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Definition of the Base Analysis Case of the Interim Performance Assessment

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Abstract: The base analysis case for the "Hanford Low-Level Tank Waste Interim Performance Assessment" is defined. Also given are brief descriptions of the sensitivity cases.

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Definition of the Base Analysis Case of the Interim Performance Assessment

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1.0 OVERVIEW

1.1 INTRODUCTION

The purpose of the Hanford Low-Level Tank Waste Interim Performance Assessment is to analyze as early as possible the long-term environmental impact of disposal of the low-level fraction of the Hanford tank waste onsite. The Interim Performance Assessment is not required by any regulation. The Interim Performance Assessment will provide an early estimate of the product and disposal facility performance needed to meet requirements.

The methods, procedures, and rigor of the performance assessment process as mandated by DOE Order 5820.2A (USDOE 1988) will be used to the maximum extent possible. However, because this analysis is being performed early in the project, much of the data is not yet specific to the project. A work plan on gathering such project-specific data has been published (PAT 1995c).

Earlier work (Rawlins 1994 and Mann 1995b) used a less stringent process and was focused on the effects of possible disposal facility components on performance. By following the performance assessment process, the resulting Interim Performance Assessment will be more extensive than this earlier work.

1.2 PURPOSE OF DOCUMENT

The purpose of this document is to define the values for all the parameters needed in the computer simulation of the best estimate case. The methods, procedures, and data to be used in the analyses that form the basis of the Interim Performance Assessment mainly come from the Data Packages for the Hanford Low-Level Tank Waste Performance Assessment (Mann 1995a). Additional data have been generated as the Tank Waste Remediation System (TWRS) privatization effort has become better defined (see Section 1.3).

1.3 RELATIONSHIP WITH TWRS PRIVATIZATION EFFORT

At the same time that the Interim Performance Assessment is being written, the U.S. Department of Energy (DOE) may obtain the services of private contractors to process the waste which will be disposed of in the disposal facility. The draft request for proposals (RFP) was released in November 1995 (USDOE 1995), with the final request for proposals to be released in the spring of 1996. Contract award for the first phase (processing 6% to 13% of the total waste) is expected in the late summer of 1996. As more becomes known about this effort, the information will be used to adjust the analyses performed for the Interim Performance Assessment.

1.4 METHOD

Calculations for the Interim Performance Assessment will be done in one of two ways:

- (1) A four-step method using sophisticated computer codes to model distinctly different physical and chemical process,
- (2) Hand calculations for simple situations.

The four-step method will be used for the base analysis case (Section 1.5) and for most of the sensitivity cases (Section 1.6). Hand calculations will be used for simple analyses such as upward diffusion of radon.

The four-step method involves separate calculations for

- (1) The release rate of contaminants from glass and the immediate effects of the local chemical environment.
- (2) The transport of contaminants through the disposal facility and the vadose zone down to the unconfined aquifer (or in certain cases up to the ground surface).
- (3) The transport of contaminants through the aquifer to the point of compliance (that is, the calculation of the so-called well intercept factor).
- (4) The integration of release, transport, inventory, decay, and dose conversion.

The base analysis case release rate of contaminants from the waste form will be determined using the specifications of the TWRS Privatization RFP (USDOE 1995) with a major sensitivity case being a deterministic prediction of the release rate using the AREST-CT computer code (McGrail 1994). The vadose zone transport will be done using the PORFLOW computer code (Piepho 1995). Because of the need to use the Hanford site-wide groundwater model, aquifer transport will be done using the VAM3D code. The integration step of combining the release rate calculations, the transport calculations, inventory, decay, and conversion of concentrations to dose exposure will be performed in a FORTRAN-based code which is being written.

The major data areas needed for the computer calculations are

- 1) Performance Objectives
- 2) Scenarios
- 3) Inventory
- 4) Location of disposal facility
- 5) Recharge rate
- 6) Geology
- 7) Initial disposal facility data
- 8) Degradation of disposal facility
- 9) Hydraulic parameters

- 10) Contamination release from the waste form
- 11) Geochemical factors
- 12) Dosimetry data
- 13) Calculational assumptions, and
- 14) Interaction with other facilities.

Table 1-1 displays in the major data areas for each analysis step.

Table 1-1. Data Areas for Each Analysis Step

Step	Data Areas
Waste Form Release Rate	Contaminant release from the waste form
Vadose Zone Transport	Scenarios Location of disposal facility Recharge rate Geology Disposal facility Hydraulic parameters Geochemical parameters Calculational assumptions
Aquifer Transport	Scenarios Location of disposal facility Recharge rate Geology Hydraulic parameters Calculational assumptions
Integration	Performance objectives Inventory Dosimetry data Interaction with other facilities

1.5 BASE ANALYSIS CASE

The base analysis case is the computer simulation case that reflects our best estimate on what the system (both man-made and natural) is and how it will behave as a function of time. As noted above, this document provides the values for all the parameters needed for the computer simulation. The descriptions and the justifications for the equations used in the computer simulation are in Mann 1995a.

1.6 SENSITIVITY CASES

Sensitivity cases are computer simulations in which the values of one or more variables differ from the values used in the base analysis case. The purpose of the sensitivity cases is to determine the effects of selected changes in important parameters. The sensitivity cases in this document focus on the parameters related to the base analysis case. It is intended that for most of the computer simulations run, the value of only one variable will be changed from the base analysis case. In some instances, however, the values for more than one variable will be changed from the values used in the base analysis case.

The sensitivity cases are not a means to address statistical uncertainty or other statistical variations. Most of the site-specific and waste-form specific data are not yet available. Therefore the uncertainties in the values of the various variables for the base analysis case can not yet be estimated.

2.0 PERFORMANCE OBJECTIVES

2.1 INTRODUCTION

The performance objectives are the standards against which compliance is judged. The objectives to be used in the Hanford Low-Level Tank Waste Interim Performance Assessment are described in PAT 1995a and are displayed in Table 2-1. PAT 1995a also describes the selection process and justifies the choices.

Failure of meeting the performance objectives should not be viewed as non-compliance but rather signals the need for further work which could include refinements of the calculational methods or approaches or additional data collection efforts.

2.2 BASE ANALYSIS CASE

The performance objectives for this analysis are based on (1) the requirements of DOE Order 5820.2A (USDOE 1988), (2) the experiences in writing performance assessments in the DOE complex, (3) the incorporation of the regulations of the state of Washington, and (4) the plans of the Storage and Disposal Project. Five general resources are protected:

- (1) The general public and workers.
- (2) Inadvertent intruders.
- (3) Groundwater resources.
- (4) Surface water resources.
- (5) Air resources.

The protection of water resources is governed both by simple drinking water requirements as well as by more sophisticated dosimetry scenarios (see next section).

Table 2-1. Performance Objectives^a
All doses are EDE (Effective Dose Equivalent)

Protection of General Public and Workers	
All-pathways:	25 mrem/year ^b
ALARA (all pathways):	500 persons - rem/year ^c
(evaluated for 10,000 years, but calculated past the time of peak dose)	
Inadvertent Intruder	
Acute exposure:	500 mrem ^b
Continuous exposure:	100 mrem/year ^b
(evaluated at 500 years, calculated from 100 to 1000 years)	
Protection of Ground Water Resources	
Alpha emitters	
Ra-226:	3 pCi/L ^d
Ra-226 + Ra-228:	5 pCi/L ^d
sum (all other alpha emitters):	15 pCi/L ^d
Beta and photon emitters	
H-3:	20,000 pCi/L ^d
Sr-90:	8 pCi/L ^d
sum (all other beta and photon emitters):	4 mrem/year ^d
(evaluated for 10,000 years, but calculated past the time of peak dose)	
Protection of Surface Water Resources	
Alpha emitters	
Ra-226 + Ra-228:	0.3 pCi/L ^e
sum (all other alpha emitters):	15 pCi/L ^d
Beta and photon emitters	
H-3:	20,000 pCi/L ^d
Sr-90:	3 pCi/L ^e
sum (all other beta and photon emitters):	1.0 mrem/year ^e
(evaluated for 10,000 years, but calculated past the time of peak dose)	
Protection of Air Resources	
Radon:	20 pCi/m ² s ^f
All other radionuclides:	10 mrem/year ^f
(evaluated for 10,000 years, but calculated past the time of peak dose)	

a Taken from PAT 1995a

b Main driver is DOE Order 5820.2A (USDOE 1988)

c Main driver is RL Order 5820.2A (USDOE/RL 1993)

d Main driver is National Primary Drinking Water Regulations (USEPA 1975)

e Main driver is Washington State Department of Health (WSDOH 1991)

f Main driver is National Emission Standards for Hazardous Air Pollutants (USEPA 1989)

3.0 SCENARIOS

3.1 INTRODUCTION

The scenarios of the analysis describe the land use and pathways to be analyzed in the Interim Performance Assessment. The scenarios are described in PAT 1995b. They are based on the land use recommended by the Hanford Future Site Uses Working Group (HFSUWG 1992).

3.2 BASE ANALYSIS CASE

The scenario for the base analysis case assumes a return to natural conditions or at least conditions where minimal additional water is discharged to the ground in the central Hanford plateau. The main exposure pathway will be water drawn from a nearby well which is no closer than 100 meters from the disposal facility. The location of the well will be selected to provide the maximum calculated exposure. The amount of pumping from the well is assumed to be low enough not to affect the groundwater flow. The area near the waste site will be either in a natural condition or used for dry-land farming. Recreational uses of the Columbia River and its shores will be assumed. There will be no intentional intrusions into the waste disposal facility for those cases used in the calculation of the protection of the general public, workers, water resources, or air resources.

Inadvertent intrusion is calculated as a separate requirement and involves the drilling of a well to the unconfined aquifer or irrigation on top of the disposal site (Rittmann 1995). The important parameters for the intrusion scenarios are displayed in Table 3-1.

Air resource protection will be calculated assuming simple models of diffusion.

Table 3-1. Important Parameters in Intrusion Analyses

Parameter	Value
Diameter of well:	0.3 meters (12 inches) ^a
Garden size:	500 m ² (5374 ft ²) ^a
Glass fines:	determined by release rate of glass (linear model)

^a Taken from Rittmann 1995

3.3 SENSITIVITY CASES

Sensitivity cases will cover different land use scenarios, different well placements and pumping rates, different intrusion scenario parameters, and different natural events.

Different land use scenarios will be treated by assuming different recharge rates (See Section 6) at the disposal facility and around the central Hanford plateau. A high recharge rate (100 mm/year) will be used to simulate the conditions in which irrigated farming might occur. This value may be too low for some crops like potatoes. However, over the long-term (hundreds of years) this recharge value is probably conservative for most crops.

One sensitivity case will assume such a farm is present over the disposal facility. Other sensitivity cases assumed irrigated farming in other parts of the plateau to determine the effect of a change in the ground water flow path. These cases assume

- (1) Irrigation in all Hanford regions except the 200 Areas and the region between 200 East and 200 West Areas
- (2) Irrigation only north of 200 Areas
- (3) Irrigation only west of 200 West Area.

The final sensitivity case dealing with a different land use investigates reduced recharge due to light industry in the 200 areas. Light industry will not be disposing liquid waste into the ground as has been done by the chemical reprocessing plants. The result will be a reduced recharge rate to the 200 areas as compared to the base analysis case. The recharge rate in the 200 Areas will be reduced by a factor of 2 from the base analysis case.

To determine the sensitivity of the results to the placement of the well, different well locations will be considered, ranging from 50 meters from the edge of the disposal site down to the Columbia River. In particular, a well location at the eastern edge of the 200 East area will be considered. In addition, the effect of distorting the ground water flow will be determined by increasing the pumping rate above the minimal level assumed in the base analysis case.

As noted in Rittmann 1995, the parameters for the intrusion scenarios are conservative. The effect of less conservative values will be investigated, in particular, increasing the area of the garden to 2500 m² and decreasing the well diameter to 0.2 meters.

Finally, sensitivity cases involving large scale natural events (such as the collapsing of dams or the occurrence of a glacial flood) will be done using simple models.

4.0 INVENTORY

4.1 INTRODUCTION

The radiological dose and radionuclide concentration levels at the location of exposure are linearly proportional to the amount of radionuclide at that point. The models used to treat the transport of the material from the waste form through the vadose zone through the aquifer to the point of exposure all assume that the transport is unaffected by the amount of radionuclides in the waste form. This means there are no saturation effects. Thus, the results of the calculations for each component of exposure are proportional to the amount of material (inventory of radionuclides) in the waste form.

4.2 BASE ANALYSIS CASE

The inventory used in this analysis is taken from Schmittroth et al (Schmittroth 1995), except where noted. They estimated the amount of radionuclides in the Hanford tanks by calculating the amount produced in Hanford's production reactors and then subtracting the relatively small amount lost in processing, spills, or transfers. They used May 1995 estimates (Shelton 1995) for the fractional amounts that end up in the waste form after chemical processing and vitrification.

Table 4-1 displays the inventory estimated to be in the low-level waste glass as of 2010. Also displayed is the fraction of the tank waste that is assumed to end up in the glass. For the base analysis case, the inventory will be assumed to be uniformly spatially distributed since very little information is presently available for the actual spatial distribution in the disposal facility.

Table 4-1. Inventory of the Base Analysis Case^a

Radionuclide	Percent to LLW glass from tanks ^f	Curies in LLW glass (yr: 2010)
¹⁴ C	1.	7.73E+0
⁷⁹ Se	100. ^g	1.03E+3
⁹⁰ Sr	3. ^b	1.61E+6 ^e
⁹³ Zr	1. ^h	4.87E+1
⁹³ Nb ^m	1. ^h	4.20E+1
⁹⁹ Tc	82.	2.23E+4
¹²⁶ Sn	100. ^g	1.58E+3
¹²⁹ I	10.	6.62E+0

Radionuclide	Percent to LLW glass from tanks ^f	Curies in LLW glass (yr: 2010)
¹³⁷ Cs	1. ^c	4.51E+5 ^e
¹⁵¹ Sm	1. ^h	3.16E+4
²²⁶ Ra	50. ^{d, h}	2.35E-3
²²⁸ Ra	50. ^{d, h}	1.38E+0
²²⁷ Ac	1. ^{d, h}	1.08E+0
²²⁹ Th	1. ^{d, h}	9.79E-3
²³² Th	1. ^{d, h}	2.68E-2
²³¹ Pa	100. ^{d, g}	1.45E+2
²³³ U	6.	2.58E+1
²³⁴ U	6.	1.80E+1
²³⁵ U	6.	7.36E-1
²³⁶ U	6.	4.47E-1
²³⁸ U	6.	1.78E+1
²³⁷ Np	5.	3.74E+0
²³⁹ Pu	6.	2.23E+3
²⁴⁰ Pu	6.	4.31E+2
²⁴¹ Am	8.	4.25E+3
²⁴³ Am	8.	2.70E+0
²⁴⁵ Cm	100. ^g	1.03E-1

- a Data are taken from Schmittroth 1995.
- b 23% of ⁹⁰Sr produced went into capsules rather than tanks.
- c 45% of ¹³⁷Cs produced went into capsules rather than tanks.
- d Also a decay product of other actinides
- e The daughters (⁹⁰Y and ¹³⁷Ba^m) are in secular equilibrium with their parents and their inventories are not included.
- f The fraction of tank waste going into the waste form was taken from Shelton 1995.
- g Because of the absence of defensible data, no credit is taken for a reduction in the amount going to the low-level fraction.
- h These values based on Petersen 1995. Schmittroth 1995 had used values of 100% because of the lack of data.

4.3 Sensitivity Cases

The inventory sensitivity cases will investigate the effects of assumed changes in inventory. Such sensitivity cases will be based on the TWRS Privatization Effort, the work supporting the petition to the Nuclear Regulatory Commission (NRC) on the classification of wastes, and on the spatial distribution of the waste in the disposal facility.

The definition of many of these cases will be postponed until more is known about the TWRS Privatization Effort. Based on the draft request for proposal (USDOE 1995), the effect of 80% removal of ^{99}Tc will be calculated.

Sensitivity cases will be run based on the work (WHC 1995) supporting the DOE petition to the NRC on waste classification. In particular, a sensitivity case will be run assuming a ^{137}Cs inventory of 5 Megacuries (a factor of about 10 larger than the base analysis case).

The sensitivity to different presumed spatial distributions will be treated by analyzing the results of other sensitivity cases (in particular, the ones dealing with the spatial aspect of the disposal facility and of contaminant transport).

5.0 LOCATION OF DISPOSAL FACILITY

The location of the disposal facility determines many subsequent parameters, for example, the thickness of geologic strata and various hydraulic parameters. The location has not yet been officially determined. However, the preferred location as given in Shord 1995 will be used for the Interim Performance Assessment. This location is just west of the PUREX facility in the south central part of the 200 East Area (see Figure 5-1).

No other locations for the disposal facility will be considered in this assessment.

Figure 5-1. Location of the Tank Waste Vitrification Area. The disposal facility is projected to be located in this area. The area is in the south central part of the 200 East Area.

6.0 RECHARGE RATE

6.1 INTRODUCTION

The recharge rate is the rate at which water enters the unconfined aquifer. In practice, it is the term that describes the net rate at which water leaves the near-surface zone (that is the zone characterized by the interaction of climate, soil, vegetation, and animals). Recharge is the rate at which moisture enters and leaves the waste disposal facility, moves through the vadose zone, and carries contaminants to the aquifer. Recharge at the disposal site is important for the vadose zone calculations, while the rate over the entire central Hanford plateau is important for aquifer transport.

6.2 BASE ANALYSIS CASE

The recharge rate for the base analysis case is based on 1995 efforts at the Pacific Northwest Laboratory (Fayer 1995, Rockhold 1995) (see Table 6-1). Fayer and Walters (Fayer 1995) provide estimates of the recharge rate based on vegetation cover and on soil type at locations around the Hanford Site. Rockhold et al. (Rockhold 1995) estimated the recharge rate for the disposal facility based on the design specifications of the Hanford surface barrier (Myers 1994) for the short-term recharge rate (0.5 mm/year) and then used the data for the disposal site from Fayer and Walters for the estimate of the long-term recharge rate (3 mm/year). Since the specifications for the surface barrier cite 1000 years for the design life, the base analysis case shall assume that the recharge rate is 0.5 mm/year for the first thousand years and then immediately increase to 3 mm/year. Although the transmission through the barrier is not expected to increase this quickly, there are no data on which to base a slower rate of increase.

Table 6-1. Recharge Rate for Base Analysis Case^a

Parameter	Recharge Rate Value
At the Disposal Facility	
First 1000 years	0.5 mm/years
Thereafter	3.0 mm/years
Hanford Site	from Fayer 1995

^a Taken from Rockhold 1995

6.3 SENSITIVITY CASES

Sensitivity cases related to various recharge rates will illustrate the effect of presently poorly known recharge rates, of extremely low recharge rates, and of different site-wide patterns.

In the first sensitivity case, no credit will be taken for the surface barrier and only the recharge rate for natural conditions at this location (3.0 mm/year) will be used forever. The second case assumes 1.0 mm/year [based on the Grout Performance Assessment (Kincaid 1995) which assumed that the surface barrier is effective forever, but the recharge rate is slightly higher (1.0 mm/year) than the recharge rate given in the surface barrier design specifications].

The third sensitivity case assumes a very low recharge rate (0.1 mm/year) in order to determine the importance of upward diffusion and upward capillary flow. Preliminary measurements using tracers indicate that if sagebrush vegetation persists at this location, then such a very low recharge rate might be appropriate.

Sensitivity cases involving different recharge rates due to different land use scenarios are described in Section 3.3. The scenario assuming irrigated farming over the disposal facility results in a recharge rate of 100 mm/year at the facility location. Other cases involved placing the irrigated farms in other locations around the central Hanford plateau. Finally a case of industrial land use is considered which results in a recharge rate of 1.5 mm/year in the 200 Areas.

7.0 GEOLOGY

7.1 INTRODUCTION

The geology underneath the disposal facility and of the surrounding region determines most of the transport parameters needed in the analyses. Different geologic strata affect water flow and contaminant transport differently.

7.2 BASE ANALYSIS CASE

The geology for this disposal site is given in Reidel 1995 and summarized in Table 7-1. The main geologic units considered are the Hanford formation and the Ringold Formation.

Table 7-1. Geology of the Base Analysis Case^a

Formation	Thickness/Location
Hanford formation gravelly sand sandy sequence gravelly sand sequence	6 meters (on surface) 60 meters 35 meters (bottom)
Ringold Formation Unit E	30 meters, below Hanford formation
Unconfined aquifer	103 meters below surface, 118 meters above mean sea level

^a Taken from Reidel 1995

The Hanford formation underneath the disposal area consists of three layers. The upper 6 meters of the Hanford formation is the gravelly sand sequence. The next 60 meters consists of the sandy sequence. The bottom of the Hanford formation, a gravelly sand sequence, is 25 to 40 meters thick. For modeling purposes a mean thickness of this bottom sequence will be taken as 35 meters. Thus, the Hanford formation is assumed to be 101 meters thick.

Below the Hanford formation lies the Ringold Formation. Only the Unit E layer is of concern for this analysis. The Unit E layer is consolidated sandy gravel to muddy sandy gravel 30 meters thick.

After Hanford operations have ceased and assuming no large-scale water discharges to the soil (such as irrigation), the top of the unconfined aquifer is predicted (Law 1995) to be 103 meters below the land surface (118 meters above mean sea level). This places the unconfined aquifer in the Ringold Formation.

7.3 SENSITIVITY CASES

Sensitivity studies related to geology fall into two categories, the placement of geologic strata and the location of the top of the unconfined aquifer.

Until additional characterization is done at the site, no sensitivity studies directly tied to geologic strata are warranted. However, since the most important effects of geologic strata are the implied hydraulic properties, some understanding of the sensitivity to the placement of strata can be inferred from changing hydraulic properties. Such sensitivity cases are described in Section 10 (Hydraulic Parameters).

The predicted position of the water table for these analyses depends on computer simulation. Such simulation may be inaccurate for a variety of reasons. Therefore two sensitivity cases are considered, one having the top of the unconfined aquifer at 96 meters below the surface (its present location) and the other at 110 meters below the surface. The former case will also allow the sensitivity of the calculation to aquifer hydraulic conditions to be inferred (see Section 10), since with the aquifer at 96 meters, the flow will be in the much more conductive Hanford formation.

8.0 INITIAL DISPOSAL FACILITY DATA

8.1 INTRODUCTION

An engineered disposal facility is needed in order for the disposal system to meet the performance objectives. Calculations in Mann 1995b show that a disposal system consisting of a glass waste form in soil will not meet the drinking water performance objectives. Instead, a disposal facility which diverts moisture from the waste form and contains materials by favorable chemical reactions is required.

For the base analysis case, disposal facility Concept 1 from Eiholzer 1995a will be used. Eiholzer 1995a presents two facility concepts. These concepts are based on a disposal vault enhanced with physical barriers to minimize water from entering the vault and with a chemical barrier to reduce glass corrosion. However, the concepts differ on how the features were implemented. Concept 1 will be used for the base analysis case because it was based on the leading vault disposal concept for the TWRS Process Design group (Eiholzer 1995a). The value of the different components of the disposal facility will be assessed by sensitivity cases. Selected aspects of disposal facility Concept 2 will be used for sensitivity studies.

The following subsections give the relevant features needed for modeling steps 2 and 3 (see Section 1). Eiholzer 1995a gives the details and explains the disposal facility and related physical barriers.

8.2 BASE ANALYSIS CASE

Concept 1 is a large concrete vault with two barriers and a water conditioning layer above it and with waste packages and filler material inside it. Figure 8-1 shows the disposal facility concept for the base analysis case. The vault portion is a reinforced Portland concrete structure that has walls, a floor, and a ceiling. The vault is divided into segments called vault bays. Six vault bays make a row. Concept 1 consists of 10 rows. Table 8-1 gives details on the vault bays and the general vault layout.

Above the overall vault is a surface barrier, a sand-gravel capillary barrier, and a water conditioning layer. These barriers and the water conditioning layer are continuous over the entire vault (see Figure 8-1). The top of the surface barrier is flush with the soil surface at an elevation of 221 meters above sea level. The surface barrier will determine the amount of recharge to the system. Between the surface barrier and the vault will be back-filled soil, a sand-gravel capillary barrier, and a water conditioning layer. The water conditioning layer is just above the roof of the vault. The sand-gravel capillary barrier is between the surface barrier and the water conditioning layer. Table 8-2 gives more details on the barriers and the water conditioning layer.

Table 8-1. Initial Disposal Design Facility Data -- Vault^a

Vault Bay	
1.	Made from reinforced Portland concrete
2.	Pad and roof are 0.76 m thick. Pad and roof are assumed to be level. The slope of 2 degrees for the Concept 2 floor is ignored.
3.	Bottom of vault pad is 20.75 m below grade, 200 meters above mean sea level.
4.	Interior walls are 1 m thick; external walls are 2 m thick. Interior height is 9 m.
5.	Interior vault space is 38 by 19.5 meters.
6.	Containers (Table 8-3) are stacked to 7.2 m high.
7.	Spacing between containers is 30 cm between short side of containers and 90 cm between long sides of containers. Spacing between containers and long wall is 45 cm. Spacing between containers and short wall is 55 cm. (Changed from Eiholzer 1995a.)
8.	Filler material is compacted back-filled soil.
Vault Layout	
1.	Six (6) vault bays are laid out forming a vault row so that short sides are next to each other.
2.	Concept 1 (base analysis case) <ul style="list-style-type: none"> a. Ten (10) vault rows are placed parallel to each other, having a common internal wall. Total width is 208 meters. (Changed from Eiholzer 1995a.)
3.	Concept 2 (sensitivity) <ul style="list-style-type: none"> a. Thirteen (13) vault rows are placed parallel to each other. (Changed from Eiholzer 1995a.) b. Vault rows are separated by 17.5 m, with walls on long side being exterior walls. Separations filled with soil. Total width of facility (vault rows plus separations) is 515.5 m.

a. Data from Eiholzer 1995a except where noted.

Three variations to Concept 1 as described in Eiholzer 1995a have been added to the base analysis case. A gravel capillary barrier is added along the sides (vertical walls) of the vault. This addition was due to favorable results shown in Mann 1995b. The material for the water conditioning layer is changed to crushed glass from silica sand. Comments from reviewers of Rawlins 1994 suggested that crushed glass would provide more silica to the moisture than silica sand. Finally, more rows were added to the disposal facility. The additional rows resulted from the change of container size used for the waste form (see paragraph below). The size of the containers changed from 8 x 2 x 2 m to 1.8 x 1.2 x 1.2 m. Three rows were added to Concept 1 and four rows were added to Concept 2. Tables 8-1 and 8-2 note these variations.

Table 8-2. Barriers and Water Conditioner Above Vault*

Surface Barrier	
1.	Top is at grade (elevation is 221 meters above mean sea level).
2.	Extends beyond waste disposal facility edge the same amount as does the sand-gravel capillary barrier.
3.	4.25 meters thick (1.0 m silt loam/admix gravel mix; 1.0 m silt loam; 0.2 m sand filter; 0.3 m gravel filter; 1.5 m fractured basalt riprap; 0.25 meter of compacted soil)
4.	Not explicitly modeled, treated as the determinant for recharge during the first 1000 years.
Sand-Gravel Capillary Barrier	
1.	Extends laterally 1 meter beyond edges of vault (Concept 1, base analysis case). Extends laterally 8.75 meters beyond sides of each vault row (Concept 2, sensitivity case).
2.	Gravel pyramid is on top of water conditioning layer. Height is determined by width and slope of pyramid [2° for Concept 1 (base analysis case), 5° for concept 2 (sensitivity case)], implying a height of 4 m for concept 1 and 2 m for concept 2.
3.	Sand layer above gravel and below surface barrier, minimum thickness is 1.0 meter.
4.	Total height is 6 meters for both Concepts 1 and 2.
5.	One (1) meter thick gravel wall (side capillary barrier) will be placed just outside of vertical concrete walls. This is an addition to facility concepts as described in Eiholzer 1995a.
Water Conditioning Layer	
1.	One (1) meter of crushed glass just above the vault roof (base analysis case). This is a variation to the facility concept as described in Eiholzer 1995a.
2.	Two (2) meters of back-filled soil (sensitivity study).

a. Data from Eiholzer 1995a except where noted.

The type of waste package to be used for the base analysis case is the TWRS Privatization waste package (USDOE 1995). The waste package consists of the waste form and the container. The waste form is assumed to be a cracked glass monolith with a specified corrosion rate. (Section 11 discusses the corrosion rate.) The conservative assumption that all crack surfaces are available to moisture will be used. The available surface area is estimated as the surface area of the monolith times 10 (Eiholzer 1995b). Also assumed is that the waste loading for the glass monolith is the same as for the glass in the waste package used to developed Concept 1 (Eiholzer 1995a). Thus, the expected amount of glass to be produced is 400,000 MT (based on an 25% waste loading).

The container used for the base analysis case has the external dimensions of 1.8(l) x 1.2 (w) x 1.2(h) meters. Details given in the draft TWRS Privatization specification will be used (USDOE 1995). The container material is assumed to have no effects on hydraulics or on chemical retardation. Table 8-3 gives information on the container and how the waste form fills the container.

Table 8-3. Initial Disposal Facility Data -- Container

Container	
1.	Exact details determined by TWRS Privatization Specifications (USDOE 1995)
2.	Carbon steel
3.	Approximate outside dimensions, 1.8 (l) x 1.2 (w) x 1.2 (h) meters
4.	stacking height - 7.2 meters (6 containers high)
5.	Top 1% of height is void. Rest is filled with waste glass (monolith).
6.	The glass monolith inside the container is assumed to be cracked. The estimated total surface area available for corrosion is 10 times the surface area of an uncracked monolith. (Eiholzer 1995b)

The waste packages will be placed in the vault as specified for Concept 1 (Eiholzer 1995a). Table 8-1 gives the spacing between waste packages in each vault bay. The base analysis case containers will be stacked 6 high or to 7.2 meters. The stacking height was based on having an even distribution of waste packages throughout the rows of the disposal facility. Compacted back-fill soil will be used as filler between and above the waste packages. The back-fill soil is assumed to have no chemical retardation effects.

8.3 SENSITIVITY CASES

There will be nine sensitivity cases related to the initial disposal facility. These sensitivity cases will determine the influence of specific disposal facility components.

Three sensitivity cases look at the effects of the sand-gravel capillary barrier. The first case looks at removing the side capillary barrier but keeping the large capillary barrier over the top of the vault. Concept 1 originally did not have a side capillary barrier (Eiholzer 1995a). For the second sensitivity case, there will be no capillary barriers above or beside the vault. The third sensitivity case related to capillary barriers examines the size of the barriers. For this case, the facility Concept 2 layout (Table 8-1) will be used since each vault row has its own sand-gravel capillary barrier (Eiholzer 1995a).

Two sensitivity cases focus on the effects of disposal components on moisture. The effect of the water conditioning layer on the silicon content in the moisture is examined by changing the material from crushed glass to back-filled soil. In the other sensitivity case, the back-filled soil is replaced with sand for the filler material within the disposal facility. The purpose of this sensitivity case is to see if one filler soil wicks moisture away from the waste packages better than another.

One sensitivity case examines the relationship between the facility orientation and the well intercept factor. The facility will be rotated 90° such that the longest dimension is perpendicular to the groundwater flow. Mann 1995b showed that the width of the facility perpendicular to the groundwater flow should be the longest side. This orientation affects the well intercept factor which relates contaminant concentration in the well to the contaminant concentration at the bottom of the vadose zone.

Two sensitivity cases focus on the impact of using a different waste form. In both cases, glass spheres with 1 cm diameters will be used. In the first case, the glass spheres are surrounded by intact sulfur polymer cement or some other potential Tc getter. The glass spheres and the sulfur polymer cement make a solid composite. The waste form volume is 70% glass spheres and 30% sulfur polymer cement. This waste form is being investigated because it has been the focus of two option papers (Rawlins 1994, Mann 1995b). The release rate from the glass will be given by the McGrail report on contamination release (see Section 11).

The other sensitivity case related to a waste form with glass spheres investigates the effects of using sand as a matrix material instead of sulfur polymer cement. Sand is used because it does not chemically interact with Tc released during the glass corrosion process. Sulfur polymer cement may interact with the released Tc. However, sulfur polymer cement may cause the local system to become acidic which enhances glass corrosion.

The last sensitivity case looks at the effects of a lower radionuclide concentration throughout the disposal facility. The radionuclide concentration will be decreased by a factor of 2. Many factors could reduce the radionuclide concentration within the facility. Some of these factors are:

- (1) More soil between stacks of containers
- (2) Decreased waste loading.
- (3) The use of a composite material such as a glass/matrix material composite.

Note that the radionuclide concentration for the base analysis case is based on:

- (1) The spacing of containers in each vault bay as given in Table 8.1,
- (2) A 25% waste loading,
- (3) The base analysis case inventory as given in Table 4.1, and
- (4) The container size and contents as given in Table 8.3.

9.0 DEGRADATION OF DISPOSAL FACILITY

9.1 INTRODUCTION

Engineered physical components of the disposal facility will degrade during the time frame of the performance assessment which is at least 10,000 years. When the components degrade, the performance of these components decreases from the initial design performance. The performance assessment needs to account for these changes.

9.2 BASE ANALYSIS CASE

For the base analysis case abrupt degradation occurs at 500 years. All concrete structures degrade to gravelly sand at 500 years. Five hundred years was chosen because of a Nuclear Regulatory Commission's draft branch technical position (USNRC 1994). The technical position suggests that one should assume that all engineered physical components are degraded by 500 years. All natural materials used as filler and in the capillary barrier are assumed not to degrade. The glass monolith will continually degrade based on the analysis presented in Section 11. Table 9-1 gives a summary of the base analysis case degradation of the disposal facility.

Table 9-1. Summary of Degradation of Disposal Facility

1.	Concrete walls, floors, ceilings degrade at 500 years to gravelly sand.
2.	Glass release rate is a function of time as described in Section 11.
3.	No degradation of natural materials (filler, capillary barrier).
4.	The container walls are assumed not to affect performance at any time.

9.3 SENSITIVITY CASES

Four sensitivity cases connected with the degradation of the disposal facility will be evaluated. For the first one, all the concrete is degraded (gravelly sand) at the time of facility closure. This calculation, when compared to the base analysis case, will indicate how important the concrete structure is to the system.

For the second sensitivity case, the concrete walls and ceiling are a gravelly sand at 500 years but the concrete floor does not degrade until 2000 years have passed. This sensitivity case is examining the "bathtub" effect. The bathtub effect is what occurs when there is standing water in the disposal facility.

The third sensitivity case is on the degradation of the capillary barrier. The material does not degrade. However, a portion of the barrier could drop due to subsidence of the disposal facility.

The fourth sensitivity case is related to the sensitivity case on the glass cullet with sulfur polymer cement waste form. In this case, the sulfur polymer cement degrades to sand at 500 years but retains its chemical properties. Again, the draft technical position is used (USNRC 1994) since how sulfur polymer cement degrades is not known.

10.0 HYDRAULIC PARAMETERS

10.1 INTRODUCTION

Hydraulic parameters describe how moisture flows through the vadose zone (the unsaturated region) and through the unconfined aquifer (the saturated region). Since contaminant transport in most cases is determined by moisture flow, these parameters are central to the analysis in steps 2 and 3 (see Section 1).

10.2 BASE ANALYSIS CASE

The hydraulic parameters to be used for the base analysis case are given in Tables 10-1 and 10-2. Table 10-1 shows the hydraulic parameters for the vadose zone and for construction materials. These values are from Khaleel and Freeman (Khaleel 1995) which also gives the justification for using these values. Values for the hydraulic parameters for degraded materials (sand and gravelly sand) shall be taken from the corresponding materials in the Hanford formation.

Table 10-2 gives the hydraulic parameters for the unconfined aquifer. These parameters were taken from the Hanford site-wide model (Law 1995). The discrepancy between the hydraulic properties for the saturated and unsaturated formations given in Tables 10-1 and 10-2 will be a subject of the data collection activities for the Preliminary Performance Assessment.

The diffusion constant for the vadose zone selected for the base analysis case is taken from the Grout Performance Assessment (Kincaid 1995),

$$D = 1.27 \times 10^{-7} \exp(-10 \theta), \text{ cm}^2/\text{s} \quad (1)$$

where θ is the volumetric moisture content.

Well intercept factors will be calculated at various locations from 50 meters downgradient from the disposal facility to the intercept of the plume with the Columbia River. Such locations will include 100 meters downgradient from the disposal facility and the boundary of the 200 East Area. At all locations the calculations will be done for a minimally pumped well and the position of the well in the aquifer will be positioned to intercept the largest concentration of contaminants.

Table 10-1. Hydraulic Parameters for Vadose Zone and for Construction Materials^a

Material	van Genuchten Curve Fitting Parameters for Moisture Retention				Saturated Hydraulic Conductivity (cm/s)
	$\Theta_s^{b,d}$	$\Theta_r^{c,d}$	$\alpha(\text{cm}^{-1})^d$	n^d	
Hanford formation sands	0.3578	0.0246	0.1566	2.1768	1.17×10^{-2}
Hanford formation gravelly sand	0.1312	0.0126	0.0125	1.530	1.32×10^{-3}
Ringold Formation	0.1342	0.022	0.0122	1.5865	8.74×10^{-5}
Back-filled soil	0.3710	0.0450	0.0683	2.080	3.00×10^{-2}
Gravel	0.5180	0.0140	3.5366	2.661	1.85
Portland Concrete	0.2258	0.0000	7.6×10^{-6}	1.393	3.75×10^{-10}
^a Data taken from Khaleel 1995 ^b The saturated volumetric moisture content. ^c The residual volumetric moisture content. ^d A van Genuchten curve fitting parameter.					

Table 10-2. Hydraulic Parameters for Unconfined Aquifer^a

Parameter	Value
Saturated hydraulic conductivity (cm/s)	
Ringold Formation	0.095
Hanford formation	3.6
Porosity	0.25
Ringold aquifer thickness (m)	20.

^a Taken from Law 1995

10.3 SENSITIVITY CASES

Three sets of sensitivity cases concerning hydraulic parameters are identified: one involving the moisture conductivity in the vadose zone, one involving diffusion in the vadose zone, and one involving flow in the aquifer.

The sensitivity cases involving moisture flow in the vadose zone will be conducted by varying the entire set of hydraulic parameters. Unsaturated hydraulic parameters are highly correlated because they are determined from fitting an equation to experimental data. Because the strong correlation among the van Genuchten curve fitting parameters is not known, it makes little sense to vary just one parameter.

Two sensitivity cases will be used to determine the importance of the hydraulic parameters of the vadose zone. The first sensitivity case considers that all of the Hanford formation is one sandy sequence. The second sensitivity case assumes that the gravelly sand sequence starts at 50 meters below the surface rather than at 66 meters.

The next sensitivity case investigates the importance of diffusion in the vadose zone by increasing the constant in the equation (equation 1) for the diffusion constant to 10^{-6} cm²/sec.

The effect of the hydraulic conductivity in the unconfined aquifer will be investigated by comparing the results of having the unconfined aquifer in the Ringold Formation (base analysis case) or in both the Ringold Formation and in the Hanford formation (see Section 7).

11.0 RADIONUCLIDE RELEASE FROM GLASS

11.1 INTRODUCTION

The radionuclide release rate from the waste form is the "source term" for the radionuclide transport calculations. This release rate depends on the waste form and the surrounding physical and chemical environments such as moisture content, pH, the oxygen potential, and the presence of key compounds such as silicic acid. The release rate is not a function of changing temperature of the waste form. Calculations show the temperature rise from the waste form in the disposal facility is less than 1°C. It is expected that the release rate will vary as a function of position in the disposal facility and a function of time.

At this time, the composition of the waste form and the physical and chemical environments are unknown. It is believed likely that at least one of the privatization vendors will use glass as the waste form. The physical and chemical environments will depend on the materials chosen and on the hydraulic and degradation properties of these materials.

11.2 BASE ANALYSIS CASE

For the base analysis case, the radionuclide release rate from the waste form will be based on the TWRS Privatization specifications (USDOE 1995). The specifications require that the initial fractional radionuclide release rate [FRRR(t=0)] from the waste form averaged over all the containers shall be no greater than

$$\text{FRRR} < 1.4 \times 10^{-11} \text{ s}^{-1} = 4.4 \text{ ppm/year,}$$

with the requirement for ^{99}Tc being five times stricter.

This limit was derived by assuming that the radionuclide release rate [RRR(t)] as a function of time is proportional to the rate of glass corrosion. By assuming that

- (1) the radionuclide release rate is proportional to the waste form corrosion rate and the inventory density at the surface,
- (2) the waste form corrosion rate is proportional to the instantaneous surface area,
- (3) in each waste form container, the radionuclide are uniformly spatially distributed, and
- (4) each linear dimension decreases at a constant rate.

The rate of radionuclides released can be calculated (see Appendix B) to be

$$RRR(t) = 3 * I * (T - t)^{-2} / T^3,$$

where I is the initial inventory, t is time since disposal facility closure, and T is the time for the waste form to release all of its radionuclides,

$$T = 3 / FRRR = 0.68 \text{ million years.}$$

The equations are summarized in Table 11-1.

Table 11-1. Relative Radionuclide Release Rate from the Waste Form for the Base Analysis Case

Relative Radionuclide Release Rate from the Waste Form
(ppm/year) =

$$4.4 * [T - \text{time}(\text{years})]^2 / T^3, \text{ where } T = 6.8 \times 10^5 \text{ years}$$

11.3 SENSITIVITY CASES

A sensitivity case will be performed where the radionuclide release rate from the waste form will be calculated in time and space using the latest available data on the corrosion of reference low-level glasses. The analysis will make use of the AREST-CT computer code (McGrail 1994) to calculate the time and spatial variation in the chemistry of water moving through the disposal system. This variation in water chemistry will affect the corrosion rate of the glass and the dissolution-precipitation reactions that may affect the solubility of each radionuclide. The corrosion rate of the glass will be evaluated using a reaction kinetics code that has been parameterized and calibrated against laboratory experiments with a low-level waste glass formulation. It is expected that additional sensitivity cases will be developed as the result of AREST-CT analyses.

The base analysis case assumes a (nearly) cubical shape for the waste form. Another sensitivity case will treat a very different geometric shape, as a thin plate. Using the TWRS Privatization Specifications, a thin plate would have a constant radionuclide release rate of 4.4 ppm/year of the initial inventory for 227,000 years.

Another sensitivity case is based on an alternative perspective of the TWRS privatization specification (USDOE 1995) for the release of Tc. Instead of assuming that the specification is met by allowing only 20% of the technetium inventory into the waste form, this sensitivity case assumes that the corrosion rate is reduced by a factor of 5. For this case, the fractional radionuclide release rate for ^{99}Tc is:

$$FRRR_{\text{Tc}}(t=0) = 2.8 \times 10^{-14} \text{ s}^{-1}.$$

The radionuclide release rate becomes

$$RRR_{Tc} \text{ (ppm/year)} = 0.88 * [T - \text{time}(\text{years})]^2 / T^3,$$

where $T = 3.4 \times 10^6$ years.

Another sensitivity case is based on various tests (McGrail 1995) run on LD6-5412 glass. These tests indicate that the forward rate (that is, the initial rate) of glass corrosion at 20 °C and pH = 9.5 is $6.1 \times 10^{-6} \text{ kg m}^{-2} \text{d}^{-1}$.

12.0 GEOCHEMICAL FACTORS

12.1 INTRODUCTION

Geochemical factors are important in any Hanford performance assessment because the thick vadose zone and the low moisture content allow chemical effects to be significant. Certain elements have their travel retarded according to the equation,

$$R = 1 + \rho K_d / \theta$$

where R is the retardation factor, ρ is the media bulk density, K_d is the chemical distribution coefficient, and θ is the volumetric moisture content. Because the contaminant transport is spread over a greater time, the peak contaminant concentration is also reduced by the factor R when the time associated with contaminant transport is longer than the time associated with contaminant release from the waste form.

12.2 BASE ANALYSIS CASE

For the base analysis case, the effects of chemical interactions in the disposal facility are only calculated for the water conditioning layer and in the release of the contaminants from the waste form. That is, no further credit is taken for chemical retardation in the disposal facility.

The chemical distribution coefficients (or K_d parameters) in the vadose zone and in the unconfined aquifer for the base analysis case are based on 1995 PNL studies (Kaplan 1995a and Kaplan 1995b). In particular, Kaplan and Serne (Kaplan 1995b) carefully reviewed all available Hanford data for the five most important elements (iodine, neptunium, selenium, technetium, and uranium).

In this analysis, instead of treating the chemical distribution coefficients as probability functions, point-estimate values are used. The PORFLOW computer code calculates the contaminant transport for only 4 K_d values at a time. Thus to reduce the number of computer simulations made, only a limited number of values are used for the distribution coefficients. Based on past experience, the most important elements in the analysis will be technetium and selenium (both having $K_d = 0$), uranium ($K_d = 0.6$ ml/g), iodine ($K_d = 3$ ml/g), carbon ($K_d = 6$), and neptunium ($K_d = 15$ ml/g). Two higher K_d values (40 and 100 ml/g) were chosen to represent more retarded elements with the knowledge that elements with such high K_d values have very little significance in Hanford vadose zone transport. The values used for the chemical distribution coefficients for the less important elements in the computer simulations are selected to be conservative [that is, the values used in the computer simulation are lower than the recommended values (Kaplan 1995)]. Table 12-1 shows the chemical distribution coefficients to be used in the

base analysis case.

Table 12-1. Chemical Distribution Coefficients (K_d) for Base Analysis Case^a

Element	K_d (ml/g)	Element	K_d (ml/g)	Element	K_d (ml/g)
Ac	67 -> 40	Am	67 -> 40	C	6
Ce	100	Cm	106 ->100	Co	1200 ->100
Cs	540 ->100	Eu	100	I	3 ^b
Nb	50 -> 40	Ni	50 -> 40	Np	15 ^b
Pa	10 -> 6	Pb	13000 ->100	Pu	80 -> 40
Ra	24 -> 15	Se	0 ^b	Sn	100
Sr	5 -> 3	Tc	0 ^b	Th	40
U	0.6 ^b	Zr	90 -> 40	others	0

- a The number to the left of the arrow is the best estimate of the K_d value, the number to the right of the arrow is a conservative estimate to minimize the number of calculations
- b Data taken from Kaplan 1995b, others from Kaplan 1995a.

12.3 SENSITIVITY CASES

Sensitivity cases will be used to judge the effects of different K_d values. In many previous environmental assessments, the value of the uranium K_d has been taken to be zero. Two sensitivity cases will be performed with a zero K_d for uranium, one where the zero K_d is used everywhere, and one where the zero value is used everywhere except in the concrete walls (where the value is taken to be 100 ml/g [Kaplan 1995b]). In addition, a sensitivity calculation with the K_d of the major mobile radioelements (Se and Tc) set to 0.1 ml/g will be made. This calculation will show how a little retardation could affect the results.

Given the base analysis case and the sensitivity cases, 8 values of the chemical distribution coefficient will be used in contaminant transport calculations (0.0, 0.1, 0.6, 3., 6., 15., 40, and 100 ml/g).

13.0 DOSIMETRY DATA

Dosimetry data allow the translation of radionuclide concentrations in air and water into dose exposure rates.

The dosimetry data for the Interim Performance Assessment come from Rittmann 1995. Table 13-1 provides the conversion factors from water concentrations into drinking water doses. It is assumed that a person drinks two liters of water per day. Table 13-2 provides the conversion into all-pathway dose. Table 13-3 provides the conversion from waste concentration in the disposal facility into driller intrusion dose rates, while Table 13-4 provides the conversion into the homesteader intrusion dose rates.

The sensitivity cases will evolve around using different dose conversion factors (see Rittmann 1995 for alternative values). Also, sensitivity cases will be run for different intrusion scenario variables: the well diameter and garden size (Section 3).

Table 13-1. Drinking Water Scenario Dose Factors^{a,b}
mrem/y per pCi/L

Nuclide	Drinking Water Dose Factor (mrem/y per pCi/L)	Nuclide	Drinking Water Dose Factor (mrem/y per pCi/L)
H-3	4.60E-05	Eu-155	9.49E-04
Be-10	3.07E-03	Gd-152	1.10E-01
C-14	1.53E-03	Ho-166m	5.69E-03
Na-22	8.76E-03	Re-187	6.06E-06
Cl-36	2.19E-03	Tl-204	2.34E-03
K-40	1.39E-02	Pb-210+D	4.92E+00
Mn-54	1.97E-03	Bi-207	3.58E-03
Fe-55	4.23E-04	Po-209	1.46E+00
Co-60	1.90E-02	Ra-226+D	8.04E-01
Ni-59	1.46E-04	Ra-228+D	8.77E-01
Ni-63	3.94E-04	Ac-227+D	1.07E+01
Se-79	6.06E-03	Th-228+D	5.50E-01
Rb-87	3.50E-03	Th-229+D	2.85E+00
Sr-90+D	1.02E-01	Th-230	3.87E-01
Zr-93	1.17E-03	Th-232	2.04E+00
Nb-93m	3.87E-04	Pa-231	8.03E+00

Nuclide	Drinking Water Dose Factor (mrem/y per pCi/L)	Nuclide	Drinking Water Dose Factor (mrem/y per pCi/L)
Nb-94	3.72E-03	U-232	9.49E-01
Mo-93	9.49E-04	U-233	1.97E-01
Tc-99	9.49E-04	U-234	1.90E-01
Ru-106+D	1.53E-02	U-235+D	1.83E-01
Pd-107	1.02E-04	U-236	1.83E-01
Ag-108m+D	5.48E-03	U-238+D	1.77E-01
Cd-109	8.76E-03	Np-237+D	2.85E+00
Cd-113m	1.10E-01	Pu-236	9.49E-01
In-115	1.02E-01	Pu-238	2.77E+00
Sn-121m+D	1.45E-03	Pu-239	3.14E+00
Sn-126+D	1.34E-02	Pu-240	3.14E+00
Sb-125+D	2.51E-03	Pu-241+D	6.28E-02
I-129	2.04E-01	Pu-242	2.99E+00
Cs-134	5.40E-02	Pu-244+D	2.92E+00
Cs-135	5.18E-03	Am-241	3.29E+00
Cs-137+D	3.65E-02	Am-242m+D	3.13E+00
Ba-133	2.34E-03	Am-243+D	3.29E+00
Pm-147	6.94E-04	Cm-243	2.12E+00
Sm-147	1.31E-01	Cm-244	1.68E+00
Sm-151	2.48E-04	Cm-245	3.29E+00
Eu-150	4.53E-03	Cm-246	3.29E+00
Eu-152	4.38E-03	Cm-247+D	2.99E+00
Eu-154	6.64E-03	Cm-248	1.17E+01

a Taken from Rittmann 1995

b Nuclides with the "+D" added to the name include the contributions from short-lived progeny, which are assumed to be in equilibrium at all times.

Table 13-2. All-Pathway Water Dose Factors^{a,b}
mrem/yr per pCi/l

Nuclide	All-Pathway Dose Factor (mrem/y per pCi/L)	Nuclide	All-Pathway Dose Factor (mrem/y per pCi/L)
H-3	5.30E-05	Eu-155	1.36E-03
Be-10	3.41E-03	Gd-152	1.28E-01
C-14	1.79E-03	Ho-166m	1.85E-02
Na-22	5.71E-02	Re-187	8.56E-06
Cl-36	3.40E-02	Tl-204	4.95E-03
K-40	3.06E-02	Pb-210+D	5.50E+00
Mn-54	6.48E-03	Bi-207	1.44E-02
Fe-55	6.57E-04	Po-209	1.69E+00
Co-60	4.84E-02	Ra-226+D	9.20E-01
Ni-59	1.90E-04	Ra-228+D	9.98E-01
Ni-63	5.13E-04	Ac-227+D	1.16E+01
Se-79	1.09E-02	Th-228+D	6.08E-01
Rb-87	7.75E-03	Th-229+D	3.11E+00
Sr-90+D	1.26E-01	Th-230	4.22E-01
Zr-93	1.42E-03	Th-232	2.23E+00
Nb-93m	3.15E-03	Pa-231	8.75E+00
Nb-94	4.12E-02	U-232	1.09E+00
Mo-93	1.28E-03	U-233	2.26E-01
Tc-99	3.12E-03	U-234	2.18E-01
Ru-106+D	1.85E-02	U-235+D	2.12E-01
Pd-107	1.99E-04	U-236	2.10E-01
Ag-108m+D	2.57E-02	U-238+D	2.04E-01
Cd-109	1.04E-02	Np-237+D	3.11E+00
Cd-113m	1.30E-01	Pu-236	1.03E+00
In-115	1.31E-01	Pu-238	3.02E+00
Sn-121m+D	4.28E-03	Pu-239	3.42E+00
Sn-126+D	5.29E-02	Pu-240	3.42E+00
Sb-125+D	5.52E-03	Pu-241+D	6.84E-02
I-129	4.13E-01	Pu-242	3.26E+00

Nuclide	All-Pathway Dose Factor (mrem/y per pCi/L)	Nuclide	All-Pathway Dose Factor (mrem/y per pCi/L)
Cs-134	1.22E-01	Pu-244+D	3.18E+00
Cs-135	1.09E-02	Am-241	3.58E+00
Cs-137+D	8.02E-02	Am-242m+D	3.41E+00
Ba-133	4.93E-03	Am-243+D	3.58E+00
Pm-147	8.31E-04	Cm-243	2.31E+00
Sm-147	1.58E-01	Cm-244	1.83E+00
Sm-151	2.98E-04	Cm-245	3.58E+00
Eu-150	1.54E-02	Cm-246	3.58E+00
Eu-152	1.28E-02	Cm-247+D	3.27E+00
Eu-154	1.61E-02	Cm-248	1.27E+01

a Taken from Rittmann 1995

b Nuclides with the "+D" added to the name include the contributions from short-lived progeny, which are assumed to be in equilibrium at all times.

Table 13-3. Driller Intrusion Dose Factors^{a,b}
mrem/yr per Ci/m³

Nuclide	Drilling Dose Factor (mrem/y per Ci/m ³)	Nuclide	Drilling Dose Factor (mrem/y per Ci/m ³)
H-3	3.63E-03	Eu-155	2.08E+01
Be-10	2.16E-01	Gd-152	3.08E+01
C-14	2.82E-02	Ho-166m	1.04E+03
Na-22	1.34E+03	Re-187	1.10E-04
Cl-36	3.00E-01	Tl-204	4.98E-01
K-40	9.75E+01	Pb-210+D	8.79E+01
Mn-54	5.11E+02	Bi-207	9.24E+02
Fe-55	7.60E-03	Po-209	2.84E+01
Co-60	1.54E+03	Ra-226+D	1.09E+03
Ni-59	2.67E-03	Ra-228+D	5.84E+02
Ni-63	7.15E-03	Ac-227+D	1.21E+03
Se-79	1.07E-01	Th-228+D	9.90E+02
Rb-87	7.67E-02	Th-229+D	4.61E+02
Sr-90+D	4.42E+00	Th-230	4.54E+01
Zr-93	5.87E-02	Th-232	2.28E+02
Nb-93m	2.19E-02	Pa-231	3.16E+02
Nb-94	9.65E+02	U-232	9.73E+01
Mo-93	8.70E-02	U-233	1.92E+01
Tc-99	3.15E-02	U-234	1.90E+01
Ru-106+D	1.31E+02	U-235+D	1.02E+02
Pd-107	3.33E-03	U-236	1.76E+01
Ag-108m+D	9.83E+02	U-238+D	3.11E+01
Cd-109	1.84E+00	Np-237+D	2.27E+02
Cd-113m	2.13E+00	Pu-236	3.57E+01
In-115	2.21E+00	Pu-238	1.03E+02
Sn-121m+D	2.67E-01	Pu-239	1.16E+02
Sn-126+D	1.20E+03	Pu-240	1.16E+02
Sb-125+D	2.52E+02	Pu-241+D	2.29E+00
I-129	5.02E+00	Pu-242	1.09E+02

Nuclide	Drilling Dose Factor (mrem/y per Ci/m ³)	Nuclide	Drilling Dose Factor (mrem/y per Ci/m ³)
Cs-134	9.53E+02	Pu-244+D	3.12E+02
Cs-135	9.41E-02	Am-241	1.24E+02
Cs-137+D	3.45E+02	Am-242m+D	1.23E+02
Ba-133	2.10E+02	Am-243+D	2.19E+02
Pm-147	2.17E-02	Cm-243	1.43E+02
Sm-147	1.08E+01	Cm-244	6.15E+01
Sm-151	7.88E-03	Cm-245	1.60E+02
Eu-150	8.90E+02	Cm-246	1.22E+02
Eu-152	6.86E+02	Cm-247+D	3.07E+02
Eu-154	7.50E+02	Cm-248	4.30E+02

a Taken from Rittmann 1995

b Nuclides with the "+D" added to the name include the contributions from short-lived progeny, which are assumed to be in equilibrium at all times.

Table 13-4. Homesteader Intrusion Dose Factors^{a,b}
mrem/Y per Ci/m³

Nuclide	External (mrem/Y per Ci/m ³)	Internal (mrem/Y per Ci/m ³)			Total (mrem/Y per Ci/m ³)
		Inhalation	Soil Ingestion	Vegetables	
H-3	0.0	4.00E-4	5.93E-4	2.85E-1	3.26E-1
Be-10	5.43E-1	1.02E+0	7.71E-1	1.67E+0	4.00E+0
C-14	6.73E-3	5.95E-3	3.76E-1	1.63E+2	1.64E+2
Na-22	5.30E+3	2.04E-2	1.93E+0	7.15E+1	5.37E+3
Cl-36	1.07E+0	5.32E-2	5.05E-1	2.23E+4	2.23E+4
K-40	4.34E+2	3.45E-2	3.46E+0	1.19E+3	1.63E+3
Mn-54	1.57E+3	1.27E-2	3.39E-1	6.14E+1	1.63E+3
Fe-55	0.0	6.65E-3	9.38E-2	1.79E-1	2.79E-1
Co-60	6.49E+3	4.07E-1	4.46E+0	3.59E+1	6.53E+3
Ni-59	0.0	3.77E-3	3.67E-2	9.68E-1	1.01E+0
Ni-63	0.0	8.68E-3	9.88E-2	2.61E+0	2.72E+0
Se-79	9.53E-3	2.58E-2	1.52E+0	2.51E+1	2.67E+1
Rb-87	7.18E-2	9.55E-3	8.78E-1	3.95E+1	4.04E+1
St-90+D	1.16E+1	6.74E-1	2.51E+1	4.11E+3	4.15E+3
Zr-93	1.25E-3	9.31E-1	2.96E-1	4.42E-1	1.67E+0
Nb-93m	5.21E-2	7.93E-2	9.49E-2	4.20E-1	5.95E-1
Nb-94	4.34E+3	9.57E-1	9.35E-1	4.10E+0	5.99E+0
Mo-93	2.99E-1	8.19E-2	2.37E-1	9.43E+0	9.75E+0
Tc-99	3.80E-2	1.29E-2	1.41E-1	1.58E+2	1.58E+2

Nuclide	External (mrem/y per Ci/m ³)	Internal (mrem/y per Ci/m ³)				Total (mrem/y per Ci/m ³)
		Inhalation	Soil Ingestion	Vegetables	Subtotal	
Ru-106+D	4.25E+2	9.22E-1	2.78E+0	3.65E+1	4.02E+1	4.65E+2
Pd-107	0.0	3.76E-2	2.56E-2	6.88E-1	7.51E-01	7.51E-1
Ag-108m+D	4.40E+3	5.78E-1	1.37E+0	6.51E+1	6.71E+1	4.47E+3
Cd-109	5.80E+0	2.23E-1	1.69E+0	1.82E+2	1.84E+2	1.90E+2
Cd-113m	3.18E-1	3.95E+0	2.67E+1	2.63E+3	2.66E+3	2.66E+3
In-115	2.03E-1	9.87E+0	2.57E+1	3.72E+1	7.27E+1	7.29E+1
Sn-121m+D	1.07E+0	2.67E-2	3.63E-1	1.85E+0	2.24E+0	3.32E+0
Sn-126+D	5.41E+3	2.19E-1	3.36E+0	1.71E+1	2.07E+1	5.43E+3
Sb-125+D	9.98E+2	2.93E-2	5.56E-1	7.45E+0	8.03E+0	1.01E+3
I-129	5.79E+0	4.56E-1	4.48E+1	1.49E+3	1.54E+3	1.54E+3
Cs-134	3.64E+3	1.16E-1	1.15E+1	3.64E+2	3.75E+2	4.01E+3
Cs-135	1.96E-2	1.31E-2	1.30E+0	3.85E+1	3.98E+1	3.98E+1
Cs-137+D	1.53E+3	9.18E-2	9.07E+0	2.69E+2	2.78E+2	1.81E+3
Ba-133	9.13E+2	1.93E-2	5.67E-1	6.75E+0	7.33E+0	9.20E+2
Pm-147	2.25E-2	8.67E-2	1.53E-1	5.94E-1	8.34E-1	8.56E-1
Sm-147	0.0	2.06E+2	3.30E+1	1.22E+2	3.61E+2	3.61E+2
Sm-151	5.03E-4	8.38E-2	6.21E-2	2.29E-1	3.75E-1	3.76E-1
Eu-150	3.96E+3	7.76E-1	1.13E+0	4.16E+0	6.06E+0	3.97E+3
Eu-152	3.01E+3	6.23E-1	1.07E+0	3.99E+0	5.69E+0	3.01E+3
Eu-154	3.24E+3	7.26E-1	1.61E+0	6.00E+0	8.34E+0	3.25E+3
Eu-155	8.71E+1	1.06E-1	2.23E-1	8.43E-1	1.17E+0	8.83E+1

Nuclide	External (mrem/y per Ci/m ³)	Internal (mrem/y per Ci/m ³)				Total (mrem/y per Ci/m ³)
		Inhalation	Soil Ingestion	Vegetables	Subtotal	
Gd-152	0.0	6.97E+2	2.75E+1	1.01E+2	8.25E+2	8.25E+2
Ho-166m	4.69E+3	2.09E+0	1.43E+0	5.26E+0	8.78E+0	4.70E+3
Re-187	0.0	1.41E-4	1.51E-3	3.44E-1	3.46E-1	3.46E-1
Tl-204	1.88E+0	6.10E-3	5.37E-1	8.05E-1	1.35E+0	3.23E+0
Pb-210+D	3.01E+0	6.13E+1	1.22E+3	5.05E+3	6.32E+3	6.33E+3
Bi-207	4.11E+3	4.02E-2	8.89E-1	4.05E+0	4.98E+0	4.11E+3
Po-209	8.86E+0	2.90E+1	3.66E+2	8.25E+2	1.22E+3	1.23E+3
Ra-226+D	4.83E+3	2.39E+1	2.21E+2	6.64E+2	9.09E+2	5.74E+3
Ra-228+D	3.07E+3	1.53E+2	2.29E+2	6.74E+2	1.06E+3	4.12E+3
Ac-227+D	9.56E+2	1.92E+4	2.64E+3	3.74E+3	2.56E+4	2.65E+4
Th-228+D	3.56E+3	7.63E+2	1.16E+2	1.57E+2	1.04E+3	4.60E+3
Th-229+D	7.57E+2	5.86E+3	7.17E+2	9.05E+2	7.48E+3	8.24E+3
Th-230	1.66E+0	9.29E+2	9.73E+1	1.23E+2	1.15E+3	1.15E+3
Th-232	1.76E+2	4.65E+3	5.28E+2	6.71E+2	5.85E+3	6.03E+3
Pa-231	1.07E+2	4.08E+3	2.06E+3	2.74E+3	8.88E+3	8.99E+3
U-232	6.76E+2	2.06E+3	2.57E+2	8.38E+2	3.16E+3	3.83E+3
U-233	7.22E-1	3.74E+2	4.91E+1	1.70E+2	5.93E+2	5.94E+2
U-234	2.03E-1	3.73E+2	4.72E+1	1.64E+2	5.84E+2	5.85E+2
U-235+D	3.74E+2	3.45E+2	4.57E+1	1.58E+2	5.49E+2	9.22E+2
U-236	1.08E-1	3.45E+2	4.54E+1	1.57E+2	5.48E+2	5.48E+2
U-238+D	6.02E+1	3.45E+2	4.41E+1	1.53E+2	5.42E+2	6.02E+2

Nuclide	External (mrem/y per Ci/m ³)	Internal (mrem/y per Ci/m ³)			Total (mrem/y per Ci/m ³)
		Inhalation	Soil Ingestion	Vegetables	
Np-237+D	5.17E+2	1.38E+3	6.94E+2	2.74E+3	4.81E+3
Pu-236	2.21E+0	4.21E+2	2.13E+2	2.69E+2	9.04E+2
Pu-238	7.70E-2	1.33E+3	6.95E+2	8.36E+2	2.86E+3
Pu-239	1.46E-1	1.48E+3	7.89E+2	9.48E+2	3.22E+3
Pu-240	7.51E-2	1.48E+3	7.89E+2	9.48E+2	3.22E+3
Pu-241+D	2.70E-2	2.95E+1	1.61E+1	1.92E+1	6.48E+1
Pu-242	6.56E-2	1.39E+3	7.53E+2	9.04E+2	3.05E+3
Pu-244+D	9.15E+2	1.39E+3	7.35E+2	8.83E+2	3.01E+3
Am-241	2.24E+1	1.51E+3	8.25E+2	1.03E+3	3.37E+3
Am-242m+D	3.35E+1	1.48E+3	7.88E+2	9.84E+2	3.25E+3
Am-243+D	4.46E+2	1.51E+3	8.27E+2	1.03E+3	3.37E+3
Cm-243	2.86E+2	1.00E+3	5.26E+2	6.35E+2	2.16E+3
Cm-244	6.34E-02	7.69E+2	4.14E+2	5.01E+2	1.69E+3
Cm-245	1.72E+2	1.57E+3	8.26E+2	9.92E+2	3.39E+3
Cm-246	5.96E-02	1.57E+3	8.26E+2	9.92E+2	3.39E+3
Cm-247+D	8.83E+2	1.42E+3	7.53E+2	9.04E+2	3.08E+3
Cm-248	4.50E-02	5.52E+3	2.94E+3	3.53E+3	1.20E+4

a Taken from Rittmann 1995

b Nuclides with the "+D" added to the name include the contributions from short-lived progeny, which are assumed to be in equilibrium at all times.

14.0 CALCULATIONAL ASSUMPTIONS

14.1 BASE ANALYSIS CASE

A number of calculational assumptions are needed for the analysis. For the base analysis case, values for dispersion and initial volumetric moisture content are assumed. These values are shown in Table 14-1.

Another calculational assumption is the grid size used in the models. The grid size has not yet been determined for the vadose zone, but is expected to be similar to that of Kline 1995 and work supporting Mann 1995b. Computers models at the scale of the disposal facility and at the scale of a container will be created. The grid size for the unconfined aquifer is specified in the Hanford site-wide model (Law 1995). Calculations for the base analysis case will be based on steady state flow simulations and transient simulation of contaminant transport.

Table 14-1. Calculational Assumptions

Parameter	Value
Dispersion	
Parallel to flow	0.1 * Length of travel
Perpendicular to flow	0.01 * Length of travel
Initial Volumetric Moisture Content	
Disposal facility	0.1
Vadose zone	Determined by initial recharge rate

14.2 SENSITIVITY CASES

Sensitivity cases will test these assumptions. One case will be a fully transient calculation for the disposal facility and for the vadose zone. Another will investigate the effect of doubling the number of grid points. Two cases will look at the effect of dispersion. One case assumes half of the base analysis case dispersion, and the other by doubles the dispersion coefficient. Finally, the dependence on the initial volumetric moisture content in the disposal facility will be determined in two cases, assuming the initial volumetric moisture content is at the residual value and assuming the initial volumetric moisture content is at 0.2.

15.0 INTERACTION WITH OTHER FACILITIES

Recommendation 94-2 of the Defense Nuclear Facility Safety Board (DNFSB 1994) requires that the effect of previous disposal activities of the Department of Energy be considered. The Hanford site-wide model (Law 1995) will be used to determine the impact of the S, SX, and SY Tank and the Environmental Restoration Disposal Facility (ERDF) on this disposal action. The inventories and other parameters will be taken from the ERDF performance assessment (Wood 1995). The work by Wood et al. assumes that 99% of the waste from the tanks would be removed. Based on the projected groundwater flow path, these are the activities that will have the most impact on the current disposal action. All other activities will be not be evaluated until shown to be warranted.

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APPENDIX A SENSITIVITY CASES (47)

Except as noted below, sensitivity cases will vary only one parameter at a time. More complex sensitivity cases await better definition of the waste form and disposal facility.

Section	Sensitivity Case
Scenario	Irrigated farming over the disposal facility, implying a recharge rate = 100 mm/year forever.
Scenario	Assume irrigation in all areas except 200 areas and region between 200 East and 200 West Areas, calculate the effect at 100 meters downgradient from disposal facility.
Scenario	Assume irrigation only north of 200 areas, calculate the effect at 100 meters downgradient from disposal facility.
Scenario	Assume irrigation only west of 200 West area, calculate the effect at 100 meters downgradient from disposal facility.
Scenario	Assume industry in 200 areas (reduced recharge in 200 Areas by a factor of 2), calculate at 100 meters downgradient.
Scenario	Assume different pumping rates at a well 100 meters downgradient from the disposal facility at a well on the 200 East Area eastern boundary.
Scenario	Assume well at different locations, ranging from 50 meters downgradient from the disposal facility to the Columbia River. Include a well at the eastern boundary of the 200 East Area.
Scenario	Assume different parameters for intrusion scenario (garden size, diameter of well).
Scenario	Treat natural events, such as glacier flooding.
Inventory	Changes in inventory caused by TWRS Privatization Effort. In particular, 80% reduction of ⁹⁹ Tc inventory.
Inventory	Changes in inventory caused by petition to NRC. In particular, increase of ¹³⁷ Cs to 5x10 ⁶ Ci.
Inventory	Treatment of non-homogeneous spatial distribution of contaminants in the disposal facility.
Recharge	Recharge rate = 3.0 mm/year forever.
Recharge	Recharge rate = 1.0 mm/year forever.
Recharge	Recharge rate = 0.1 mm/year forever (also output results at the top of model to determine upward diffusion and upward capillary flow).

Section	Sensitivity Case
Geology	Top of unconfined aquifer is at 96 meters below the surface.
Geology	Top of unconfined aquifer is at 110 meters below the surface.
Facility	No side capillary barrier.
Facility	No capillary barrier.
Facility	Shorter capillary barrier (Concept 2 layout).
Facility	Water-conditioning layer replaced with back-filled soil.
Facility	Sand used as filler.
Facility	Rotate the disposal facility by 90° (with the longest dimension perpendicular to the groundwater flow).
Facility	Waste form is glass spheres with a diameter of 1 cm surrounded by a matrix of sulfur polymer cement (waste form volume: 70% glass spheres, and 30% sulfur polymer cement).
Facility	Sand used as matrix material inside container.
Facility	Reduce radionuclide density in waste form by a factor of 2, increase the number of vault rows by a factor of 2.
Degradation	Concrete degrades at 0 years.
Degradation	Concrete walls and ceiling degrade at 500 years, floor degrades at 2000 years.
Degradation	Degraded capillary barrier. (The degradation point is at $2/3 \times 1$ from the apex of the barrier where 1 is half the width of the barrier.)
Degradation	Sulfur polymer cement degrades to sand at 500 years but retains chemical properties.
Hydraulics	Change hydraulic parameters in vadose zone so that the entire zone has parameters corresponding to the Hanford formation sandy sequence.
Hydraulics	Change hydraulic parameters in vadose zone so that the bottom half of the zone has parameters corresponding to the Hanford formation gravelly sand sequence.
Hydraulics	Change diffusion constant to 10^{-6} cm ² /sec
Release Rate	Contaminant release rate from glass as specified by McGrail 1996 report.

Section	Sensitivity Case
Release Rate	Waste form has the geometry of a thin plate, implying a constant radionuclide release rate.
Release Rate	Contaminant release rate reduced by 5.
Release Rate	Contaminant release rate taken as the forward rate of glass corrosion.
Geochemical	For uranium: $K_d = 0$.
Geochemical	For uranium: $K_d = 0$ in vadose zone; $= 100$ ml/g in concrete.
Geochemical	For major elements (Se and Tc) : $K_d = 0.1$ ml/g.
Exposure	Different dose factor sets.
Calculational	Transient calculation for flow simulation.
Calculational	Double number of grid points.
Calculational	Halved dispersion.
Calculational	Twice dispersion.
Calculational	Initial volumetric moisture content in the disposal facility = residual moisture content of material.
Calculational	Initial volumetric moisture content in disposal facility = 20%.

APPENDIX B RADIONUCLIDE RELEASE RATE DERIVATION

The radionuclide release rate [RRR(t)] as a function of time t can be calculated based on a set of assumptions:

- (1) the radionuclide release rate is proportional to the waste form corrosion rate [WFCR(t)] and the inventory density at the surface [ID_{sur}],
- (2) the waste form corrosion rate is proportional to the instantaneous surface area [S(t)],
- (3) in each waste form container, the radionuclides are uniformly spatially distributed [that is I(t)/V(t) = constant, where I is the inventory left in the container and V is the instantaneous volume], and
- (4) each linear dimension decreases at a constant rate.

Using the first three assumptions and use k_i's as constants,

$$\begin{aligned} \text{RRR}(t) &= k_1 \text{WFCR}(t) * \text{ID}_{\text{sur}} \\ &= k_1 * [k_2 * S(t)] * [k_3 * I(t) / V(t)] \\ &= k_4 * I(t) * S(t) / V(t) \end{aligned} \quad 1)$$

Equation 1 forms the basis of the TWRS Privatization specifications (USDOE 1995). Assumption 3 also applies at the initial time (t = 0), so

$$I(t) / V(t) = I(0) / V(0).$$

Thus

$$\text{RRR}(t) = k_4 * I(0) * S(t) / V(0). \quad 2)$$

Along with assumption 4, the shape of the waste form determines the time dependence of the surface area. If the waste form is cubical or spherical in shape, then the surface area becomes

$$\begin{aligned} S(t) &= k_5 * x(t)^2 = k_5 * [k_6 * (T - t)]^2 \\ &= k_7 * (T - t)^2, \end{aligned} \quad 3)$$

where x is the time-dependent length or radius and T is the time for the waste form to release all its radionuclides. Combining equations 2 and 3, the radionuclide release rate for a cubical or spherical waste form becomes

$$\begin{aligned} \text{RRR}(t) &= k_4 * k_7 * I(0) * (T - t)^2 / V(0) \\ &= k_8 * I(0) * (T - t)^2. \end{aligned} \quad 4)$$

The constant k₇ can be determined by noting that the time integral of the radionuclide release rate from 0 to T is the total inventory, I(0). Thus

$$k_8 = 3 / T^3.$$

Substituting the value of k_8 into equation 4, the radionuclide release rate becomes

$$RRR(t) = 3 * I(0) * (T - t)^2 / T^3. \quad 5)$$

The value of T can be calculated by noting that the value of $RRR(0)/I(0)$ is given in the TWRS Privatization specification (USDOE 1995) as the "fractional radionuclide release rate" $[FRRR(0)]$. That is

$$T = 3 * I(0) / [RRR(0)] = 3 / FRRR(0). \quad 6)$$

Equations 5 and 6 are used in the base analysis case description.

It is expected that the waste form will be nearly cubical as the containers are 1.2 meters by 1.2 meters by 1.8 meters. However, other shapes are possible. If the shape of the waste form is more like a long cylinder, then the surface area as a function of time becomes

$$S_{cylinder}(t) = k_4 * r(t) * h(t) + k'_4 * r(t)^2,$$

where $r(t)$ is the time-dependent radius and $h(t)$ is the time-dependent height of the cylinder. Note since $h(0)$ is assumed to be much greater than $r(0)$, the second term is much smaller than the first term. In addition, h remains nearly constant [since $h(T) = h(0) - r(0)$, but $h(0) \gg r(0)$]. Thus the equivalent of equation 3 becomes

$$S_{cylinder}(t) = k_6 * (T - t) \quad 3')$$

and the equivalents of equation 5 and 6 become

$$RRR(t) = 2 * I(0) * (T - t) / T^2 \quad 5')$$

and

$$T = 2 / FRRR. \quad 6')$$

If the shape of the waste form is more like a thin plate, then the surface area as a function of time becomes

$$S_{plate}(t) = k_4 * a(t) * b(t) + k'_4 * b(t) * c(t) + k''_4 * a(t) * c(t),$$

where $a(t)$, $b(t)$, and $c(t)$ are the time-dependent plate dimensions. In this case $a(0)$ and $b(0)$ are assumed to be much greater than $c(0)$. Thus the second and third terms are much smaller than the first term and a and b remain nearly constant as a function of time. Thus the equivalent of equation 3 becomes

$$S_{plate}(t) = k_6 \quad 3'')$$

and the equivalents of equation 5 and 6 become

$$RRR(t) = I(0) / T \quad 5'')$$

and

$$T = 1 / FRRR. \quad 6'')$$

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