OFFICE OF CIVILIAN RADIOACTIVE WASTE MANAGEMENT
ANALYSIS/MODEL COVER SHEET

1. QA: QA

Complete Only Applicable Items

2. ☒ Analysis — Check all that apply

Type of Analysis	☐ Engineering ☒ Performance Assessment ☐ Scientific
Intended Use of Analysis	☐ Input to Calculation ☒ Input to another Analysis or Model ☐ Input to Technical Document ☐ Input to other Technical Products

Describe use:

The inventory abstraction feeds TSPA-SR and TSPA-EIS. It determines which radionuclides will be modeled in TSPA-SR and provides radionuclide gram inputs for CSNF and codisposal waste packages for TSPA-SR.

3. ☐ Model — Check all that apply

Type of Model	☐ Conceptual Model ☐ Abstraction Model ☐ Mathematical Model ☐ System Model ☐ Process Model
Intended Use of Model	☐ Input to Calculation ☐ Input to another Model or Analysis ☐ Input to Technical Document ☐ Input to other Technical Products

Describe use:

4. Title:

Inventory Abstraction

5. Document Identifier (including Rev. No. and Change No., if applicable):

ANL-WIS-MD-000006 REV 00 ICN 03

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OFFICE OF CIVILIAN RADIOACTIVE WASTE MANAGEMENT
ANALYSIS/MODEL REVISION RECORD

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Inventory Abstraction

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ANL-WIS-MD-000006 REV 00 ICN 03

4. Revision/Change No.	5. Description of Revision/Change
REV 00	Initial Issue
REV 00 ICN 01	Changed accounting for naval fuel
REV 00 ICN 02	Replace citations of input transmittals with citations of calculations. Remove redundant data tracking numbers. Cite corrected calculation CAL-WIS-MD-000004 REV 00 ICN 01. Cite the technical work plan instead of the development plan. Add two new references to improve justification of solubility and sorption groups and inclusion of Ra-228. Add a new reference for justification of the bounding high-level waste form. Add a new reference to proposed regulations in 64 CFR 46976. Make editorial clarifications as needed. Modify text and DIRS to reflect changes in reference citations and the latest procedural requirements. Vertical bars in the right margin indicate changes with respect to ICN 01.
REV 00 ICN 03	Add Attachment II to consider neutron-activation products outside the commercial spent nuclear fuel matrix. Add Assumptions 5.10 and 5.11. Correct a typographical error in the activity of Np-237 in Table I-7. Add new references as required to cite new technical work plan and revised procedures. Make minor adjustments and editorial corrections elsewhere. Vertical bars in the right margin indicate changes with respect to ICN 02. The following pages of the report text are affected by the ICN: 10, 11, 14, 30 through 32, 37 through 39, 41 through 45, I-1, I-3 through I-5, I-7, I-8, I-16, II-1 through II-9.

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ACRONYMS AND ABBREVIATIONS

BWR	Boiling Water Reactor
CLST IRSR	Container Life and Source Term Issue Resolution Status Report
CSNF	Commercial Spent Nuclear Fuel
DOE	U.S. Department of Energy
DSNF	DOE Spent Nuclear Fuel
EBS	Engineered Barrier System
EPA	Environmental Protection Agency
FEIS	Final Environmental Impact Statement
HLW	High-level Waste
IPA	Iterative Performance Assessment
KTI	Key Technical Issue
NAS	National Academy of Sciences
NRC	U.S. Nuclear Regulatory Commission
QA	Quality Assurance
PWR	Pressurized Water Reactor
SNF	Spent Nuclear Fuel
TSPA-FEIS	Total System Performance Assessment for the Final Environmental Impact Statement
TDMS	Technical Data Management System
TSPA	Total System Performance Assessment
TSPA-SR	Total System Performance Assessment for the Site Recommendation
TSPA-VA	Total System Performance Assessment for the Viability Assessment

1. PURPOSE

The purpose of the inventory abstraction, which has been prepared in accordance with a technical work plan (CRWMS M&O 2000e for ICN 02 of the present analysis, and BSC 2001e for ICN 03 of the present analysis), is to:

- Interpret the results of a series of relative dose calculations (CRWMS M&O 2000c, 2000f).
- Recommend, including a basis thereof, a set of radionuclides that should be modeled in the Total System Performance Assessment in Support of the Site Recommendation (TSPA-SR) and the Total System Performance Assessment in Support of the Final Environmental Impact Statement (TSPA-FEIS).
- Provide initial radionuclide inventories for the TSPA-SR and TSPA-FEIS models.
- Answer the U.S. Nuclear Regulatory Commission (NRC)'s Issue Resolution Status Report *Key Technical Issue: Container Life and Source Term* (CLST IRSR) key technical issue (KTI): "The rate at which radionuclides in SNF [spent nuclear fuel] are released from the EBS [engineered barrier system] through the oxidation and dissolution of spent fuel" (NRC 1999, Subissue 3).

The scope of the radionuclide screening analysis encompasses the period from 100 years to 10,000 years after the potential repository at Yucca Mountain is sealed for scenarios involving the breach of a waste package and subsequent degradation of the waste form as required for the TSPA-SR calculations. By extending the time period considered to one million years after repository closure, recommendations are made for the TSPA-FEIS. The waste forms included in the inventory abstraction are Commercial Spent Nuclear Fuel (CSNF), DOE Spent Nuclear Fuel (DSNF), High-Level Waste (HLW), naval Spent Nuclear Fuel (SNF), and U.S. Department of Energy (DOE) plutonium waste.

The intended use of this analysis is in TSPA-SR and TSPA-FEIS. Based on the recommendations made here, models for release, transport, and possibly exposure will be developed for the isotopes that would be the highest contributors to the dose given a release to the accessible environment. The inventory abstraction is important in assessing system performance because radionuclide screening determines the scope for several TSPA models, and the abstraction provides input to the TSPA.

2. QUALITY ASSURANCE

An activity evaluation (CRWMS M&O 2000e, Enclosure 1), which was prepared in accordance with AP-2.21Q, *Quality Determinations and Planning for Scientific, Engineering, and Regulatory Compliance Activities*, determined that the Quality Assurance (QA) program applies to the activity under which REV 00 ICN 02 of this analysis was developed. Control of the electronic management of information was accomplished in accordance with the controls specified by CRWMS M&O (2000e, Enclosure 4). An activity evaluation (BSC 2001e, Attachment 1), which was prepared in accordance with AP-2.21Q, *Quality Determinations and Planning for Scientific, Engineering, and Regulatory Compliance Activities*, determined that the Quality Assurance (QA) program applies to the activity under which ICN 03 of the present analysis was developed. ICN 03 of the present analysis was prepared in accordance with AP-3.10Q, *Analyses and Models* and AP-3.15Q, *Managing Technical Product Inputs*.

3. COMPUTER SOFTWARE AND MODEL USAGE

3.1 SOFTWARE APPROVED FOR QUALITY ASSURANCE (QA) WORK

None used.

3.2 COMMERCIALLY AVAILABLE SOFTWARE USED

Microsoft's Excel 97 SR-2, a commercially available standard spreadsheet software package, was used for manipulation of inputs in Attachment I. Excel is an appropriate application because the calculations require only simple mathematical expressions and operations that are standard in Excel to derive the results. The specific built-in functions of Excel that were used for the calculations in Attachment I are described in the attachment at the point of use.

3.3 MODELS

None used.

4. INPUTS

4.1 DATA AND PARAMETERS

The input for this analysis comes from two sources:

1. *Relative Contribution of Individual Radionuclides to Inhalation and Ingestion Dose*, CAL-WIS-MD-000002 REV 00 (CRWMS M&O 2000c). The cited calculation will be referred to below as Calculation 2, for short, based on the document identifier.

2. *Relative Contribution of Individual Radionuclides to Inhalation and Ingestion Dose--One Million Years*, CAL-WIS-MD-000005 REV 00 (CRWMS M&O 2000f). The cited calculation will be referred to below as Calculation 5, for short, based on the document identifier.

Sections 4.1.1 and 4.1.2 summarize the information in these two calculations.

4.1.1 Relative Contribution of Individual Radionuclides to Inhalation and Ingestion Dose – 10,000 Years

In Calculation 2 (CRWMS M&O 2000c) the relative importance of individual radionuclides for the estimation of inhalation and ingestion doses was determined. "Relative importance," as used here, denotes a ranking of radionuclides according to dose contributions. The higher dose contributors have higher relative importance.

The analytical method used to determine the relative importance involved five steps. First, for the waste form under consideration, the relative dose contribution from an individual radionuclide was calculated by multiplying its inventory abundance (curies in the waste form) by the radionuclide's dose conversion factor. This gives a number that is not significant by itself, but when compared to values derived in the same manner for other radionuclides in the waste form, the radionuclide that contributes more to the dose can be determined. Second, the individual radionuclides were ranked with the highest contributor to the dose given the highest ranking. Third, each relative dose value calculated in the first step was converted to a percent contribution to the dose by summing all of the values calculated in the first step, calling this the total, and dividing each individual value by the total and multiplying by 100. At this point one knows the percent contribution to the total dose for each radionuclide. Fourth, a cumulative sum of the percent dose contributions was calculated for the radionuclides in ranked order. After Step Four, when a radionuclide is added to the calculation, the percentage of the dose that is represented by each radionuclide is known. Finally, the fifth step is to choose radionuclides for the calculation (starting with the highest ranked radionuclide) to ensure that a reasonable fraction of the dose is accounted for. For this screening analysis, the goal was to identify the minimal set of radionuclides that contributes 95 percent of the dose.

4.1.1.1 Screening Based on Inventory Abundance

The analytical method described above identifies which radionuclides should be modeled if all of the radionuclides in a waste form are released to the environment in proportion to their inventory abundance. Calculation 2 examines "average" and "bounding" waste forms corresponding to Pressurized Water Reactor (PWR) SNF assemblies and Boiling Water Reactor (BWR) SNF assemblies. The characteristics of the "average" CSNF waste forms were determined by weighted averages of the reported enrichments, burnups, and ages, where the weights are the numbers of assemblies with a given value of each characteristic in the waste stream. The characteristics of the "bounding" PWR and BWR waste forms are the maximum reported burnup, the maximum reported enrichment, and the minimum reported age in the waste stream for each fuel type (CRWMS M&O 2000c, pp. 7, 8). Calculation 2 also considers "average" and "bounding" waste forms corresponding to DSNF and HLW canisters (CRWMS M&O 2000c, pp. 8, 9). For DSNF and HLW canisters, the "average" inventories are averages calculated dividing total inventories of each radionuclide by the numbers of canisters expected to be produced. For DSNF and HLW canisters, the "bounding" inventories are averages calculated for specific waste groups: uranium/thorium carbide for DSNF and HLW glass from the Savannah River Site for HLW. Uranium/thorium carbide was chosen as the "bounding" DSNF waste form for the screening calculation because, unlike CSNF and other DSNF, it exhibits significant U-233 and Th-230 activity, which may prove to be important contributors to dose. Savannah River Site HLW was chosen as the "bounding" HLW waste form due to its high total activity per canister as compared to glass from the other sites where HLW will be produced (CRWMS M&O 2000g, Table 6-1).

Sometimes radionuclides are not released in proportion to their inventory abundance. Factors that can affect releases of radionuclides, depending on the scenario being considered, include radionuclide longevity, element solubility, and element transport affinity. Consequently, screening on inventory alone is not bounding. The screening approach used here involves grouping the radionuclides into subsets based on radionuclide longevity, element solubility, and element transport affinity. Radionuclides that may be important given a variety of operative transport mechanisms are identified by grouping the radionuclides into subsets and screening each subset by itself.

4.1.1.2 Screening Based on Radionuclide Longevity

If a radionuclide has a short half-life, it will have a higher activity in the waste form at early times (close to repository closure), but at later times, the radionuclide will have all but disappeared from the waste form. Therefore, it is important to examine the waste forms at a number of times, especially if the phenomenon that ultimately leads to a release occurs at later times. Calculation 2 examines waste activity at 100; 200; 300; 400; 500; 1,000; 2,000; 5,000; and 10,000 years (CRWMS M&O 2000c).

4.1.1.3 Screening Based on Element Solubility

If a radionuclide is not soluble in the near-field environment around the waste package, it may not be released to the environment via groundwater transport, even if it is available in high abundance. Therefore, it is important to examine alternative hypotheses about element solubility

and determine which radionuclides are the highest contributors to the dose if some of the more abundant radionuclides are not released because of low solubility. Calculation 2 (CRWMS M&O 2000h) examines one solubility hypothesis: a hypothesis that Am, Cm, Zr, Th, Nb, Pa, and Sn are not soluble in the near-field environment. Corroboration of this hypothesis is provided by CRWMS M&O (2000h, Tables 18, 19; the latest revision is not cited because it does not provide all the needed solubilities).

4.1.1.4 Screening Based on Transport Affinity

Transport affinity is used here as a global term that describes a radionuclide's potential for movement from the source to the environment. The movement can be due to a number of mechanisms: matrix advection and matrix diffusion, fracture flow, or colloidal transport. In this analysis, transport affinity is used as a qualitative description of the likelihood of transport, not as a measurable property. If a group of radionuclides transports via a particular mechanism and that mechanism dominates release, the group of radionuclides will be preferentially released (relative to radionuclides not in the group) to the environment. The following hypotheses, which are more fully developed in Assumptions 5.5, 5.6, and 5.7, support the screening based on transport affinity: (1) highly sorbing radionuclides are most likely to transport via colloidal transport; (2) moderately sorbing radionuclides are most likely to transport via fracture flow (they do not necessarily adsorb to colloids and are retained by matrix diffusion); and (3) slightly to non-sorbing radionuclides are most likely to transport via advection or diffusion.

Calculation 2 accounts for all of the identified transport mechanisms by dividing the radionuclides into three groups: (1) highly sorbing, (2) moderately sorbing, and (3) slightly to non-sorbing, and examining the relative dose contributions from the radionuclides within each group (CRWMS M&O 2000c). Each group is examined individually. For example, the relative dose contribution from each member of the highly sorbing group is compared to the relative dose contributions from the other members of the same group.

4.1.1.5 Results of Relative Inhalation and Ingestion Dose Calculations; 100 – 10,000 Years

Table 1 provides a key to Tables 2 through 17, which present the results for inventory screening from Calculation 2 (CRWMS M&O 2000c, Tables 1 through 16).

Table 1. Key to the Tables for the 100- to 10,000-Year Calculation

Solubility Hypothesis Mitigates Release	Radionuclide Group Transported			
	All Groups	Highly Sorbing Only	Moderately Sorbing Only	Slightly to Nonsorbing Only
Yes	Tables 4 & 5	Tables 6 & 7	Tables 8 & 9	Tables 10 & 11
No	Tables 2 & 3	Tables 12 & 13	Tables 14 & 15	Tables 16 & 17

NOTE: The first table listed in each cell provides inputs for average waste forms and the second provides inputs for bounding waste forms.

Table 2. Radionuclides Required to Account for Ninety-five Percent of the Inhalation and Ingestion Dose for Average Waste Forms When Radionuclides are Released in Proportion to Their Inventory Abundance; 100 to 10,000 Years

Radionuclides Required to Account for 95% of the Dose	Applicable to the Following Waste Forms	Applicable to the Following Exposure Pathways	Applicable to the Following Time Periods After Repository Closure
Sr-90	BWR, HLW	Ingestion	100 – 200 years
Cs-137	HLW	Ingestion	100 years
Pu-238	ALL	Inhalation, ingestion	100 – 500 years
Pu-239	ALL	Inhalation, ingestion	100 – 10,000 years
Pu-240	ALL	Inhalation, ingestion	100 – 10,000 years
Am-241	ALL	Inhalation, ingestion	100 – 2,000 years
Am-243	PWR	Inhalation, Ingestion	5,000 years

Table 3. Radionuclides Required to Account for Ninety-five Percent of the Inhalation and Ingestion Dose for Bounding Waste Forms When Radionuclides Are Released in Proportion to Their Inventory Abundance; 100 to 10,000 Years

Radionuclides Required to Account for 95% of the Dose	Applicable to the Following Waste Forms	Applicable to the Following Exposure Pathways	Applicable to the Following Time Periods After Repository Closure
Sr-90	ALL	Ingestion	100 – 200 years
Cs-137	HLW, BWR, DSNF	Ingestion	100 years
Pb-210	DSNF	Ingestion	10,000 years
Ac-227	DSNF	Inhalation, ingestion	300 – 5,000 years
Pa-231	DSNF	Ingestion	1,000 – 2,000 years
Th-229	DSNF	Inhalation, ingestion	100 – 10,000 years
U-232	DSNF	Inhalation	100 – 200 years
U-233	DSNF	Inhalation, ingestion	100 – 10,000 years
U-234	DSNF	Inhalation	2000 years
Pu-238	ALL	Inhalation, ingestion	100 – 500 years
Pu-239	ALL	Inhalation, ingestion	100 – 10,000 years
Pu-240	ALL	Inhalation, ingestion	100 – 10,000 years
Am-241	ALL	Inhalation, ingestion	100 – 2,000 years
Am-243	PWR, BWR	Inhalation, ingestion	2,000 – 10,000 years

Table 4. Radionuclides Required to Account for Ninety-five Percent of the Inhalation and Ingestion Dose for Average Waste Forms When Radionuclide Release is Mitigated by the Element Solubility Hypothesis[a]; 100 to 10,000 Years

Radionuclides Required to Account for 95% of the Dose	Applicable to the Following Waste Forms	Applicable to the Following Exposure Pathways	Applicable to the Following Time Periods After Repository Closure
Sr-90	ALL	Ingestion	100 – 200 years
Cs-137	HLW	Ingestion	100 years
Pu-238	ALL	Inhalation, ingestion	100 – 500 years
Pu-239	ALL	Inhalation, ingestion	100 – 10,000 years
Pu-240	ALL	Inhalation, ingestion	100 - 10,000 years

[a] The element solubility hypothesis is that Am, Cm, Zr, Th, Nb, Pa, and Sn are not soluble.

Table 5. Radionuclides Required to Account for Ninety-five Percent of the Inhalation and Ingestion Dose for Bounding Waste Forms When Radionuclide Release is Mitigated by the Element Solubility Hypothesis[a]; 100 to 10,000 Years

Radionuclides Required to Account for 95% of the Dose	Applicable to the Following Waste Forms	Applicable to the Following Exposure Pathways	Applicable to the Following Time Periods After Repository Closure
Sr-90	ALL	Ingestion	100 – 200 years
Cs-137	HLW, BWR, DSNF	Ingestion	100 years
U-232	DSNF	Inhalation	100 – 200 years
U-233	DSNF	Inhalation, ingestion	100 – 10,000 years
U-234	DSNF	Inhalation, ingestion	500 – 10,000 years
Pb-210	DSNF	Ingestion	5,000 - 10,000 years
Pu-238	ALL	Inhalation, ingestion	100 – 500 years
Pu-239	ALL	Inhalation, ingestion	100 – 10,000 years
Pu-240	ALL	Inhalation, ingestion	100 – 10,000 years

[a] The element solubility hypothesis is that Am, Cm, Zr, Th, Nb, Pa, and Sn are not soluble.

Table 6. Radionuclides Required to Account for Ninety-five Percent of the Inhalation and Ingestion Dose for Average Waste Forms When Only the Highly Sorbing Transport Group[a] is Released and Radionuclide Release is Mitigated by the Element Solubility Hypothesis[b]; 100 to 10,000 Years

Radionuclides Required to Account for 95% of the Dose	Applicable to the Following Waste Forms	Applicable to the Following Exposure Pathways	Applicable to the Following Time Periods After Repository Closure
Sr-90	ALL	Ingestion	100 – 200 years
Cs-137	HLW	Ingestion	100 years
Pu-238	ALL	Inhalation, ingestion	100 – 500 years
Pu-239	ALL	Inhalation, ingestion	100 – 10,000 years
Pu-240	ALL	Inhalation, ingestion	100 – 10,000 years

[a] Ca, Co, Sr, Ac, Am, Be, Bi, Ce, Cm, Cs, Fe, Hf, Ho, Nb, Ni, Pa, Pb, Po, Pu, Ra, Sm, Sn, Ta, Te, Th, Y, Zn, Zr, Ba, Eu, Bk, Cf, Fr, La, Lu, Nd, Pm, Pr, Tb, and Tm are the highly sorbing elements.

[b] The element solubility hypothesis is that Am, Cm, Zr, Th, Nb, Pa, and Sn are not soluble.

Table 7. Radionuclides Required to Account for Ninety-five Percent of the Inhalation and Ingestion Dose for Bounding Waste Forms When Only the Highly Sorbing Transport Group[a] is Released and Radionuclide Release is Mitigated by the Element Solubility Hypothesis[b]; 100 to 10,000 Years

Radionuclides Required to Account for 95% of the Dose	Applicable to the Following Waste Forms	Applicable to the Following Exposure Pathways	Applicable to the Following Time Periods After Repository Closure
Sr-90	ALL	Ingestion	100 – 200 years
Cs-137	HLW, BWR, DSNF	Ingestion	100 years
Pb-210	DSNF	Ingestion	5,000 – 10,000 years
Pu-238	ALL	Inhalation, ingestion	100 – 500 years
Pu-239	ALL	Inhalation, ingestion	100 – 10,000 years
Pu-240	ALL	Inhalation, ingestion	100 – 10,000 years

[a] Ca, Co, Sr, Ac, Am, Be, Bi, Ce, Cm, Cs, Fe, Hf, Ho, Nb, Ni, Pa, Pb, Po, Pu, Ra, Sm, Sn, Ta, Te, Th, Y, Zn, Zr, Ba, Eu, Bk, Cf, Fr, La, Lu, Nd, Pm, Pr, Tb, and Tm are the highly sorbing elements.

[b] The element solubility hypothesis is that Am, Cm, Zr, Th, Nb, Pa, and Sn are not soluble.

Table 8. Radionuclides Required to Account for Ninety-five Percent of the Inhalation and Ingestion Dose for Average Waste Forms When Only the Moderately Sorbing Transport Group[a] is Released and Radionuclide Release is Mitigated by the Element Solubility Hypothesis[b]; 100 to 10,000 Years

Radionuclides Required to Account for 95% of the Dose	Applicable to the Following Waste Forms	Applicable to the Following Exposure Pathways	Applicable to the Following Time Periods After Repository Closure
U-232	DSNF	Inhalation, ingestion	100 – 500 years
U-233	HLW, DSNF	Inhalation, ingestion	100 – 10,000 years
U-234	ALL	Inhalation, ingestion	100 – 10,000 years
U-236	PWR, BWR	Inhalation, ingestion	100 – 10,000 years
U-238	ALL	Inhalation, ingestion	100 – 10,000 years
Np-237	ALL	Inhalation, ingestion	100 – 10,000 years

[a] Np, Ag, Cd, K, Mn, Pd, Rb, Ru, Sb, U, and Se are the moderately sorbing elements.

[b] The element solubility hypothesis is that Am, Cm, Zr, Th, Nb, Pa, and Sn are not soluble.

Table 9. Radionuclides Required to Account for Ninety-five Percent of the Inhalation and Ingestion Dose for Bounding Waste Forms When Only the Moderately Sorbing Transport Group[a] is Released and Radionuclide Release is Mitigated by the Element Solubility Hypothesis[b]; 100 to 10,000 Years

Radionuclides Required to Account for 95% of the Dose	Applicable to the Following Waste Forms	Applicable to the Following Exposure Pathways	Applicable to the Following Time Periods After Repository Closure
U-232	DSNF	Inhalation, ingestion	100 – 300 years
U-233	DSNF	Inhalation, ingestion	100 – 10,000 years
U-234	ALL	Inhalation, ingestion	100 – 10,000 years
U-236	PWR, BWR	Inhalation, ingestion	100 – 10,000 years
U-238	BWR, PWR	Inhalation	100 years
Np-237	ALL	Inhalation, ingestion	100 – 10,000 years

[a] Np, Ag, Cd, K, Mn, Pd, Rb, Ru, Sb, U, and Se are the moderately sorbing elements.

[b] The element solubility hypothesis is that Am, Cm, Zr, Th, Nb, Pa, and Sn are not soluble.

Table 10. Radionuclides Required to Account for Ninety-five Percent of the Inhalation and Ingestion Dose for Average Waste Forms When Only the Slightly to Non-sorbing Transport Group[a] is Released and Radionuclide Release is Mitigated by the Element Solubility Hypothesis[b]; 100 to 10,000 Years

Radionuclides Required to Account for 95% of the Dose	Applicable to the Following Waste Forms	Applicable to the Following Exposure Pathways	Applicable to the Following Time Periods After Repository Closure
C-14	DSNF, BWR	Ingestion	100 – 5,000 years
Tc-99	ALL	Inhalation, ingestion	100 – 10,000 years
I-129	PWR, BWR, DSNF	Inhalation, ingestion	100 – 10,000 years

[a] C, H, I, Mo, P, Re, Tc, Br, Si, Cl, V, Ar, At, Kr, and S are the slightly to non-sorbing elements.

[b] The element solubility hypothesis is that Am, Cm, Zr, Th, Nb, Pa, and Sn are not soluble.

Table 11. Radionuclides Required to Account for Ninety-five Percent of the Inhalation and Ingestion Dose for Bounding Waste Forms When Only the Slightly to Non-sorbing Transport Group[a] is Released and Radionuclide Release is Mitigated by the Element Solubility Hypothesis[b]; 100 to 10,000 Years

Radionuclides Required to Account for 95% of the Dose	Applicable to the Following Waste Forms	Applicable to the Following Exposure Pathways	Applicable to the Following Time Periods After Repository Closure
C-14	DSNF, BWR	Inhalation, ingestion	100 – 10,000 years
Tc-99	ALL	Inhalation, ingestion	100 – 10,000 years
I-129	PWR, BWR, DSNF	Inhalation, ingestion	100 – 10,000 years

[a] C, H, I, Mo, P, Re, Tc, Br, Si, Cl, V, Ar, At, Kr, and S are the slightly to non-sorbing elements.

[b] The element solubility hypothesis is that Am, Cm, Zr, Th, Nb, Pa, and Sn are not soluble.

Table 12. Radionuclides Required to Account for Ninety-five Percent of the Inhalation and Ingestion Dose for Average Waste Forms When Only the Highly Sorbing Transport Group[a] is Transported and Radionuclide Release is Not Mitigated by the Element Solubility Hypothesis[b]; 100 to 10,000 Years

Radionuclides Required to Account for 95% of the Dose	Applicable to the Following Waste Forms	Applicable to the Following Exposure Pathways	Applicable to the Following Time Periods After Repository Closure
Sr-90	BWR, HLW	Ingestion	100 – 200 years
Cs-137	HLW	Ingestion	100 years
Pu-238	ALL	Inhalation, ingestion	100 – 500 years
Pu-239	ALL	Inhalation, ingestion	100 – 10,000 years
Pu-240	ALL	Inhalation, ingestion	100 – 10,000 years
Am-241	ALL	Inhalation, ingestion	100 – 2,000 years

[a] Ca, Co, Sr, Ac, Am, Be, Bi, Ce, Cm, Cs, Fe, Hf, Ho, Nb, Ni, Pa, Pb, Po, Pu, Ra, Sm, Sn, Ta, Te, Th, Y, Zn, Zr, Ba, Eu, Bk, Cf, Fr, La, Lu, Nd, Pm, Pr, Tb, and Tm are the highly sorbing elements.

[b] No mitigation based on element solubility implies that all elements are considered soluble.

Table 13. Radionuclides Required to Account for Ninety-five Percent of the Inhalation and Ingestion Dose for Bounding Waste Forms When Only the Highly Sorbing Transport Group[a] is Transported and Radionuclide Release is Not Mitigated by the Element Solubility Hypothesis[b]; 100 to 10,000 Years

Radionuclides Required to Account for 95% of the Dose	Applicable to the Following Waste Forms	Applicable to the Following Exposure Pathways	Applicable to the Following Time Periods After Repository Closure
Sr-90	ALL	Ingestion	100 – 200 years
Cs-137	HLW, DSNF, BWR	Ingestion	100 years
Th-229	DSNF	Inhalation, ingestion	100 – 10,000 years
Ac-227	DSNF, BWR	Inhalation, ingestion	300 – 5,000 years
Pa-231	DSNF	Ingestion	1,000 years
Pu-238	ALL	Inhalation, ingestion	100 – 500 years
Pu-239	ALL	Inhalation, ingestion	100 – 10,000 years
Pu-240	ALL	Inhalation, ingestion	100 – 10,000 years
Am-241	ALL	Inhalation, ingestion	100 – 2,000 years
Am-243	PWR, BWR	Inhalation, ingestion	2,000 – 10,000 years

[a] Ca, Co, Sr, Ac, Am, Be, Bi, Ce, Cm, Cs, Fe, Hf, Ho, Nb, Ni, Pa, Pb, Po, Pu, Ra, Sm, Sn, Ta, Te, Th, Y, Zn, Zr, Ba, Eu, Bk, Cf, Fr, La, Lu, Nd, Pm, Pr, Tb, and Tm are the highly sorbing elements.

[b] No mitigation based on element solubility implies that all elements are considered soluble.

Table 14. Radionuclides Required to Account for Ninety-five Percent of the Inhalation and Ingestion Dose for Average Waste Forms When Only the Moderately Sorbing Transport Group[a] is Transported and Radionuclide Release is Not Mitigated by the Element Solubility Hypothesis[b]; 100 to 10,000 Years

Radionuclides Required to Account for 95% of the Dose	Applicable to the Following Waste Forms	Applicable to the Following Exposure Pathways	Applicable to the Following Time Periods After Repository Closure
Np-237	ALL	Inhalation, ingestion	100 – 10,000 years
U-232	DSNF	Inhalation, ingestion	100 – 500 years
U-233	DSNF, HLW	Inhalation, ingestion	100 – 10,000 years
U-234	ALL	Inhalation, ingestion	100 – 10,000 years
U-236	PWR, BWR	Inhalation, ingestion	100 – 10,000 years
U-238	ALL	Inhalation, ingestion	100 – 10,000 years

[a] Np, Ag, Cd, K, Mn, Pd, Rb, Ru, Sb, U, and Se are the moderately sorbing elements.

[b] No mitigation based on element solubility implies that all elements are considered soluble.

Table 15. Radionuclides Required to Account for Ninety-five Percent of the Inhalation and Ingestion Dose for Bounding Waste Forms When Only the Moderately Sorbing Transport Group[a] is Transported and Radionuclide Release is Not Mitigated by the Element Solubility Hypothesis[b]; 100 to 10,000 Years

Radionuclides Required to Account for 95% of the Dose	Applicable to the Following Waste Forms	Applicable to the Following Exposure Pathways	Applicable to the Following Time Periods After Repository Closure
Np-237	ALL	Inhalation, ingestion	100 – 10,000 years
U-232	DSNF	Inhalation, ingestion	100 – 300 years
U-233	DSNF	Inhalation, ingestion	100 – 10,000 years
U-234	ALL	Inhalation, ingestion	100 – 10,000 years
U-236	PWR, BWR	Inhalation, ingestion	100 – 10,000 years
U-238	BWR, PWR	Inhalation, ingestion	100 years

[a] Np, Ag, Cd, K, Mn, Pd, Rb, Ru, Sb, U, and Se are the moderately sorbing elements.

[b] No mitigation based on element solubility implies that all elements are considered soluble.

Table 16. Radionuclides Required to Account for Ninety-five Percent of the Inhalation and Ingestion Dose for Average Waste Forms When Only the Slightly to Non-sorbing Transport Group[a] is Transported and Radionuclide Release is Not Mitigated by the Element Solubility Hypothesis[b]; 100 to 10,000 Years

Radionuclides Required to Account for 95% of the Dose	Applicable to the Following Waste Forms	Applicable to the Following Exposure Pathways	Applicable to the Following Time Periods After Repository Closure
C-14	DSNF, BWR	Ingestion	100 – 5,000 years
Tc-99	ALL	Inhalation, ingestion	100 – 10,000 years
I-129	PWR, BWR, DSNF	Inhalation, ingestion	100 – 10,000 years

[a] C, H, I, Mo, P, Re, Tc, Br, Si, Cl, V, Ar, At, Kr, and S are the slightly to non-sorbing elements.

[b] No mitigation based on element solubility implies that all elements are considered soluble.

Table 17. Radionuclides Required to Account for Ninety-five Percent of the Inhalation and Ingestion Dose for Bounding Waste Forms When Only the Slightly to Non-sorbing Transport Group[a] is Transported and Radionuclide Release is Not Mitigated by the Element Solubility Hypothesis[b]; 100 to 10,000 Years

Radionuclides Required to Account for 95% of the Dose	Applicable to the Following Waste Forms	Applicable to the Following Exposure Pathways	Applicable to the Following Time Periods After Repository Closure
C-14	BWR, DSNF	Inhalation, ingestion	100 – 10,000 years
Tc-99	ALL	Inhalation, ingestion	100 – 10,000 years
I-129	PWR, DSNF, BWR	Inhalation, ingestion	100 –10,000 years

[a] C, H, I, Mo, P, Re, Tc, Br, Si, Cl, V, Ar, At, Kr, and S are the slightly to non-sorbing elements.

[b] The element solubility hypothesis is that Am, Cm, Zr, Th, Nb, Pa, and Sn are not soluble.

4.1.2 Relative Contribution of Individual Radionuclides to Inhalation and Ingestion Dose – One Million Years

This section covers input for the radionuclide screening analysis for the extended time period required for TSPA-FEIS. Calculation 5 (CRWMS M&O 2000f) is like Calculation 2 (CRWMS M&O 2000c) except that the assumptions have been extended to include the times that are

required for the TSPA-FEIS. The times considered are 20,000; 30,000; 100,000; 300,000; and 1,000,000 years after repository closure. Table 18 provides a key to Tables 19 through 34 which present the results for inventory screening from Calculation 5 (CRWMS M&O 2000f, Tables 1 through 16).

Table 18. Key to the Tables for the 20,000- to 1,000,000-Year Calculation

Solubility Hypothesis Mitigates Release	Radionuclide Group Transported			
	All Groups	Highly Sorbing Only	Moderately Sorbing Only	Slightly to Nonsorbing Only
Yes	Tables 21 & 22	Tables 23 & 24	Tables 25 & 26	Tables 27 & 28
No	Tables 19 & 20	Tables 29 & 30	Tables 31 & 32	Tables 33 & 34

NOTE: The first table listed in each cell provides inputs for average waste forms and the second provides inputs for bounding waste forms.

Table 19. Radionuclides Required to Account for Ninety-five Percent of the Inhalation and Ingestion Dose for Average Waste Forms When Radionuclides are Released in Proportion to Their Inventory Abundance; 20,000 to 1,000,000 Years

Radionuclides Required to Account for 95% of the Dose	Applicable to the Following Waste Forms	Applicable to the Following Exposure Pathways	Applicable to the Following Time Periods After Repository Closure
Pb-210	ALL	Ingestion	30,000 – 1,000,000 years
Ra-226	ALL	Ingestion	100,000 – 1,000,000 years
Ac-227	ALL	Inhalation, ingestion	20,000 – 1,000,000 years
Th-229	ALL	Inhalation, ingestion	20,000 – 1,000,000 years
Th-230	ALL	Inhalation, ingestion	100,000 – 1,000,000 years
Pa-231	ALL	Inhalation, ingestion	300,000 – 1,000,000 years
U-233	DSNF, HLW, PWR	Inhalation, ingestion	100,000 – 1,000,000 years
U-234	ALL	Inhalation, ingestion	100,000 – 1,000,000 years
U-236	BWR	Inhalation, ingestion	1,000,000 years
U-238	DSNF, HLW	Inhalation	300,000 – 1,000,000 years
Np-237	ALL	Inhalation, ingestion	100,000 – 1,000,000 years
Pu-239	ALL	Inhalation, ingestion	20,000 – 100,000 years
Pu-240	ALL	Inhalation, ingestion	20,000 – 30,000 years
Pu-242	BWR, DSNF, PWR	Inhalation, ingestion	30,000 – 1,000,000 years

Table 20. Radionuclides Required to Account for Ninety-five Percent of the Inhalation and Ingestion Dose for Bounding Waste Forms When Radionuclides are Released in Proportion to Their Inventory Abundance; 20,000 to 1,000,000 Years

Radionuclides Required to Account for 95% of the Dose	Applicable to the Following Waste Forms	Applicable to the Following Exposure Pathways	Applicable to the Following Time Periods After Repository Closure
Pb-210	ALL	Inhalation, ingestion	20,000 – 1,000,000 years
Ra-226	ALL	Ingestion	100,000 – 1,000,000 years
Ac-227	ALL	Inhalation, ingestion	300,000 – 1,000,000 years
Th-229	ALL	Inhalation, ingestion	20,000 – 1,000,000 years
Th-230	ALL	Inhalation, ingestion	100,000 – 1,000,000 years
Th-232	DSNF	Inhalation	1,000,000 years
Pa-231	DSNF	Ingestion	1,000,000 years
U-233	ALL	Inhalation, ingestion	20,000 – 1,000,000 years
U-234	BWR, HLW, PWR	Inhalation, ingestion	30,000 – 1,000,000 years
U-236	BWR	Inhalation	1,000,000 years
U-238	HLW	Inhalation	1,000,000 years
Np-237	ALL	Inhalation, ingestion	100,000 – 1,000,000 years
Pu-239	ALL	Inhalation, ingestion	20,000 – 100,000 years
Pu-240	BWR, HLW, PWR	Inhalation, ingestion	20,000 – 300,000 years
Pu-242	BWR, PWR, HLW	Inhalation, ingestion	30,000 – 1,000,000 years
Am-243	BWR, PWR	Inhalation, ingestion	20,000 – 30,000 years

Table 21. Radionuclides Required to Account for Ninety-five Percent of the Inhalation and Ingestion Dose for Average Waste Forms When Radionuclide Release is Mitigated by the Element Solubility Hypothesis[(a)]; 20,000 to 1,000,000 Years

Radionuclides Required to Account for 95% of the Dose	Applicable to the Following Waste Forms	Applicable to the Following Exposure Pathways	Applicable to the Following Time Periods After Repository Closure
Pb-210	ALL	Inhalation, ingestion	100,000 – 1,000,000 years
Ra-226	ALL	Inhalation, ingestion	100,000 – 1,000,000 years
U-233	ALL	Inhalation, ingestion	100,000 – 1,000,000 years
U-234	ALL	Inhalation, ingestion	100,000 – 1,000,000 years
U-235	DSNF	Inhalation	1,000,000 years
U-236	BWR, HLW, PWR	Inhalation	300,000 – 1,000,000 years
U-238	ALL	Inhalation, ingestion	300,000 – 1,000,000 years
Np-237	ALL	Inhalation, ingestion	100,000 – 1,000,000 years
Pu-239	ALL	Inhalation, ingestion	20,000 – 300,000 years
Pu-240	ALL	Inhalation, ingestion	20,000 – 30,000 years
Pu-242	ALL	Inhalation, ingestion	100,000 – 1,000,000 years

[(a)] The element solubility hypothesis is that Am, Cm, Zr, Th, Nb, Pa, and Sn are not soluble.

Table 22. Radionuclides Required to Account for Ninety-five Percent of the Inhalation and Ingestion Dose for Bounding Waste Forms When Radionuclide Release is Mitigated by the Element Solubility Hypothesis[a]; 20,000 to 1,000,000 Years

Radionuclides Required to Account for 95% of the Dose	Applicable to the Following Waste Forms	Applicable to the Following Exposure Pathways	Applicable to the Following Time Periods After Repository Closure
Pb-210	ALL	Inhalation, ingestion	20,000 – 1,000,000 years
Ra-226	ALL	Inhalation, ingestion	20,000 – 1,000,000 years
U-233	ALL	Inhalation, ingestion	20,000 – 1,000,000 years
U-234	ALL	Inhalation, ingestion	20,000 – 1,000,000 years
U-236	BWR, DSNF, PWR	Inhalation	300,000 – 1,000,000 years
U-238	HLW	Inhalation	1,000,000 years
Np-237	ALL	Inhalation, ingestion	100,000 – 1,000,000 years
Pu-239	ALL	Inhalation, ingestion	20,000 – 100,000 years
Pu-240	ALL	Inhalation, ingestion	20,000 – 30,000 years
Pu-242	BWR, HLW, PWR	Inhalation, ingestion	30,000 – 1,000,000 years

[a] The element solubility hypothesis is that Am, Cm, Zr, Th, Nb, Pa, and Sn are not soluble.

Table 23. Radionuclides Required to Account for Ninety-five Percent of the Inhalation and Ingestion Dose for Average Waste Forms When Only the Highly Sorbing Transport Group[a] is Released and Radionuclide Release is Mitigated by the Element Solubility Hypothesis[b]; 20,000 to 1,000,000 Years

Radionuclides Required to Account for 95% of the Dose	Applicable to the Following Waste Forms	Applicable to the Following Exposure Pathways	Applicable to the Following Time Periods After Repository Closure
Ra-226	ALL	Inhalation, ingestion	100,000 – 1,000,000 years
Pb-210	ALL	Inhalation, ingestion	100,000 – 1,000,000 years
Pu-239	ALL	Inhalation, ingestion	20,000 – 300,000 years
Pu-240	ALL	Inhalation, ingestion	20,000 – 30,000 years
Pu-242	ALL	Inhalation, ingestion	100,000 – 1,000,000 years

[a] Ca, Co, Sr, Ac, Am, Be, Bi, Ce, Cm, Cs, Fe, Hf, Ho, Nb, Pa, Pb, Po, Pu, Ra, Sm, Sn, Ta, Te, Th, Y, Zn, Zr, Ba, Ni, Eu, Bk, Cf, Fr, La, Lu, Nd, Pm, Pr, Tb, and Tm are the highly sorbing elements.

[b] The element solubility hypothesis is that Am, Cm, Zr, Th, Nb, Pa, and Sn are not soluble.

Table 24. Radionuclides Required to Account for Ninety-five Percent of the Inhalation and Ingestion Dose for Bounding Waste Forms When Only the Highly Sorbing Transport Group[a] is Released and Radionuclide Release is Mitigated by the Element Solubility Hypothesis[b]; 20,000 to 1,000,000 Years

Radionuclides Required to Account for 95% of the Dose	Applicable to the Following Waste Forms	Applicable to the Following Exposure Pathways	Applicable to the Following Time Periods After Repository Closure
Pb-210	ALL	Inhalation, ingestion	20,000 – 1,000,000 years
Ra-226	ALL	Inhalation, ingestion	20,000 – 1,000,000 years
Pu-239	ALL	Inhalation, ingestion	20,000 – 300,000 years
Pu-240	ALL	Inhalation, ingestion	20,000 – 30,000 years
Pu-242	ALL	Inhalation, ingestion	100,000 – 1,000,000 years

[a] Ca, Co, Sr, Ac, Am, Be, Bi, Ce, Cm, Cs, Fe, Hf, Ho, Nb, Pa, Pb, Po, Pu, Ra, Sm, Sn, Ta, Te, Th, Y, Zn, Zr, Ba, Ni, Eu, Bk, Cf, Fr, La, Lu, Nd, Pm, Pr, Tb, and Tm are the highly sorbing elements.

[b] The element solubility hypothesis is that Am, Cm, Zr, Th, Nb, Pa, and Sn are not soluble.

Table 25. Radionuclides Required to Account for Ninety-five Percent of the Inhalation and Ingestion Dose for Average Waste Forms When Only the Moderately Sorbing Transport Group[a] is Released and Radionuclide Release is Mitigated by the Element Solubility Hypothesis[b]; 20,000 to 1,000,000 Years

Radionuclides Required to Account for 95% of the Dose	Applicable to the Following Waste Forms	Applicable to the Following Exposure Pathways	Applicable to the Following Time Periods After Repository Closure
U-233	ALL	Inhalation, ingestion	20,000 – 1,000,000 years
U-234	ALL	Inhalation, ingestion	20,000 – 1,000,000 years
U-236	BWR, DSNF, PWR	Inhalation, ingestion	20,000 – 1,000,000 years
U-238	BWR, DSNF, HLW	Inhalation, ingestion	20,000 – 1,000,000 years
Np-237	ALL	Inhalation, ingestion	20,000 – 1,000,000 years

[a] Np, Ag, Cd, K, Mn, Pd, Rb, Ru, Sb, U, and Se are the moderately sorbing elements.

[b] The element solubility hypothesis is that Am, Cm, Zr, Th, Nb, Pa, and Sn are not soluble.

Table 26. Radionuclides Required to Account for Ninety-five Percent of the Inhalation and Ingestion Dose for Bounding Waste Forms When Only the Moderately Sorbing Transport Group[a] is Released and Radionuclide Release is Mitigated by the Element Solubility Hypothesis[b]; 20,000 to 1,000,000 Years

Radionuclides Required to Account for 95% of the Dose	Applicable to the Following Waste Forms	Applicable to the Following Exposure Pathways	Applicable to the Following Time Periods After Repository Closure
U-233	ALL	Inhalation, ingestion	20,000 – 1,000,000 years
U-234	ALL	Inhalation, ingestion	20,000 – 1,000,000 years
U-236	BWR, DSNF, PWR	Inhalation, ingestion	20,000 – 1,000,000 years
U-238	HLW	Inhalation	1,000,000 years
Np-237	ALL	Inhalation, ingestion	20,000 – 1,000,000 years

[a] Np, Ag, Cd, K, Mn, Pd, Rb, Ru, Sb, U, and Se are the moderately sorbing elements.

[b] The element solubility hypothesis is that Am, Cm, Zr, Th, Nb, Pa, and Sn are not soluble.

Table 27. Radionuclides Required to Account for Ninety-five Percent of the Inhalation and Ingestion Dose for Average Waste Forms When Only the Slightly to Non-Sorbing Transport Group[a] is Released and Radionuclide Release is Mitigated by the Element Solubility Hypothesis[b]; 20,000 to 1,000,000 Years

Radionuclides Required to Account for 95% of the Dose	Applicable to the Following Waste Forms	Applicable to the Following Exposure Pathways	Applicable to the Following Time Periods After Repository Closure
Tc-99	BWR, DSNF, PWR	Inhalation, ingestion	20,000 – 1,000,000 years
I-129	ALL	Inhalation, ingestion	20,000 – 1,000,000 years

[a] C, H, I, Mo, P, Re, Tc, Br, Si, Cl, V, Ar, At, Kr, and S are the slightly to non-sorbing elements.

[b] The element solubility hypothesis is that Am, Cm, Zr, Th, Nb, Pa, and Sn are not soluble.

Table 28. Radionuclides Required to Account for Ninety-five Percent of the Inhalation and Ingestion Dose for Bounding Waste Forms When Only the Slightly to Non-Sorbing Transport Group[a] is Released and Radionuclide Release is Mitigated by the Element Solubility Hypothesis[b]; 20,000 to 1,000,000 Years

Radionuclides Required to Account for 95% of the Dose	Applicable to the Following Waste Forms	Applicable to the Following Exposure Pathways	Applicable to the Following Time Periods After Repository Closure
Tc-99	ALL	Inhalation, ingestion	20,000 – 1,000,000 years
I-129	BWR, DSNF, PWR	Inhalation, ingestion	20,000 – 1,000,000 years

[a] C, H, I, Mo, P, Re, Tc, Br, Si, Cl, V, Ar, At, Kr, and S are the slightly to non-sorbing elements.

[b] The element solubility hypothesis is that Am, Cm, Zr, Th, Nb, Pa, and Sn are not soluble.

Table 29. Radionuclides Required to Account for Ninety-five Percent of the Inhalation and Ingestion Dose for Average Waste Forms When Only the Highly Sorbing Transport Group[a] is Transported and Radionuclide Release is Not Mitigated by the Element Solubility Hypothesis[b]; 20,000 to 1,000,000 Years

Radionuclides Required to Account for 95% of the Dose	Applicable to the Following Waste Forms	Applicable to the Following Exposure Pathways	Applicable to the Following Time Periods After Repository Closure
Pb-210	ALL	Inhalation, ingestion	100,000 – 1,000,000 years
Ra-226	ALL	Ingestion	100,000 – 1,000,000 years
Ac-227	ALL	Inhalation, ingestion	100,000 – 1,000,000 years
Th-229	ALL	Inhalation, ingestion	20,000 – 1,000,000 years
Th-230	ALL	Inhalation, ingestion	100,000 – 1,000,000 years
Pa-231	DSNF, PWR, HLW	Inhalation, ingestion	300,000 – 1,000,000 years
Pu-239	ALL	Inhalation, ingestion	20,000 – 1,000,000 years
Pu-240	ALL	Inhalation, ingestion	20,000 – 30,000 years
Pu-242	BWR, PWR	Inhalation, ingestion	100,000 – 1,000,000 years

[a]Ca, Co, Sr, Ac, Am, Be, Bi, Ce, Cm, Cs, Fe, Hf, Ho, Nb, Pa, Pb, Po, Pu, Ra, Sm, Sn, Ta, Te, Th, Y, Zn, Zr, Ba, Ni, Eu, Bk, Cf, Fr, La, Lu, Nd, Pm, Pr, Tb, and Tm are the highly sorbing elements.

[b]No mitigation based on element solubility implies that all elements are considered soluble.

Table 30. Radionuclides Required to Account for Ninety-five Percent of the Inhalation and Ingestion Dose for Bounding Waste Forms When Only the Highly Sorbing Transport Group[a] is Transported and Radionuclide Release is Not Mitigated by the Element Solubility Hypothesis[b]; 20,000 to 1,000,000 Years

Radionuclides Required to Account for 95% of the Dose	Applicable to the Following Waste Forms	Applicable to the Following Exposure Pathways	Applicable to the Following Time Periods After Repository Closure
Ac-227	DSNF, HLW	Inhalation, ingestion	300,000 – 1,000,000 years
Pb-210	ALL	Inhalation, ingestion	20,000 – 1,000,000 years
Ra-226	ALL	Ingestion	100,000 – 1,000,000 years
Th-229	ALL	Inhalation, ingestion	20,000 – 1,000,000 years
Th-230	ALL	Inhalation, ingestion	100,000 – 1,000,000 years
Pa-231	DSNF	Ingestion	1,000,000 years
Pu-239	ALL	Inhalation, ingestion	20,000 – 100,000 years
Pu-240	BWR, HLW, PWR	Inhalation, ingestion	20,000 – 30,000 years
Pu-242	HLW	Inhalation, ingestion	100,000 – 1,000,000 years
Am-243	BWR, PWR	Inhalation, ingestion	20,000 – 30,000 years

[a]Ca, Co, Sr, Ac, Am, Be, Bi, Ce, Cm, Cs, Fe, Hf, Ho, Nb, Pa, Pb, Po, Pu, Ra, Sm, Sn, Ta, Te, Th, Y, Zn, Zr, Ba, Ni, Eu, Bk, Cf, Fr, La, Lu, Nd, Pm, Pr, Tb, and Tm are the highly sorbing elements.

[b]No mitigation based on element solubility implies that all elements are considered soluble.

Table 31. Radionuclides Required to Account for Ninety-five Percent of the Inhalation and Ingestion Dose for Average Waste Forms When Only the Moderately Sorbing Transport Group[a] is Transported and Radionuclide Release is Not Mitigated by the Element Solubility Hypothesis[b]; 20,000 to 1,000,000 Years

Radionuclides Required to Account for 95% of the Dose	Applicable to the Following Waste Forms	Applicable to the Following Exposure Pathways	Applicable to the Following Time Periods After Repository Closure
U-233	ALL	Inhalation, ingestion	20,000 – 1,000,000 years
U-234	ALL	Inhalation, ingestion	20,000 – 1,000,000 years
U-236	BWR, DSNF, PWR	Inhalation, ingestion	20,000 – 1,000,000 years
U-238	BWR, DSNF, HLW	Inhalation, ingestion	20,000 – 1,000,000 years
Np-237	ALL	Inhalation, ingestion	20,000 – 1,000,000 years

[a] Np, Ag, Cd, K, Mn, Pd, Rb, Ru, Sb, U, and Se are the moderately sorbing elements.

[b] No mitigation based on element solubility implies that all elements are considered soluble.

Table 32. Radionuclides Required to Account for Ninety-five Percent of the Inhalation and Ingestion Dose for Bounding Waste Forms When Only the Moderately Sorbing Transport Group[a] is Transported and Radionuclide Release is Not Mitigated by the Element Solubility Hypothesis[b]; 20,000 to 1,000,000 Years

Radionuclides Required to Account for 95% of the Dose	Applicable to the Following Waste Forms	Applicable to the Following Exposure Pathways	Applicable to the Following Time Periods After Repository Closure
U-233	ALL	Inhalation, ingestion	20,000 – 1,000,000 years
U-234	ALL	Inhalation, ingestion	20,000 – 1,000,000 years
U-236	BWR, DSNF, PWR	Inhalation, ingestion	20,000 – 1,000,000 years
U-238	HLW, PWR, DSNF	Inhalation, ingestion	20,000 – 1,000,000 years
Np-237	ALL	Inhalation, ingestion	20,000 – 1,000,000 years

[a] Np, Ag, Cd, K, Mn, Pd, Rb, Ru, Sb, U, and Se are the moderately sorbing elements.

[b] No mitigation based on element solubility implies that all elements are considered soluble.

Table 33. Radionuclides Required to Account for Ninety-five Percent of the Inhalation and Ingestion Dose for Average Waste Forms When Only the Slightly to Non-sorbing Transport Group[a] is Transported and Radionuclide Release is Not Mitigated by the Element Solubility Hypothesis[b]; 20,000 to 1,000,000 Years

Radionuclides Required to Account for 95% of the Dose	Applicable to the Following Waste Forms	Applicable to the Following Exposure Pathways	Applicable to the Following Time Periods After Repository Closure
Tc-99	BWR, DSNF, PWR	Inhalation, ingestion	20,000 – 1,000,000 years
I-129	ALL	Inhalation, ingestion	20,000 – 1,000,000 years

[a] C, H, I, Mo, P, Re, Tc, Br, Si, Cl, V, Ar, At, Kr, and S are the slightly to non-sorbing elements.

[b] The element solubility hypothesis is that Am, Cm, Zr, Th, Nb, Pa, and Sn are not soluble.

Table 34. Radionuclides Required to Account for Ninety-five Percent of the Inhalation and Ingestion Dose for Bounding Waste Forms When Only the Slightly to Non-sorbing Transport Group[a] is Transported and Radionuclide Release is Not Mitigated by the Element Solubility Hypothesis[b]; 20,000 to 1,000,000 Years

Radionuclides Required to Account for 95% of the Dose	Applicable to the Following Waste Forms	Applicable to the Following Exposure Pathways	Applicable to the Following Time Periods After Repository Closure
Tc-99	ALL	Inhalation, ingestion	20,000 – 1,000,000 years
I-129	BWR, DSNF, PWR	Inhalation, ingestion	20,000 – 1,000,000 years

[a] C, H, I, Mo, P, Re, Tc, Br, Si, Cl, V, Ar, At, Kr, and S are the slightly to non-sorbing elements.

[b] No mitigation based on element solubility implies that all elements are considered soluble.

4.2 CRITERIA

There are no criteria for radionuclide screening in the project-requirements documents (i.e., System Description Documents). The NRC criteria that this document addresses are specified in the Container Life and Source Term Issue Resolution Status Report (CLST IRSR) Subissue 3 ("The rate at which radionuclides in SNF [Spent Nuclear Fuel] are released from the EBS [Engineered Barrier System] through the oxidation and dissolution of spent fuel") and Subissue 4 ("The rate at which radionuclides in High-Level Waste Glass are released from the EBS through

the oxidation and dissolution of spent fuel"). Although Subissue 5 ("The Effects of In-Package Criticality on Waste Package and Engineered Barrier Subsystem Performance") is relevant to radionuclide inventory estimation, it is not addressed by this analysis. The other Subissues in the CLST IRSR are not relevant to radionuclide screening or radionuclide inventory estimation. The following sections paraphrase the NRC review and acceptance criteria for Subissues 3 and 4 that are addressed by this analysis (NRC 1999).

4.2.1 Acceptance Criteria Applicable to All Six Subissues from the CLST IRSR

- The collection and documentation of data, as well as development and documentation of analyses, methods, models, and codes, must be accomplished under approved quality assurance and control procedures and standards.

- The structure and organization of process and abstracted models must adequately incorporate important design features, physical phenomena, and coupled processes.

4.2.2 Acceptance Criteria for Subissue 3 and 4 from the CLST IRSR

- All categories of SNF and HLW planned for disposal at the proposed YM repository must be considered.

- The selection of radionuclides tracked in the release models from SNF and HLW and their related release parameters must be adequately justified.

4.3 CODES AND STANDARDS

There are no codes and standards associated with this analysis. The output from this analysis will be used in the TSPA-SR, which will be compared, according to the DOE interim guidance (Dyer 1999), to specific Subparts or Sections of the proposed NRC high-level waste regulation, 10 CFR Part 63 (64 FR 8640). The DOE interim guidance (Dyer 1999) directs the use of specific Subparts or Sections of the proposed NRC high-level waste regulation, 10 CFR Part 63 (64 FR 8640). The subpart of the proposed regulation that is relevant to the TSPA-SR use of this analysis is Subpart E, Section 114 (Requirements for Performance Assessment).

5. ASSUMPTIONS

The assumptions stated below for the TSPA-SR also apply to the analysis for the TSPA-FEIS except that the time period defined for the FEIS is extended to one million years.

The following assumptions produce bounding results or are otherwise sufficiently justified such that further confirmation is not needed. Bounding in this context means that the subset of radionuclides recommended for modeling in TSPA-SR is larger than it would be if more limiting assumptions were made.

5.1 For the direct release scenario, it is assumed that radionuclides are directly released into the surface environment at the times under consideration by a disruptive event such as a volcano or a major tectonic event. The rationale for this assumption is that such an event is possible, though unlikely, at any time. This assumption is used in Sections 6.3, 6.4, and 6.5 where the relative dose contribution from each radionuclide is examined at early times and at times up to 10,000 years.

5.2 It is assumed that all types of waste form disposed in the repository have the potential to contribute to the dose. Because some scenarios could lead to failure of only a few waste packages before 10,000 years, obscure types of waste form, although they may not be prevalent in the repository, could contribute to the dose. The rationale for this assumption is that it is bounding because it does not preclude contributions from any type of waste form. This assumption is used in Sections 6.3, 6.4, and 6.5 where the relative dose contribution from individual PWR, BWR, and DSNF packages is examined.

5.3 It is assumed that inhalation- and ingestion-exposure pathways could contribute to the dose. The rationale for this assumption is as follows. For a direct release under volcanic conditions, inhalation may dominate the dose. On the other hand, when radionuclides migrate from an undisturbed repository to a groundwater source, ingestion may dominate the dose. This assumption is used in Sections 6.3, 6.4, and 6.5 where the relative dose contributions for both inhalation and ingestion doses are examined.

5.4 It is assumed that radionuclides that are treated as insoluble under the element solubility hypothesis (Section 4.1.1.3) might nevertheless find a migration pathway to the accessible environment under some conditions. The rationale for this assumption is as follows. Under some conditions, low pH waters could appear around the waste form. Elements that would otherwise be considered insoluble can dissolve in low pH waters. Furthermore, even insoluble elements can be bound up in waste-form colloids, which are transportable. This assumption is bounding because it does not preclude consideration of any radionuclides. This assumption is used in Sections 6.4 and 6.5.

5.5 It is assumed that highly sorbing radionuclides (isotopes of Ca, Co, Sr, Ac, Am, Be, Bi, Ce, Cm, Cs, Fe, Hf, Ho, Nb, Ni, Pa, Pb, Po, Pu, Ra, Sm, Sn, Ta, Te, Th, Y, Zn, Zr, Ba, Eu, Bk, Cf, Fr, La, Lu, Nd, Pm, Pr, Tb, and Tm) are most likely to transport via colloidal transport. The rationale for assuming that isotopes of the listed elements are highly sorbing is as follows. The elements are chemically similar inasmuch as they tend to form cations with

relatively high charge densities—a feature that causes them to adsorb readily. Estimated sorption-coefficient distributions applicable to the potential repository site are provided by CRWMS M&O (2001a, Section 6.4.2) for many of the elements covered by this assumption (Sr, Ac, Am, Cs, Nb, Ni, Pa, Pb, Pu, Ra, Sm, Sn, Th, and Zr). The rationale for assigning the most likely transport mechanism is as follows. The colloidal transport mechanism envisions adsorption of radionuclides to mobile colloids, which is more apt to occur for highly sorbing radionuclides. Likewise, the tendency of the highly sorbing radionuclides to adsorb to the rock matrix would limit their transport by fracture flow, matrix advection, and matrix diffusion. This assumption is used in Sections 6.4 and 6.5 where the primary dose contributors from each of three distinct transport groups, highly sorbing, moderately sorbing, and slightly to non-sorbing, are examined.

5.6 It is assumed that moderately sorbing radionuclides (isotopes of Np, Ag, Cd, K, Mn, Pd, Rb, Ru, Sb, U, and Se) are most likely to transport via fracture flow. The rationale for assuming that isotopes of the listed elements are moderately sorbing is as follows. The elements are chemically similar inasmuch as they tend to form cations with charge densities that are lower than the charge densities of the cations formed by the highly sorbing radionuclides. The lower charge densities make them less susceptible to sorption. CRWMS M&O (2001a, Section 6.4.2) provides estimated sorption-coefficient distributions for some of the elements covered by this assumption (Np, U, and Se). The rationale for assigning the most likely transport mechanism is as follows. Moderately sorbing radionuclides are less apt to adsorb to colloids; yet, during the prolonged intimate contact with the rock matrix that is implied by matrix diffusion and matrix advection, they would likely be detained by the matrix. The remaining transport mechanism is fracture flow, which requires less intimate contact with the rock. This assumption is used in Sections 6.4 and 6.5 where the primary dose contributors from each of three distinct transport groups, highly sorbing, moderately sorbing, and slightly to non-sorbing, are examined.

5.7 It is assumed that slightly to non-sorbing radionuclides (isotopes of C, H, I, Mo, P, Re, Tc, Br, Si, Cl, V, Ar, At, Kr, and S) are most likely to transport via matrix advection or matrix diffusion. The rationale for assuming that isotopes of the listed elements are slightly to non-sorbing is as follows. Two of the elements (Ar and Kr) will not sorb readily because they are inert gasses. The rest of the elements are chemically similar to each other inasmuch as they tend to form anions or anionic complexes with low charge densities, which are not very susceptible to sorption. CRWMS M&O (2001a, Section 6.4.2) provides estimated sorption-coefficient distributions for some of the elements covered by this assumption (C, I, Tc, and Cl). The rationale for assigning the most likely transport mechanism is as follows. Slightly to non-sorbing radionuclides are apt to dominate transport by matrix advection and matrix diffusion because moderately and highly sorbing radionuclides would not transport readily by this mechanism because they would be preferentially detained by the matrix as discussed in Assumptions 5.5 and 5.6. This assumption is used in Sections 6.4 and 6.5 where the primary dose contributors from each of three distinct transport groups, highly sorbing, moderately sorbing, and slightly to non-sorbing, are examined.

Given the assumptions listed above, all radionuclides that could significantly contribute to the dose will be modeled in TSPA-SR. The assumptions listed below determine which radionuclides

do not need to be modeled in TSPA-SR because they will not contribute significantly to the dose. The following assumptions are bounding or are otherwise sufficiently justified such that further confirmation is not needed.

5.8 It is assumed that radionuclides with half-lives less than approximately twenty years will not contribute significantly to the dose for postclosure scenarios. The rationale for this assumption is that radionuclides with half-lives less than twenty years will have decayed significantly (less than 3 percent remaining by 100 years) by the time the repository closes. This assumption is used in Sections 6.3, 6.4, 6.5, and Attachment II.

5.9 It is assumed that screening radionuclides according to a criterion that accounts for 95 percent of the cumulative dose under the identified release scenarios is adequate for the TSPA-SR. By definition, radionuclide screening requires that a subset of the full inventory of radionuclides be modeled in TSPA-SR and, therefore, that the dose contributions from some radionuclides will not be included in the dose estimates. The rationale for this assumption is that neglected dose contributions are negligible compared to the uncertainties in the dose estimates from the TSPA-SR model. This assumption is used in Sections 6.3, 6.4, and 6.5.

5.10 It is assumed that the as-built characteristics of PWR and BWR assemblies and the calculated radionuclide inventories that are developed by CRWMS M&O (1999a, 1999b, 1999c, and 1999d) are adequate for this analysis. The rationale for this assumption is that this is most recent information available. This assumption is used in Sections 6.3, 6.4, and 6.5 and in Attachments I and II.

5.11 For the evaluation in Attachment II of the propriety of lumping hardware activation products with radionuclides from the spent fuel matrix, it is assumed that the exposed stainless steel components of the CSNF assemblies will degrade and release their C-14 content much more quickly than the CSNF will release C-14 from the spent fuel matrix (excluding the fast-release portion). The rationale for this assumption is developed as follows. Measurements of the penetration rate for aqueous general corrosion of stainless steel 304 are summarized in the cumulative log-uniform distribution implied by $F(x) = 57.657 \times \log_{10}(x) - 38.597$, where x is the degradation rate in μm/y and $F(x)$ is the cumulative probability in percent (BSC 2001d, Figure 12). Substituting $F(x) = 0$ and solving for x gives the minimum of the range of the distribution as 4.7 μm/y. Substituting $F(x) = 100$ percent and solving for x gives the maximum of the range of the distribution as 250 μm/y. Substituting $F(x) = 50$ percent and solving for x gives the median of the distribution as 34 μm/y. The mean of the distribution is given by (250 - 4.7) / [ln(250) - ln(4.7)] = 62 μm/y (Ragan 1998, p. 2). Thicknesses of stainless steel components of CSNF assemblies vary. Thicknesses from 0.197 in. (5 mm) to 0.85 in (22 mm) can be found in typical BWR assemblies (Larsen et al. 1976, pp. C-10 through C-12). Taking 0.5 in. (13 mm) as representative for CSNF assemblies generally, consider how long it would take for corrosion to penetrate the entire thickness if the attack proceeds from two opposite surfaces according to the mean rate of the distribution given above. Thus: 13×10^3 μm / (2 × 62 μm/y) = 100 y. Repeating the calculation for the minimum, median, and maximum degradation rates gives 1400 y, 190 y, and 26 y.

Therefore, the time from waste-package breach to complete release of the C-14 from the stainless steel hardware is expected to be very short compared to the 10,000-y regulatory period for the potential repository. Because almost all of the highly corrosion resistant CSNF cladding (BSC 2001a, Attachment II) will be intact at the time of waste-package breach (CRWMS M&O 2001b, p. 67), the time from waste-package breach to complete release of the C-14 from the CSNF spent fuel matrix will not be short compared to the 10,000-y regulatory period. Therefore, the assumption is justified. This assumption is used in Section II-4.2

6. ANALYSIS/MODEL

6.1 REGULATORY FRAMEWORK

The Nuclear Waste Policy Act of 1982 directed the NRC to develop technical criteria for HLW disposal in mined geologic repositories. The NRC was directed in part to develop disposal criteria that are consistent with environmental standards promulgated by the U.S. Environmental Protection Agency (EPA) pursuant to the Nuclear Waste Policy Act of 1982. To meet this obligation, the NRC promulgated technical criteria in 10 CFR 60 (in 1983) on the assumption that the EPA would issue standards limiting cumulative radionuclide releases from a geologic repository in 40 CFR 191. Thus, 10 CFR 60, the governing NRC regulation for the proposed Yucca Mountain repository from 1983 to 1998, became a generic standard intended to be consistent with standards established two years later (in 1985) by the EPA in 40 CFR 191.

Two years after 10 CFR 60 was published, the EPA issued final standards in 40 CFR 191, which not only contained cumulative release limits but also provided criteria for individual and ground-water protection that had not been included in the EPA's rulemaking proposal. Further, in 1992, Congress directed the EPA to contract with the National Academy of Sciences (NAS) to advise EPA on the appropriate technical basis for public health and safety standards governing the proposed Yucca Mountain repository. In its final report, NAS recommended an approach and content that is significantly different from that adopted by EPA for its disposal standards in 40 CFR 191, as well as from those adopted by NRC for its existing generic regulations in 10 CFR 60.

As a result, the NRC is proposing new licensing criteria for disposal of spent nuclear fuel and high-level radioactive wastes in the proposed geologic repository at Yucca Mountain, Nevada (64 FR 8640). The licensing criteria will address the performance of the proposed repository system at Yucca Mountain over a 10,000-year regulatory period. Having considered both technical and policy concerns, the NRC decided that a 10,000-year period should be used to evaluate compliance with the system performance. In addition, the performance requirements proposed by the NRC are designed to implement a health-based safety objective for long-term repository performance that fully protects the public health and safety, and the environment, and is consistent with national and international recommendations for radiation protection standards.

The importance of this regulatory evolution for radionuclide screening is two-fold. First, performance assessment calculations for the Site Recommendation will encompass a time frame of 10,000 years. Second, there has been a shift from regulation based on radionuclide release limits to regulation based on radiation dose. Radionuclide screening for the last three performance assessments has been based in large part on the release limits set in 40 CFR 191 and has considered times up to a million years. Now, radionuclide screening for TSPA-SR must focus on the contribution that each radionuclide makes to the radiation dose within a 10,000-year time frame.

6.2 PREVIOUS RADIONUCLIDE SCREENING ACTIVITIES

Radionuclide screening started with the 1993 TSPA (Wilson et al. 1994) and was carried forward into the 1995 TSPA (CRWMS M&O 1995) and the Total System Performance Assessment in Support of the Viability Assessment (TSPA-VA) (CRWMS M&O 1998). In an activity parallel to the TSPA, the NRC performed an Iterative Performance Assessment (IPA) (Wescott et al. 1995). The results of the cited radionuclide screening activities are provided in Table 35.

6.3 SCREENING FOR THE DISRUPTIVE EVENTS SCENARIOS

The TSPA-SR will include a direct release via a disruptive event scenario. A direct surface release may occur as a result of an eruptive center (i.e., a volcanic vent) that transports waste to the surface resulting in dispersal of contaminated volcanic ash in the vicinity of the eruption. For this scenario, radionuclide screening is based on inventory abundance and radionuclide longevity. Element solubility and transport-affinity are not relevant for a direct release scenario. As a result, the radionuclides listed in Tables 2 and 3 (for times up to 10,000 years) and Tables 19 and 20 (for times from 20,000 to 1,000,000 years) account for 95 percent of the dose. These are the radionuclides that are prevalent in the inventory over the duration of the calculation, and therefore, they will contribute the most to the dose.

6.4 SCREENING FOR THE NOMINAL RELEASE SCENARIOS

The TSPA-SR will also include a nominal release scenario. The nominal release scenario involves an undisturbed repository. According to the scenario, water seeps into the repository over time and corrodes the waste package materials until some waste packages fail. At that point water comes in contact with the waste form, and radionuclides released into the water can migrate from the repository to the accessible environment. For nominal release, radionuclide screening must consider inventory abundance, radionuclide longevity, and transport affinity.

Tables 4 through 17 (for times up to 10,000 years) and Tables 19 through 34 (for times from 20,000 to 1,000,000 years) list the isotopes that account for ninety-five percent of the dose if inventory abundance, radionuclide longevity, solubility, and transport affinity are the criteria considered for the screening. With the exception of Sr-90 and Cs-137, all of the isotopes that appear in Tables 4 through 17 (for times up to 10,000 years) and Tables 19 through 34 (for times from 20,000 to 1,000,000 years) should be modeled in the nominal release scenario. Sr-90 and Cs-137 can be eliminated from the TSPA-SR and FEIS analyses in the nominal case because their contribution is limited to 200 years after repository closure. It is believed that, given the time required to produce waste package failures and the groundwater travel time, Sr-90 and Cs-137 will decay entirely before they ever reach the accessible environment.

Table 35. Radionuclides Included in Previous TSPAs

Radionuclide	TSPA 1993[a]	TSPA 1995[b]	TSPA-VA 1998[c]	NRC IPA[d]
Ac-227	Ac-227	Ac-227		
Ag-108m	Ag-108m			
Am-241	Am-241	Am-241		Am-241
Am-242m	Am-242m	Am-242m		
Am-243	Am-243	Am-243		Am-243
C-14	C-14	C-14	C-14	C-14
Cl-36	Cl-36	Cl-36		
Cm-243	Cm-243			
Cm-244	Cm-244	Cm-244		
Cm-245	Cm-245	Cm-245		Cm-245
Cm-246	Cm-246	Cm-246		Cm-246
Cs-135	Cs-135	Cs-135		Cs-135
Cs-137	Cs-137			Cs-137
I-129	I-129	I-129	I-129	I-129
Mo-93	Mo-93			
Nb-93m		Nb-93m		
Nb-94	Nb-94	Nb-94		Nb-94
Ni-59	Ni-59	Ni-59		Ni-59
Ni-63	Ni-63	Ni-63		
Np-237	Np-237	Np-237	Np-237	Np-237
Pa-231	Pa-231	Pa-231	Pa-231	
Pb-210	Pb-210	Pb-210		Pb-210
Pd-107	Pd-107	Pd-107		
Pu-238	Pu-238	Pu-238		
Pu-239	Pu-239	Pu-239	Pu-239	Pu-239
Pu-240	Pu-240	Pu-240		Pu-240
Pu-241	Pu-241	Pu-241		
Pu-242	Pu-242	Pu-242	Pu-242	
Ra-226	Ra-226	Ra-226		Ra-226
Ra-228		Ra-228		
Se-79	Se-79	Se-79	Se-79	Se-79
Sm-151	Sm-151	Sm-151		
Sn-121m	Sn-121m			
Sn-126	Sn-126	Sn-126		
Sr-90	Sr-90			
Tc-99	Tc-99	Tc-99	Tc-99	Tc-99
Th-229	Th-229	Th-229		
Th-230	Th-230	Th-230		Th-230
Th-232		Th-232		
U-232	U-232			
U-233	U-233	U-233		
U-234	U-234	U-234	U-234	U-234
U-235	U-235	U-235		
U-236	U-236	U-236		
U-238	U-238	U-238		U-238
Zr-93	Zr-93	Zr-93		

SOURCES: [a]Wilson et al. 1994; [b]CRWMS M&O 1995; [c]CRWMS M&O 1998; [d]Wescott et al. 1995

6.5 SCREENING FOR THE HUMAN-INTRUSION SCENARIOS

The TSPA-SR will include a human-intrusion scenario. The human-intrusion scenario involves a drilling event in which a waste package is breached and radioactive material is pushed into the saturated zone. Once released to the saturated zone, radionuclides can migrate from the

repository to the accessible environment. For this scenario, screening is based on inventory abundance, radionuclide longevity, and transport affinity.

Tables 4 through 17 (for times up to 10,000 years) and Tables 19 through 34 (for times from 20,000 to 1,000,000 years) list the isotopes that account for 95 percent of the dose if inventory abundance, radionuclide longevity, solubility, and transport affinity are used for screening. All of the isotopes that appear in Tables 4 through 17 (for times up to 10,000 years) and Tables 19 through 34 (for times from 20,000 to 1,000,000 years) should be modeled in the human-intrusion scenario. Sr-90 and Cs-137 cannot be eliminated from the TSPA-SR analyses for human intrusion because the drilling event accelerates waste package breach, and, given uncertainties in groundwater travel time, Sr-90 and Cs-137 may not decay entirely before they reach the accessible environment.

6.6 RADIONUCLIDE INVENTORY IN GRAMS FOR CSNF AND CODISPOSAL WASTE PACKAGES FOR TSPA-SR

The radionuclide inventory in grams (Table 36) was developed in Attachment I based on average waste form characteristics and should be used for initial radionuclide inventories in CSNF and codisposal waste packages for TSPA-SR and TSPA-FEIS. This data has been submitted to the Technical Data Management System under DTN: SN0009T0810599.014.

7. CONCLUSIONS

This analysis provides radionuclide screening and radionuclide inventories for TSPA-SR and TSPA-FEIS.

7.1 INITIAL RADIONUCLIDE INVENTORIES

For the radionuclides identified for the various scenarios in Sections 7.2 and 7.3, initial inventories, in grams, for each radionuclide based on average waste form characteristics (Table 36) were derived in Attachment I.

Attachment II demonstrates that it is appropriate for this screening analysis and for performance assessment in general to neglect the radionuclide contribution from activated mineral deposits (crud) on commercial SNF assemblies.

Attachment II identifies Tc-99 and C-14 as potentially significant hardware-activation products in commercial SNF assemblies. As demonstrated in Attachment II, a negligible fraction of the Tc-99 in commercial SNF is due to hardware activation. Lumping the inventory of Tc-99 from CSNF hardware-activation products together with the Tc-99 in the commercial SNF matrix, as has been done in the supporting calculations for this analysis, is an acceptable approximation for repository performance assessment because the Tc-99 inventory from CSNF hardware is overwhelmed by the Tc-99 from DSNF in codisposal waste packages, which is assumed not to be impeded by cladding.

Attachment II estimates that about 18 percent of the C-14 inventory in CSNF originates from neutron activation of stainless steel hardware outside the fuel rods. Lumping the inventory of C-14 from CSNF hardware-activation products together with the C-14 in the commercial SNF matrix is a nonconservative approximation for repository performance assessment because the C-14 in the hardware may be released much sooner than the C-14 within the fuel matrix. Due to the importance of C-14 to the early dose and the significance of the C-14 contribution from CSNF hardware, the C-14 from the hardware should not be lumped with the C-14 from the fuel matrix in future TSPAs.

7.2 RECOMMENDATIONS FOR TSPA-SR

Examining relative inhalation and ingestion doses from 100 to 10,000 years for average and bounding spent nuclear fuel and high-level waste leads to the following conclusions:

- For a direct release from a disruptive event scenario, the radionuclides that should be modeled for times up to 10,000 years (that is, in the TSPA-SR calculations) are listed in Table 37. These radionuclides account for at least 95 percent of the dose in the screening analysis when release is not mitigated by either solubility or transport.

- The radionuclides that should be included in nominal release calculations for TSPA-SR are listed in Table 37. By modeling the plutonium isotopes (Pu-238, Pu-239, Pu-240), the americium isotopes (Am-241, Am-243), Th-229, and Ac-227, doses that could result from colloidal transport of radioactive material to the biosphere will be adequately represented in

the TSPA-SR. By modeling C-14, Tc-99, I-129, the uranium isotopes (U-232, U-233, U-234, U-236, U-238), and Np-237, doses that could result from transport of solutes, either by fracture flow or matrix diffusion, will be adequately represented in the TSPA-SR.

- The radionuclides recommended for TSPA-SR calculations for the human-intrusion scenario in are listed in Table 37. The set of radionuclides recommended for the human-intrusion scenario is the same as the set recommended for the nominal release scenario except that Sr-90 and Cs-137 are added. Sr-90 and Cs-137 are included because human intrusion could occur as early as 100 years after repository closure.

- Three radionuclides that were not needed to capture 95 percent of the dose in this screening analysis have been added to Table 36 and Table 37: U-235, Ra-228, and Th-232. U-235 must be tracked as a precursor through the transport calculations if accurate releases of Pa-231 and Ac-227, which are important contributors to dose, are to be calculated. Ra-228 is recommended because proposed EPA regulations (64 FR 46976) give a groundwater-concentration limit for the combined activity of Ra-226 and Ra-228 (Ra-226 was already screened in by the screening analysis). Th-232 is a precursor of Ra-228, so it must be tracked through the transport calculation.

7.3 RECOMMENDATIONS FOR TSPA IN SUPPORT OF THE FEIS

The radionuclides that should be included in the various scenarios in support of the FEIS include those listed in Table 37 for times up to 10,000 years as well as those listed for times from >10,000 to 1,000,000 years. Note that a few additional radionuclides are recommended for the FEIS analyses because the screening for >10,000 to 1,000,000 years allows longer-lived radionuclides to dominate as the shorter-lived radionuclides decay. In particular, Ra-226, Th-230, and Pu-242 are recommended for the TSPA-FEIS model.

Table 36. Average Radionuclide Inventory in Grams in CSNF and Codisposal Waste Packages for TSPA-SR[a]

Isotope	Grams in TSPA-SR CSNF Packages	Grams in TSPA-SR Codisposal Packages	
		From Spent Fuel	From HLW glass
Ac-227	3.09E-06	1.13E-04	4.67E-04
Am-241	1.09E+04	1.17E+02	6.57E+01
Am-243	1.29E+03	1.49E+00	3.99E-01
C-14	1.37E+00[b]	4.96E-02	6.43E-03
Cs-137	5.34E+03	1.12E+02	4.51E+02
I-129	1.80E+03	2.51E+01	4.80E+01
Np-237	4.74E+03	4.79E+01	7.23E+01
Pa-231	9.87E-03	3.25E-01	7.96E-01
Pb-210	0.00E+00	1.40E-08	1.14E-07
Pu-238	1.51E+03	6.33E+00	9.33E+01
Pu-239	4.38E+04	2.30E+03	3.89E+03
Pu-240	2.09E+04	4.89E+02	3.81E+02
Pu-242	5.41E+03	1.11E+01	7.77E+00
Ra-226	0.00E+00	1.87E-06	1.67E-05
Ra-228	0.00E+00	6.98E-06	3.19E-06
Sr-90	2.24E+03	5.54E+01	2.88E+02
Tc-99	7.68E+03	1.15E+02	7.29E+02
Th-229	0.00E+00	2.66E-02	4.08E-03
Th-230	1.84E-01	1.06E-02	7.82E-03
Th-232	0.00E+00	1.49E+04	7.31E+03
U-232	1.01E-02	1.47E-01	8.23E-04
U-233	7.00E-02	2.14E+02	1.11E+01
U-234	1.83E+03	5.72E+01	4.72E+01
U-235	6.28E+04	8.31E+03	1.70E+03
U-236	3.92E+04	8.53E+02	3.98E+01
U-238	7.92E+06	5.09E+05	2.61E+05

[a] This data has been submitted to the TDMS with the following DTN: SN0009T0810599.014.

[b] Attachment II estimates that about 18 percent of the C-14 inventory in CSNF originates from neutron activation of stainless steel hardware outside the fuel rods.

Table 37. Radionuclides Recommended for Modeling Various Exposure Scenarios

Radionuclide	Exposure Scenario					
	Direct		Nominal		Human Intrusion	
	10^2 to 10^4 years	$>10^4$ to 10^6 years	10^2 to 10^4 years	$>10^4$ to 10^6 years	10^2 to 10^4 years	$>10^4$ to 10^6 years[a]
Ac-227	Ac-227	Ac-227	Ac-227	Ac-227	Ac-227	Ac-227
Am-241	Am-241		Am-241		Am-241	
Am-243	Am-243	Am-243	Am-243	Am-243	Am-243	Am-243
C-14			C-14		C-14	
Cs-137	Cs-137				Cs-137	
I-129			I-129	I-129	I-129	I-129
Np-237		Np-237	Np-237	Np-237	Np-237	Np-237
Pa-231	Pa-231	Pa-231	Pa-231	Pa-231	Pa-231	Pa-231
Pb-210	Pb-210	Pb-210	Pb-210	Pb-210	Pb-210	Pb-210
Pu-238	Pu-238		Pu-238		Pu-238	
Pu-239	Pu-239	Pu-239	Pu-239	Pu-239	Pu-239	Pu-239
Pu-240	Pu-240	Pu-240	Pu-240	Pu-240	Pu-240	Pu-240
Pu-242		Pu-242		Pu-242		Pu-242
Ra-226		Ra-226		Ra-226		Ra-226
Ra-228	Ra-228[b]	Ra-228[b]	Ra-228[b]	Ra-228[b]	Ra-228[b]	Ra-228[b]
Sr-90	Sr-90				Sr-90	
Tc-99			Tc-99	Tc-99	Tc-99	Tc-99
Th-229	Th-229	Th-229	Th-229	Th-229	Th-229	Th-229
Th-230		Th-230		Th-230		Th-230
Th-232	Th-232[c]	Th-232	Th-232[c]	Th-232[c]	Th-232[c]	Th-232[c]
U-232	U-232		U-232		U-232	
U-233	U-233	U-233	U-233	U-233	U-233	U-233
U-234	U-234	U-234	U-234	U-234	U-234	U-234
U-235	U-235[c]	U-235[c]	U-235[c]	U-235[c]	U-235[c]	U-235[c]
U-236		U-236	U-236	U-236	U-236	U-236
U-238		U-238	U-238	U-238	U-238	U-238

[a] Same as the Nominal case corresponding to $>10^4$ to 10^6 years.

[b] Added because 64 FR 46976 proposes a limit for the combined activity of Ra-226 and Ra-228 in groundwater.

[c] Added because radionuclide tracking is needed to account for decay daughters.

7.4 DIFFERENCES FROM NRC IPA

The radionuclides recommended for TSPA-SR and TSPA-FEIS differ slightly from those being modeled in the NRC IPA. Namely, the curium isotopes (Cm-245 and Cm-246), Ni-59, Se-79, Cl-36, and Nb-94 are not included in the list for TSPA-SR or TSPA-FEIS. Differences between the TSPA-SR list and the NRC list can be attributed to:

- Differences in the inventory data used as a basis for the analysis (this analysis used the most recent inventory data available to the Yucca Mountain project).

- Differences in the screening technique; specifically, this analysis looked at three transport groups rather than the inventory of radionuclides as a whole.

7.5 UNCERTAINTIES AND RESTRICTIONS FOR SUBSEQUENT USE

The assumptions made in this analysis are considered bounding to the degree that further confirmation is not needed for the set of radionuclides determined in this analysis. The radionuclide inventory values presented in Table 36 will be valid only for the configurations shown in Table I-1. The fractional inventory of C-14 from CSNF hardware activation presented in Table 36 is based on the hardware characteristics of the average BWR assembly discussed in Section II-2 and is reliable to the extent that that assembly represents the CSNF portion of the waste stream.

8. INPUTS AND REFERENCES

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40 CFR 191. Protection of Environment: Environmental Radiation Protection Standards for Management and Disposal of Spent Nuclear Fuel, High-Level and Transuranic Radioactive Wastes. Readily available.

64 FR 46976. Environmental Radiation Protection Standards for Yucca Mountain, Nevada. Proposed rule 40 CFR Part 197. Readily available.

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ATTACHMENT I—CALCULATION OF RADIONUCLIDE INVENTORY IN GRAMS PER WASTE PACKAGE FOR TSPA-SR

I-1. PURPOSE

The purpose of this attachment is to develop initial radionuclide inventories for CSNF and codisposal waste packages that will be used as input to TSPA-SR models.

I-2. INPUTS

I-2.1 DATA AND PARAMETERS

This attachment has three sources of input. The first source of input is the *Monitored Geologic Repository Project Description Document* (CRWMS M&O 2000d). The second source of input is the calculation, *Waste Package Radionuclide Inventory Approximations for TSPA-SR*, CAL-WIS-MD-000004 REV00 (BSC 2001b). The third source of input is the calculation *Radioactive Decay and In-Growth Modeling Approximations for TSPA-SR*, CAL-WIS-MD-000003 (CRWMS M&O 2000b). The following sections indicate what information that these sources provide.

I-2.1.1 Approach to Implementing the Site Recommendation Design Baseline

The *Monitored Geologic Repository Project Description Document* specifies the loading configurations and number of CSNF and codisposal waste packages, which are summarized in Table I-1 (CRWMS M&O 2000d, Table 5-5).

I-2.1.2 Waste Package Radionuclide Inventory Approximations for TSPA-SR

Waste Package Radionuclide Inventory Approximations for TSPA-SR (BSC 2001b, Section 6) provides average radionuclide activities for each of the thirteen waste package configurations listed (Table I-1).

I-2.1.3 Radioactive Decay and In-Growth Modeling Approximations for TSPA-SR

Radioactive Decay and In-Growth Modeling Approximations for TSPA-SR, CAL-WIS-MD-000003 (CRWMS M&O 2000b) provides estimates of the quantities of Am-241 that result from decay of Pu -241 and Cm-245 for CSNF waste packages, for DSNF in codisposal waste packages, and for HLW in codisposal waste packages.

I-3. RADIONUCLIDE INVENTORY

A TSPA involves the analysis of engineered and natural systems to determine the potential long-term release of radionuclides from a nuclear waste repository to a location where a regulatory standard is applied. In a TSPA, models for the behavior of the waste forms, the waste packages, the near-field environment, the far-field environment, and the biosphere are applied to determine the performance of a proposed repository. One cornerstone of determining repository performance is knowing the chemical and radiological composition of the wastes destined for disposal in the repository. This attachment addresses the radiological composition of the wastes.

Table I-1. Design Basis Waste Package Configurations for TSPA-SR

Configuration Number	Type of Fuel	Description	Number of Waste Packages
Configuration 1	CSNF	Waste package with absorber plates for criticality control that will hold a capacity of 21 PWR assemblies	4500
Configuration 2	CSNF	Waste packages with control rods for criticality control that will hold a capacity of 21 PWR assemblies	100
Configuration 3	CSNF	Waste package with absorber plates for criticality control that will hold a capacity of 12 PWR assemblies	170
Configuration 4	CSNF	Waste package with absorber plates for criticality control that will hold a capacity of 44 BWR assemblies	3000
Configuration 5	CSNF	Waste package with thick absorber plates for criticality control that will hold a capacity of 24 BWR assemblies	90
Configuration 6	DSNF/HLW	Waste package containing five short HLW glass canisters and one short DSNF canister	1100
Configuration 7	DSNF/HLW	Waste package containing 5 long HLW glass canisters and one long DSNF canister	1500
Configuration 8	DSNF/HLW	Waste package containing 5 long HLW glass canisters and one short DSNF canister	130
Configuration 9	HLW	Waste package containing 5 long HLW glass canisters	600
Configuration 10	DSNF/HLW	Waste package containing 2 multi-canister overpacks and 2 long HLW glass canisters	160
Configuration 11	Naval Fuel	Waste package containing one short naval canister	200
Configuration 12	Naval Fuel	Waste package containing one long naval canister	100
Configuration 13	Immobilized Plutonium Waste Form	Waste package containing 5 Immobilized Plutonium Waste Form canisters.	100

SOURCE: CRWMS M&O 2000d, Table 5-5.

Table I-2. Average Radionuclide Activities for CSNF Waste Package Configurations

	Configuration Number				
	1	2	3	4	5
	Average Curies in a Waste Package Configuration				
Ac-227	3.26E-04	2.90E-04	1.92E-04	7.70E-05	1.43E-05
Am-241	3.74E+04	1.66E+04	2.50E+04	2.08E+04	2.03E+03
Am-243	3.23E+02	3.32E+01	2.53E+02	1.73E+02	1.41E+00
C-14	6.05E+00	1.15E+01	4.18E+00	6.25E+00	7.03E-01
Cs-137	5.44E+05	1.52E+05	4.78E+05	3.61E+05	2.64E+04
I-129	3.65E-01	1.44E-01	2.70E-01	2.46E-01	2.88E-02
Np-237	4.18E+00	1.55E+00	3.04E+00	2.26E+00	2.16E-01
Pa-231	5.48E-04	4.98E-04	3.74E-04	3.56E-04	1.88E-04
Pb-210	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Pu-238	3.28E+04	4.68E+03	2.64E+04	1.69E+04	3.34E+02
Pu-239	3.28E+03	2.42E+03	2.34E+03	1.98E+03	6.48E+02
Pu-240	5.44E+03	2.31E+03	4.00E+03	3.94E+03	4.37E+02
Pu-242	2.52E+01	4.56E+00	1.93E+01	1.66E+01	3.31E-01
Ra-226	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Ra-228	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Sr-90	3.59E+05	1.13E+05	3.17E+05	2.42E+05	2.03E+04
Tc-99	1.51E+02	6.72E+01	1.11E+02	1.06E+02	1.45E+01
Th-229	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Th-230	4.26E-03	5.96E-03	2.34E-03	3.14E-03	2.81E-03
Th-232	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
U-232	2.90E-01	3.70E-02	2.36E-01	1.32E-01	2.69E-03
U-233	9.01E-04	4.98E-04	5.46E-04	3.72E-04	2.40E-05
U-234	1.32E+01	1.21E+01	9.00E+00	8.98E+00	4.85E+00
U-235	1.56E-01	3.09E-01	1.06E-01	1.00E-01	1.53E-01
U-236	2.96E+00	1.66E+00	2.15E+00	2.01E+00	3.94E-01
U-238	2.84E+00	2.52E+00	2.03E+00	2.49E+00	1.32E+00

SOURCE: BSC 2001b, Section 6.

Table I-3. Average Radionuclide Activities from DSNF for Codisposal Waste Package Configurations

	Configuration Number							
	6	7	8	9	10	11[a]	12[a]	13
	Average Curies in a Waste Package Configuration							
Ac-227	1.61E-04	1.95E-02	1.61E-04	N/A	9.56E-05	N/A	N/A	N/A
Am-241	6.08E+01	3.67E+02	6.08E+01	N/A	2.60E+03	N/A	N/A	N/A
Am-243	2.45E-01	4.73E-01	2.45E-01	N/A	3.80E-01	N/A	N/A	N/A
C-14	8.33E-02	1.03E-01	8.33E-02	N/A	3.36E+00	N/A	N/A	N/A
Cs-137	9.27E+03	1.03E+04	9.27E+03	N/A	4.94E+04	N/A	N/A	N/A
I-129	5.00E-03	3.08E-03	5.00E-03	N/A	3.04E-02	N/A	N/A	N/A
Np-237	2.37E-02	2.32E-02	2.37E-02	N/A	3.58E-01	N/A	N/A	N/A
Pa-231	3.73E-04	3.64E-02	3.73E-04	N/A	1.28E-04	N/A	N/A	N/A
Pb-210	1.45E-08	2.54E-06	1.45E-08	N/A	6.96E-10	N/A	N/A	N/A
Pu-238	4.72E+01	1.58E+02	4.72E+01	N/A	5.90E+02	N/A	N/A	N/A
Pu-239	8.52E+00	2.13E+02	8.52E+00	N/A	1.14E+03	N/A	N/A	N/A
Pu-240	9.66E+00	1.87E+02	9.66E+00	N/A	6.64E+02	N/A	N/A	N/A
Pu-242	2.30E-02	5.14E-02	2.30E-02	N/A	3.20E-01	N/A	N/A	N/A
Ra-226	4.73E-08	3.26E-06	4.73E-08	N/A	1.06E-05	N/A	N/A	N/A
Ra-228	6.59E-08	4.55E-03	6.59E-08	N/A	9.50E-09	N/A	N/A	N/A
Sr-90	8.44E+03	7.26E+03	8.44E+03	N/A	3.74E+04	N/A	N/A	N/A
Tc-99	2.26E+00	1.32E+00	2.26E+00	N/A	1.39E+01	N/A	N/A	N/A
Th-229	4.94E-08	1.36E-02	4.94E-08	N/A	8.62E-08	N/A	N/A	N/A
Th-230	1.93E-06	5.19E-04	1.93E-06	N/A	9.44E-06	N/A	N/A	N/A
Th-232	9.46E-09	3.94E-03	9.46E-09	N/A	1.12E-09	N/A	N/A	N/A
U-232	3.72E-04	7.73E+00	3.72E-04	N/A	0.00E+00	N/A	N/A	N/A
U-233	1.89E-05	4.95E+00	1.89E-05	N/A	5.28E-05	N/A	N/A	N/A
U-234	1.42E-02	3.65E-01	1.42E-02	N/A	4.48E+00	N/A	N/A	N/A
U-235	1.89E-02	9.25E-03	1.89E-02	N/A	1.71E-01	N/A	N/A	N/A
U-236	3.45E-02	3.45E-02	3.45E-02	N/A	6.50E-01	N/A	N/A	N/A
U-238	8.11E-03	2.56E-02	8.11E-03	N/A	3.54E+00	N/A	N/A	N/A

SOURCE: BSC 2001b, Section 6.

[a]These waste packages are not included in the average value for CSNF or codisposal waste packages. See Mowbray (2000) for information about modeling of naval SNF waste packages in TSPA-SR.

Table I-4. Average Radionuclide Activities from HLW for Codisposal Waste Package Configurations

	Configuration Number							
	6	7	8	9	10	11	12	13
	Average Curies in a Waste Package Configuration							
Ac-227	9.15E-03	4.85E-02	4.85E-02	4.85E-02	1.94E-02	N/A	N/A	2.50E-06
Am-241	2.48E+02	2.46E+01	2.46E+01	2.46E+01	9.84E+00	N/A	N/A	4.00E+03
Am-243	2.51E-01	3.21E-03	3.21E-03	3.21E-03	1.28E-03	N/A	N/A	2.54E-02
C-14	9.35E-02	3.30E-05	3.30E-05	3.30E-05	1.32E-05	N/A	N/A	0.00E+00
Cs-137	9.10E+04	1.34E+04	1.34E+04	1.34E+04	5.34E+03	N/A	N/A	9.50E+04
I-129	4.11E-03	1.11E-02	1.11E-02	1.11E-02	4.42E-03	N/A	N/A	0.00E+00
Np-237	5.75E-02	4.90E-02	4.90E-02	4.90E-02	1.96E-02	N/A	N/A	7.60E-02
Pa-231	1.01E-02	5.40E-02	5.40E-02	5.40E-02	2.16E-02	N/A	N/A	7.05E-06
Pb-210	1.46E-06	1.65E-05	1.65E-05	1.65E-05	6.60E-06	N/A	N/A	1.34E-07
Pu-238	4.71E+03	6.65E-01	6.65E-01	6.65E-01	2.66E-01	N/A	N/A	5.60E+03
Pu-239	6.45E+01	1.35E+01	1.35E+01	1.35E+01	5.40E+00	N/A	N/A	7.65E+03
Pu-240	3.80E+01	3.07E+00	3.07E+00	3.07E+00	1.23E+00	N/A	N/A	2.62E+03
Pu-242	5.20E-02	4.00E-04	4.00E-04	4.00E-04	1.60E-04	N/A	N/A	5.15E-01
Ra-226	8.35E-06	2.18E-05	2.18E-05	2.18E-05	8.72E-06	N/A	N/A	6.05E-07
Ra-228	1.09E-03	8.30E-04	8.30E-04	8.30E-04	3.32E-04	N/A	N/A	1.46E-04
Sr-90	9.70E+04	1.08E+04	1.08E+04	1.08E+04	4.32E+03	N/A	N/A	1.02E+05
Tc-99	1.57E+01	1.13E+01	1.13E+01	1.13E+01	4.50E+00	N/A	N/A	1.35E+01
Th-229	1.67E-04	1.29E-03	1.29E-03	1.29E-03	5.14E-04	N/A	N/A	8.70E-09
Th-230	4.11E-04	5.05E-05	5.05E-05	5.05E-05	2.02E-05	N/A	N/A	1.18E-04
Th-232	1.09E-03	7.30E-04	7.30E-04	7.30E-04	2.92E-04	N/A	N/A	1.50E-04
U-232	3.15E-03	2.69E-02	2.69E-02	2.69E-02	1.07E-02	N/A	N/A	0.00E+00
U-233	6.35E-03	1.64E-01	1.64E-01	1.64E-01	6.56E-02	N/A	N/A	7.40E-06
U-234	6.50E-01	1.20E-01	1.20E-01	1.20E-01	4.78E-02	N/A	N/A	6.85E-01
U-235	5.35E-04	5.00E-03	5.00E-03	5.00E-03	2.00E-03	N/A	N/A	1.13E-02
U-236	1.31E-03	3.31E-03	3.31E-03	3.31E-03	1.32E-03	N/A	N/A	2.33E-03
U-238	4.25E-02	1.11E-01	1.11E-01	1.11E-02	4.44E-02	N/A	N/A	1.36E-01

SOURCE: BSC 2001b, Section 6.

I-3.1 RADIOACTIVE MATERIALS PROPOSED FOR DISPOSAL IN THE POTENTIAL YUCCA MOUNTAIN REPOSITORY

Radioactive materials that would be placed in a proposed repository at Yucca Mountain are primarily irradiated nuclear fuel elements or solidified waste from reprocessing of irradiated reactor fuel.

Irradiated fuel will come from commercial utilities, either PWR or BWR assemblies, and from the DOE, which has commercial fuels and fuels from reactors used in defense related programs (CRWMS M&O 1998).

HLW is the result of reprocessing spent nuclear fuel (some CSNF but mostly DSNF). Four DOE sites, the Savannah River Site, Hanford, the Idaho National Engineering and Environmental Laboratory, and West Valley report having high-level waste in storage (CRWMS M&O 1998).

Aside from irradiated nuclear fuel and high-level waste, the DOE also has a plutonium surplus that has been proposed for disposal at the Yucca Mountain repository (CRWMS M&O 1998). Some of the plutonium will become PWR mixed-oxide reactor fuel that would be irradiated in commercial reactors. The plutonium that is not converted to mixed-oxide fuel will be immobilized in plutonium-ceramic disks that will be placed in HLW canisters that are subsequently filled with a HLW glass.

I-3.2 RADIOACTIVE ISOTOPES

Radioactive isotopes contained in the materials destined for disposal at Yucca Mountain include fission products from nuclear fission during reactor operations, assorted actinides from neutron capture in uranium and plutonium, light elements, and activation products from neutron irradiation of structural materials and trace elements. The isotopes that were recommended on the basis of direct dose contributions for modeling one or more scenarios (Sections 7.2 and 7.3 of this report) are: Ac-227, Am-241, Am-243, C-14, Cs-137, I-129, Np-237, Pa-231, Pb-210, Pu-238, Pu-239, Pu-240, Pu-242, Ra-226, Sr-90, Tc-99, Th-229, Th-230, Th-232, U-232, U-233, U-234, U-236, and U-238.

C-14, Tc-99, I-129, Sr-90, Cs-137, and U-232 are not members of decay chains and, while they do decay over time, they do not experience in-growth over time. On the other hand, Am-243, Pu-239, U-235, Pa-231, Ac-227 are part of the actinium series shown in Equation 1.

$$\text{Am-243} \rightarrow \text{Pu-239} \rightarrow \text{U-235} \rightarrow \text{Pa-231} \rightarrow \text{Ac-227} \qquad \text{(Eq. 1)}$$

Note: Tracking U-235 in the transport calculation is necessary, even though U-235 is not an important contributor to dose, because the activity of U-235 determines the activity of Pa-231 and Ac-227, which are important contributors to dose. Therefore, an initial inventory of U-235 is also calculated here.

Am-241, Np-237, U-233, and Th-229 are part of the neptunium series shown in Equation 2.

$$\text{Am-241} \rightarrow \text{Np-237} \rightarrow \text{U-233} \rightarrow \text{Th-229} \qquad \text{(Eq. 2)}$$

Pu-240, U-236, Th-232, and Ra-228 are part of the thorium series shown in Equation 3.

$$\text{Pu-240} \rightarrow \text{U-236} \rightarrow \text{Th-232} \rightarrow \text{Ra-228} \qquad \text{(Eq. 3)}$$

Note: Having an initial inventory of Th-232 and Ra-228 is necessary for the groundwater protection scenario, which was not addressed in this AMR. However, requisite activities for Th-232 and Ra-228 were calculated here.

Pu-242, U-238, Pu-238, U-234, Th-230, Ra-226, and Pb-210 are part of the uranium series shown in Equation 4.

$$\text{Pu-242} \rightarrow \text{U-238 (and Pu-238)} \rightarrow \text{U-234} \rightarrow \text{Th-230} \rightarrow \text{Ra-226} \rightarrow \text{Pb-210} \qquad \text{(Eq. 4)}$$

In Equations 1 through 4, intermediate members of the chain are omitted if they are not in the set recommended for TSPA-SR. In Equation 4, Pu-238 joins the chain as a result of the decay to U-234.

Am-243, Pu-240, and Pu-242 are the starting isotopes for TSPA-SR modeling of the actinium series, the thorium series, and uranium series, respectively. The principal production method for these three isotopes is multiple neutron capture from U-238 and Pu-239. They are not produced in any significant quantities from the decay of other isotopes. On the other hand, the starting isotope for the neptunium series is Am-241. The primary production method for Am-241 is decay from Pu-241, which in turn is derived from decay of Cm-245. Thus in TSPA-SR, the amount of Am-241 in waste packages at the beginning of the simulation is modeled as a sum of the original quantity of Am-241 plus the quantity of Am-241 that would be produced from decay of Pu-241 and Cm-245 over the lifetime of the repository.

I-3.3 WASTE PACKAGES FOR TSPA-SR

The TSPA-SR will model two basic waste packages, a representative waste package for CSNF and a representative waste package for DSNF and HLW (referred to henceforth as a codisposal package). All of the waste forms that are counted as part of the CSNF allocation for Yucca Mountain are represented by an average CSNF waste package in TSPA-SR. With the exception of naval SNF, all of the waste forms that are counted as part of the DOE allocation for Yucca Mountain are represented by an average codisposal waste package. This includes HLW packages, which will not contain SNF. All packages are represented by the average.

In addition, there are 300 waste packages containing naval SNF destined for disposal in the proposed repository (CRWMS M&O 2000d). To allow releases from naval fuel to be conservatively represented by releases from CSNF waste packages in support of site recommendation and future TSPAs, the inventory from naval waste packages is not included in the inventory for CSNF or codisposal waste packages. Because of the robust design of naval fuel, releases from naval SNF will be significantly less than releases from CSNF (BSC 2001c, Section 6.1.1); therefore it is very conservative to represent releases from naval SNF waste packages with releases from CSNF waste packages (DOE 2001, Section 4.2.6.3.9). The reader is

referred to Mowbray (2000) for further information about modeling of naval SNF waste packages for TSPA.

I-3.4 COMMERCIAL SPENT NUCLEAR FUEL WASTE PACKAGES

I-3.4.1 Number of Waste Packages

The number of CSNF waste packages that should be modeled in TSPA-SR is the sum of the values for Configurations 1 through 5 in Table I-1. The total is 7,860 CSNF waste packages.

I-3.4.2 Radionuclide Inventories

Equations I-1 and I-2 show how the radionuclide activities (from Table I-2) for each of the CSNF waste package configurations (Configurations 1 through 5 in Table I-1) were combined to produce the inventory in grams of radionuclides for a CSNF waste package for TSPA-SR. Table I-5 provides the results; some intermediate results are also provided. Microsoft Excel 97 SR-2 was used to perform the required computations. Note that the only operations required for the calculations are multiplication, addition, and division, which are standard functions in Microsoft Excel 97 SR-2.

$$(a_i)_{\substack{\text{A CSNF Waste} \\ \text{Package for TSPA-SR}}} = \frac{(4500)\bullet(a_i)_1 + (100)\bullet(a_i)_2 + (170)\bullet(a_i)_3 + (3000)\bullet(a_i)_4 + (90)\bullet(a_i)_5}{7860} \quad \text{Eq (I-1)}$$

Where:

$(a_i)_1$ is the activity in curies of isotope "i" in an average CSNF waste package with Configuration 1.
$(a_i)_2$ is the activity in curies of isotope "i" in an average CSNF waste package with Configuration 2.
$(a_i)_3$ is the activity in curies of isotope "i" in an average CSNF waste package with Configuration 3.
$(a_i)_4$ is the activity in curies of isotope "i" in an average CSNF waste package with Configuration 4.
$(a_i)_5$ is the activity in curies of isotope "i" in an average CSNF waste package with Configuration 5.

All activity values are from Table I-2.

$$(m_i)_{\substack{\text{A CSNF Waste} \\ \text{Package for TSPA-SR}}} = \frac{B\bullet MW_i\bullet t_i\bullet (a_i)_{\substack{\text{A CSNF Waste} \\ \text{Package for TSPA-SR}}}}{\ln(2)\bullet N_a} \quad \text{Eq (I-2)}$$

Where:

m_i is the average grams of isotope "i" in an average CSNF waste package for TSPA-SR.
a_i is the average activity in curies of isotope "i" in a CSNF waste package for TSPA-SR (from Equation I-1).
MW_i is the molecular weight in grams per mole of isotope "i" (Walker et al. 1984).
t_i is the half-life of isotope "i" in seconds (Walker et al. 1984).
N_a is Avogadro's number, 6.022045E+23 (Walker et al. 1984).
B is the conversion from curies to decays per second, 3.7E+10 (Walker et al. 1984).

I-3.4.3 Inventory of Am-241 in CSNF WPs

The inventory of Am-241 in CSNF WPs is 1.09E+04 grams per CSNF WP, which is calculated as the sum of 8.76E+03 grams (Table I-5) and the estimated amount from decay of Pu-241 and Cm-245, 2.16E+03 grams (CRWMS M&O 2000b, p. 16).

Table I-5. Calculation of Radionuclide Inventory in Grams in a CSNF Waste Package for TSPA-SR

Configuration	1	2	3	4	5			
	Number of Waste Packages							
	4500	100	170	3000	90			
	Fraction of Waste Packages					Curies per CSNF Waste Package	Specific Activity Ci/gram	Grams per CSNF Waste Package
	0.57	0.01	0.02	0.38	0.01			
Isotope	Weighted Value Of Curies Per Waste Package Configuration							
Ac-227	1.86E-04	3.69E-06	4.15E-06	2.94E-05	1.63E-07	2.24E-04	7.24E+01	3.09E-06
Am-241	2.14E+04	2.11E+02	5.40E+02	7.93E+03	2.33E+01	3.01E+04	3.44E+00	8.76E+03
Am-243	1.85E+02	4.22E-01	5.48E+00	6.62E+01	1.61E-02	2.57E+02	2.00E-01	1.29E+03
C-14	3.46E+00	1.46E-01	9.03E-02	2.38E+00	8.05E-03	6.09E+00	4.46E+00	1.37E+00
Cs-137	3.11E+05	1.94E+03	1.03E+04	1.38E+05	3.02E+02	4.62E+05	8.65E+01	5.34E+03
I-129	2.09E-01	1.83E-03	5.84E-03	9.40E-02	3.30E-04	3.11E-01	1.73E-04	1.80E+03
Np-237	2.39E+00	1.97E-02	6.57E-02	8.63E-01	2.48E-03	3.34E+00	7.05E-04	4.74E+03
Pa-231	3.14E-04	6.33E-06	8.10E-06	1.36E-04	2.15E-06	4.66E-04	4.72E-02	9.87E-03
Pb-210	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	7.64E+01	0.00E+00
Pu-238	1.88E+04	5.96E+01	5.71E+02	6.43E+03	3.82E+00	2.58E+04	1.71E+01	1.51E+03
Pu-239	1.88E+03	3.07E+01	5.06E+01	7.56E+02	7.42E+00	2.72E+03	6.21E-02	4.38E+04
Pu-240	3.11E+03	2.94E+01	8.64E+01	1.50E+03	5.00E+00	4.74E+03	2.27E-01	2.09E+04
Pu-242	1.44E+01	5.80E-02	4.18E-01	6.35E+00	3.79E-03	2.13E+01	3.93E-03	5.41E+03
Ra-226	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	9.89E-01	0.00E+00
Ra-228	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	2.72E+02	0.00E+00
Sr-90	2.06E+05	1.43E+03	6.85E+03	9.24E+04	2.32E+02	3.06E+05	1.37E+02	2.24E+03
Tc-99	8.66E+01	8.55E-01	2.41E+00	4.03E+01	1.66E-01	1.30E+02	1.70E-02	7.68E+03
Th-229	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	2.14E-01	0.00E+00
Th-230	2.44E-03	7.59E-05	5.06E-05	1.20E-03	3.22E-05	3.80E-03	2.06E-02	1.84E-01
Th-232	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.10E-07	0.00E+00
U-232	1.66E-01	4.70E-04	5.11E-03	5.04E-02	3.08E-05	2.22E-01	2.20E+01	1.01E-02
U-233	5.16E-04	6.33E-06	1.18E-05	1.42E-04	2.75E-07	6.76E-04	9.64E-03	7.00E-02
U-234	7.56E+00	1.54E-01	1.95E-01	3.43E+00	5.55E-02	1.14E+01	6.24E-03	1.83E+03
U-235	8.95E-02	3.93E-03	2.30E-03	3.83E-02	1.75E-03	1.36E-01	2.16E-06	6.28E+04
U-236	1.70E+00	2.11E-02	4.65E-02	7.67E-01	4.51E-03	2.53E+00	6.47E-05	3.92E+04
U-238	1.62E+00	3.21E-02	4.39E-02	9.49E-01	1.51E-02	2.66E+00	3.36E-07	7.92E+06

I-3.5 CODISPOSAL WASTE PACKAGES

I-3.5.1 Number of Waste Packages

The number of codisposal waste packages that should be modeled in TSPA-SR is the sum of the values for Configurations 6 through 13 (excluding 11 and 12) in Table I-1. The total is 3,590 codisposal waste packages.

I-3.5.2 DSNF Radionuclide Inventories

Equations I-3 and I-4 show how the radionuclide activities (from Table I-3) for DSNF in each of the codisposal waste package configurations (Configurations 6, 7, 8, and 10) were combined to produce the inventory in grams of radionuclides from DSNF for a codisposal waste package for TSPA-SR. Table I-6 provides the results; some intermediate results are also provided. Microsoft Excel 97 SR-2 was used to perform the required computations. Note that the only operations required for the calculations are multiplication, addition, and division, which are standard functions in Microsoft Excel 97 SR-2.

$$(a_i)_{\text{DSNF in a Codisposal Waste Package for TSPA-SR}} = \frac{(1100)\bullet(a_i)_6 + (1500)\bullet(a_i)_7 + (130)\bullet(a_i)_8 + (160)\bullet(a_i)_{10}}{3590} \qquad \text{Eq (I-3)}$$

Where:

$(a_i)_6$ is the activity from DSNF in curies of isotope "i" in an average waste package with Configuration 6.
$(a_i)_7$ is the activity from DSNF in curies of isotope "i" in an average waste package with Configuration 7.
$(a_i)_8$ is the activity from DSNF in curies of isotope "i" in an average waste package with Configuration 8.
$(a_i)_{10}$ is the activity from DSNF in curies of isotope "i" in an average waste package with Configuration 10.

All activity values are from Table I-3.

$$(m_i)_{\text{DSNF in a Codisposal Waste Package for TSPA-SR}} \qquad \frac{B\bullet MW_i\bullet t_i\bullet(a_i)_{\text{DSNF in a Codisposal Waste Package for TSPA-SR}}}{\ln(2)\bullet N_a} \qquad \text{Eq (I-4)}$$

Where:

m_i is the average grams of isotope "i" from DSNF in a codisposal waste package for TSPA-SR.
a_i is the average activity in curies of isotope "i" from DSNF in a codisposal waste package for TSPA-SR (from Equation I-3).
MW_i is the molecular weight in grams per mole of isotope "i" (Walker et al. 1984).
t_i is the half-life of isotope "i" in seconds (Walker et al. 1984).
N_a is Avogadro's number, 6.022045E+23 (Walker et al. 1984).
B is the conversion from curies to decays per second, 3.7E+10 (Walker et al. 1984).

I-3.5.3 Inventory of Am-241 from DSNF in Codisposal WPs

The inventory of Am-241 from DSNF in codisposal WPs is 1.17E+02 grams from DSNF per codisposal WP, which is calculated as the sum of 8.44E+01 grams (Table I-6) and the estimated amount from decay of Pu-241 and Cm-245, 3.28E+01 grams (CRWMS M&O 2000b, p. 16).

I-3.5.4 HLW Radionuclide Inventories

Equations I-5 and I-6 show how the radionuclide activities (from Table I-4) for HLW in each of the codisposal waste package configurations (Configurations 6, 7, 8, and 10) were combined to produce the inventory in grams of radionuclides from HLW for a codisposal waste package for TSPA-SR. Table I-7 provides the results; some intermediate results are also provided in Table I-7. Microsoft Excel 97 SR-2 was used to perform the required computations. Note that the only operations required for the calculations are multiplication, addition, and division, which are standard functions in Microsoft Excel 97 SR-2.

$$(a_i)_{\substack{\text{HLW in a Codisposal Waste} \\ \text{Package for TSPA-SR}}} = \frac{(1100)\bullet(a_i)_6 + (1500)\bullet(a_i)_7 + (130)\bullet(a_i)_8 + (600)\bullet(a_i)_9}{3590} + \frac{(160)\bullet(a_i)_{10} + (100)\bullet(a_i)_{13}}{3590} \qquad \text{Eq (I-5)}$$

Where:

$(a_i)_6$ is the activity from HLW in curies of isotope "i" in an average waste package with Configuration 6.
$(a_i)_7$ is the activity from HLW in curies of isotope "i" in an average waste package with Configuration 7.
$(a_i)_8$ is the activity from HLW in curies of isotope "i" in an average waste package with Configuration 8.
$(a_i)_9$ is the activity from HLW in curies of isotope "i" in an average waste package with Configuration 9.
$(a_i)_{10}$ is the activity from HLW in curies of isotope "i" in an average waste package with Configuration 10.
$(a_i)_{13}$ is the activity from HLW in curies of isotope "i" in an average waste package with Configuration 13.

All activity values are from Table I-4.

$$(m_i)_{\text{HLW in a Codisposal Waste Package for TSPA-SR}} = \frac{B \bullet MW_i \bullet t_i \bullet (a_i)_{\text{HLW in a Codisposal Waste Waste Package for TSPA-SR}}}{\ln(2) \bullet N_a} \quad \text{Eq (I-6)}$$

Where:

m_i is the average grams of isotope "i" from HLW in a codisposal waste package for TSPA-SR.
a_i is the average activity in curies of isotope "i" from HLW in a codisposal waste package for TSPA-SR (from Equation I-5).
MW_i is the molecular weight in grams per mole of isotope "i" (Walker et al. 1984).
t_i is the half-life of isotope "i" in seconds (Walker et al. 1984).
N_a is Avogadro's number, 6.022045E+23 (Walker et al. 1984).
B is the conversion from curies to decays per second, 3.7E+10 (Walker et al. 1984).

I-3.5.5 Inventory of Am-241 from HLW in Codisposal WPs

The inventory of Am-241 from HLW in codisposal WPs is 6.57E+01 grams from HLW per codisposal WP, which is calculated as the sum of 5.91E+01 grams (Table I-7) and the estimated amount from decay of Pu-241 and Cm-245, 6.58E+00 grams (CRWMS M&O 2000b, p. 16).

Table I-6. Calculation of Radionuclide Inventory in Grams from DSNF in a Codisposal Waste Package for TSPA-SR

Configuration	6	7	8	9	10	13			
	Number Of Waste Packages						Curies from DSNF In a Codisposal Waste Package	Specific Activity Ci/gram	Grams from DSNF In a Codisposal Waste Package
	1100	1500	130	600	160	100			
	Fraction of Waste Packages								
	0.31	0.42	0.04	0.17	0.04	0.03			
Isotope	Weighted Value Of Curies Per Waste Package Configuration								
Ac-227	4.92E-05	8.15E-03	5.82E-06	N/A	4.26E-06	N/A	8.21E-03	7.24E+01	1.13E-04
Am-241	1.86E+01	1.53E+02	2.20E+00	N/A	1.16E+02	N/A	2.90E+02	3.44E+00	8.44E+01
Am-243	7.51E-02	1.98E-01	8.87E-03	N/A	1.69E-02	N/A	2.99E-01	2.00E-01	1.49E+00
C-14	2.55E-02	4.30E-02	3.02E-03	N/A	1.50E-01	N/A	2.21E-01	4.46E+00	4.96E-02
Cs-137	2.84E+03	4.30E+03	3.36E+02	N/A	2.20E+03	N/A	9.68E+03	8.65E+01	1.12E+02
I-129	1.53E-03	1.29E-03	1.81E-04	N/A	1.35E-03	N/A	4.35E-03	1.73E-04	2.51E+01
Np-237	7.27E-03	9.69E-03	8.59E-04	N/A	1.60E-02	N/A	3.38E-02	7.05E-04	4.79E+01
Pa-231	1.14E-04	1.52E-02	1.35E-05	N/A	5.69E-06	N/A	1.53E-02	4.72E-02	3.25E-01
Pb-210	4.44E-09	1.06E-06	5.24E-10	N/A	3.10E-11	N/A	1.07E-06	7.64E+01	1.40E-08
Pu-238	1.45E+01	6.60E+01	1.71E+00	N/A	2.63E+01	N/A	1.08E+02	1.71E+01	6.33E+00
Pu-239	2.61E+00	8.90E+01	3.08E-01	N/A	5.07E+01	N/A	1.43E+02	6.21E-02	2.30E+03
Pu-240	2.96E+00	7.81E+01	3.50E-01	N/A	2.96E+01	N/A	1.11E+02	2.27E-01	4.89E+02
Pu-242	7.04E-03	2.15E-02	8.32E-04	N/A	1.43E-02	N/A	4.36E-02	3.93E-03	1.11E+01
Ra-226	1.45E-08	1.36E-06	1.71E-09	N/A	4.74E-07	N/A	1.85E-06	9.89E-01	1.87E-06
Ra-228	2.02E-08	1.90E-03	2.39E-09	N/A	4.23E-10	N/A	1.90E-03	2.72E+02	6.98E-06
Sr-90	2.59E+03	3.03E+03	3.06E+02	N/A	1.67E+03	N/A	7.59E+03	1.37E+02	5.54E+01
Tc-99	6.94E-01	5.52E-01	8.20E-02	N/A	6.21E-01	N/A	1.95E+00	1.70E-02	1.15E+02
Th-229	1.51E-08	5.68E-03	1.79E-09	N/A	3.84E-09	N/A	5.68E-03	2.14E-01	2.66E-02
Th-230	5.92E-07	2.17E-04	7.00E-08	N/A	4.21E-07	N/A	2.18E-04	2.06E-02	1.06E-02
Th-232	2.90E-09	1.65E-03	3.43E-10	N/A	4.97E-11	N/A	1.65E-03	1.10E-07	1.49E+04
U-232	1.14E-04	3.23E+00	1.35E-05	N/A	0.00E+00	N/A	3.23E+00	2.20E+01	1.47E-01
U-233	5.78E-06	2.07E+00	6.84E-07	N/A	2.35E-06	N/A	2.07E+00	9.64E-03	2.14E+02
U-234	4.35E-03	1.53E-01	5.14E-04	N/A	2.00E-01	N/A	3.57E-01	6.24E-03	5.72E+01
U-235	5.79E-03	3.86E-03	6.85E-04	N/A	7.63E-03	N/A	1.80E-02	2.16E-06	8.31E+03
U-236	1.06E-02	1.44E-02	1.25E-03	N/A	2.90E-02	N/A	5.52E-01	6.47E-05	8.53E+02
U-238	2.49E-03	1.07E-02	2.94E-04	N/A	1.58E-01	N/A	1.71E-01	3.36E-07	5.09E+05

Table I-7. Calculation of Radionuclide Inventory in Grams from HLW in a Codisposal Waste Package for TSPA-SR

Configuration	6	7	8	9	10	13			
	Number Of Waste Packages						Curies from HLW In a Codisposal Waste Package	Specific Activity Ci/gram	Grams from HLW In a Codisposal Waste Package
	1100	1500	130	600	160	100			
	Fraction of Waste Packages								
	0.31	0.42	0.04	0.17	0.04	0.03			
Isotope	Weighted Value Of Curies Per Waste Package Configuration								
Ac-227	2.80E-03	2.03E-02	1.76E-03	8.11E-03	8.65E-04	6.96E-08	3.38E-02	7.24E+01	4.67E-04
Am-241	7.60E+01	1.03E+01	8.91E-01	4.11E+00	4.39E-01	1.11E+02	2.03E+02	3.44E+00	5.91E+01
Am-243	7.69E-02	1.34E-03	1.16E-04	5.36E-04	5.71E-05	7.08E-04	7.97E-02	2.00E-01	3.99E-01
C-14	2.86E-02	1.38E-05	1.19E-06	5.51E-06	5.87E-07	0.00E+00	2.87E-02	4.46E+00	6.43E-03
Cs-137	2.79E+04	5.58E+03	4.83E+02	2.23E+03	2.38E+02	2.65E+03	3.91E+04	8.65E+01	4.51E+02
I-129	1.26E-03	4.62E-03	4.00E-04	1.85E-03	1.97E-04	0.00E+00	8.32E-03	1.73E-04	4.80E+01
Np-237	1.76E-02	2.05E-02	1.77E-03	8.18E-03	8.73E-04	2.12E-03	5.10E-02	7.05E-04	7.23E+01
Pa-231	3.09E-03	2.26E-02	1.96E-03	9.03E-03	9.63E-04	1.96E-07	3.76E-02	4.72E-02	7.96E-01
Pb-210	4.47E-07	6.89E-06	5.97E-07	2.76E-06	2.94E-07	3.73E-09	1.10E-05	7.64E+01	1.44E-07
Pu-238	1.44E+03	2.78E-01	2.41E-02	1.11E-01	1.19E-02	1.56E+02	1.60E+03	1.71E+01	9.33E+01
Pu-239	1.98E+01	5.64E+00	4.89E-01	2.26E+00	2.41E-01	2.13E+02	2.41E+02	6.21E-02	3.89E+03
Pu-240	1.16E+01	1.28E+00	1.11E-01	5.12E-01	5.46E-02	7.30E+01	8.66E+01	2.27E-01	3.81E+02
Pu-242	1.59E-02	1.67E-04	1.45E-05	6.69E-05	7.13E-06	1.43E-02	3.05E-02	3.93E-03	7.77E+00
Ra-226	2.56E-06	9.11E-06	7.89E-07	3.64E-06	3.89E-07	1.69E-08	1.65E-05	9.89E-01	1.67E-05
Ra-228	3.34E-04	3.47E-04	3.01E-05	1.39E-04	1.48E-05	4.07E-06	8.68E-04	2.72E+02	3.19E-06
Sr-90	2.97E+04	4.51E+03	3.91E+02	1.81E+03	1.93E+02	2.84E+03	3.95E+04	1.37E+02	2.88E+02
Tc-99	4.80E+00	4.70E+00	4.07E-01	1.88E+00	2.01E-01	3.76E-01	1.24E+01	1.70E-02	7.29E+02
Th-229	5.12E-05	5.37E-04	4.65E-05	2.15E-04	2.29E-05	2.42E-10	8.72E-04	2.14E-01	4.08E-03
Th-230	1.26E-04	2.11E-05	1.83E-06	8.44E-06	9.00E-07	3.29E-06	1.61E-04	2.06E-02	7.82E-03
Th-232	3.34E-04	3.05E-04	2.64E-05	1.22E-04	1.30E-05	4.18E-06	8.05E-04	1.10E-07	7.31E+03
U-232	9.64E-04	1.12E-02	9.72E-04	4.49E-03	4.79E-04	0.00E+00	1.81E-02	2.20E+01	8.23E-04
U-233	1.95E-03	6.85E-02	5.94E-03	2.74E-02	2.92E-03	2.06E-07	1.07E-01	9.64E-03	1.11E+01
U-234	1.99E-01	4.99E-02	4.33E-03	2.00E-02	2.13E-03	1.91E-02	2.95E-01	6.24E-03	4.72E+01
U-235	1.64E-04	2.09E-03	1.81E-04	8.36E-04	8.91E-05	3.15E-04	3.67E-03	2.16E-06	1.70E+03
U-236	4.00E-04	1.38E-03	1.20E-04	5.52E-04	5.89E-05	6.49E-05	2.58E-03	6.47E-05	3.98E+01
U-238	1.30E-02	4.64E-02	4.02E-03	1.86E-02	1.98E-03	3.79E-03	8.77E-02	3.36E-07	2.61E+05

ATTACHMENT II—NEUTRON-ACTIVATION PRODUCTS OUTSIDE THE SPENT-FUEL MATRIX

II-1. PURPOSE

Most of the radioactivity associated with SNF assemblies is contained within the spent-fuel matrix. To the extent that the cladding is credited as a barrier to release of radioactivity, the release of radioactivity from within the cladding is associated with cladding failure. However, during reactor operation, some materials outside the fuel rods become radioactive due to neutron activation. Activation products outside the fuel rods may become available for release after breach of the waste package but long before the bulk of the radionuclide inventory from the fuel matrix is released. Two kinds of materials are candidates for neutron activation: (1) accumulated mineral deposits (crud) on the surface of the cladding that can build up during reactor operation, and (2) assembly hardware such as the cladding itself, top and bottom tie plates or nozzles, grid plates, plenum springs, end plugs, guide tubes, and instrument tubes. The radionuclide inventories that are inputs to the radionuclide screening that is covered in the main body of this analysis include activation products from the hardware but not from the crud. Activation products from the hardware have been lumped together with the inventory of radionuclides within the fuel matrix in the radionuclide inventory presented in Table 36 of the present document. The purpose of this attachment is to examine the appropriateness of (1) neglecting the crud and (2) lumping the inventory of hardware-activation products in commercial SNF together with radionuclides in the fuel matrix for repository performance assessment.

II-2. INPUTS

This attachment draws on the results of two radionuclide-inventory calculations: *PWR Source Term Generation and Evaluation* (CRWMS M&O 1999d) and *BWR Source Term Generation and Evaluation* (CRWMS M&O 1999a). Detailed output from the two calculations is given by CRWMS M&O (1999c and 1999b). The two calculations project radionuclide inventories as functions of time for average and bounding SNF assemblies (see Section 4.1.1.1). It is assumed that the as-built characteristics of PWR and BWR assemblies and the calculated radionuclide inventories that are provided by CRWMS M&O (1999a, 1999b, 1999c, and 1999d) are adequate for the analysis conducted in this attachment (Assumption 5.10).

II-3. CRUD

The composition of the crud is determined by the conditions within the reactor during operation. A number of studies, which are summarized by CRWMS M&O (1999d, pp. 13, 14; 1999a, pp. 21, 22), have identified the following radionuclides in PWR or BWR crud: Cr-51, Mn-54, Fe-55, Co-58, Fe-59, Co-60, Ni-63, Zn-65, and Zr-95. With the exception of Ni-63, these radionuclides need not be considered further because they have half-lives of less than 20 years (y) and have been screened out on that basis (Assumption 5.8).

Ni-63, which has a much longer half-life of about 100 y, is screened out by the scenario analyses described in Section 6. However, because the crud contribution was not included as input to the radionuclide-screening analysis, it is important now to consider the Ni-63 in the crud. There is estimated to be no Ni-63 in the crud present on BWR fuel (CRWMS M&O 1999a, p. 52). The amount of Ni-63 present in 30-year-old PWR crud is estimated to be 0.55 Ci (CRWMS M&O 1999d, p. VII-3). The amount of Ni-63 in hardware is apt to be much greater. For example, for an average 30-year old PWR assembly, 20.5 Ci of Ni-63 is calculated for the top-region hardware such as the top nozzle, spring retainer, upper end plug, and upper nuts (CRWMS M&O 1999c, Waste.Stream.E5.R4.B9.cut). Thus, the contribution from the crud is a negligible fraction of the Ni-63 from hardware activation. Therefore, it is appropriate for the screening analysis in particular and for performance assessment generally to neglect the radionuclides present in SNF crud.

II-4. HARDWARE

The elements that are included as constituents of the hardware in PWR and BWR assemblies by CRWMS M&O (1999d, p. III-3; 1999a, p. II-8) are listed in Table II-1. Tc-99 and C-14 have been screened in and are expected to be present in hardware as neutron activation products. Nuclides that have been screened out but that have half-lives greater than 20 y and are present in the hardware are Zr-93, Ni-59, Ni-63, and Nb-94. Co-60 and Sn-125 have half-lives less than 20 y and are not considered further (Assumption 5.8).

The radionuclide-inventory calculations divide the PWR and BWR assemblies into four regions: fuel, bottom, plenum, and top. The calculations preserve the distinction between activation products (called light elements in the computer output) and fission products. All of the activation products in the bottom, plenum, and top regions originate from hardware because there is no fuel in those regions. In the fuel region, the distinction between activation products from hardware and from constituents of the fuel is not maintained. However, by noting the relative amounts of an element in the hardware and fuel that activates to a radionuclide of interest, it is often possible to determine the primary location of the activation product of interest.

II-4.1 TECHNETIUM-99

Tc-99 is an abundant fission product (Parrington et al. 1996). Therefore, the inventory of Tc-99 that is produced as a fission product is likely to be much greater than the inventory of Tc-99 that is produced by hardware activation. However, at least for CSNF and naval fuel, the corrosion-resistant fuel cladding will impede the release of the bulk of the radionuclides from the fuel. For codisposal waste packages, no credit is taken in the TSPA-SR for cladding (CRWMS M&O 2000i, p. 252).

For CSNF, the amount of radioactivity released shortly after the breach of the waste package depends on the fraction of fuel rods with perforated cladding and the fraction of a perforated fuel rod's radionuclide inventory that can escape before corrosion products plug the cracks in the fuel matrix and the perforations in the cladding. The fraction of fuel rods whose cladding will have failed by the time the waste package is breached depends on the condition of the fuel as emplaced and on repository conditions. Although the proportion of rods whose cladding will

have failed by the time the waste package is breached is uncertain, a typical fraction is estimated at 2.54 percent (CRWMS M&O 2001b, p. 67), which will be used in this attachment for illustrative calculations.

A fraction of the fission-product inventory of a perforated fuel rod, the fast-release fraction, will migrate through cracks and gaps in perforated fuel rods soon after waste-package breach (CRWMS M&O 2001b, Section 6.5). The fast-release phase ends when corrosion products plug the cracks and gaps. The recommended fast-release fraction for a perforated rod is given as a uniform distribution between 0 and 0.004 (CRWMS M&O 2001b, Table 17a). Illustrative calculations in this attachment will use the corresponding mean value, 0.002.

For the idealized PWR assembly that represents the average PWR assembly in the waste stream, the estimated inventory of fission-product Tc-99 in the year 2040 is 8.99 Ci (Table II-2). Because PWR fuel has a very low concentration of Mo (CRWMS M&O 1999d, p. III-3), which activates to Tc-99 (Table II-1), nearly all of the Tc-99 activation product in the fuel region originates in the fuel-region hardware. The estimated total neutron-activation inventory of Tc-99 in the year 2040 is 1.10×10^{-3} Ci (Table II-2), which is greater than the mean fast-release inventory of Tc-99 that would be available at that time from fission products upon waste package breach, $0.0254 \times 0.002 \times 8.99$ Ci $= 4.6 \times 10^{-4}$ Ci. Similarly, for a bounding PWR assembly in 2040, the inventory of Tc-99 from activation is greater than the fission product inventory that would be available from fast release of fission products (Table II-2). This observation may seem to militate against treating the Tc-99 from CSNF hardware activation as if it were part of the fuel matrix. However, Tc-99 from DSNF will be available soon after waste package breach because the TSPA-SR model does not take credit for the DSNF cladding in codisposal waste packages. In fact, the dissolution rate for DSNF is conservatively assumed in the TSPA-SR to result in complete dissolution of the fuel in a single time step (CRWMS M&O 2000i, p. 297). Therefore, it is important to consider the Tc-99 contribution from DSNF in codisposal waste packages.

First, consider the inventory of Tc-99 in CSNF waste packages that originates from activation of Mo in the hardware (Table II-1). Based on the representative assemblies that were used in the radionuclide inventory calculations, the fractions originating in hardware are: 0 for average BWR assemblies and $1.10 \times 10^{-3} / (8.99 + 1.10 \times 10^{-3}) = 1.22 \times 10^{-4}$ for average PWR assemblies (Table II-2). Similar fractions are obtained for bounding assemblies. The great difference between the BWR and PWR fractions appears because the Babcock and Wilcox PWR assembly that was used for the inventory calculations has top and bottom nozzles composed of stainless steel CF3M, which contains 2.5 percent Mo (CRWMS M&O 1999d, p. III-1). The top and bottom nozzles or tie plates of most other assemblies (including Westinghouse and Combustion Engineering PWR assemblies and the representative General Electric BWR assembly) are made of stainless steel 304 (DOE 1987, various tables throughout labeled "Fuel Assembly Hardware Parts and Materials Report"), which does not contain Mo (CRWMS M&O 1999a, p. II-1). Therefore, an upper bound for the repository's Tc-99 inventory in 2040 from CSNF hardware is given by the product of three numbers: (1) the fraction just computed for the Babcock and Wilcox PWR assembly, 1.22×10^{-4}; (2) the Tc-99 inventory in a commercial SNF waste package, 7.68×10^{3} g per waste package from Table 36; and (3) the number of commercial SNF waste packages, 7,860 (Section I-3.4.1): 7.4×10^{3} g.

Now consider the Tc-99 contribution from DSNF in codisposal waste packages. The amount of Tc-99 available soon after waste package breach from DSNF in codisposal waste packages may be estimated as 3,590 waste packages (Section I-3.5.1) times the 115 g per waste package from DSNF (Table 36): 4.1×10^5 g.

The upper bound CSNF hardware inventory of Tc-99, 7.4×10^3 g, is negligible in comparison to the estimated amount of Tc-99 that will be available soon after waste package breach from DSNF in codisposal waste packages, 4.1×10^5 g. Therefore, lumping the inventory of Tc-99 from CSNF hardware-activation products together with the Tc-99 in the commercial SNF matrix is an acceptable approximation for repository performance assessment.

II-4.2 CARBON-14

C-14 is not produced in appreciable amounts as a fission product (Parrington et al. 1996). It is produced by activation of N, C, and O in the fuel and hardware (Table II-1). To judge the relative importance of the three elements as sources of C-14, consider the product of the reaction cross-section and the relative abundance (see Parrington et al. 1996, pp. 18 and 19 for the cross-sections and relative abundances). For O, the O-17 abundance is 0.04 percent and the thermal (n, α) cross-section is 0.24 barns, yielding 9.6×10^{-5} barns per O atom. For C, the C-13 abundance is 1.1 percent and the thermal (n, γ) cross section is 1.4 millibarns, yielding 1.5×10^{-5} barns per C atom. For N, the N-14 abundance is 99.63 percent and the thermal (n, p) cross-section is 1.83 barns yielding 1.8 barns per N atom. Therefore, unless concentrations of O or C exceed those of N by many orders of magnitude, N is the most important source of C-14.

Hardware in the fuel region contains little N, O, or C in comparison to the fuel (CRWMS M&O 1999a, p. II-8; CRWMS M&O 1999d, p. III-3). Therefore, the entire C-14 inventory in the fuel region can be considered part of the fuel.

Hardware outside the fuel region does contain elements that activate to C-14. Typically, the top and bottom nozzles or tie plates are composed of stainless steel 304, though other stainless steels are found (DOE 1987, tables throughout labeled "Fuel Assembly Hardware Parts and Materials Report"). The top and bottom tie plates or nozzles account for most of the mass of the top- and bottom-region hardware and contain C and N (CRWMS M&O 1999a, p. II-6; CRWMS M&O 1999d, p. III-1). All of the Zircaloy components contain some O, but this source of C-14 can be neglected because the mass of O is comparable to or less than that of N (CRWMS M&O 1999a, p. II-6; CRWMS M&O 1999d, p. III-11). The plenum springs and the plenum getters are the only other sources of C-14 outside the fuel region that are accounted for in the radionuclide inventory calculations (CRWMS M&O 1999a, p. II-6; CRWMS M&O 1999d, p. III-1). The plenum springs and getters are protected by the cladding, so they should be lumped with the fuel for the purposes of this section.

For the average BWR assembly in 2040 (Table II-2), there is only about five times more C-14 in the fuel matrix and the plenum region as in the top and bottom hardware $(1.62 \times 10^{-1} + 4.75 \times 10^{-3}) / (7.91 \times 10^{-3} + 2.82 \times 10^{-2}) = 4.6$. The ratio of the C-14 inventory in the top and bottom hardware to that available by fast release (Section II-4.1) in the fuel region is estimated illustratively for an average BWR assembly as $(7.91 \times 10^{-3} + 2.82 \times 10^{-2}) / (1.62 \times 10^{-1} \times 0.0254 \times 0.002) = 4{,}400$ (Table II-2). Thus, there is much more C-14 available from activation of

exposed stainless steel components of the hardware than from fast release from the fuel. Similarly, for average PWR and for bounding PWR and BWR assemblies, there is much more C-14 available from activation of exposed stainless steel components of the hardware than from fast release from the fuel (Table II-2). This observation militates against treating the C-14 from CSNF hardware activation as if it were part of the fuel matrix. However, C-14 from DSNF will be available soon after waste package breach because the TSPA-SR model does not take credit the DSNF cladding in codisposal waste packages. In fact, the dissolution rate for DSNF is conservatively assumed in the TSPA-SR to result in complete dissolution of the fuel in a single time step (CRWMS M&O 2000i, p. 297). Therefore, it is important to consider the C-14 contribution from DSNF in codisposal waste packages.

First, consider the fraction of the C-14 in CSNF waste packages that originates from hardware activation. Based on the representative assemblies that were used in the radionuclide inventory calculations, the ratios of top and bottom region inventory to total inventory for PWR and BWR assemblies from Table II-2 are $(7.91 \times 10^{-3} + 2.82 \times 10^{-2}) / 2.03 \times 10^{-1} = 0.178$ for average BWR assemblies, and $(2.26 \times 10^{-3} + 0) / 3.32 \times 10^{-1} = 0.00681$ for average PWR assemblies. Similar ratios are obtained for bounding assemblies. The great difference between the BWR and PWR fractions appears because the Babcock and Wilcox PWR assembly that was used for the inventory calculations has top and bottom nozzles composed of stainless steel CF3M, which does not contain N as a constituent of the alloy (CRWMS M&O 1999d, p. III-1). The top and bottom nozzles or tie plates of most other assemblies (including Westinghouse and Combustion Engineering PWR assemblies and the representative General Electric BWR assembly) are made of stainless steel 304 (DOE 1987, Fuel Assembly Hardware Parts and Materials Reports throughout), which does contain N (CRWMS M&O 1999a, p. II-1). Therefore, the fraction computed for the General Electric BWR assembly is taken to represent CSNF in general. Thus, based on the representative BWR assembly, approximately 18 percent of the C-14 inventory for commercial SNF assemblies originates from hardware activation.

The repository's C-14 inventory from CSNF can be estimated as the product of the C-14 inventory in a commercial SNF waste package, 1.37 g per waste package (Table 36); and the number of commercial SNF waste packages, 7,860 (Section I-3.4.1): 1.1×10^4 g. The repository's C-14 inventory from CSNF hardware may be estimated as 18 percent of the total, that is, 2.0×10^3 g.

Now consider the C-14 contribution from DSNF in codisposal waste packages. The amount of C-14 available soon after waste package breach from codisposal waste packages may be estimated as 3,590 waste packages (Section I-3.5.1) times 4.96×10^{-2} g per waste package from DSNF (Table 36): 1.8×10^2 g.

Because the amount of C-14 available from CSNF hardware (2.0×10^3 g.) greatly exceeds that available from codisposal waste packages (1.8×10^2), the consequence of lumping hardware and fuel-matrix contributions is less benign than it is for Tc-99. As modeled in the TSPA-SR, the early release from C-14 is, roughly speaking, proportional to the contribution from codisposal waste packages plus the fast release contribution from CSNF waste packages: 1.8×10^2 g + $0.0254 \times 0.002 \times 1.1 \times 10^4$ g $\cong 1.8 \times 10^2$ g. Note that lumping the C-14 from CSNF hardware

with the fuel, and applying protective effect of the cladding effectively removes C-14 due to CSNF from consideration.

A more realistic model would allow the portion of the C-14 inventory that is contained in the hardware to be released independent of the failure of the cladding. Depending on the degradation rate of the material containing the C-14, hardware degradation could be a significant contributor to the early release of C-14. At one extreme, and one that appears to be realistic, hardware inventory could be released soon after breach of the waste package (Assumption 5.11) so that it would be available at roughly the same time as the fast-release inventory from the spent fuel; this would yield an early release roughly proportional to 1.8×10^2 g + 2.0×10^3 g = 2.2×10^3 g. The ratio of the early release contributions from the two approaches (2.2×10^3 g / 1.8×10^2 g) is a rough correction factor for early releases due to C-14 equal to about 12. Thus, lumping the inventory of C-14 from CSNF hardware-activation products together with the C-14 in the commercial SNF matrix may cause a substantial underestimate in the early release of C-14. With time, more and more of the C-14 from the fuel matrix would be released, so the magnitude of the underestimate would diminish with time.

Although C-14 is not one of the primary contributors to general dose rate in the TSPA-SR model (CRWMS M&O 2000j, Figure 6.1-8), it is first among the lesser contributors before about 20,000 y (CRWMS M&O 2000j, Figure 4.1-7). As shown by CRWMS M&O (2000j, Figure 6.1-7), C-14, along with Tc-99, is an important contributor to the dose from photon- and beta-emitting radionuclides in groundwater shortly after the end of the 10,000-y regulatory period for the EPA groundwater-protection standard (66 FR 32074). Due to the importance of C-14 to the early dose and the significance of the C-14 contribution from CSNF hardware, the C-14 from the hardware should not be lumped with the C-14 from the fuel matrix in future TSPAs.

II-4.3 ZIRCONIUM-93

Zr-93 is produced by activation of Zr-92 (Table II-1), which is a constituent of Zircaloy components, most notably the cladding, and is not present in other hardware (CRWMS M&O 1999d, Table 5; CRWMS M&O 1999a, Table 12). Because Zircaloy is very resistant to corrosion under credible repository conditions (BSC 2001a, Attachment II), significant release of Zr-93 will be delayed well beyond waste-package breach. Moreover, Zr-93 has been screened out (Table 37). Therefore, the Zr-93 produced by hardware activation may be neglected in assessing repository performance.

II-4.4 NICKEL-59, NICKEL-63, AND NIOBIUM-94

Ni-59, Ni-63, and Nb-94 are not produced in appreciable amounts as fission products (Parrington et al. 1996). They are produced by activation of Ni and Nb in hardware (Table II-1). Some of the Ni-59, Ni-63, and Nb-94 will originate in Inconel components. Because Inconel, like Zircaloy, is very corrosion resistant, the release of some fraction of the Ni-59, Ni-63, and Nb-94 would be delayed well beyond waste package breach and should not be treated as available upon waste package breach. Ni-59, Ni-63, and even Nb-94 are also found in stainless steel components, which would degrade more quickly than Inconel would and release the radionuclides sooner. However, because Ni-59, Ni-63, and Nb-94 have been screened out by the

inventory screening analysis (see Table 37, which lists the screened-in radionuclides), they may be neglected in assessing repository performance.

II-5. CONCLUSION

It is appropriate for the screening analysis and for performance assessment to neglect the radionuclide contribution from crud on commercial SNF assemblies.

A negligible fraction of the Tc-99 in commercial SNF originates from neutron activation of hardware. Lumping the inventory of Tc-99 from CSNF hardware-activation products together with the Tc-99 in the commercial SNF matrix is an acceptable approximation for repository performance assessment because the Tc-99 inventory from CSNF hardware is overwhelmed by the Tc-99 from DSNF in codisposal waste packages, which is assumed not to be impeded by cladding.

About 18 percent of the C-14 inventory in CSNF originates from neutron activation of stainless steel hardware outside the fuel rods. Lumping the inventory of C-14 from CSNF hardware-activation products together with the C-14 in the commercial SNF matrix is a nonconservative approximation for repository performance assessment. Due to the importance of C-14 to the early dose and the significance of the C-14 contribution from CSNF hardware, the C-14 from the hardware should not be lumped with the C-14 from the fuel matrix in future TSPAs.

Table II-1. Identification and Screening Status of Hardware-Activation Products

Element	Nuclear Reactions Considered (Half-lives in Parentheses) [a, b]	Products of Concern	Screening Status	
			In	Out
Al	Al-27 (n,γ) Al-28 (2 m) → Si-28 (stable)	None		
B	B-11 (n,γ) B-12 (20 ms) → C-12 (stable)	None		
C	C-13 (n,γ) C-14 (5.7E3 y)	C-14	✔	
Co	Co-59 (n,γ) Co-60 (5.3 y)	Co-60		✔
Cr	Cr-50 (n,γ) Cr-51(27 d) → V-51 (stable)	None		
	Cr-54 (n,γ) Cr-55 (3 m) → Mn-55 (stable)	None		
Cu	Cu-63 (n,γ) Cu-64 (13 h) → Zn-64 (stable), Ni-64 (stable)	None		
	Cu-65 (n,γ) Cu-66 (5 m) → Zn-66 (stable)	None		
Fe	Fe-54 (n,γ) Fe-55 (2.7 y) → Mn-55 (stable)	None		
	Fe-54 (n,α) Cr-51(27 d) → V-51 (stable)	None		
	Fe-58 (n,γ) Fe-59 (45 d) → Co-59 (stable)	None		
Mn	Mn-55 (n,γ) Mn-56 (2.6 h) → Fe-56 (stable)	None		
Mo	Mo-92 (n,γ) Mo-93 (6.9 h) → Nb-93 (stable)	None		
	Mo-98 (n,γ) Mo-99 (2.7 d) → Tc-99 (2.1E5 y)	Tc-99	✔	
	Mo-100 (n,γ) Mo-101 (15 m) → Tc-101 (14 m) → Ru-100 (stable)	None		
N	N-14 (n, p) C-14 (5.7E3 y)	C-14	✔	
	N-15 (n,γ) N-16 (7 s) → O-16 (stable)	None		
Nb	Nb-93 (n,γ) Nb-94 (2.0E4 y)	Nb-94		✔
Ni	Ni-58 (n,γ) Ni-59 (7.6E4 y)	Ni-59		✔
	Ni-62 (n,γ) Ni-63 (1E2 y)	Ni-63		✔
	Ni-64 (n,γ) Ni-63 (2.5 h) → Cu-65 (stable)	None		
O	O-18 (n,γ) O-19 (27 s) → F-19 (stable)	None		
	O-17 (n,α) C-14 (5.7E3 y)	C-14	✔	
P	P-31 (n,α) P-32 (14 d) → S-32 (stable)	None		
S	S-34 (n,γ) S-35 (87 d) → Cl-35 (stable)	None		
	S-36 (n,γ) S-37 (87 d) → Cl-37 (stable)	None		
Si	Si-30 (n,γ) Si(31) (2.6 h) → P-31 (stable)	None		
Sn	Sn-112 (n,γ) Sn-113 (115 d) → In-113 (stable)	None		
	Sn-120 (n,γ) Sn-121 (1.1 d) → Sb-121 (stable)	None		
	Sn-122 (n,γ) Sn-123 (129 d) → Sb-123 (stable)	None		
	Sn-124 (n,γ) Sn-125 (9.6 d) → Sb-125 (2.7 y)	Sb-125		✔
Ti	Ti-50 (n,γ) Ti-51 (5.8 m) → V-51 (stable)	None		
Zr	Zr-92 (n,γ) Zr-93 (1.5E6 y)	Zr-93		✔
	Zr-94 (n,γ) Zr-95 (64 d) → Nb-95 (35 d) → Mo-95 (stable)	None		
	Zr-96 (n,γ) Zr-97 (17 h) → Nb-97 (1.2 h) → Mo-97 (stable)	None		

NOTES: [a]Activation of reaction products ignored.
[b]Parrington et al. 1996.

Table II-2. Calculated C-14 and Tc-99 Inventories in PWR and BWR Assemblies in 2040

	Average PWR Assembly[a]			Average BWR Assembly[b]		
	Fission-Product Inventory[c] (Ci)	Neutron-Activation Inventory (Ci)		Fission-Product Inventory[c] (Ci)	Neutron-Activation Inventory (Ci)	
	Tc-99	C-14	Tc-99	Tc-99	C-14	Tc-99
Fuel[d]	8.99E+00	3.30E-01	6.14E-04	3.16E+00	1.62E-01	0.00E+00
Total Nonfuel	0.00E+00	2.26E-03	4.87E-04	0.00E+00	4.09E-02	0.00E+00
Bottom[e]	0.00E+00	0.00E+00	2.91E-04	0.00E+00	2.82E-02	0.00E+00
Plenum[f]	0.00E+00	0.00E+00	3.78E-05	0.00E+00	4.75E-03	0.00E+00
Top[g]	0.00E+00	2.26E-03	1.58E-04	0.00E+00	7.91E-03	0.00E+00
Total	8.99E+00	3.32E-01	1.10E-03	3.16E+00	2.03E-01	0.00E+00
	Bounding PWR Assembly[h]			Bounding BWR Assembly[i]		
	Fission-Product Inventory[c] (Ci)	Neutron-Activation Inventory (Ci)		Fission-Product Inventory[c] (Ci)	Neutron-Activation Inventory (Ci)	
	Tc-99	C-14	Tc-99	Tc-99	C-14	Tc-99
Fuel[j]	1.28E+01	4.85E-01	9.20E-04	5.02E+00	2.52E-01	1.26E-05
Total Nonfuel	0.00E+00	3.31E-03	7.27E-04	0.00E+00	6.35E-02	0.00E+00
Bottom[k]	0.00E+00	0.00E+00	4.34E-04	0.00E+00	4.38E-02	0.00E+00
Plenum[l]	0.00E+00	0.00E+00	5.66E-05	0.00E+00	7.38E-03	0.00E+00
Top[m]	0.00E+00	3.31E-03	2.36E-04	0.00E+00	1.23E-02	0.00E+00
Total	1.28E+01	4.88E-01	1.65E-03	5.02E+00	3.15E-01	1.26E-05

SOURCE: CRWMS M&O 1999c (for PWR fuel) and 1999b (for BWR fuel); file names are as specified in Notes d thru g and j thru m below.

NOTES:

[a]32-year-old average PWR assembly (Section 4.1.1.1). 32 y represents the age of the average PWR assembly in 2040.

[b]32-year-old BWR assembly that corresponds to the average (Section 4.1.1.1) except with 3% enrichment instead of 3.5%, the detailed results for which are not presented in the calculation. 32 y represents the approximate age of the average BWR assembly in 2040.

[c]Fission-product inventories of C-14 are negligible.

[d]PWR: Waste.Stream.E5.R1.B9.cut; BWR: 3.0%.40GWd.fuel.cut.

[e]PWR: Waste.Stream.E5.R2.B9.cut; BWR: 3.0%.40GWd.bottom.cut.

[f]PWR: Waste.Stream.E5.R3.B9.cut; BWR: 3.0%.40GWd.plenum.cut.

[g]PWR: Waste.Stream.E5.R4.B9.cut; BWR: 3.0%.40GWd.top.cut.

[h]12-year-old bounding PWR assembly (Section 4.1.1.1). 12 y is the approximate age of the bounding PWR assembly in 2040.

[i]12-year-old bounding BWR assembly (Section 4.1.1.1). 12 y is the approximate age of the bounding PWR assembly in 2040.

[j]PWR: Waste.Stream.E2.R1.B13.cut; BWR: 4.5%.70GWd.fuel.cut.

[k]PWR: Waste.Stream.E2.R2.B13.cut; BWR: 4.5%.70GWd.bottom.cut.

[l]PWR: Waste.Stream.E2.R3.B13.cut; BWR: 4.5%.70GWd.plenum.cut.

[m]PWR: Waste.Stream.E2.R4.B13.cut; BWR: 4.5%.70GWd.top.cut.