267±0.0013	1.0293	0.1791
24g9k	0.90132	37.50	9000	0.9263±0.0013	0.9289	0.1995
wif2d5	0.90132	48.64	0	1.0857±0.0012	1.0881	0.1616
25g10	0.90132	48.64	10000	0.9651±0.0015	0.9680	0.1844
25g18k	0.90132	48.64	18000	0.9233±0.0015	0.9262	0.1921
wif8d1	1.15132	0.00	0	0.8294±0.0011	0.8315	0.2036
wif8d2	1.15132	16.67	0	0.9910±0.0012	0.9934	0.1521
82g3k	1.15132	16.67	3000	0.9240±0.0012	0.9264	0.1638
wif8d3	1.15132	28.57	0	1.0789±0.0013	1.0814	0.1306
83g5k	1.15132	28.57	5000	0.9537±0.0013	0.9562	0.1492
83g10	1.15132	28.57	10000	0.8915±0.0012	0.8938	0.1592
wif8d4	1.15132	37.50	0	1.1301±0.0012	1.1325	0.1200
84g10	1.15132	37.50	10000	0.9235±0.0012	0.9260	0.1491
wif8d5	1.15132	48.64	0	1.1923±0.0014	1.1952	0.1088
85g10	1.15132	48.64	10000	0.9645±0.0013	0.9672	0.1350
85g18	1.15132	48.64	18000	0.8874±0.0012	0.8899	0.1469
wif3d1	1.40132	0.00	0	0.8685±0.0011	0.8708	0.1524
wif3d2	1.40132	16.67	0	1.0281±0.0012	1.0306	0.1140
32g4k	1.40132	16.67	4000	0.8904±0.0012	0.8928	0.1335
wif3d3	1.40132	28.57	0	1.1087±0.0007	1.1101	0.0946
33g3k	1.40132	28.57	3000	0.9676±0.0013	0.9702	0.1145
33g6k	1.40132	28.57	6000	0.8897±0.0012	0.8921	0.1253
wif3d4	1.40132	37.50	0	1.1612±0.0012	1.1636	0.0915
34g3k	1.40132	37.50	3000	1.0078±0.0013	1.0103	0.1051
34g7k	1.40132	37.50	7000	0.8982±0.0012	0.9005	0.1172
wif3d5	1.40132	48.64	0	1.2196±0.0013	1.2222	0.0827
35g9k	1.40132	48.64	9000	0.8965±0.0012	0.8990	0.1125
wif7d1	1.65132	0.00	0	0.8810±0.0011	0.8832	0.1223
wif7d2	1.65132	16.67	0	1.0243±0.0011	1.0266	0.0947
72g3k	1.65132	16.67	3000	0.7699±0.0012	0.7723	0.1275

File Name	Pitch (cm)	Vol.% of Water in the Clay	Mass of Gd in the Clay (g)	$k_{eff}\pm\sigma$	$k_{eff}+2\sigma$	AENCF (MeV)
wif7d3	1.65132	28.57	0	1.0934±0.0013	1.0960	0.0823
73g3k	1.65132	28.57	3000	0.7845±0.0012	0.7869	0.1163
wif7d4	1.65132	37.50	0	1.1397±0.0012	1.1421	0.0754
74g35k	1.65132	37.50	3500	0.9155±0.0013	0.9181	0.0960
wif7d5	1.65132	48.64	0	1.1937±0.0012	1.1960	0.0699
75g3k	1.65132	48.64	3000	0.9811±0.0012	0.9836	0.0848
75g5k	1.65132	48.64	5000	0.8988±0.0013	0.9014	0.0927
tif1d1	0.40132	0.00	0	0.7942±0.0009	0.7961	0.8521
tif1d2	0.40132	16.67	0	0.8063±0.0011	0.8084	0.8002
tif1d3	0.40132	28.57	0	0.8141±0.0011	0.8162	0.7678
tif1d4	0.40132	37.50	0	0.8205±0.0012	0.8228	0.7431
tif1d5	0.40132	48.64	0	0.8323±0.0011	0.8344	0.7188
tif2d1	0.90132	0.00	0	0.8717±0.0011	0.8739	0.2824
tif2d2	0.90132	16.67	0	1.0050±0.0013	1.0075	0.2218
t22g10	0.90132	16.67	10000	0.9346±0.0013	0.9372	0.2422
t22g12	0.90132	16.67	12000	0.9252±0.0012	0.9277	0.2454
tif2d3	0.90132	28.57	0	1.0865±0.0014	1.0892	0.1924
t23g12	0.90132	28.57	12000	0.9719±0.0012	0.9744	0.1995
tif2d4	0.90132	37.50	0	1.1409±0.0014	1.1437	0.1743
t24g12	0.90132	37.50	12000	1.0186±0.0013	1.0212	0.1871
tif2d5	0.90132	48.64	0	1.1999±0.0014	1.2027	0.1593
t25g12	0.90132	48.64	12000	1.0674±0.0013	1.0699	0.1823
t25g18	0.90132	48.64	18000	1.0294±0.0012	1.0317	0.1871
t25g30	0.90132	48.64	30000	0.9789±0.0007	0.9803	0.1977

As it can be seen, some combinations are extremely reactive, and the amounts of neutron absorber required to bring the k_{eff} below the criticality limit are excessive. Since the assumption used in this representation (homogeneous mixture of degraded products in WP) is very unlikely, a more realistic configuration was investigated (see Section 5.3.2).

6.2.2 The Products Resulting from the Degradation of the DOE SNF Canister Form a Layer at the Bottom of the WP (SNF intact)

The investigated arrangement (Figures 5-11 and 5-12) assures that the intact fuel will be surrounded by the degradation products resulting from DOE SNF canister components. Additional description of the cases is listed in Table 5-10. This configuration is a logical result of a subsequent degradation of the configuration depicted in Figure 5-2. Parametric studies similar to those presented in the above section have been performed for these configurations. The results presented in Tables 6-22 and 6-23 demonstrate that 8 kg of Gd (12.8 kg $GdPO_4$) is sufficient to keep the most reactive configuration below the criticality limit.

Table 6-22. Moderation Ratio for the Cases where the Intact Fuel Pins are Surrounded by the Degraded Components of the DOE SNF Canister Only

Pitch (cm)	H/X for Degraded Fe and Al with 28.57 vol.% of Water	H/X for Degraded Fe and Al with 37.50 vol.% of Water	H/X for Degraded Fe and Al with 50.00 vol.% of Water
0.40132	1.07E+00	1.16E+00	1.28E+00
0.90132	2.12E+01	2.30E+01	2.55E+01

Table 6-23. k_{eff} for the Cases where the Intact Fuel Pins are Surrounded by the Degraded Components of the DOE SNF Canister Only

File Name	Pitch (cm)	Vol.% of Water in Goethite and Diaspore Layer	Mass of Gd in the Goethite and Diaspore Layer (g)	$k_{eff}\pm\sigma$	$k_{eff}+2\sigma$	AENCF (MeV)
l15-4	0.40132	28.57	0	0.7098±0.0011	0.7119	0.6700
l25-4	0.90132	28.57	0	1.1013±0.0012	1.1038	0.1515
25-4g3k	0.90132	28.57	3000	0.8856±0.0013	0.8882	0.1894
l85-4	1.15132	28.57	0	1.1937±0.0014	1.1964	0.1023
85-4g3	1.15132	28.57	3000	0.7977±0.0011	0.7998	0.1524
l15-6	0.40132	37.50	0	0.7180±0.0011	0.7202	0.6562
l25-6	0.90132	37.50	0	1.1295±0.0013	1.1321	0.1459
25-6g3k	0.90132	37.50	3000	0.9024±0.0014	0.9053	0.1839
l85-6	1.15132	37.50	0	1.2169±0.0012	1.2193	0.0977
85-6g3	1.15132	37.50	3000	0.8161±0.0012	0.8186	0.1475
l15-10	0.40132	50.00	0	0.7268±0.0011	0.7290	0.6365
l25-10	0.90132	50.00	0	1.1632±0.0013	1.1657	0.1371
25-1035	0.90132	50.00	3500	0.9187±0.0009	0.9205	0.1772
25-10g3	0.90132	50.00	3000	0.9384±0.0013	0.9409	0.1716
l85-10	1.15132	50.00	0	1.2573±0.0013	1.2599	0.0926
85-10g3	1.15132	50.00	3000	0.8481±0.0012	0.8505	0.1394
l35-10	1.40132	50.00	0	1.2546±0.0012	1.2569	0.0718
35-10g3	1.40132	50.00	3000	0.7151±0.0012	0.7175	0.1278
tl14-4	0.40132	28.57	0	0.8337±0.0011	0.8359	0.7123
tl14-6	0.40132	37.50	0	0.8375±0.0012	0.8398	0.7028
tl14-10	0.40132	50.00	0	0.8468±0.0011	0.8491	0.6867
tl24-10	0.90132	50.00	0	1.2794±0.0013	1.2820	0.1353
tl20g7k	0.90132	50.00	7000	0.9280±0.0012	0.9304	0.1899
tl20g8k	0.90132	50.00	8000	0.9073±0.0012	0.9098	0.1937
tl208rw	0.90132	50.00	8000	0.9114±0.0012	0.9139	0.1925
tl208rs	0.90132	50.00	8000	0.9155±0.0013	0.9180	0.1897
tl20g9k	0.90132	50.00	9000	0.8934±0.0012	0.8958	0.1966
tl209r	0.90132	50.00	9000	0.9192±0.0012	0.9216	0.1900

6.2.3 Results for Fully Degraded DOE SNF Canister and WP Internal Structures

In order to analyze the configurations with completely degraded DOE SNF canister and WP internals (described in Section 5.3.2.3), a parametric study was performed to determine the optimum moderation and layout. A system similar to that presented in Figure 5.13 was used as a base case for the parametric study. The MCNP input files were constructed using data evaluated in spreadsheet “book2.xls” from Attachment V.

To study the effect of water content on the effective neutron multiplication factor, several cases were investigated considering different volume fractions of water mixed with the layers. Table 6-24 and Table 6-25 show the results of these calculations. The base configuration assumes that the fuel (UO_2) mixture with diaspore (“mix-fuel”) preserves the initial footprint of the fuel. No neutron absorber is considered in these cases.

Table 6-24. Results for Various Volume Fractions of Water in Layers

Case Name	Volume Fraction of Water in Mix-Fuel Layer	Volume Fraction of Water in FeOOH Layer	Volume Fraction of Water in Clay Layer	$k_{eff}\pm\sigma$	$k_{eff}+2\sigma$	H/X	AENCF (MeV)
inp00	0	0	0	0.8714±0.0010	0.8734	6.5274	0.3255
inp10	0.0909	0.10	0.10	0.9143±0.0011	0.9165	8.8653	0.2823
inp20	0.1667	0.20	0.20	0.9583±0.0011	0.9605	11.2032	0.2467
inp30	0.2308	0.30	0.30	0.999±0.0012	1.0014	13.5411	0.2196
inp40	0.2857	0.40	0.40	1.0345±0.0013	1.0371	15.8789	0.1971
inp344	0.35	0.40	0.40	1.0776±0.0012	1.0800	19.1160	0.1737
inp444	0.4118	0.40	0.40	1.1239±0.0012	1.1263	22.8926	0.1535
inp644	0.6667	0.40	0.40	1.1163±0.0013	1.1189	29.9062	0.0639

Table 6-25. Additional Results for Various Volume Fractions of Water in Layers

Case Name	Volume Fraction of Water in Mix-Fuel Layer	Volume Fraction of Water in FeOOH Layer	Volume Fraction of Water in Clay Layer	$k_{eff}\pm\sigma$	$k_{eff}+2\sigma$	H/X	AENCF (MeV)
inp001	0	0	0	0.8721±0.0011	0.8743	6.5274	0.3244
inp011	0	0.10	0.10	0.8651±0.0011	0.8673	6.5274	0.3270
inp012	0	0.20	0.20	0.8638±0.0010	0.8658	6.5274	0.3271
inp123	0.0909	0.30	0.30	0.9122±0.0012	0.9146	8.8653	0.2371
inp234	0.1667	0.40	0.40	0.9580±0.0011	0.9591	11.2032	0.2464

As expected, the results from Tables 6-24 and 6-25 show that addition of water in the layers that have no fuel decreases the reactivity of the system. An optimum moderation for this configuration was found for a volume fraction of water in the mix-fuel layer close to 0.41.

A similar type of parametric evaluation was performed by varying the volume fraction of goethite that is mixed with the fuel mixture. All layers were kept dry and the footprint of the fuel mixture was preserved. The results are listed in Table 6-26.

Table 6-26. Results for Different FeOOH Volume Fractions in the Fuel Mixture

Case Name	Volume Fraction of FeOOH in Mix-Fuel	$k_{eff}\pm\sigma$	$k_{eff}+2\sigma$	H/X	AENCF (MeV)
inp+20	0.2413	0.9378±0.0011	0.9400	9.746	0.2426
inp+40	0.3888	0.9768±0.0011	0.9790	12.965	0.1999
inp+60	0.4883	1.0176±0.0011	1.0198	16.183	0.1660
inp+80	0.5599	1.0602±0.0011	1.0624	19.402	0.1418

The series of the dry cases were continued using the most reactive case from Table 6-26 and mixing the layers above the fuel mixture. The results for these cases are included in Table 6-27. Two additional cases were run to evaluate a reduced fuel mixture length (114 cm) and the effect of a reflective boundary at the WP outer surface.

Table 6-27. Results on Effect of Mixing Clay with Goethite

Case Name	Volume Fraction of FeOOH in Mix-Fuel Layer	Volume Fraction of Clay in FeOOH Layer	$k_{eff}\pm\sigma$	$k_{eff}+2\sigma$	H/X	AENCF (MeV)
inp+81	0.5599	0.10	1.0590±0.0011	1.0612	19.402	0.14217
inp+81L114 (reduced length)	0.5599	0.10	1.1236±0.0011	1.1258	19.402	0.1418
inp+82	0.5599	0.20	1.0569±0.0011	1.0591	19.402	0.1424
inp+83	0.5599	0.30	1.0577±0.0011	1.0599	19.402	0.1425
inp+83R (reflected b.c.)	0.5599	0.30	1.1300±0.0011	1.1322	19.402	0.1334
inp+84	0.5599	0.40	1.0541±0.0011	1.0563	19.402	0.1433

It can be noticed that mixing the layer above the fuel mixture has a minor influence on k_{eff}. A subsequent step in the parametric evaluation was the addition of water in the most reactive case from Table 6-26. The water was added in all three layers, trying to simulate the most likely configuration. The density of the mixtures was checked to preserve the higher density layers at the bottom. The length of the fuel slurry was kept equal to that of the initial fuel footprint for the first case but was increased to 194.94 cm for the next cases to accommodate the expanded volume of the fuel slurry. The amount of goethite in the mixture is constant for all cases. The results for these cases are summarized in Table 6-28.

Table 6-28. Effect of Water Addition to the Fuel Mixture Containing FeOOH

Case Name	Volume Fraction of FeOOH in Mix-Fuel layer	Volume Fraction of Water in Mix-Fuel Layer	Volume Fraction of Water in FeOOH Layer	Volume Fraction of Water in Clay Layer	$k_{eff}\pm\sigma$	$k_{eff}+2\sigma$	H/X	AENCF (MeV)
inp8012	0.5599	0	0.10	0.10	1.0411±0.0012	1.0435	19.402	0.1460
inp8123	0.4311	0.2301	0.20	0.20	1.1383±0.0011	1.1405	27.339	0.0969
inp8234	0.3504	0.3741	0.30	0.30	1.2364±0.0012	1.2388	35.276	0.0727

A configuration with the fuel mixture containing all goethite and placed on top of the clay (Figure 5-14) was also investigated. The length of the fuel mixture is equal to the WP length. The results are included in Table 6-29.

Table 6-29. Results for Configuration with Clay on the Bottom and Fuel Mixture with FeOOH on Top

Case Name	Volume Fraction of FeOOH in Mix-Fuel layer	Volume Fraction of Water in Mix-Fuel Layer	k_{eff}±σ	k_{eff}+2σ	H/X	AENCF (MeV)
inp10-0	0.83	0	0.8409±0.0011	0.8431	54.191	0.0568
inp10-10	0.74	0.11	0.8982±0.0011	0.9004	70.065	0.0490
inp10-50	0.55	0.33	0.9077±0.0011	0.9099	120.934	0.0490

This configuration is significantly less reactive than the configuration with the fuel mixture at the bottom and was excluded from the subsequent analyses. Extensive sets of calculations were performed for the most likely configurations. These arrangements assume a full mixture of UO_2 with diaspore and goethite at the bottom of the WP along its full length. The results are presented in Table 6-30.

Table 6-30. Results for Configurations with Fuel Mixture (excepting clay) at the Bottom of WP

Case Name	Volume Fraction of FeOOH in Mix-Fuel Layer	Volume Fraction of Water in Mix-Fuel Layer	Volume Fraction of Water in Clay Layer	k_{eff}±σ	k_{eff}+2σ	H/X	AENCF (MeV)
inp10-0	0.825	0	0.0	1.0586±0.0010	1.0606	54.191	0.6600
inp10-1	0.825	0	0.10	1.0496±0.0010	1.0516	54.191	0.6596
inp111	0.750	0.091	0.10	1.0955±0.0011	1.0977	67.540	0.0521
inp121	0.687	0.167	0.10	1.1350±0.0011	1.1372	80.888	0.0456
inp131	0.635	0.231	0.10	1.1657±0.0011	1.1679	94.237	0.0404
inp141	0.589	0.286	0.10	1.1933±0.0010	1.1953	107.586	0.0365
inp151	0.550	0.333	0.20	1.2111±0.0010	1.2131	120.934	0.0336
inp161	0.516	0.375	0.30	1.2230±0.0009	1.2248	134.283	0.0316
inp174	0.485	0.412	0.40	1.2393±0.0010	1.2413	147.631	0.0288
inp185	0.458	0.444	0.50	1.2560±0.0009	1.2578	160.980	0.0271
inp195	0.434	0.474	0.50	1.2607±0.0010	1.2627	174.329	0.0254
inp1106	0.412	0.500	0.60	1.2682±0.0010	1.2702	187.677	0.0240
inp1159	0.402	0.512	0.90	1.2610±0.0010	1.2630	194.351	0.0235

The results from Table 6-30 show a maximum in k_{eff} obtained for an optimum moderation in the system. This case was used to identify the minimum amount of neutron absorber necessary to bring the effective neutron multiplication factor of the system below the criticality limit (0.93). Table 6-31 contains the results for two amounts of gadolinium phosphate dispersed in the mix-fuel slurry. The water content of the slurry is varied to check the effectiveness of the neutron absorber, and the goethite amount is kept constant. Table 6-31 results show that 0.94 kg of Gd (1.5 kg $GdPO_4$) are sufficient to keep the system below criticality limit of 0.93 for all H/X ratios.

Table 6-31. Impact of Gadolinium Phosphate as Neutron Absorber on k_{eff}

Case Name	Volume Fraction of FeOOH in Mix-Fuel Layer	Volume Fraction of Water in Mix-Fuel Layer	Gadolinium Content (g)	k_{eff}±σ	k_{eff}+2σ	H/X	AENCF (MeV)
inp152	0.374	0.545	935	0.8954±0.0009	0.8972	214.37	0.0309
inp151	0.392	0.523	935	0.8951±0.0009	0.8969	201.03	0.0324
inp150	0.412	0.500	935	0.8943±0.0008	0.8959	187.68	0.0340
inp59	0.434	0.473	935	0.8931±0.0008	0.8947	174.33	0.0357
inp58	0.458	0.444	935	0.8915±0.0009	0.8933	160.98	0.0382
inp57	0.485	0.411	935	0.8910±0.0008	0.8926	147.63	0.0404
inp56	0.515	0.375	935	0.8877±0.0009	0.8895	134.28	0.0427
inp55	0.549	0.333	935	0.8807±0.0009	0.8825	120.93	0.0457
inp11	0.392	0.524	10597	0.3706±0.0003	0.3712	201.03	0.0797
inp10	0.412	0.500	10597	0.3789±0.0003	0.3795	187.68	0.0799
inp9	0.434	0.473	10597	0.4084±0.0003	0.4090	174.33	0.0443
inp0	0.824	0	10597	0.5435±0.0005	0.5445	54.19	0.0690

Using one of the most likely cases from above (input file "inp152"), the influence of the slurry length on k_{eff} was reassessed. The results are listed in Table 6-32.

Table 6-32. Impact of Slurry Length on k_{eff}

Case Name	Slurry Length (cm)	Gadolinium Content (g)	k_{eff}±σ	k_{eff}+2σ	H/X	AENCF (MeV)
inp200L	200	935	0.9298±0.0009	0.9316	214.37	0.0328
inp154L	154.94	935	0.9424±0.0009	0.9442	214.37	0.0320
inp100L	100	935	0.9549±0.0008	0.9565	214.37	0.0323
inp80L	80	935	0.9563±0.0008	0.9579	214.37	0.0322

Keeping the slurry length to 80 cm, two other conservative conditions have been evaluated. First one applies reflective boundary conditions and the second one considers replacement of U-238 with void. The results are listed in Table 6-33.

Table 6-33. Impact of Reflective Boundary Conditions and U-238 Removal on k_{eff}

Case Name	Description	Gadolinium Content (g)	k_{eff}±σ	k_{eff}+2σ	H/X	AENCF (MeV)
inp80L	Base case (slurry length =80 cm)	935	0.9563±0.0008	0.9579	214.37	0.0322
inp80LR	Reflective boundary	935	0.9610±0.0009	0.9638	214.37	0.0322
inp80L-U238	No U-238	935	1.0218±0.0009	1.0236	214.37	0.0150
inp80LNU238	No U-238	3584	0.6356±0.0006	0.6368	214.37	0.0239
inp80LNU+G	No U-238	11500	0.3994±0.0003	0.4000	214.37	0.0377

It can be seen than no more than 3.5 kg of Gd is sufficient to keep the most reactive configuration from this group well below a k_{eff} of 0.9.

After 250,000 years, all materials present inside WP are degraded to clay (post-breach clay). Its composition was used to construct a set of cases in which the clay is mixed with various fractions of water. The post-breach clay composition is listed on the spreadsheet "Book2.xls" (Attachment V).

Table 6-34. Results for Configurations with Post-breach Clay

Case Name	Water Fraction	k_{eff}±σ	k_{eff}±2σ	H/X	AENCF (MeV)
inpPostB	0	0.3988±0.0004	0.3996	0.012	0.0458
inpPostB+1	0.09	0.3883±0.0004	0.3891	189.62	0.0384
inpPostB+2	0.17	0.3735±0.0004	0.3743	379.12	0.0330
inpPostB+3	0.29	0.3622±0.0003	0.3630	758.12	0.0298

No additional gadolinium is necessary for this configuration.

7. REFERENCES

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8. ATTACHMENTS

Five attachments are referenced in this calculation. A brief description of each attachment follows.

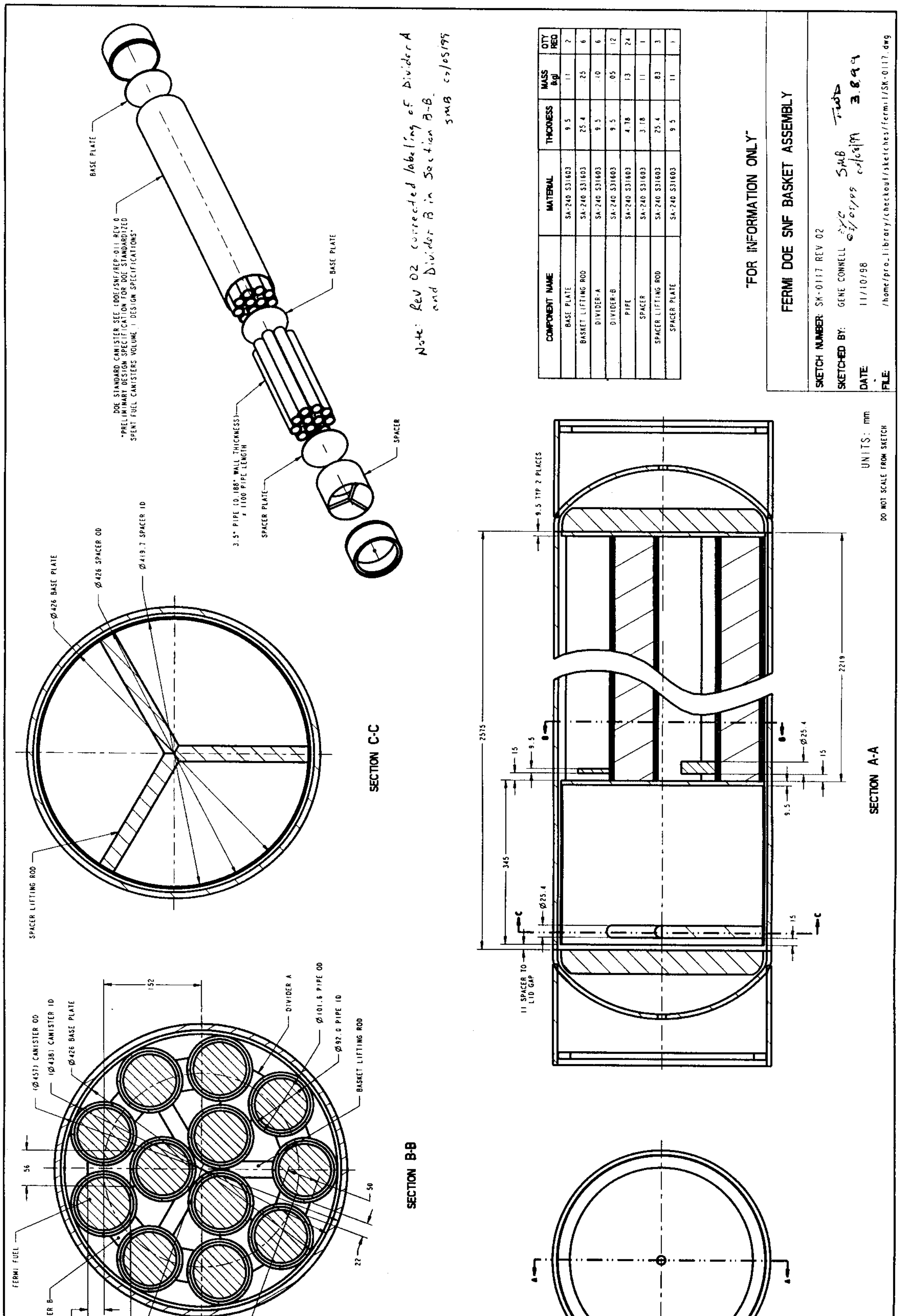
Attachment I (Sketch SK-0117 REV 02) shows a sketch of the DOE Enrico Fermi fuel basket assembly.

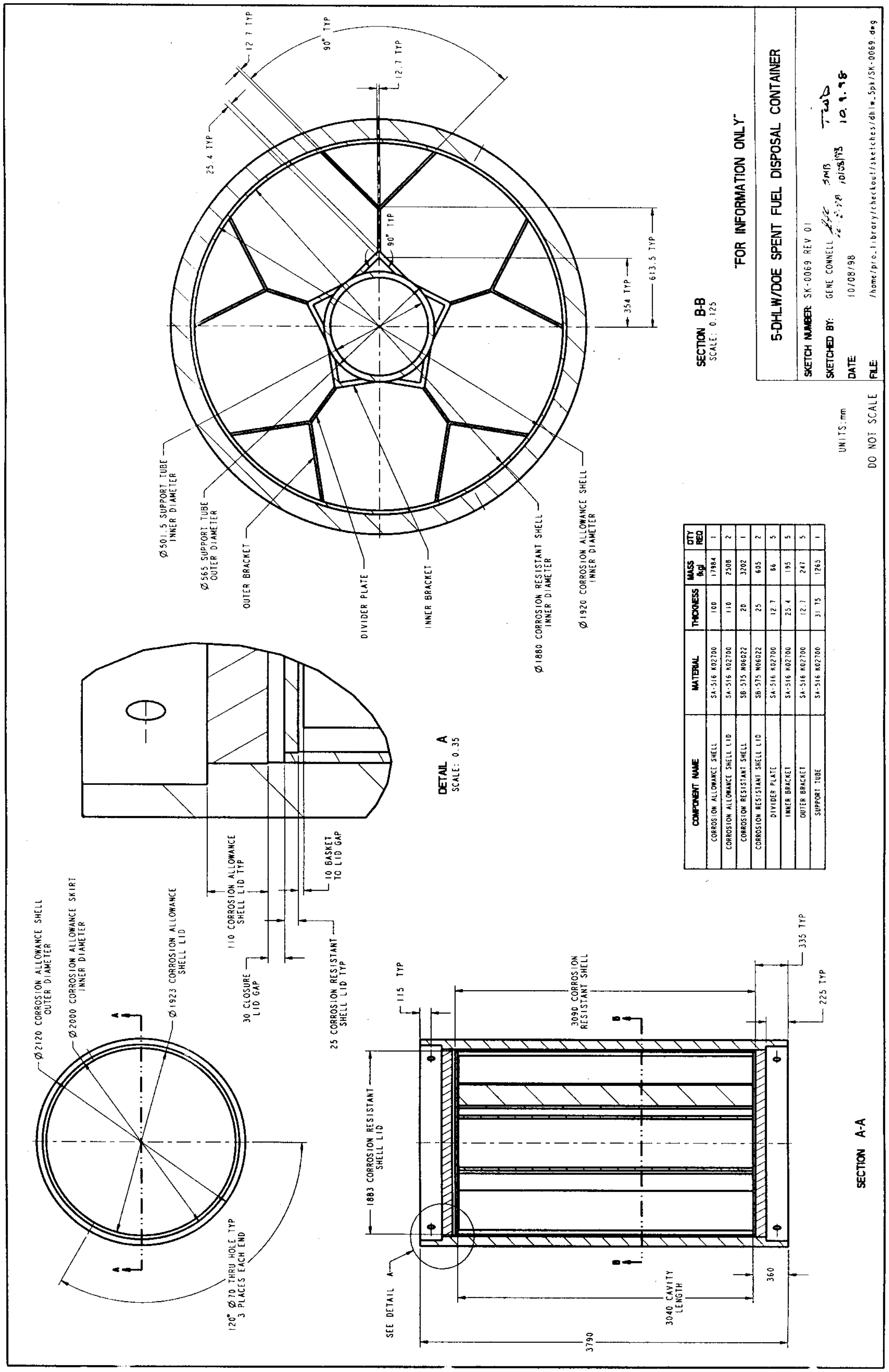
Attachment II (Sketch SK-0069 REV 01) shows a sketch of the 5-DHLW/DOE SNF disposal container.

Attachment III shows a sketch of the 18-inch OD DOE standardized SNF canister, referred to as the DOE SNF 18-inch canister (Ref. 6, p.12). The short canister, with an internal length of 2575 mm and an external length of 2999 mm, is utilized for the codisposal of the Enrico Fermi SNF.

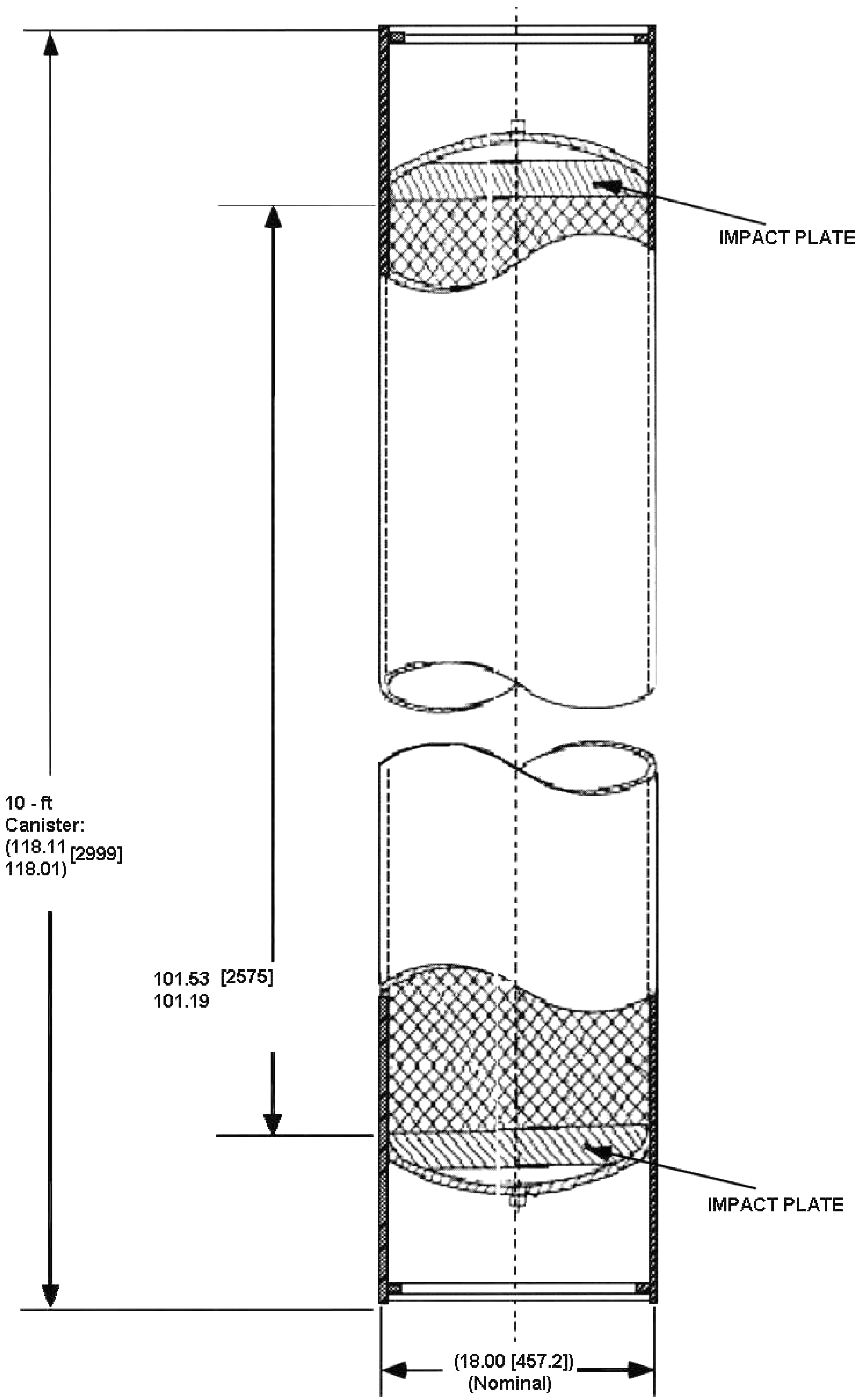
Attachment IV lists the electronic files that are contained on compact disk (CD) (Attachment V). The MCNP input and output files are the actual listings of the cases evaluated. The spreadsheet files were used to perform the necessary supporting calculations such as number densities, mass densities, and volumetric calculation. The calculated values were used as input data for the MCNP cases evaluated.

Attachment V contains on CD the electronic files listed in Attachment IV.


"FOR INFORMATION ONLY"
FERMI DOE SNF BASKET ASSEMBLY
SKETCH NUMBER: SK-0117 REV 02
SKETCHED BY: GENE CONNELL
DATE: 11/10/98
FILE: /home/pro_library/checkout/sketches/fermi1/SK-0117.dwg
COMPONENT NAME | MATERIAL | THICKNESS | MASS (kg) | QTY REQ
BASE PLATE | SA-240 S31603 | 9.5 | 11 | 2
BASKET LIFTING ROD | SA-240 S31603 | 25.4 | 25 | 6
DIVIDER-A | SA-240 S31603 | 9.5 | 10 | 6
DIVIDER-B | SA-240 S31603 | 9.5 | 05 | 12
PIPE | SA-240 S31603 | 4.78 | 13 | 24
SPACER | SA-240 S31603 | 3.18 | 11 | 1
SPACER LIFTING ROD | SA-240 S31603 | 25.4 | 83 | 3
SPACER PLATE | SA-240 S31603 | 9.5 | 11 | 1
UNITS: mm
DO NOT SCALE FROM SKETCH
SECTION A-A
SECTION B-B
SECTION C-C
BASE PLATE
SPACER
SPACER PLATE
SPACER LIFTING ROD
DIVIDER A
DIVIDER B
FERMI FUEL
BASKET LIFTING ROD
Ø426 BASE PLATE
Ø426 SPACER OD
Ø419.7 SPACER ID
Ø101.6 PIPE OD
Ø92.0 PIPE ID
(Ø457) CANISTER OD
(Ø438) CANISTER ID
3.5" PIPE (0.188" WALL THICKNESS) × 1100 PIPE LENGTH
DOE STANDARD CANISTER SEE (DOE/SNF/REP-011 REV 0 "PRELIMINARY DESIGN SPECIFICATION FOR DOE STANDARDIZED SPENT FUEL CANISTERS VOLUME 1 DESIGN SPECIFICATIONS")
11 SPACER TO LID GAP
9.5 TYP 2 PLACES
2575
2219
345
152
Note: Rev 02 corrected labeling of Divider A and Divider B in Section B-B.



COMPONENT NAME	MATERIAL	THICKNESS	MASS (kg)	QTY REQ
CORROSION ALLOWANCE SHELL	SA-516 K02700	100	17984	1
CORROSION ALLOWANCE SHELL LID	SA-516 K02700	110	2508	2
CORROSION RESISTANT SHELL	SB-575 N06022	20	3202	1
CORROSION RESISTANT SHELL LID	SB-575 N06022	25	605	2
DIVIDER PLATE	SA-516 K02700	12.7	66	5
INNER BRACKET	SA-516 K02700	25.4	195	5
OUTER BRACKET	SA-516 K02700	12.7	247	5
SUPPORT TUBE	SA-516 K02700	31.75	1265	1


IMPACT PLATE
10 - ft
Canister:
(118.11 [2999]
118.01)
101.53 [2575]
101.19
IMPACT PLATE
(18.00 [457.2])
(Nominal)

Attachment IV

This attachment provides a hardcopy listing of the contents of the CD, as provided in Table IV-1. The CD contains MCNP input files, MCNP output files, and Excel spreadsheets used in this calculation. The MCNP input and output files were transferred from a Hewlett Packard (HP) Series 9000 workstation to a Pentium Personal Computer using a file transfer protocol (FTP). The HP file sizes differ from the file sizes on the CD due to the difference in block sizes between the HP and the personal computer.

Table IV-1 Contents of the CD

Directory: **input**

Subdirectory: **table6-1**

File Name	*Size (Bytes)*	*Date and Time Last Accessed*
icpa00n	9,278	05-08-00 8:14a
icpa02n	9,284	05-03-00 8:57a
icpa03n	9,280	05-03-00 8:57a
icpa04n	9,288	05-03-00 8:57a

table6-2

circ00n	9,404	05-03-00 8:53a
circ02n	9,405	05-03-00 8:53a
circ04n	9,398	05-03-00 8:53a
circ05n	9,405	05-03-00 8:54a

table6-3

cial00n	9,817	05-03-00 8:52a
cial02n	9,818	05-03-00 8:53a
cial04n	9,817	05-03-00 8:53a
cial05n	9,818	05-03-00 8:53a

table6-4

cial00z	10,094	05-03-00 8:54a
cial02z	17,967	05-03-00 8:54a
cial04z	10,084	05-03-00 8:54a
cial05z	10,012	05-03-00 8:54a

table6-5

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gd02-3z        18,085  05-03-00  8:54a
gd02-4z        18,086  05-03-00  8:54a
gd02-5z        18,085  05-03-00  8:54a
gd02-9z        18,129  07-06-00  9:08a
gd04-2z        10,217  05-03-00  8:54a
gd04-3z        10,217  05-03-00  8:55a
gd04-4z        10,217  05-03-00  8:55a
gd04-5z        10,215  05-03-00  8:55a
gd04-9z        10,356  07-06-00  9:08a
gd05-1z        10,156  05-03-00  8:55a
gd05-2z        10,157  05-03-00  8:55a
gd05-3z        10,156  05-03-00  8:56a
gd05-4z        10,158  05-03-00  8:56a
gd05-5z        10,156  05-03-00  8:56a
gd05-9z        10,298  07-06-00  9:08a
```

table6-6

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gd02-95        17,760  07-06-00  9:07a
gd04-95        10,296  07-06-00  9:08a
gd05-3a        10,225  05-03-00  8:55a
gd05-3i        14,016  05-03-00  8:55a
gd05-3j        13,949  05-03-00  8:55a
gd05-3w        10,242  07-06-00  9:29a
gd05-3z        10,156  05-03-00  8:56a
gd05-95        10,237  07-06-00  9:08a
```

table6-7

```
gd04-5s        10,259  05-03-00  8:55a
gd05-4s        10,219  05-03-00  8:56a
```

table6-8

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gd04-5v        10,247  05-03-00  8:55a
gd04-9v        10,247  05-03-00  8:55a
gd0410v        10,251  05-03-00  8:55a
gd05-3v        10,237  05-03-00  8:56a
gd05-4v        10,239  05-03-00  8:56a
gd05-5v        10,238  05-03-00  8:56a
gd05-6v        10,236  05-03-00  8:56a
```

table6-9

p-3a	16,791	07-06-00	9:08a
p-3b	16,668	07-06-00	9:08a
p-3c	16,647	07-06-00	9:08a
p-3d	16,648	07-06-00	9:08a
p-3e	16,648	07-06-00	9:08a
p-3f	16,666	07-06-00	9:09a
p-4a	16,851	07-06-00	9:09a
p-4b	16,718	07-06-00	9:09a
p-4c	16,700	07-06-00	9:09a
p-4d	16,701	07-06-00	9:09a
p-4e	16,701	07-06-00	9:09a
p-4f	16,712	07-06-00	9:09a
p-6a	16,837	07-06-00	9:09a
p-6b	16,718	07-06-00	9:09a
p-6c	16,700	07-06-00	9:09a
p-6d	16,701	07-06-00	9:09a
p-6e	16,701	07-06-00	9:10a
p-6f	16,719	07-06-00	9:10a

table6-10

p-6f	16,719	07-06-00	9:10a
p-6fs	16,775	07-06-00	9:10a
p-6fv	16,791	07-06-00	9:10a
p-9fv	16,814	07-06-00	9:10a

table6-11

r-6a	17,154	07-06-00	9:10a
r-6b	17,257	07-06-00	9:10a
r-6d	17,240	07-06-00	9:12a
r-6e	17,243	07-06-00	9:12a
r-6f	17,153	07-06-00	9:12a
r-9a	17,118	07-06-00	9:13a
r-9b	17,257	07-06-00	9:13a
r-9d	17,240	07-06-00	9:13a
r-9e	17,245	07-06-00	9:13a
r-9f	17,151	07-06-00	9:13a

table6-12

r-6b	17,257	07-06-00	9:10a
r-6bnw	17,229	07-06-00	9:10a
r-6brf	17,294	07-06-00	9:12a

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r-6bsh              17,341  07-06-00  9:12a
r-6bt               16,986  07-06-00  9:12a
r-6bv               17,328  07-06-00  9:12a
r-9b                17,257  07-06-00  9:13a
r-9bt               16,979  07-06-00  9:13a
r-9bv               17,282  07-06-00  9:13a
```

table6-13

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df1                  7,974  07-06-00 11:05a
df2                  8,077  07-06-00 11:05a
df3                  8,067  07-06-00 11:05a
df4                  8,073  07-06-00 11:05a
df5                  8,064  07-06-00 11:05a
df51                 8,192  07-06-00 11:05a
df52                 8,192  07-06-00 11:05a
df53                 8,186  07-06-00 11:05a
df54                 8,320  07-06-00 11:05a
```

table6-14

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dfa1                 8,167  07-06-00 11:05a
dfa2                 8,169  07-06-00 11:05a
dfa3                 8,168  07-06-00 11:05a
dfa31                8,128  07-06-00 11:05a
dfa32                8,123  07-06-00 11:05a
dfa33                8,123  07-06-00 11:05a
dfa34                8,129  07-06-00 11:05a
dfa4                 8,129  07-06-00 11:05a
dfa41                8,125  07-06-00 11:05a
dfa42                8,120  07-06-00 11:05a
dfa43                8,120  07-06-00 11:05a
dfa44                8,125  07-06-00 11:05a
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table6-15

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dfab1gd              8,313  07-06-00 11:05a
dfam1gd              8,489  07-06-00 11:05a
dfat1gd              8,474  07-06-00 11:05a
```

table6-16

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dfab1gd10w           8,374  07-06-00 11:05a
dfab81gd             8,332  07-06-00 11:05a
dfabh1gd             8,291  07-06-00 11:05a
dfabr1gd             8,357  07-06-00 11:05a
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table6-17

d03gd	8,311	07-06-00	11:05a
da13gd	8,353	07-06-00	11:05a
dfa13gd	8,341	07-06-00	11:05a
dfa23gd	8,343	07-06-00	11:05a
dfa33gd	8,341	07-06-00	11:05a
dfa413gd	8,315	07-06-00	11:05a
dfa423gd	8,312	07-06-00	11:05a
dfa433gd	8,319	07-06-00	11:05a
dfa43gd	8,302	07-06-00	11:05a
dfa443gd	8,318	07-06-00	11:05a

table6-18

dfab3gd	8,318	07-06-00	11:05a
dfam3gd	8,349	07-06-00	11:05a
dfat3gd	8,317	07-06-00	11:05a

table6-19

dfab3gd10w	8,420	07-06-00	11:05a
dfab3gd1w	8,418	07-06-00	11:06a
dfab83gd	8,303	07-06-00	11:06a
dfab85gd	8,303	07-06-00	11:06a
dfabh3gd	8,261	07-06-00	11:06a
dfabhw3gd	8,194	07-06-00	11:06a
dfabr3gd	8,323	07-06-00	11:06a

table6-21

23g4k	4,541	04-25-00	5:11p
24g9k	4,595	04-25-00	5:11p
25g10	4,540	04-25-00	5:11p
25g18k	4,541	04-25-00	5:11p
32g4k	4,542	04-25-00	5:11p
33g3k	4,546	04-25-00	5:11p
33g6k	4,546	04-25-00	5:11p
34g3k	4,598	04-25-00	5:11p
34g7k	4,598	04-25-00	5:11p
35g9k	4,541	04-25-00	5:11p
72g3k	4,544	04-25-00	5:11p
73g3k	4,546	04-25-00	5:11p
74g35k	4,597	04-25-00	5:11p
75g3k	4,541	04-25-00	5:11p

```
75g5k                  4,541  04-25-00  5:11p
82g3k                  4,541  04-25-00  5:11p
83g10                  4,537  04-25-00  5:11p
83g5k                  4,537  04-25-00  5:11p
84g10                  4,595  04-25-00  5:11p
85g10                  4,538  04-25-00  5:11p
85g18                  4,538  04-25-00  5:11p
t22g10                 4,586  04-25-00  5:11p
t22g12                 4,586  04-25-00  5:11p
t23g12                 4,587  04-25-00  5:11p
t24g12                 4,646  04-25-00  5:11p
t25g12                 4,581  04-25-00  5:11p
t25g18                 4,581  04-25-00  5:11p
t25g30                 4,581  04-25-00  5:11p
tif1d1                 4,463  04-25-00  5:11p
tif1d2                 4,550  04-25-00  5:11p
tif1d3                 4,552  04-25-00  5:11p
tif1d4                 4,605  04-25-00  5:11p
tif1d5                 4,548  04-25-00  5:11p
tif2d1                 4,548  04-25-00  5:11p
tif2d2                 4,553  04-25-00  5:11p
tif2d3                 4,555  04-25-00  5:11p
tif2d4                 4,611  04-25-00  5:11p
tif2d5                 4,548  04-25-00  5:11p
wif1d1                 4,512  04-25-00  5:11p
wif1d2                 4,511  04-25-00  5:11p
wif1d3                 4,513  04-25-00  5:11p
wif1d4                 4,563  04-25-00  5:11p
wif1d5                 4,508  04-25-00  5:11p
wif2d1                 4,509  04-25-00  5:11p
wif2d2                 4,509  04-25-00  5:11p
wif2d3                 4,508  04-25-00  5:11p
wif2d4                 4,560  04-25-00  5:11p
wif2d5                 4,507  04-25-00  5:11p
wif3d1                 4,516  04-25-00  5:11p
wif3d2                 4,509  04-25-00  5:11p
wif3d3                 4,513  04-25-00  5:11p
wif3d4                 4,563  04-25-00  5:11p
wif3d5                 4,508  04-25-00  5:12p
wif7d1                 4,506  04-25-00  5:12p
wif7d2                 4,511  04-25-00  5:12p
wif7d3                 4,513  04-25-00  5:12p
wif7d4                 4,562  04-25-00  5:12p
wif7d5                 4,508  04-25-00  5:12p
wif8d1                 4,508  04-25-00  5:12p
wif8d2                 4,508  04-25-00  5:12p
```

```
wif8d3              4,504  04-25-00  5:12p
wif8d4              4,560  04-25-00  5:12p
wif8d5              4,505  04-25-00  5:12p
```

table6-23

```
25-1035             5,255  04-25-00  5:13p
25-10g3             5,256  04-25-00  5:13p
25-4g3k             5,253  04-25-00  5:13p
25-6g3k             5,240  04-25-00  5:13p
35-10g3             5,263  04-25-00  5:13p
85-10g3             5,255  04-25-00  5:13p
85-4g3              5,250  04-25-00  5:13p
85-6g3              5,235  04-25-00  5:13p
l15-10              5,226  04-25-00  5:13p
l15-4               5,220  04-25-00  5:13p
l15-6               5,212  04-25-00  5:13p
l25-10              5,223  04-25-00  5:13p
l25-4               5,220  04-25-00  5:13p
l25-6               5,206  04-25-00  5:13p
l35-10              5,225  04-25-00  5:13p
l85-10              5,223  04-25-00  5:13p
l85-4               5,220  04-25-00  5:13p
l85-6               5,206  04-25-00  5:13p
tl14-10             5,247  04-25-00  5:13p
tl14-4              5,248  04-25-00  5:13p
tl14-6              5,244  04-25-00  5:13p
tl208rs             5,578  04-25-00  5:13p
tl208rw             5,605  04-25-00  5:13p
tl209r              5,350  06-30-00  9:27a
tl20g7k             5,241  04-25-00  5:13p
tl20g8k             5,241  04-25-00  5:13p
tl20g9k             5,241  06-30-00  9:27a
tl24-10             5,242  04-25-00  5:13p
```

table6-24

```
inp00               5,245  05-08-00  5:25p
inp10               5,382  05-08-00  5:25p
inp20               5,396  05-08-00  5:25p
inp30               5,396  05-08-00  5:25p
inp344              5,414  05-08-00  8:31p
inp40               5,405  05-08-00  5:25p
inp444              5,405  05-08-00  5:25p
inp644              5,407  05-08-00  5:25p
```

table6-25

```
inp001                    5,383  05-08-00  5:25p
inp011                    5,399  05-08-00  5:25p
inp012                    5,422  05-08-00  5:25p
inp123                    5,460  05-08-00  5:25p
inp234                    5,459  05-08-00  5:25p
```

table6-26

```
inp+20                    5,325  05-08-00  5:25p
inp+40                    5,323  05-08-00  5:25p
inp+60                    5,323  05-08-00  5:25p
inp+80                    5,323  05-08-00  5:25p
```

table6-27

```
inp+81                    6,369  05-08-00  5:24p
inp+81L114                6,385  05-08-00  5:24p
inp+82                    6,369  05-08-00  5:24p
inp+83                    6,352  05-08-00  5:24p
inp+83R                   6,352  05-08-00  5:24p
inp+84                    6,353  05-08-00  5:25p
```

table6-28

```
inp8012                   5,423  05-08-00  5:25p
inp8123                   5,485  05-08-00  5:25p
inp8234                   5,486  05-08-00  5:25p
```

table6-29

```
inp10-0                   4,846  05-08-00  5:24p
inp10-10                  4,897  05-08-00  5:24p
inp10-50                  4,899  05-08-00  5:24p
```

table6-30

```
inp10-0                   4,823  05-08-00  5:24p
inp10-1                   4,869  05-08-00  5:24p
inp1106                   4,940  05-08-00  5:24p
inp111                    4,913  05-08-00  5:24p
inp1159                   4,939  05-08-00  5:24p
inp121                    4,913  05-08-00  5:24p
inp131                    4,923  05-08-00  5:24p
inp141                    4,922  05-08-00  5:24p
```

```
inp151              4,935  05-08-00  5:24p
inp161              4,935  05-08-00  5:24p
inp174              4,935  05-08-00  5:24p
inp185              4,935  05-08-00  5:24p
inp195              4,935  05-08-00  5:24p
```

table6-31

```
inp0                4,993  05-08-00  5:24p
inp10               5,015  05-08-00  5:24p
inp11               5,015  05-08-00  5:24p
inp150              5,019  05-08-00  5:24p
inp151              5,019  05-08-00  5:24p
inp152              5,018  05-08-00  5:24p
inp55               5,015  05-08-00  5:24p
inp56               5,015  05-08-00  5:24p
inp57               5,015  05-08-00  5:24p
inp58               5,019  05-08-00  5:24p
inp59               5,019  05-08-00  5:24p
inp9                5,009  05-08-00  5:24p
```

table6-32

```
inp100L             5,113  05-08-00  5:24p
inp154L             5,121  05-08-00  5:24p
inp200L             5,123  05-08-00  5:24p
inp80L              5,114  05-08-00  5:24p
```

table6-33

```
inp80L-U238         5,093  05-08-00  5:24p
inp80LNU+G          5,113  05-08-00  5:24p
inp80LNU238         5,110  05-08-00  5:24p
inp80LR             5,115  05-08-00  5:24p
```

table6-34

```
inpPostB            4,851  05-08-00  5:24p
inpPostB+1          4,893  05-08-00  5:24p
inpPostB+2          4,902  05-08-00  5:24p
InpPostB+3          4,910  05-08-00  5:24p
```

Directory: **output**

Subdirectory: **table6-1**

```
icpa00no            371,436  05-03-00  8:56a
icpa02no            371,990  05-03-00  8:57a
icpa03no            371,827  05-03-00  8:57a
icpa04no            372,039  05-03-00  8:57a
```

table6-2

```
circ00no            379,860  05-03-00  8:53a
circ02no            379,493  05-03-00  8:53a
circ04no            379,621  05-03-00  8:54a
circ05no            379,493  05-03-00  8:54a
```

table6-3

```
cial00no            381,202  05-03-00  8:53a
cial02no            465,434  05-03-00  8:53a
cial04no            381,905  05-03-00  8:53a
cial05no            465,072  05-03-00  8:53a
```

table6-4

```
cial00zo            389,676  05-03-00  8:54a
cial02zo            471,474  05-03-00  8:54a
cial04zo            389,399  05-03-00  8:54a
cial05zo            389,030  05-03-00  8:54a
```

table6-5

```
gd02-3zo            473,395  05-03-00  8:54a
gd02-4zo            472,679  05-03-00  8:54a
gd02-5zo            474,015  05-03-00  8:54a
gd02-9zo            473,745  07-06-00  9:08a
gd04-2zo            390,630  05-03-00  8:54a
gd04-3zo            390,373  05-03-00  8:55a
gd04-4zo            390,840  05-03-00  8:55a
gd04-5zo            390,155  05-03-00  8:55a
gd04-9zo            390,696  07-06-00  9:08a
gd05-1zo            390,584  05-03-00  8:55a
gd05-2zo            390,152  05-03-00  8:55a
gd05-3zo            390,716  05-03-00  8:56a
gd05-4zo            390,631  05-03-00  8:56a
gd05-5zo            390,708  05-03-00  8:56a
```

```
gd05-9zo            390,887  07-06-00  9:08a
```

table6-6

```
gd02-95o            474,047  07-06-00  9:07a
gd04-95o            390,843  07-06-00  9:08a
gd05-3ao            390,644  05-03-00  8:55a
gd05-3io            490,898  05-03-00  8:55a
gd05-3jo            488,851  05-03-00  8:56a
gd05-3wo            390,811  07-06-00  9:29a
gd05-3zo            390,716  05-03-00  8:56a
gd05-95o            390,491  07-06-00  9:08a
```

table6-7

```
gd04-5so            389,450  05-03-00  8:55a
gd05-4so            390,081  05-03-00  8:56a
```

table6-8

```
gd04-5vo            390,461  05-03-00  8:55a
gd04-9vo            390,239  05-03-00  8:55a
gd0410vo            390,253  05-03-00  8:55a
gd05-3vo            390,363  05-03-00  8:56a
gd05-4vo            389,690  05-03-00  8:56a
gd05-5vo            390,261  05-03-00  8:56a
gd05-6vo            390,120  05-03-00  8:56a
```

table6-9

```
p-3ao               508,178  07-06-00  9:08a
p-3bo               507,250  07-06-00  9:08a
p-3co               506,272  07-06-00  9:08a
p-3do               507,102  07-06-00  9:08a
p-3eo               507,170  07-06-00  9:08a
p-3fo               507,408  07-06-00  9:09a
p-4ao               509,654  07-06-00  9:09a
p-4bo               507,247  07-06-00  9:09a
p-4co               505,979  07-06-00  9:09a
p-4do               506,957  07-06-00  9:09a
p-4eo               507,114  07-06-00  9:09a
p-4fo               507,037  07-06-00  9:09a
p-6ao               509,608  07-06-00  9:09a
p-6bo               506,453  07-06-00  9:09a
p-6co               507,412  07-06-00  9:09a
p-6do               507,305  07-06-00  9:09a
```

```
p-6eo              507,114  07-06-00  9:10a
p-6fo              506,988  07-06-00  9:10a
```

table6-10

```
p-6fo              506,988  07-06-00  9:10a
p-6fso             507,181  07-06-00  9:10a
p-6fvo             506,989  07-06-00  9:10a
p-9fvo             506,969  07-06-00  9:10a
```

table6-11

```
r-6ao              511,426  07-06-00  9:10a
r-6bo              508,573  07-06-00  9:12a
r-6do              509,706  07-06-00  9:12a
r-6eo              509,750  07-06-00  9:12a
r-6fo              510,797  07-06-00  9:12a
r-9ao              512,354  07-06-00  9:13a
r-9bo              510,914  07-06-00  9:13a
r-9do              510,866  07-06-00  9:13a
r-9eo              510,679  07-06-00  9:13a
r-9fo              510,640  07-06-00  9:13a
```

table6-12

```
r-6bnwo            509,713  07-06-00  9:11a
r-6bo              508,573  07-06-00  9:12a
r-6brfo            508,766  07-06-00  9:12a
r-6bsho            510,135  07-06-00  9:12a
r-6bto             523,280  07-06-00  9:12a
r-6bvo             510,001  07-06-00  9:12a
r-9bo              510,914  07-06-00  9:13a
r-9bto             523,109  07-06-00  9:13a
r-9bvo             510,508  07-06-00  9:13a
```

table6-13

```
df1o               323,205  07-06-00 11:06a
df2o               324,142  07-06-00 11:06a
df3o               324,234  07-06-00 11:06a
df4o               324,646  07-06-00 11:06a
df51o              324,571  07-06-00 11:06a
df52o              324,361  07-06-00 11:06a
df53o              323,597  07-06-00 11:06a
df54o              323,033  07-06-00 11:06a
df5o               324,509  07-06-00 11:06a
```

table6-14

```
dfa1o              324,706  07-06-00 11:06a
dfa2o              325,013  07-06-00 11:06a
dfa31o             325,114  07-06-00 11:06a
dfa32o             324,404  07-06-00 11:06a
dfa33o             323,773  07-06-00 11:06a
dfa34o             323,773  07-06-00 11:06a
dfa3o              324,499  07-06-00 11:06a
dfa41o             324,540  07-06-00 11:06a
dfa42o             323,917  07-06-00 11:06a
dfa43o             323,516  07-06-00 11:07a
dfa44o             324,072  07-06-00 11:07a
dfa4o              325,037  07-06-00 11:07a
```

table6-15

```
dfab1gdo           326,306  07-06-00 11:07a
dfam1gdo           327,471  07-06-00 11:07a
dfat1gdo           321,553  07-06-00 11:07a
```

table6-16

```
dfab1gd10wo        326,160  07-06-00 11:07a
dfab81gdo          325,610  07-06-00 11:07a
dfabh1gdo          325,999  07-06-00 11:07a
dfabr1gdo          326,257  07-06-00 11:07a
```

table6-17

```
d03gdo             325,489  07-06-00 11:07a
da13gdo            325,747  07-06-00 11:07a
dfa13gdo           325,862  07-06-00 11:07a
dfa23gdo           326,031  07-06-00 11:07a
dfa33gdo           326,384  07-06-00 11:07a
dfa413gdo          324,910  07-06-00 11:07a
dfa423gdo          325,841  07-06-00 11:07a
dfa433gdo          323,023  07-06-00 11:07a
dfa43gdo           326,034  07-06-00 11:07a
dfa443gdo          325,467  07-06-00 11:07a
```

table6-18

```
dfab3gdo           325,936  07-06-00 11:07a
dfam3gdo           326,450  07-06-00 11:08a
```

```
dfat3gdo            326,573  07-06-00 11:08a
```

table6-19

```
dfab3gd10wo         326,879  07-06-00 11:08a
dfab3gd1wo          326,830  07-06-00 11:08a
dfab83gdo           325,414  07-06-00 11:08a
dfab85gdo           326,013  07-06-00 11:08a
dfabh3gdo           325,422  07-06-00 11:08a
dfabhw3gdo          323,887  07-06-00 11:08a
dfabr3gdo           325,979  07-06-00 11:08a
```

table6-21

```
23g4ko              334,004  04-25-00  5:12p
24g9ko              334,298  04-25-00  5:12p
25g10o              333,327  04-25-00  5:12p
25g18ko             333,327  04-25-00  5:12p
32g4ko              334,053  04-25-00  5:12p
33g3ko              334,192  04-25-00  5:12p
33g6ko              334,151  04-25-00  5:12p
34g3ko              334,151  04-25-00  5:12p
34g7ko              334,339  04-25-00  5:12p
35g9ko              333,188  04-25-00  5:12p
72g3ko              334,200  04-25-00  5:12p
73g3ko              334,347  04-25-00  5:12p
74g35ko             325,967  04-25-00  5:12p
75g3ko              325,249  04-25-00  5:12p
75g5ko              333,259  04-25-00  5:12p
82g3ko              334,290  04-25-00  5:12p
83g10o              334,094  04-25-00  5:12p
83g5ko              334,437  04-25-00  5:12p
84g10o              334,437  04-25-00  5:12p
85g10o              333,425  04-25-00  5:12p
85g18o              333,017  04-25-00  5:12p
t22g10o             332,329  04-25-00  5:12p
t22g12o             332,287  04-25-00  5:12p
t23g12o             332,630  04-25-00  5:12p
t24g12o             332,763  04-25-00  5:12p
t25g12o             332,704  04-25-00  5:12p
t25g18o             333,725  04-25-00  5:12p
t25g30o             415,924  04-25-00  5:12p
tif1d1o             329,913  04-25-00  5:12p
tif1d2o             331,930  04-25-00  5:12p
tif1d3o             332,126  04-25-00  5:12p
tif1d4o             332,123  04-25-00  5:12p
```

```
tif1d5o             331,418  04-25-00  5:12p
tif2d1o             330,868  04-25-00  5:12p
tif2d2o             331,903  04-25-00  5:12p
tif2d3o             331,854  04-25-00  5:12p
tif2d4o             332,093  04-25-00  5:12p
tif2d5o             333,014  04-25-00  5:12p
wif1d1o             333,577  04-25-00  5:12p
wif1d2o             416,551  04-25-00  5:12p
wif1d3o             333,889  04-25-00  5:12p
wif1d4o             333,840  04-25-00  5:13p
wif1d5o             332,828  04-25-00  5:13p
wif2d1o             333,120  04-25-00  5:13p
wif2d2o             333,530  04-25-00  5:13p
wif2d3o             333,481  04-25-00  5:13p
wif2d4o             333,620  04-25-00  5:13p
wif2d5o             332,559  04-25-00  5:13p
wif3d1o             332,680  04-25-00  5:13p
wif3d2o             333,383  04-25-00  5:13p
wif3d3o             416,811  04-25-00  5:13p
wif3d4o             333,767  04-25-00  5:13p
wif3d5o             332,567  04-25-00  5:13p
wif7d1o             333,259  04-25-00  5:13p
wif7d2o             333,481  04-25-00  5:13p
wif7d3o             333,425  04-25-00  5:13p
wif7d4o             324,505  04-25-00  5:13p
wif7d5o             324,481  04-25-00  5:13p
wif8d1o             333,301  04-25-00  5:13p
wif8d2o             333,326  04-25-00  5:13p
wif8d3o             333,481  04-25-00  5:13p
wif8d4o             333,579  04-25-00  5:13p
wif8d5o             332,665  04-25-00  5:13p
```

table6-23

```
25-1035o            342,611  04-25-00  5:13p
25-10g3o            342,398  04-25-00  5:13p
25-4g3ko            342,341  04-25-00  5:13p
25-6g3ko            342,488  04-25-00  5:13p
35-10g3o            342,439  04-25-00  5:13p
85-10g3o            342,243  04-25-00  5:14p
85-4g3o             342,439  04-25-00  5:14p
85-6g3o             342,439  04-25-00  5:14p
l15-10o             339,519  04-25-00  5:14p
l15-4o              340,597  04-25-00  5:14p
l15-6o              340,597  04-25-00  5:14p
l25-10o             341,697  04-25-00  5:14p
```

l25-4o	341,746	04-25-00	5:14p
l25-6o	341,558	04-25-00	5:14p
l35-10o	341,648	04-25-00	5:14p
l85-10o	341,550	04-25-00	5:14p
l85-4o	341,509	04-25-00	5:14p
l85-6o	341,550	04-25-00	5:14p
tl14-10o	340,056	04-25-00	5:14p
tl14-4o	340,056	04-25-00	5:14p
tl14-6o	340,105	04-25-00	5:14p
tl208rso	341,909	04-25-00	5:14p
tl208rwo	345,296	04-25-00	5:14p
tl209ro	335,182	06-30-00	9:27a
tl20g7ko	338,777	04-25-00	5:14p
tl20g8ko	339,659	04-25-00	5:15p
tl20g9ko	339,749	06-30-00	9:28a
tl24-10o	338,816	04-25-00	5:15p

table6-24

out00	363,259	05-08-00	5:28p
out10	363,883	05-08-00	5:28p
out20	364,162	05-08-00	5:28p
out30	363,931	05-08-00	5:28p
out344	363,883	05-08-00	5:28p
out40	363,871	05-08-00	5:28p
out444	364,271	05-08-00	5:28p
out644	364,124	05-08-00	5:28p

table6-25

out001	363,273	05-08-00	5:28p
out011	363,530	05-08-00	5:28p
out012	363,578	05-08-00	5:28p
out123	363,919	05-08-00	5:28p
out234	364,210	05-08-00	5:28p

table6-26

out+20	363,464	05-08-00	5:28p
out+40	363,511	05-08-00	5:28p
out+60	363,559	05-08-00	5:28p
out+80	363,559	05-08-00	5:28p

table6-27

out+81	370,077	05-08-00	5:27p

```
out+81L114          369,870  05-08-00  5:27p
out+82              369,693  05-08-00  5:27p
out+83              369,337  05-08-00  5:27p
out+83R             368,845  05-08-00  5:27p
out+84              369,675  05-08-00  5:27p
```

table6-28

```
out8012             363,914  05-08-00  5:27p
out8123             364,267  05-08-00  5:27p
out8234             364,087  05-08-00  5:27p
```

table6-29

```
out10-0             354,027  05-08-00  5:27p
out10-10            354,162  05-08-00  5:27p
out10-50            354,345  05-08-00  5:27p
```

table6-30

```
out10-0             355,123  05-08-00  5:27p
out10-1             354,087  05-08-00  5:27p
out1106             354,430  05-08-00  5:27p
out111              354,138  05-08-00  5:27p
out1159             354,430  05-08-00  5:27p
out121              354,229  05-08-00  5:27p
out131              354,229  05-08-00  5:27p
out141              354,046  05-08-00  5:27p
out151              354,229  05-08-00  5:27p
out161              354,430  05-08-00  5:27p
out174              354,650  05-08-00  5:27p
out185              354,529  05-08-00  5:27p
out195              354,430  05-08-00  5:27p
```

table6-31

```
out0                354,526  05-08-00  5:26p
out10               355,418  05-08-00  5:26p
out11               355,418  05-08-00  5:26p
out150              355,334  05-08-00  5:26p
out151              355,418  05-08-00  5:26p
out152              354,146  05-08-00  5:26p
out55               355,319  05-08-00  5:26p
out56               355,334  05-08-00  5:26p
out57               355,418  05-08-00  5:26p
out58               355,418  05-08-00  5:26p
```

```
out59               355,334  05-08-00  5:26p
out9                355,479  05-08-00  5:26p
```

table6-32

```
out100L             362,959  05-08-00  5:26p
out154L             362,959  05-08-00  5:26p
out200L             362,731  05-08-00  5:26p
out80L              362,911  05-08-00  5:26p
```

table6-33

```
out80L-U238         362,490  05-08-00  5:26p
out80LNU+G          362,117  05-08-00  5:26p
out80LNU238         361,439  05-08-00  5:26p
out80LR             363,007  05-08-00  5:26p
```

table6-34

```
outPostB            354,049  05-08-00  5:26p
outPostB+1          355,002  05-08-00  5:26p
outPostB+2          355,002  05-08-00  5:27p
outPostB+3          354,690  05-08-00  5:27p
```

Directory: s**preadsheets**

```
At_weights.xls                             27,648  07-06-00  7:19p
Book2.xls                                 296,448  07-06-00  7:48p
Clayey Material_Pre Breach.xls             37,376  07-06-00  7:49p
Degrade DOE SNF Canister Contents.xls      76,800  07-11-00 11:28a
Intact fuel pins in degraded DOE
canister.xls                               62,976  07-06-00  7:55p
new_intact_pipes.xls                       73,728  07-06-00  7:52p
part3final.xls                            142,336  07-06-00  7:57p
```