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Technical Assistance for Regulatory Development:
A Simplified Repository Analysis in a Hypothetical Bedded Salt Formation

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I. Introduction

Background

The Environmental Protection Agency (EPA) has drafted a standard for protection against highly radioactive wastes to be stored underground. The standard, which will apply to all geologic repositories, is still being developed and an internal working draft is available [1]. The Nuclear Regulatory Commission (NRC) will enforce the standard, and is developing appropriate Federal regulations [2].

To assign quantitative, that is, numerical values to such factors as release of radionuclides from a geologic repository, the EPA used simple computer models [3]. The agency expects the NRC to use computer modeling to assess compliance with the EPA standard. To support NRC, Sandia National Laboratories (SNL) is developing computer models that may be used in such a compliance assessment [4]. We expect that NRC will use the models to evaluate applications to construct actual repositories.

The Department of Energy (DOE) is also involved in that it selects actual sites for geologic repositories and submits applications to construct them. To determine their suitability for waste disposal, the DOE is investigating basalt and tuff flows, bedded salt and granite formations, and salt domes. None of these geologic formations are characterized well enough to choose specific sites. Neither are they modeled in enough detail to evaluate any given site to the rigorous compliance requirements set down by the draft EPA standard. However, whatever information does exist can be supplemented with general information taken from such sources as similar formations or host-rock descriptions, hydraulic properties, and geochemical characteristics. We can then apply the models thus developed to evaluate a similar but hypothetical repository. Using the capability of SNL models as a base, we then determine how well the hypothetical site meets the draft EPA Standard: do they or do they not comply? Such questions we hope to answer below.

Hypothetical Repositories

To develop credible models, SNL uses information from several repositories hypothetically constructed in candidate host-rocks. In fact, results from such a hypothetical repository in a sequence of basalt flows have been informally presented [5]. We are presently analyzing repositories in the following formations:

- A sequence of basalt flows,
- A sequence of welded and non-welded tuff,
- A sequence of sedimentary rocks and bedded salt, the salt acting as the host-rock; this repository is the subject of this report.

All data on the hypothetical repositories have been taken from the open literature. Generally, however, the quality of such data is not high enough to accompany a characterization report of an actual site. Also, in some cases, data for a given rock unit had to be assumed from known properties of similar formations. Therefore, whatever results we arrived at must not be interpreted as a definitive statement on any specific site or formation.

Scenarios

To select scenarios for detailed analysis, we used the results of risk analysis methods development programs at SNL [6]. In that work a number of scenarios were identified that may be important in understanding risks from real repositories. Most of those scenarios involved flowing groundwater intruding into the backfilled regions of the repository. Various water-bearing geologic strata were the sources of groundwater as well as the potential paths for migrating radionuclides.

After considering the previous scenario development efforts and the details of the repository (discussed below) we chose two types of scenarios: groundwater transport and disinterment. In the first type of scenario radionuclides are presumed to be released at low rates over an extended period. Radionuclides are transported to the accessible environment by the natural, or slightly perturbed, groundwater flow system. In disinterment scenarios, radionuclides are transported rapidly to the accessible environment over a short period.

II. The Draft EPA Standard

The EPA assumes that natural or man-induced disruptions will cause the repository to release some radionuclides and that they will find their way to the accessible environment.* In Draft #19 of its standard, the EPA sets the limits for total integrated discharges that may be expected from such disruptions (Equation (1)):

$$\text{EPA Sum} = \sum_{i} \frac{Qi}{EPAi} \qquad (1)$$

where: Qi = total integrated release of radionuclide i
EPAi = release limit for radionuclide i.

The sum over i includes all radionuclide present in the waste. The proposed release limits are listed in Table 1.

We determine Qi by estimating discharge rates to the surface and integrating those rates over 10,000 years, the period after sealing the repository that the draft EPA standard addresses. The draft EPA standard requires that EPA Sum $\leq$ 1.0 and that it will not be exceeded at probability of greater than 0.01/10,000 years; these values result from the so-called "expected releases." The EPA also requires that EPA Sum $\leq$ 10.0 at a probability greater than 0.0001/10,000 years -- the so-called "unlikely releases."

To enforce the EPA standard, the NRC must ensure that any repository is designed such that radionuclide releases are kept low and that the site is chosen such that disruptions that could lead to releases are not likely. However, to enforce compliance, the NRC must understand a particular planned repository well enough to quantify potential disruptions and to estimate releases that they cause. In other words, each potential disruption (i) must have a numerical value assigned to the probability that it will occur. Likewise, the amount of radionuclides thus released must have a numerical value in terms of Equation 1.

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*The accessible environment is "any location on the surface where radionuclides may be released or any aquifer that may be contaminated by radionuclides at a distance of 1 mile from the perimeter of the underground facility.

Table 1

Cumulative Releases to the Accessible Environment for 10,000 Years After Disposal

Radionuclide	Release Limit
Americium-241	10
Americium-243	4
Carbon-14	200
Cesium-135	2000
Cesium-137	500
Neptunium-237	20
Plutonium-238	400
Plutonium-239	100
Plutonium-240	100
Plutonium-242	100
Radium-226	3
Strontium-90	80
Technetium-99	2000
Tin-126	80
Any other alpha-emitting radionuclide	10
Any other radionuclide which does not emit alpha particles	500

The following are examples of i and how we can estimate their probabilities:

- Inadvertant drill holes; we consider similar activities, such as present-day exploratory drilling in similar media.
- Failure of shaft or borehole seals; thoroughly investigate properties of sealing materials.
- Geologic faulting; investigate seismic activity at the site.

We can estimate radionuclide releases by modeling the processes that tend to transport nuclides. This aspect is covered in the following sections.

Where sufficient data are available the following procedures can be used to estimate how well an application complies with the draft EPA Standard [7]:

1. Examine each potential disruption (i; hereafter called "a scenario") and estimate its probability, pi. Next, use numerical modeling to estimate the consequences Ci, of that scenario. Ci is numerically equal to the EPA Sum obtained by evaluating Equation 1. Thus, after completing the analyses, you will have a set of doublets (pi, Ci) that can be displayed graphically (Figure 1).

2. To start estimating compliance, integrate results from Step 1 to produce a Complementary Cumulative Distribution Function (CCDF) of the following consequences:

$$p> = \sum_i pi \cdot U\,(Ci - C_>) \qquad (2)$$

where p>, C> are the ordinate and abscissa of the CCDF respectively

U(x) = unit step function,

$$U(x) = \begin{cases} 1 : & x > 0 \\ 0 : & x < 0. \end{cases} \tag{3}$$

The CCDF can be constructed from Figure 1, as shown in Figure 2.

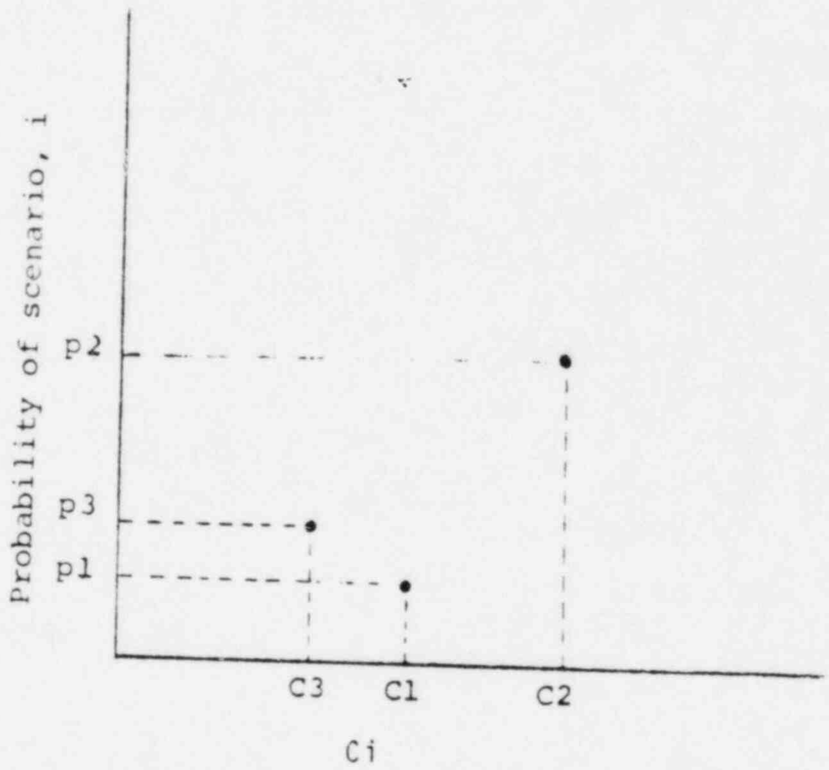

Figure 1. Expected EPA Sum, Ci, from Scenario i

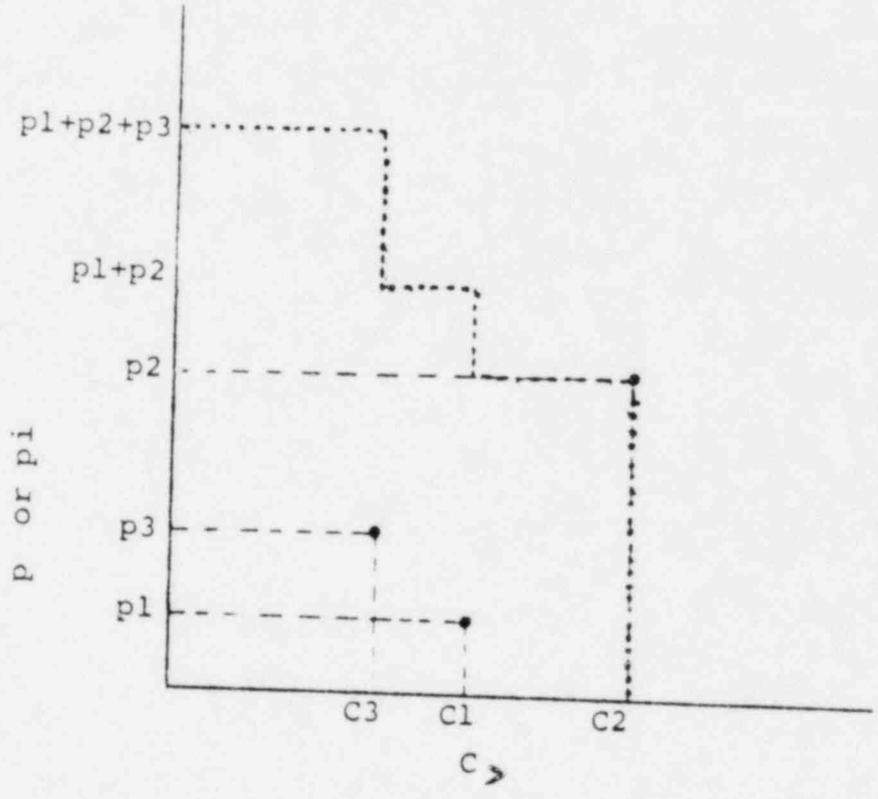

Figure 2. Complementary Cumulative Distribution Function (CCDF)

3. Lay Figure 2 over the CCDF implied by the EPA Standard (Figure 3). If Figure 2 falls outside the Standard's CCDF (shaded area in the figure), a violation is indicated.

When calculating estimates of the consequences mentioned in Step 2, there are built-in uncertainties that result from uncertainties in data inserted into the model for estimating releases. The following, for example, are some factors that may contain such uncertainties:

- hydraulic properties along paths for groundwater that could transport radionuclides;
- geochemical properties along the groundwater paths;
- when calculating groundwater transport rates, those very parameters that define the source of radionuclides.

The effect of such uncertainties as listed above is to produce a family of estimates, Cij, where j denotes the jth estimate of the EPA Sum for a certain scenario, i (Figure 4). In the situation illustrated, which we use later, each Cij has the same probability, pi, as any other one. We accomplish this by using a sampling procedure to sample equally probable combinations of the input data such that, if N combinations of input data are chosen, the probability associated with Cij, that is pi', is:

$$pi' = \frac{pi}{N} \qquad (4)$$

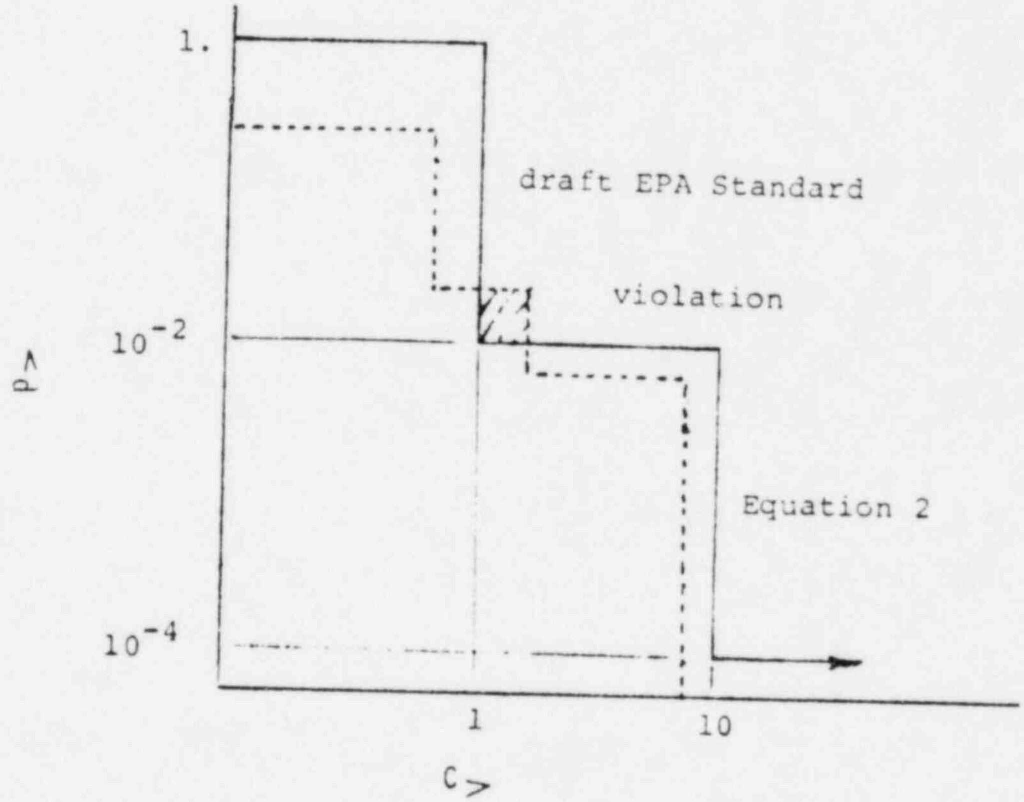

Figure 3. Compliance Estimation: Comparison of the Constructed CCDF With the Draft EPA Standard.

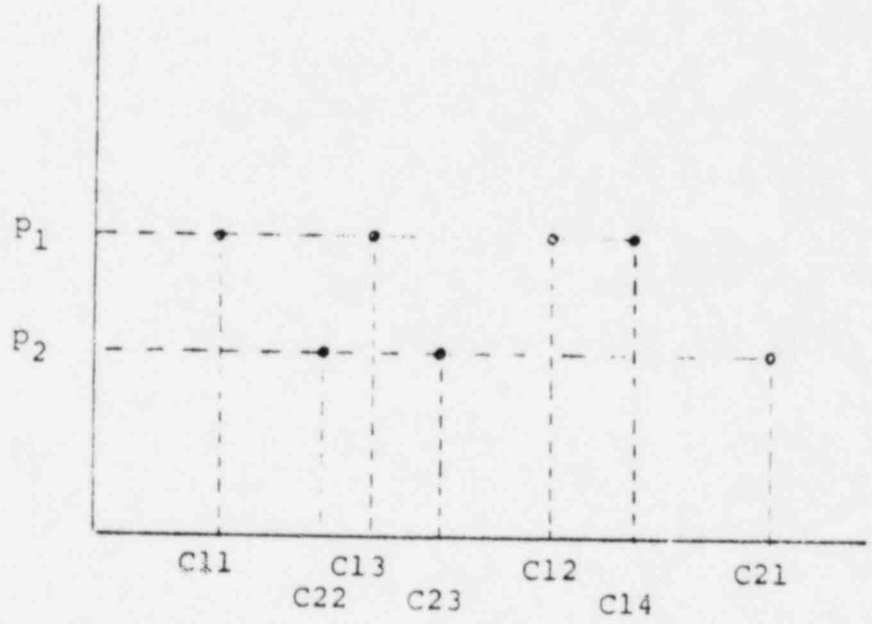

Figure 4. Consequence Estimates for Two Scenarios With Sampled Input.

III. Sequence of Discussion

Below we will discuss our findings as follows:

1. Description of the hypothetical repository --
   - -rock types found at the site
   - -hydraulic properties of the rock formations
   - -properties of any aquifers
   - -various sizes of all formations,
2. Scenarios -- such situations or potential states of the repository that may lead to release of radionuclides -- and their probabilities of occurrence,
3. Models -- description and details of their application to this analysis.
4. Required geochemical data,
5. Quantitative data -- numerical results from this analysis: how much, when, how long?

As we discuss our findings, we are assuming that the reader is familiar with the problems of disposal of radioactive wastes and the methods developed at SNL to address them. Nevertheless, we will endeavor to avoid highly technical language and will provide complete citations when we feel it will behoove the reader to seek further clarification from the open literature.

IV. The Hypothetical Repository

If we are to use the SNL models to verify compliance with the draft EPA Standard, we need a description of the repository to be licensed. The description should include the geologic, hydrologic, and geochemical properties of the site; the shape, size, and layout of the excavation, that is, the engineered underground facility; and the nature of the nuclear waste.

Bedded-Salt Site

The bedded-salt repository site is located in a subsidiary basin within a major sedimentary basin. The crust of the region sank, allowing sediments to accumulate. Beginning 300 million years ago, within this depressed region, small blocks of the crust were displaced along deep-seated faults, creating a system of subbasins separated by basement uplifts. The subbasin where the site is located (Figure 5) is bounded on the north by Uplift A and on the south by Arch M. River C, approximately 40 to 50 miles to the north, flows eastward and a small river, River R, about 25 miles to the east, flows northwest to southeast. The uplift and the arch are bounded by high-angle reverse faults that steepen with depth, indicating that the subbasin is a block of crust that was uplifted with respect to surrounding regions. The subbasin is situated within a tectonically stable region that is associated with a shield area to the north. Several faults strike northwest just south of the uplift, but the rest of the subbasin lacks evidence of faulting or volcanism.

Current seismicity in the region is localized along the uplift, which is the dominant structural feature and the focus of any seismic energy release; most earthquakes in the area have foci in the basement. In the past, only a few earthquakes with intensities between V and VI on the Modified Mercalli Intensity Scale have been registered, and none with destructive intensities of VII and above. Accordingly, this region is in Zone 1 on a seismic-risk map, which means that minor earthquake damage is expected in the next 100 years. However, the level of shaking hazards is expected to be less than 4 percent of that of the force of gravity.

Active subsurface dissolution is evident along the northern and eastern margins of the subbasin; collapse features such as sinkholes, depressions, small faults, and fractures are common within the salt dissolution zone, which is at least 10 miles from the site. The mean rates of salt dissolution range from 19 feet (6 m) to 1150 feet

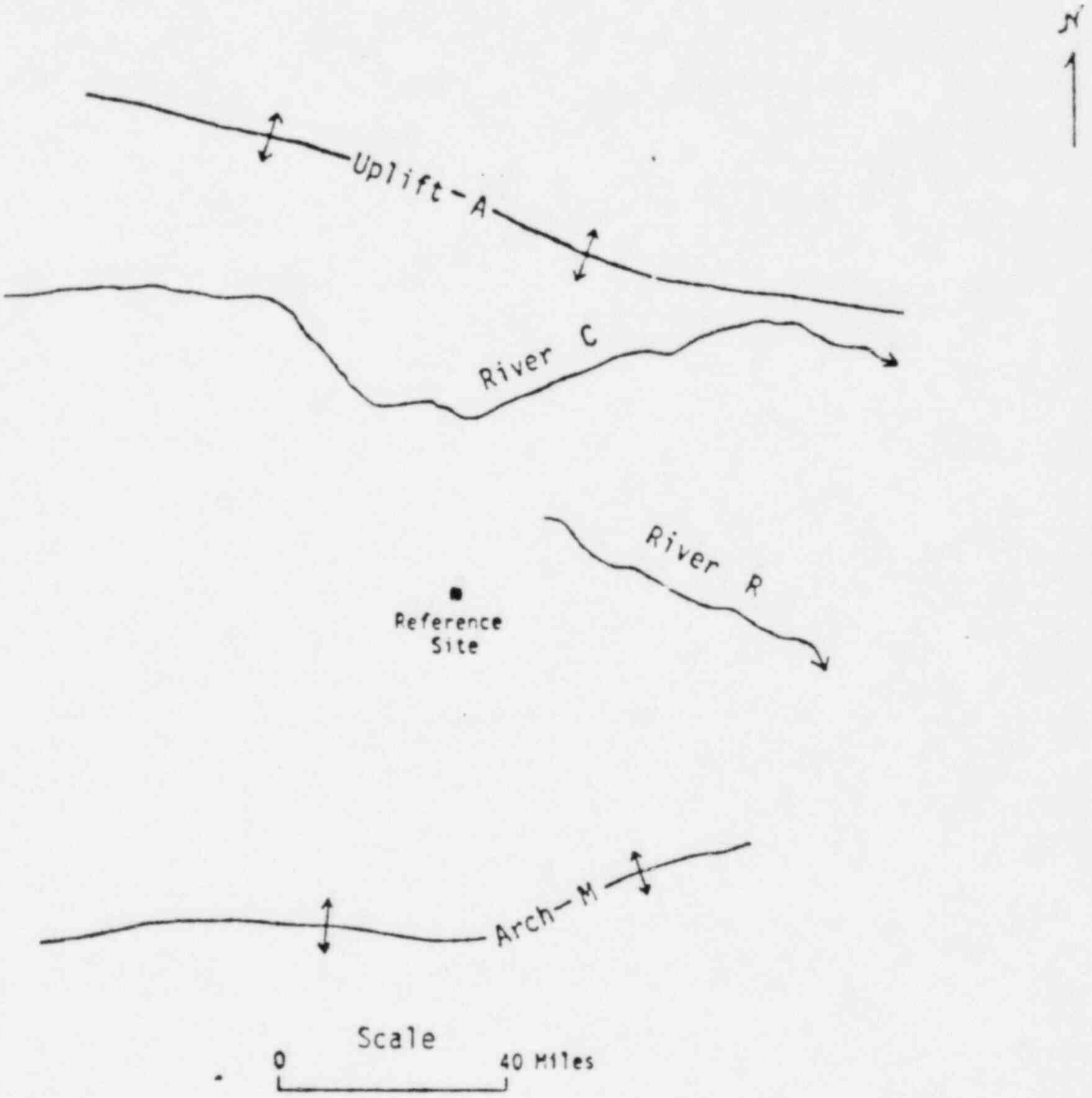

Figure 5. General Setting of the Bedded Salt Reference Site (Plan View).

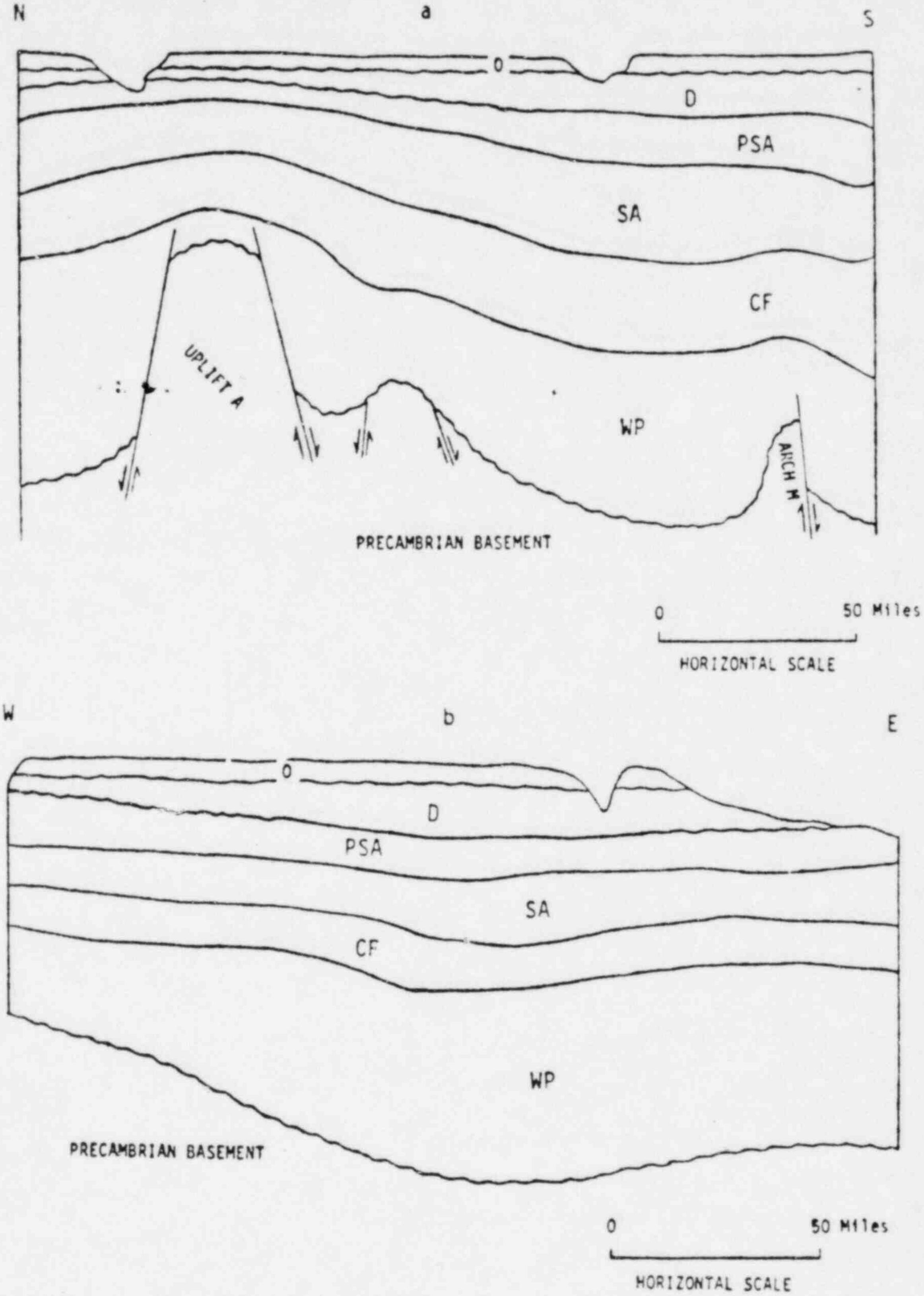

Figure 6. Schematic Cross-Section Across the Subbasin.

(350 m) per 10,000 years. Salt dissolution along the north side is slower than along the east side of the subbasin.

The subbasin is a relatively shallow, continental-interior basin. The Precambrian basement is at most 10,000 feet below the surface. The repository is located in the center of Unit SA, which consists of 1,000 to 1,200 feet of evaporites, mainly halite with small amounts of anhydrite and dolomite (Table 2). Unit SA is overlain by Unit PSA, which ranges in thickness from 550 to 850 feet and consists of siltstone, sandstone, salt and anhydrite. Unit PSA is an aquitard slowing the downward movement of groundwater. Overlaying the unit is 300- to 900- foot-thick Unit D, which consists of sand and clay, and is a minor aquifer. Unit O, which overlays Unit D, is between 50 to 300 feet thick and is the major unconfined aquifer in the area. The major constituents of Unit O are sand and clay, with small amounts of gravel and some caliche that thinly covers the surface.

Below Unit SA is Unit CF, which ranges from 1,750 to 2,050 feet in thickness and is composed predominantly of halite, anhydrite, and clay. CF is also an aquitard. Below Unit CF is Unit WP, which is from 2,300 to 4,200 feet thick and consists mainly of shale, limestone, and sandstone. This unit, which is brine-saturated, is considered an aquifer but with such low conductivity that no pumping at all takes place.

Geochemical analyses of shale samples from Unit WP show an average 2.4 percent total organic carbon and as high as 5.38 percent sediments of the layers deposited after Unit WP. Kerogen color, which indicates thermal maturity when plotted against kerogen type, shows that samples from this unit are in transition between maturity and immaturity, and that those of post unit WP never reached temperatures high enough to generate hydrocarbons. This means that, since the site is away from any potential hydrocarbon reservoir, intensive exploration and drilling will not likely take place within the area.

About 50 miles west of the site, the shallow aquifers (Units O and D), are recharged at a rate of between 0.2 and 1.0 inches/year, but discharge along the eastern margin of the subbasin. In these aquifers, the groundwater flows slowly from west to east, several inches to a few feet per year. Flow in the overlying aquifers is driven by gravity. The aquifer Units O and D, dip over a range of 10 to 50 feet

Table 2

Stratigraphic Units, Lithology, and Thickness of Hypothetical Repository Site

Unit	Thickness (Ft)	Lithology	% Thickness
O	50 - 300	silt clay	45
		sand gravel	50
		caliche	< 5
D	300 - 900	shale clay	30
		siltstone	7
		sandstone conglomerate	60
		limestone	< 3
PSA	550 - 850	anhydrite	7
		claystone	8
		salt	23
		mudstone	22
		siltstone	28
		sandstone	12

Table 2 (Cont'd)

Stratigraphic Units, Lithology, and Thickness of Hypothetical Repository Site

Unit	Thickness (Ft)	Lithology	% Thickness
SA	1000 - 1200	dolomite	13
		anhydrite	22
		claystone	5
		salt	59
		mudstone siltstone sandstone	< 1
CF	1750 - 2050	dolomite	< 5
		anhydrite	20
		claystone	15
		salt	50
		mudstone	5
		siltstone	5
		sandstone	< 1
WP	2300 - 4200	limestone	55
		sandstone	9
		claystone shale	36

per mile. This results in a head gradient of 2 to 10 $\times 10^{-3}$ driving horizontal flow within Units O and D. Vertical gradients in Units O and D are downward and small in magnitude. The dispersivity of Units O and D is small, less than 100 feet, and typically tens of feet.

Unit WP recharges very slowly -- much slower than the shallow aquifers -- a few hundred miles west of the site and discharges several hundred miles southeast of the subbasin. The briny groundwater in this unit flows slowly, mostly from west to east, at a rate of a few inches per year. Its hydraulic gradient varies between 10 and 30 feet/mile, i.e., from 2 to 6 $\times 10^{-3}$. The vertical hydraulic gradient, in this unit, however, is steep, about 1 foot/foot, and is directed upward

Table 3 lists ranges of horizontal and vertical hydraulic conductivities and porosities for each unit. Values of conductivities for the O and D units mean that approximately 50 percent of conductivity measurements made in these units would fall in the given range. For the remaining units, the values indicate that 85 percent of the measurements would fall in the given range.

Engineered Underground Facility

The DOE has conceived a design for a subsurface facility where nuclear wastes can be emplaced [8-10]. We will use this facility for our analyses. Since the facility has already been described elsewhere [11], we will present only the few gross features that are important to our analyses. The reader is cautioned that the repository is merely hypothetical, although we will assume it to be real for modeling purposes.

Dimensions -- The mined repository, which is located at a depth of 2,300 feet, has a storage area that extends over a 3,000 acres, rectangular area 15,370 by 8,600 feet (Figure 7). A shaft pillar area extends 2,000 feet horizontally away from the waste storage area, the "panhandle" area shown in Figure 7.

Each storage room is 4,000 feet long by 17.5 feet wide, by 19 feet high. For our calculations, we will assume the height to be 15 feet because of creep closure that takes place over the operational life of the repository, that is, during the waste emplacement period. The central corriders, which are 18.5 feet wide, will also be calculated as being 15 feet high.

Table 3

Hydraulic Properties of Geologic Units

Unit	Horizontal Hydraulic Conductivity (ft/d)	Vertical Hydraulic Conductivity (ft/d)	Porosity (dimensionless)
O	4 - 25	0.4 - 3	0.1 - 0.2
D	0.4 - 2.5	0.04 - 0.25	0.05 - 0.1
PSA	10^{-5} - 10^{-2}	10^{-6} - 10^{-3}	0.01 - 0.05
SA	10^{-7} - 10^{-3}	10^{-8} - 10^{-4}	0.001 - 0.01
CF	10^{-6} - 10^{-3}	10^{-7} - 10^{-4}	0.005 - 0.05
WP	10^{-5} - 10^{-2}	10^{-6} - 10^{-3}	0.01 - 0.05

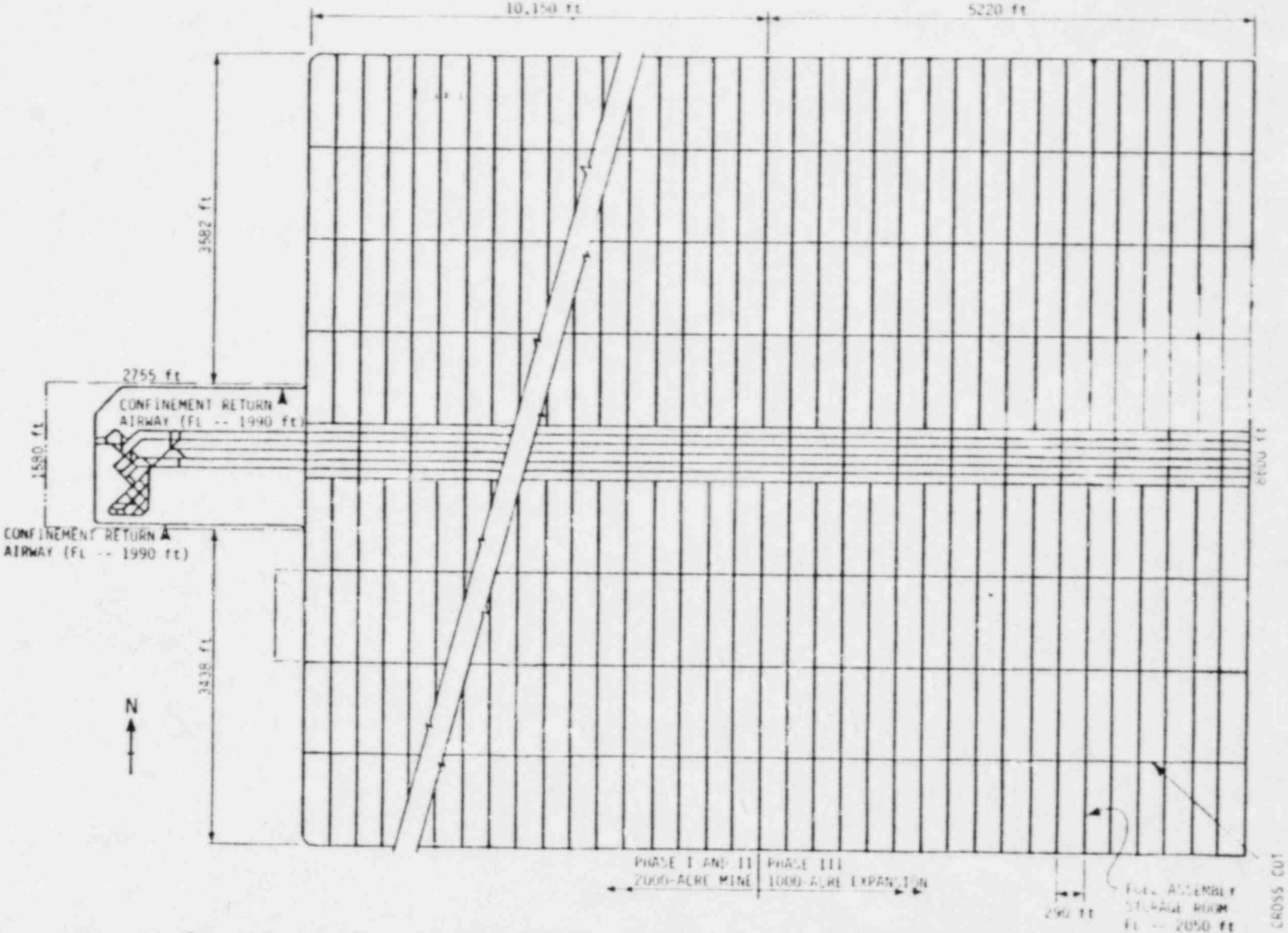

Figure 7. Floor Plan of the Reference Underground Facility. Shafts are located in the panhandle section at the left.

Capacity -- The mine can accept approximately 86,000 metric tons of unreprocessed spent fuel asemblies. This translates to about 204,000 canisters containing either one assembly from a pressurized water reactor (PWR) or two from a boiling water reactor (BWR). The cylindrical canisters, which are 14 inches in diameter and 15 feet long, are to be placed in vertical holes drilled into the floor of the storage rooms. Total volume of excavated salt is 1.56×10^8 feet^3.

Backfill -- After waste emplacement is completed, the mine is backfilled with crushed salt, leaving a residual porosity of 20 percent.

Waste Inventory

The EPA Standard requires that all radionuclides in the waste inventory (Table 1) be considered. However, we have found through experience that a subset of the inventory (Table 4) is most important to estimate compliance. Therefore, we will use this subset in this study.

The inventory listed in Table 4 is that of the full repository at the time it is sealed closed ($t = 0$). Although the inventory varies from canister to canister because of reactor type (BWR/PWR), we will assume that each canister contains a uniform fraction of the entire inventory: 4.9×10^{-6}, that is, 1/204,000.

Table 4

Radionuclide Inventories (Ci) at Time of Closure (t = 0)

Radioisotope	Half-Life (years)	Ci at t=0
252CF	.265E1	9.5E-2
248Cm	.352E6	8.03E-2
244Pu	.828E8	1.15E-8
244Cm	.181E2	1.19E8
240U	.161E-2	0
240Np(m)	.120E-3	0
240Pu	.676E4	4.61E7
236U	.239E8	3.16E4
236Pu	.285E1	9.70E2
232Th	.141E11	3.22E-5
232U	.72E2	2.06E3
228Ra	.67E1	8.95E-6
228Ac	.699E-3	8.95E-6
228Th	.191E1	2.05E3
224RA	.997E-2	2.05E3
220Rn	.177E-5	2.05E3
216Po	.475E-8	0
212Pb	.121E-2	2.05E3
212Bi	.115E-3	2.05E3
212Po	.951E-14	0
208Tl	.589E-5	7.38E2
208Pb	Stable	

Radioisotope	Half-Life (years)	Ci at t=0
249Cf	.352E+03	9.93E-1
245Cm	.827E+04	3.34E4
241Pu	.146E+02	4.4E9
241Am	.433E+03	2.0E8
237U	.185E-01	1.06E5
237Np	.214E+07	4.04E4
233Pa	.750E-01	4.04E4
233U	.162E+06	7.96E0
229Th	.730E+04	1.55E-2
225Ra	.405E-01	1.55E-2
225Ac	.274E-01	1.54E-2
221Fr	.913E-05	6.77E-3
217At	.101E-08	0
213Bi	.894E-04	6.77E-3
213Pb	.133E-12	0
209Tl	.418E-05	1.49E-4
209Pb	.376E-03	6.77E-3
209Bi	Stable	---

Table 4 (Continued)

Radionuclide Inventories (Ci) at Time of Closure (t = 0)

Radioisotope	Half-Life (years)	Ci at t=0	Radioisotope	Half-Life (years)	Ci at t=0
250Cf	.131E+02	1.54E0	251Cf	.900E+03	2.83E-2
246Cm	.471E+04	6.64E3	247Cm	.164E+08	2.51E-2
242Pu	.379E+06	1.30E5	243Pu	.568E-03	0
238U	.451E+10	3.03E4	243Am	.765E+04	1.73E6
238Pu	.890E+02	3.08E8	243Cm	.320E+02	2.42E5
234U	.247E+06	9.95E4	239Np	.643E-02	1.73E6
234Th	.660E-01	3.03E4	239Pu	.244E+05	3.19E7
234Pa	.22E-7	3.03E4	235U	.710E+09	1.6E3
230Th	.800E+05	1.68E1	231Th	.292E-02	1.6E3
226Ra	.160E+04	8.09E-2	231Pa	.325E+05	3.39
222Rn	.105E-01	3.08E-2	227Ac	.216E+02	1.44
218Po	.580E-05	3.68E-2	227Th	.498E-01	1.41
218At	.634E-07	0	223Fr	.418E-04	8.90
218Rn	.111E-08	0	223Ra	.312E-01	1.43
214Pb	.510E-04	3.68E-2	219At	.171E-05	0
214Bi	.375E-04	3.68E-2	219Rn	.127E-06	6.32E-1
214Po	.520E-11	0	215Bi	.133E-04	0
210Tl	.247E-05	0	215Po	.570E-10	0
210Pb	.210E+02	1.78E-2	215At	.317E-11	0
210Bi	.137E-01	8.21E-3	215At	.317E-11	6.32E-1
210Po	.378E+00	1.66E-2	211Pb	.686E-04	6.32E-1
206Hg	.154E-04	0	211Bi	.409E-05	0
206Tl	.796E-07	0	211Po	.165E-07	6.30E-1
206Pb	Stable	---	207Tl	.911E-05	6.30E-1
			207Pb	Stable	---

Table 4 (Continued)

Radionuclide Inventories (Ci) at Time of Closure (t = 0)

Radioisotope	Half-Life (years)	Ci at t=0
14C	5730.	4.83E4
90Sr	28.8	4.84E9
99Tc	2.14E5	1.31E6
126Sn	1.0E5	5.15E4
129I	1.6E7	2.98E3
135Cs	3.0E6	3.33E4
137Cs	30.	6.65E9

V. Radionuclide Release Scenarios and Probabilities

The three scenarios with radionuclide transport that we analyzed were groundwater transport, drilling into a canister, and brine pocket penetration.

In all cases, the sealed repository is violated either because mineshaft seals fail or because exploratory drill holes penetrate the underground engineered facility. Therefore, the draft EPA Standard requires that each radionuclide release have an associated probability assigned to it. Since all scenarios that we considered were caused by either the shaft seal failing or by drilling, we had to determine the likelihood that either would happen.

Since Unit WP has low hydraulic conductivity and groundwater flows through it extremely slowly -- inches per year -- we will ignore it as a source of groundwater or a migration path.

Wells sunk into Unit WP could shorten the path of radionuclides to the accessible environment. However, because of its tightness, salinity, and overlying units of greater transmissivity, we do not feel that wells are likely to be drilled into the lower units for the extraction of water. Also, the natural discharge location for the unit is farther than 100 miles away. With the groundwater moving at 1 mile/1,000 years (5.28 inches/year) it would take over 100,000 years for the radionuclides to escape. This time is much greater than the 10,000 year limit set by the draft EPA Standard.

We should note that the objective of this study is to choose and analyze a set of representative scenarios. As will be shown the scenarios chosen will indeed be important scenarios in the compliance assessment of the assumed repository. This is not to say that they are the only scenarios. A full scenario development, characterization, and analysis is beyond the scope of this work.

Probability of Seal Failure

Without a detailed study of the properties of sealing materials, we can only assume a non-mechanistic probability to their failure. Thus, we assume that:

$$\left.\begin{array}{l}\text{Probability of}\\ \text{shaft seal failure}\\ \text{at 1000 years}\end{array}\right\} = 0.001$$

For our calculations, we also assume that the shafts seal remains defective throughout the calculation, that is, it is not resealed.

Groundwater Transport Scenarios

In order that the units (O and D) overlying the backfilled repository be able to transport radionuclides, two hydraulic conduits are required between them. One allows water to enter and contact the canisters. The other carries contaminated water back to the geologic units. The two conduits and the repository would thus form a U-shaped path, called a U-tube (Figure 8).

The vertical conduits could be formed along former mine shafts leading to the repository whose seals had failed. Another possibility would be inadvertant penetration by exploratory drill holes made by future generations seeking petrochemicals or evaporite minerals.

In Figure 8, the conduit to the left is either a mine shaft whose seal has failed, or a borehole. The one to the right is a borehole. Water is driven through the U-tube by the head difference between the vertical conduits and the units overlying the repository. The difference is caused by the water flowing horizontally through Units O and D.

Below, we analyze two variations of the characteristics of the overlying aquifer. In one we assume that Unit O is nearly saturated and that the vertical legs of Figure 8 connect with it. Water and radionuclides flow from the backfilled regions back into Unit O. Once there, the radionuclides are transported through the unit.

In the other variation, we assume that Unit O has been depleted, say for irrigation. Unit D is then the migration path for radionuclides, although more slowly because of its lower conductivity.

Probability of U-Tube Formation -- To determine the likelihood that a borehole will intrude into the repository, we first assume that the drilling rate into the 3,000-acre tract is 1.9×10^{-3}/year. This rate is relatively low for drilling into strata containing bedded salt [4]. However, it is a reasonable value considering the thermal maturity of the strata, discussed previously in the description of the report. The floor space of engineered facility covers a smaller area than that of its gross extent, typically

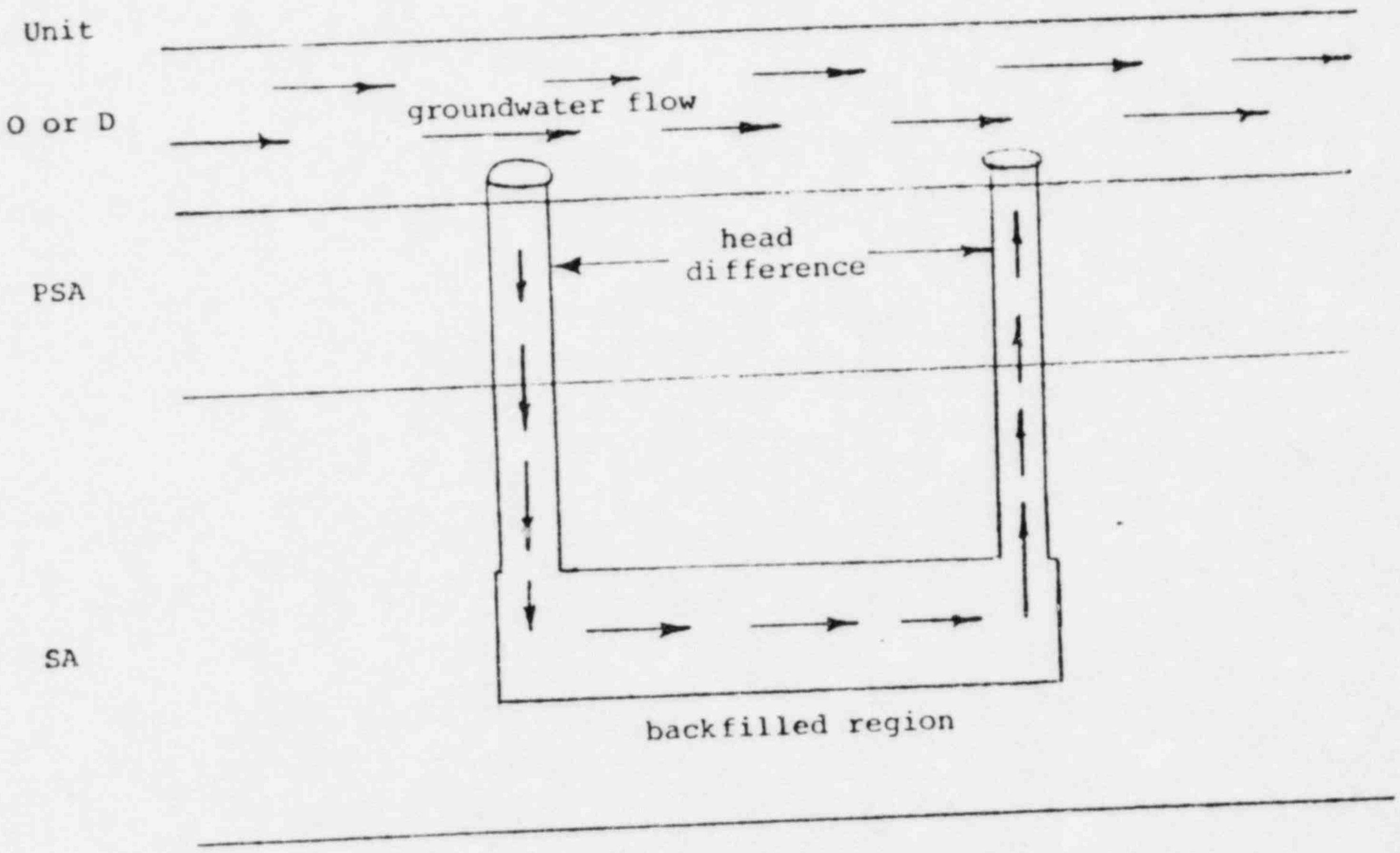

Figure 8. The U-Tube Flow and Migration Pattern for the Groundwater Transport Scenario.

25 percent or less. In the assumed design this fraction is less than 10 percent [8-10]. For the calculations presented in this report, we assumed this fraction to be about 15 percent so that the number of boreholes expected to penetrate the backfilled regions in 10,000 years is:

$$19 * 15\% \approx 3.$$

We can thus assume that three boreholes are expected to penetrate the backfilled regions during the 10,000 year period.

However, other factors enter the picture. If water is to flow through a U-tube, there must be enough driving head. For example, in the case where water originates in Unit 0 and returns loaded with radionuclides, there is a minimum distance that must separate the vertical legs of the U-tube. This distance is determined by applying the DNET Model [12]. The water in the U-tube's entry leg is fresh until it comes into contact with the salt. Therefore, the exit leg contains saturated brine, which is heavier. Given the hydraulic gradient of Unit 0, the minimum downdip separation calculates as 11,500 feet.

In the case where water originates from and returns to Unit D, both vertical legs are filled with brine. Therefore, there is no difference in their weights and two or more holes, regardless of separation, may form a successful U-tube, as long as both penetrate the backfilled regions.

To implement all our assumptions, we further assume that exploratory drilling is a Poisson process with a distribution on the number of boreholes into the 450-acre (15 percent of 3,000) target area given by

$$P(N) = \frac{(\lambda T)^N e^{-\lambda T}}{N!}, \qquad (5)$$

where: $\lambda T = 3$.

In the Unit 0 case, where we require a minimum distance of 11,500 feet, we must adjust the value of λT. The adjustment needed is a scaling of the value of λT by the ratio of the target area to 3,000 acres.

We will consider four variations on the U-tube scenario. In two of the variations, the Unit O will be assumed to transport the radionuclides. In the other two, Unit D will be assumed to transport the radionuclides. For each of the assumed major transporting units, two types of vertical conduits (Figure 8) will be considered. In all U-tube scenarios analyzed, the vertical conduit at the right in Figure 8 will be assumed to be formed by one or more boreholes. The conduit at the left of Figure 8 will be assumed to be one or more failed shaft seals, in one case, and one or more boreholes in the other. In the discussion that follows, probabilities for these scenarios will be given. In order to describe the hydraulic properties of the vertical legs, conditional probabilities will also be needed to describe the number of boreholes that may occur. These will also be given in the following discussion.

Scenario I -- Water originates in and returns to Unit O. The entrance leg is a shaft whose seal has failed and the exit leg is one or more boreholes. Both legs are separated by at least 11,500 feet. The size of the target area (Figure 7) is approximately

$$\text{Area} = (17{,}000 - 11{,}500) \times 8{,}600 \text{ feet}^2 = 1{,}086 \text{ acres.}$$

Thus, we scale λT appropriately to get $(\lambda T)'$:

$$(\lambda T)' = \lambda T \, \frac{1{,}086 \text{ Acres}}{3{,}000 \text{ Acres}} = 1.09 \qquad (6)$$

Using Equation (5), $P(0) = 0.34$ and the probability of one or more holes penetrating the target is

$$P_{\geq 1} = 1 - 0.34 = 0.66.$$

Therefore, the probability that Scenario I will occur is

$$P_1 = P_{\text{shaft}} * P_{\geq 1} = 0.001 * 0.66 = 0.00066. \qquad (7)$$

We can now use Equation (5) to generate a conditional probability distribution on the number of boreholes in the 1,086 x 15 percent target area, Pc(n), which will be needed for computing:

n	1	2	3	4	5	6	7	≥ 8
Pc(n)	0.56	0.30	0.11	0.03	0.01	0.0011	1.7×10^{-4}	nil

Scenario II -- Water originates from and returns to Unit 0. Both legs of the U-tube are two or more boreholes separated by at least 11,500 feet. Since any two boreholes separated by that distance can form a successful U-tube, we need a convolution of probabilities of boreholes in differential target areas at greater than minimum separation. To avoid this complicated computation, we present a simplified treatment to estimate the number of boreholes, ignoring the 2,000-foot-long "panhandle" of the repository since no waste is stored there (Figure 9).

The two 2,700 foot sections at each end of the repository are targets for the boreholes forming a U-tube with those at the opposite end. The size of each target area is thus 2,700 feet x 8,600 feet = 533 acres. Therefore, adjusting λT gives us

$$(\lambda T)' = \lambda T \cdot \frac{533}{3000} = 0.53. \tag{8}$$

The probability that there will be no boreholes in a target area that is 15 percent of 533 acres is 0.59 [Equation (5)], so that the probability of more than one boreholes at each end is

$$P_2 = (1 - .59)^2 = 0.17. \tag{9}$$

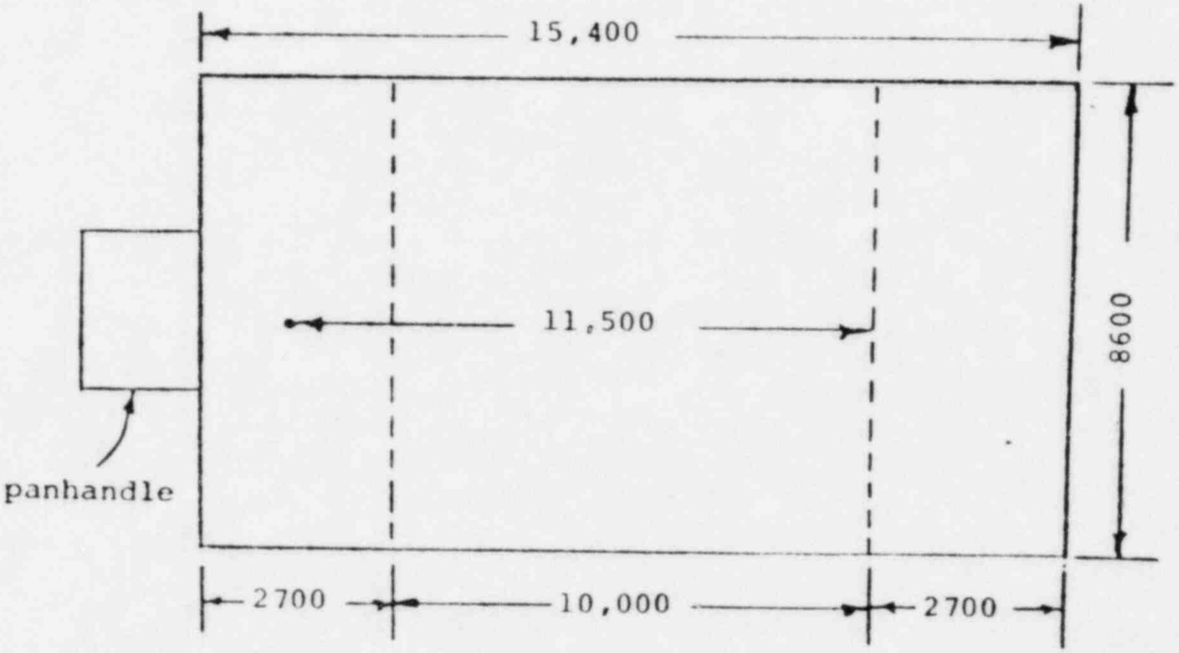

Figure 9. Scenario II geometry.

However, in order to perform our calculations, we need the distribution of the number of boreholes. This number can be generated from Equation (5) to give us a conditional probability distribution of boreholes in each target area:

n	1	2	3	4	5	6	≥ 7
$P_c(n)$	.7549	.2031	.0364	.0049	.0005	.00005	nil

Scenario III -- Water originates in and returns to Unit D. One leg of the U-tube is a shaft whose seal has failed and the other is one or more boreholes at any distance, not exceeding the size of the backfilled regions. We use the same calculations as for Scenarios I and II. However, we do not adjust for target area and use instead $\lambda T = 3$. Using Equation (5), we calculate the probability of one or more boreholes penetrating the target area as $P_{>1} = 0.95$ so that the probability of this scenario occurring is:

$$P_3 = P_{shaft} \star P_{\geq 1} = 0.001 \star 0.95 = 0.00095. \qquad (10)$$

Thus, the conditional probability distribution on the number of boreholes is:

n	$P_c(n)$	n	$P_c(n)$
1	0.16	6	0.05
2	0.24	7	0.02
3	0.24	8	0.01
4	0.18	9	0.003
5	0.11	10	0.001
		≥ 11	nil.

Scenario IV -- Water originates in and returns to Unit D. Both legs of the U-tube are boreholes with no minimum separation. No adjustment of λT is needed and we use $\lambda T = 3$. By using Equation (5), we calculate the probability of two or more boreholes penetrating the target area as $P_{>2} = 0.80 \equiv P_4$. The conditional probability of distribution is

n	$P_c(n)$	n	$P_c(n)$
2	0.28	7	0.03
3	0.28	8	0.01
4	0.21	9	0.003
5	0.13	10	0.001
6	0.06	≥ 11	nil.

Since we can not assume Unit O to be both saturated and depleted, we assume each of these possibilities to be equally probable. This translates to an additional 1/2 on the probabilities above. Also, we treat only one scenario at a time. For example, we do not consider a U-tube formed by a failed shaft seal which, after subsequent drilling, becomes a U-tube with boreholes providing additional water conduits. Thus, the shaft seal failures compete with boreholes for U-tube formation. Including the factors of 1/2 for Unit O vs Unit D scenarios, we calculate probabilities for the mutually exclusive scenarios, P',

$$P_1' = 1/2\ P_1\ (1 - 1/2\ P_2)$$

$$P_2' = 1/2\ P_2\ (1 - 1/2\ P_1)$$

$$P_3' = 1/2\ P_3\ (1 - 1/2\ P_4)$$

$$P4' = 1/2\ P_4\ (1 - 1/2\ P_3)$$

In summary, the probability assigned to each scenario, pi', is:

Scenario	Pi	Pi'
1	.00066	.00030
2	.17	.0850
3	.00095	.00029
4	.80	.40

Disinterment

Scenario 1: The canister "direct hit."

In this disinterment scenario, the radionuclides move to the surface directly and rapidly. While sinking a borehole, possibly while exploring for minerals, the drill bit strikes a waste canister and brings a fraction of the contents to the surface.

In the scenarios previously described, we determine that in 10,000 years, 19 boreholes would have been expected over the 3,000 acre site. The same probability applies to this disinterment scenario. Each borehole will have a fixed probability of making a "direct hit" on a canister. The probability is determined by comparing the area of the waste canisters with that of the facility.

Since there are 204,000 canisters, each with an end area of 1.15 foot^2, any drill bit penetrating the back-filled repository has a probability of hitting a canister of

$$P_{hit} = \frac{2.04 * 10^5 \text{ canisters} * 1.15 \text{ foot}^2/\text{canister}}{15{,}370 \text{ feet} * 86{,}000 \text{ feet}} \qquad (11)$$

$$= 1.2 * 10^{-3}$$

For n boreholes, the probability of N direct hits will be given by a binomial distribution,

$$P(N,n) = \frac{n!}{N!\,(n-N)!}\, P_{hit}{}^N (1-P_{hit})^{n-N} \quad 0 \le N \le n. \qquad (12)$$

Thus, the probability of N hits is:

$$P(N) = \sum_{n=1}^{N} p(n) \cdot P(N,n)$$

$$(13)$$

$$= \sum_n \frac{(\lambda T)^n e^{-\lambda T}}{n!} \cdot \frac{n!}{N!(n-N)!}\, P_{hit}{}^N (1 - P_{hit})^{n-N}$$

where $\lambda T = 19$

$P_{hit} = 1.2E-3$

A more detailed analysis of this scenario might include the spatial extent of the drill bit, the drilling direction, and the distribution of wastes within the canister.

Scenario 2: Brine-pocket penetration

We have not had time during this study to analyze this scenario in detail. However, it has been suggested as a potentially important scenario to be considered when analyzing risks from nuclear waste disposal [13]. The suggestion is that for an actual respository site, approximately 1 borehole in 25 will hit a brine pocket. Therefore, we use this number with some other assumptions to decribe this scenario.

We use the probabilistic expression of Equation (13) because conceptually, the disinterment scenario is the same as that of the brine pocket penetration (Figure 10), the brine pocket now being the target, rather than the canister. Therefore, we have to develop an expression for P_{hit}.

As indicated in Figure 10, we assume that M brine pockets exist below the horizon of the subsurface facility, with an area, A_m. Each brine pocket is spherical with a cross-sectional area, a, projecting to the surface. We assume that the ratio of total brine pocket area, M.a, to A_m is a constant, α ,

$$M \cdot a = \alpha A_m .$$

The constant, α , then gives the probability that a random drill bit will penetrate a brine pocket. The value of α = 1/25 was given with no mention of the thickness of the salt layer [13]. However, since we are concerned only with the lower half of the salt layer, we will assume that

$$\alpha = 0.02$$

This value will be used for P_{hit} in Equation (13) to evaluate this scenario.

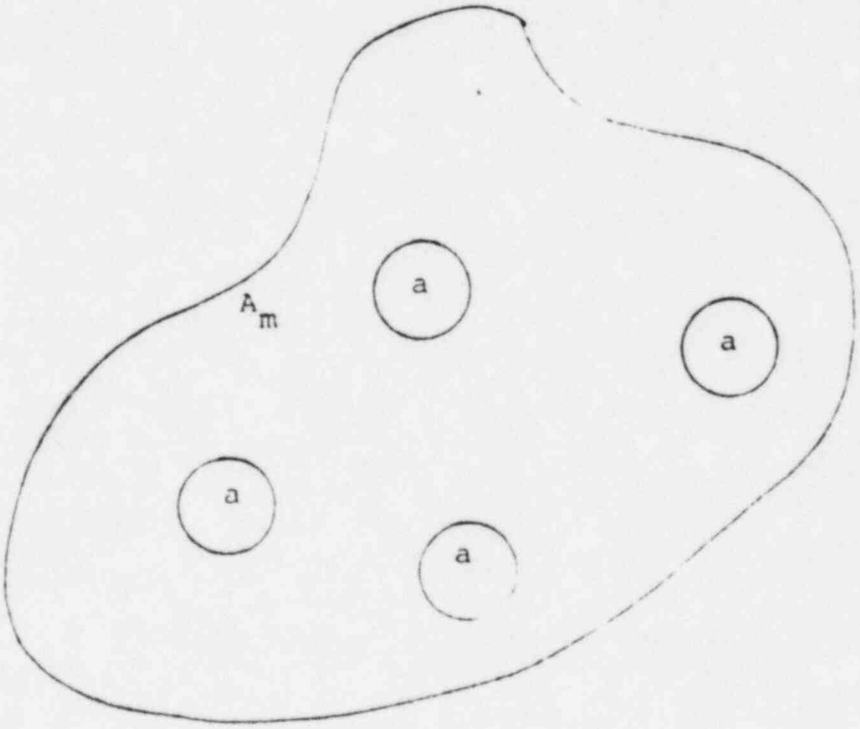

Figure 10. Reference Area, A_m, Containing M Spherical Brine Pockets. Each brine pocket has a projected area, a, at the surface.

VI. Computer Models (NWFT/DVM) Used for Groundwater Transport Scenarios

We used different models to estimate discharges expected from the various scenarios. For groundwater transport (U-tube) scenarios, we used the NWFT/DVM [14] model developed at SNL for the NRC. For the disinterment scenarios, we used more simplistic models.

A. The Groundwater Transport Scenarios NWFT/DVM

This model is used to calculate time-dependent discharge rates of radionuclides into the accessible environment for the four groundwater transport scenarios. Figure 11 shows the simple network of points and distances used in the calculations. In the figure, "ℓ" indicates the length between junctions at elevations, "d," and "p" is the hydraulic pressure of the aquifer.

The upper horizontal legs represent the overlying aquifer, either Unit O or Unit D, the vertical legs represent the borehole(s) or failed shaft, and the lower horizontal leg represents the backfilled region.

The numerical values assigned to the ℓ's and d's vary from scenario to scenario. These values are presented in Table 5. Note that we have consistently assumed the maximum lateral separation between the vertical legs for simplicity. This is most important for Scenarios 3 and 4 since the vertical legs can be much closer. This assumption will generally tend to overestimate groundwater and radionuclide flow velocities in legs #5 and #6. This assumption is of little consequence until the actual vertical leg separation becomes so small that a significant fraction of the migration time is represented by transport through legs #5 and #6.

The cross-sectional area of the U-tube legs (ℓ_4, ℓ_5, and ℓ_6) depends on whether the legs are mineshafts (2,000 feet^2) or boreholes (0.8 foot^2/hole). We also assume that the inlet and outlet pressures (p_1 and p_4) are zero since the aquifers are unconfined.

We used the Latin Hypercube Sampling Method [15] to select input data for flow and transport calculations (Table 6). For example, to calculate discharges in each

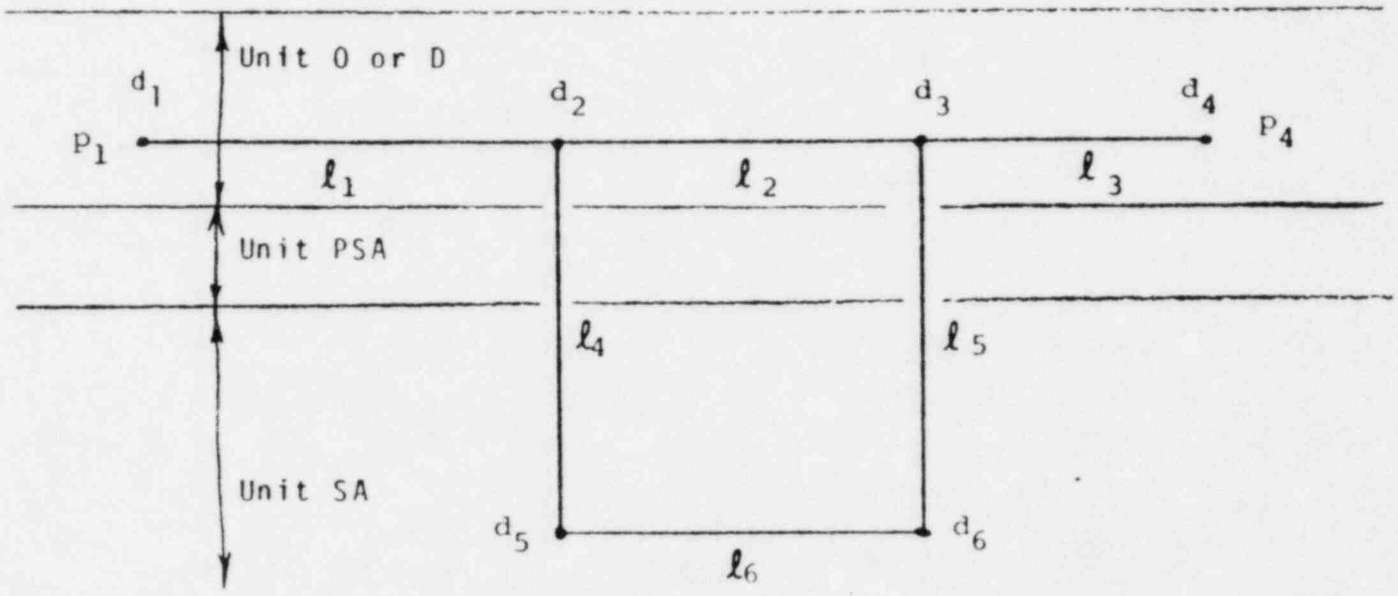

Figure 11. Flow and Transport Network Assumed by NWFT/DVM.

Table 5

Lengths and Elevations, ℓ_i; and d_i, Corresponding to Figure 10 for the Groundwater Transport Scenarios.

	Index, i:	1	2	3	4	5	6
Lengths		lengths, ℓ_i (feet)					
Groundwater transport scenario	I	100,000	17,370	5,280	2,000	1,878	17,370
	II	102,000	15,370	5,280	1,986	1,878	15,370
	III	100,000	17,370	5,280	1,500	1,378	17,370
	IV	102,000	15,370	5,280	1,486	1,378	15,370

Elevations, d_i (feet)

		1	2	3	4	5	6
Groundwater transport scenario	I	859	159	37	0	-1,841	-1,841
	II	859	145	37	0	-1,841	-1,841
	III	359	-341	-463	-500	-1,841	-1,841
	IV	359	-355	-463	-500	-1,841	-1,841

Table 6

Hydraulic Properties

Conductivities are assumed to be lognormally distributed. Porosities are assumed to be normally distributed. The given ranges specify the 0.001 and 0.999 quantiles of the assumed distributions.

Property	0.001 Quantile	0.999 Quantile
1. Hydraulic Conductivity (ft/day) of Unit O	0.15	680.
2. Porosity of Unit O	0.1	0.2
3. Hydraulic Conductivity (ft/day) of Unit D	0.015	68
4. Porosity of Unit D	0.05	0.1
5. Hydraulic Conductivity (ft/day) of Failed Shaft	0.05	50.0
6. Porosity of Failed Shaft	0.05	0.5
7. Hydraulic Conductivity (ft/day) of Boreholes	0.05	25.0
8. Porosity of Boreholes	0.05	0.5

groundwater transport scenario, we chose 50 combinations of input data (vectors) from the distributions in the table. We repeated this procedure three times so as to observe the effects of sampling error on the calculated discharges.

In order to avoid physically unreasonable combinations of porosity and hydraulic conductivity, we assumed a rank correlation of 0.7 when sampling these parameters for any feature [15]. Leg 6 is the backfilled repository, which is a hydraulic "short circuit" between legs 4 and 5 and has a hydraulic conductivity of 10^6 feet/day.

Model NWFT/DVM also requires that we assign a value to cross-sectional area of this "short circuit." Depending on the source model (see below), we assigned an end-view, cross-sectional area of 1.3 x 10^5 ft^2 if the entire waste inventory is available to access by groundwater. If the available fraction is proportional to the number of boreholes, the cross-sectional area can be deduced by the number of boreholes multiplied by the cross-sectional area of the penetrated storage room: 262.5 ft^2. Actually, since leg 6 is a "short-circuit" anyway, these assignments are of little practical value, but are assigned because the model requires them.

We have neglected dispersivity from our NWFT/DVM calculations. We feel this is justified since the dispersivity is small for the assumed repository. More importantly, the effect of dispersivity is to make the leading edge of the discharge curve more diffuse. Since we are calculating time-integrated discharges, we expect little error from the neglect of dispersion. The error is largest when integration begins or ends during the diffuse part of the discharge. The effect is to assign a portion of the discharge to the adjacent 10,000-year period.

In our calculations, we have assumed three models for NWFT/DVM, each describing a different source of nuclide release (Table 7). We did not perform detailed modeling of each source; the sources are simply assumptions chosen to demonstrate their efficacy.

Source #1 -- This source exceeds the minimum release rate required by NRC [10CFR60(2)], that is, 10^{-5}/year of the entire radionuclide inventory shown in Table 4. We have assumed that the inventory is homogeneously dispersed throughout the wasteform so that if $N_i(t)$ denotes the ith radionuclide in the inventory at time, t, in the absence of release, the release rate of that radionuclide is (10^{-5} to 10^{-7}) x $N_i(t)$. We assume that the entire waste inventory is available for transport.

Source #2 -- This source resembles Source #1 in release rate, but the amount of waste available for transport is reduced. Each borehole allows only that waste in the particular backfilled storage room that it penetrates to be available for transport. This model would be valid if we assumed that flow through the backfilled regions would be localized to the vicinity of the borehole (there are 106 storage rooms).

Source #3 -- This source resembles Source #2 but allows the backfilled rooms to be modeled as a mixing cell where wasteforms are leached uniformly (Appendix A). The range of leach limits has been changed to allow a more rapid rate in the breakdown of wasteforms. The calculated discharges thus show how a less stable wasteform can be compensated if mixing mechanisms can be assumed. We also allow solubility limits to apply to radionuclide concentrations in the mixing cell.

Geochemical Data

We assume that retardation of radionuclides occur only in the aquifer units (O and D) of the transport path. The retardation factor, R, is thus given by

$$R = 1 + \rho K_d \frac{(1-\phi)}{\phi} \qquad (14)$$

where

ρ = the assumed rock density (2.7 g/cm^3)

ϕ = the unit's porosity (see Table 6)

K_d = the sorption equilibrium constant (Table 8)

Table 7

NWFT/DVM Source Models

Model Number	Source Type	Amount of Inventory Available for Access	Leaching (Release) Range (yr^{-1})	Leach Distribution
1	Leach Limited	1.00	10^{-5} to 10^{-7}	Log Uniform
2	Leach Limited	$\frac{\text{\# of boreholes}}{106^*}$	10^{-5} to 10^{-7}	Log Uniform
3	Mixing Cell	$\frac{\text{\# of boreholes}}{106}$	10^{-3} to 10^{-7}	Log Uniform

---

*106 denotes the number of storage rooms in the repository

Table 8

K_d - Assumptions

Element	percentiles of assumed lognormal distribution 0.001	0.999
Cm	10^2	10^5
Am	50	10^4
Pu	30	10^4
Np	2	400
U	.01	270
Th	10^3	10^5
Ac	10^2	10^5
Pb	100	500
Ra	100	500
Pa	0.01	10^4
Sr	1.0	2000
Cs	0.01	3000
I	0.01	100
Sn	0.01	500
Tc	0.01	3

^{14}C is assumed to be completely unretarded, ie. $K_d=0$.

The LHS method is also used to select values from the distributions for each input vector according to the distributions given in Table 8. Data appearing in Table 8 are taken from Reference 16 and supplemental information from the open literature.

Solubility limits are needed for Source #3 to treat concentration limits on each radionuclide. These data are presented in Table 9. Elements not appearing in Table 9 are assumed to have unlimited solubility.

Table 9

Solubility Limits (gm/gm)

The given ranges specify the 0.001 and 0.999 quantiles of an assumed lognormal distribution.

Element	quantile	
	0.001	0.999
Pu	1.6E-16	4.0E-4
U	1.6E-8	3.0E-2
Th	1.1E-9	5.8E-6
Ra	7.9E-12	1.3E-5
Np	1.3E-25	5.0E-7
Pb	2.5E-11	4.0E-5
Pa	1.4E-7	7.2E-4
Sn	6.3E-17	1.6E-4
Tc	1.9E-9	9.5E-5
Sr	2.2E-6	2.8E-3

B. Disinterment Scenarios

The disinterment scenarios are different enough from our usual analyses so that the manner in which we evaluated their consequences is discussed here. For each, the consequence of the scenario depends on the time of its occurrence and each consequence depends on the inventory at the time of penetration.

As a measure of the time-dependent consequence, Table 10 shows the hazard represented by the waste inventory in terms of EPA release limits. We obtained the table by evaluating Equation (1) for the entire inventory.

Table 10

Repository Hazard Index

Time (yr)	EPA Sum (Eq. (1))
1,000	8.3E7
1,500	4.3E6
2,000	2.5E6
5,000	8.9E5
10,000	6.4E5

In the direct hit scenario, for example, to use Table 10 to find the hazard on a per-canister basis, divide its value in the second column by 204,000 (the number of canisters). The disinterment scenarios have been described in terms of the number of boreholes expected to cause them, independent of when these boreholes occur. Since the consequences are time dependent, it is essential for consequence evaluation that a time of occurrence be assumed. The assumption made is that the N boreholes considered occur uniformly over the period of interest. For the "direct hit" scenario, the period is the 9900 years following loss of administrative control after 100 years. For the brine-pocket scenario, the period is the 9000 years following containment lifetime (1000 years) when all waste packages are assumed to fail simultaneously and completely. Thus, for N boreholes causing the scenarios, each is assumed to occur at a time, t_j, where

$$t_j = \begin{cases} \dfrac{9900}{N}\left(j - \dfrac{1}{2}\right) + 100 & \text{"direct hit"} \\ \dfrac{9000}{N}\left(j - \dfrac{1}{2}\right) + 1000 & \text{brine pocket} \end{cases} \qquad (15)$$

In the "direct hit", we assume that a fraction, f_o, of the canister contents are removed with:

$$f_o = 1/4$$

Thus, a 1-borehole, direct hit occurs at 5150 years with a consequence (Table 10) of approximately,

$$C(1)_{\text{direct hit}} = 1/4 \cdot \frac{8.9 \times 10^5}{204{,}000} = 1.1 \qquad (16)$$

For the brine pocket scenario, we assume the pressure in the pocket is relieved by expelling a fraction of its volume. This brine flows up the borehole into a backfilled room. We assume that the backfilled rooms have become resaturated before the waste packages fail at 1000 years. When the waste package fails, its contents are assumed to be released uniformly to the entire volume of water in the backfilled regions, at a constant rate over a period, τ. Thus, at time t_j the fraction of wastes that have been released is f_1:

$$f_1 = \frac{t_j - 1000}{\tau}$$

We assume that the brine flow will be of short duration and will remove only those radionuclides in the water volume in the immediate vicinity of the borehole. No modeling was used to test this assumption. We assumed 1/40 of the water in the backfilled room is mixed with the flowing brine and released to the accessible environment. This choice corresponds to the water volume contained in a 100 foot length (50 feet either way from the borehole) of the 4,000 foot long room.

The consequence from this scenario is obtained by evaluating Equation 1 (through interpolation of Table 10) with the assumptions made,

$$C(N)_{\text{brine pocket}} = \sum_{j=1}^{N} \left(\frac{1}{40}\right)\left(\frac{t_j - 1000}{\tau}\right) \left(\frac{\text{Table 10}(t_j)}{106}\right) \qquad (17)$$

We will assume $\tau = 100{,}000$ years. For example, a one-brine pocket scenario occurs at $t_j = 5{,}500$ years and has a consequence of approximately,

$$C(1)_{\text{brine pocket}} = \frac{1}{40} \left(\frac{4500}{100000}\right)\left(\frac{8.9 \times 10^5}{106}\right) = 9.45$$

Since both disinterment scenarios involve a relatively small fraction of the waste inventory, we do not consider them as competing with the groundwater transport scenarios. The boreholes that cause them, however, may also contribute to the U-tube formation. We have neglected the small perturbation the disinterment scenarios may have on the consequence of the groundwater transport scenarios.

C. Construction of the CCDFs

As we stated previously, assessing compliance with the draft EPA Standard should combine all scenarios to produce a final CCDF. For the scenarios analyzed, it is more illuminating to examine them individually. We will first present the disinterment scenarios followed by the groundwater transport scenarios. CCDFs for the groundwater transport scenarios have been constructed for each of the three source models described previously.

Disinterment Scenario 1: The "Direct Hit"

Equation (13) was evaluated to give probabilities, P(N), of the N hit scenario. Equation (15) gives the time, t_j, for each of the N direct hits. Values from Table 10 were interpolated at t_j to give values of the EPA Sum, as illustrated in Equation (16). These results are presented in Table 11 and Figure 12. As can be seen in Figure 12, this scenario alone is enough to violate the draft EPA Standard.

Table 11

Probabilities (per 10,000 yr) and Consequences for the "Direct Hit" Scenario*

N	P(N)	Consequence (EPA Sum)
0	.982	0
1	1.95E-2	1.09
2	2.04E-4	1.88
3	1.40E-6	2.65
4	7.08E-9	3.45

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*Contributions with probabilities of less than 10^{-4} need not be considered.

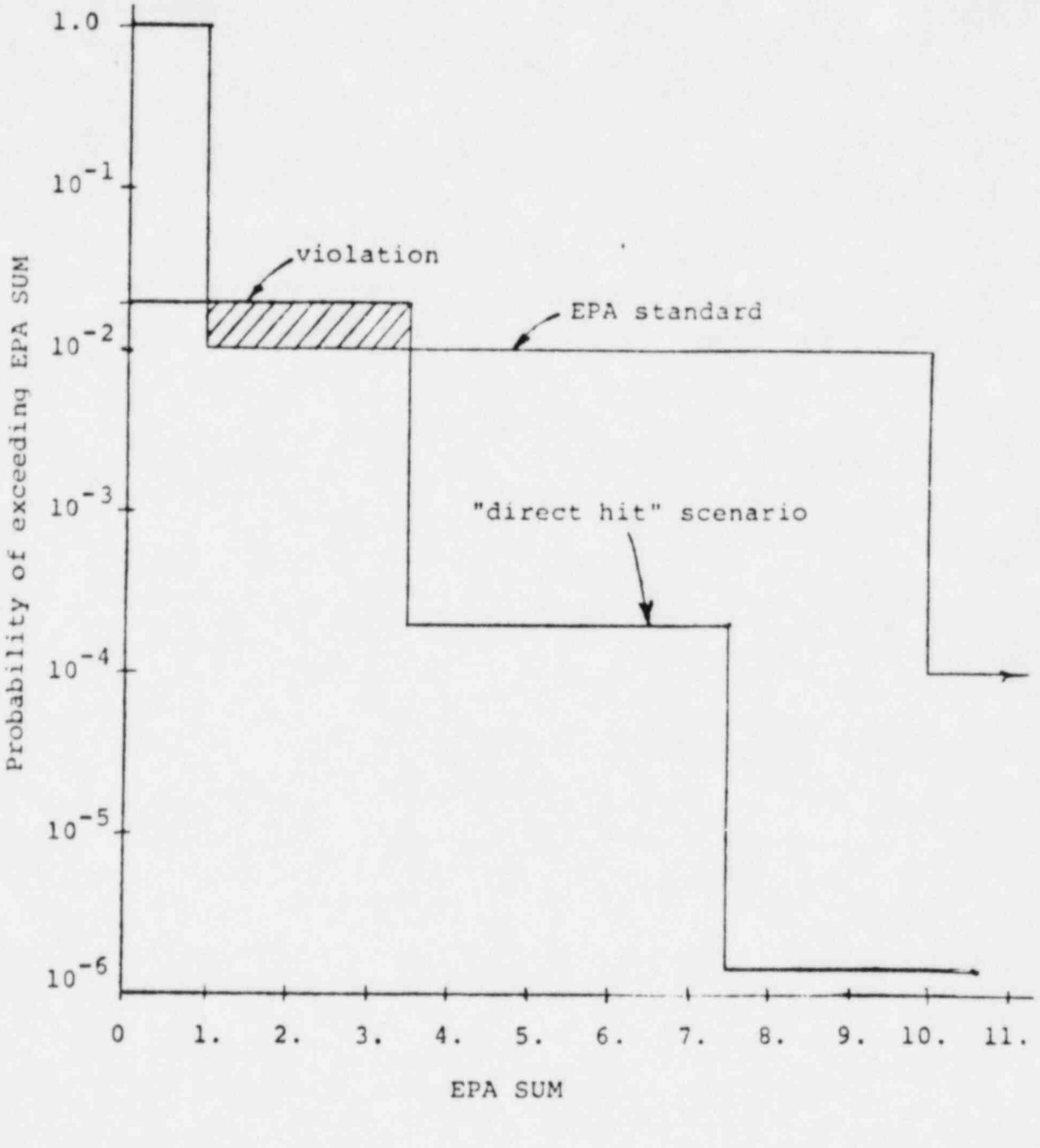


Figure 12. CCDF for Disinterment Scenario 1: The Direct Hit. The Shaded Area Indicates Violation of the Draft EPA Standard.

Brine-Pocket Penetration Scenario

Equation (13) was evaluated with P_{hit} = .02 probabilities, P(N), of N brine pocket penetrations that release radionuclides. Equation (15) was used to evaluate t_j and the EPA Sum was evaluated according to Equation (17). Table 10 values were interpolated to give values at t_j. These results are tabulated in Table 11 and the resulting CCDF is presented in Figure 13. As can be seen from Figure 13, this scenario alone is enough to violate the draft EPA Standard.

Groundwater Transport Scenarios

We evaluated the groundwater transport scenarios for three source term assumptions discussed previously:

Source #1: fractional release of 10^{-5} to 10^{-7}/year of entire inventory,

Source #2: fractional release of 10^{-5} to 10^{-7}/year of a fraction of the inventory, that is given by considering the number of boreholes and assigning one roomful of waste to each borehole,

Source #3: fractional release rate from the waste form of 10^{-3} to 10^{-7} with the same waste fraction assumption of Source #2. In addition we considered solubility limits and mixing assumed in the backfilled regions (Appendix A). This is the standard SNL source model assumption.

In addition, for these scenarios, we sampled the variables required for the analysis from the ranges given in Tables 6, 7, 8, and 9 by the LHS technique [15]. We chose 50 combinations of input and calculated an EPA Sum (Equation 1) for each. Also, we chose three independent samples to estimate the effects of sampling error.

We calculated radionuclide discharge rates for 50,000 years following waste emplacement. We intergrated these discharge rates over each of five 10,000 year periods and evaluated Equation (1). Thus, we calculated a CCDF for each of the five 10,000 year periods for each of the three independent samples and for each of the source term assumptions. When appropriate room number and release rates were also sampled. Figures, 14, 15, and 16 give the resulting CCDF's.

Table 12

Probabilities and Consequences for the Brine Pocket Scenario

N	P(N)	Consequence (EPA Sum)
0	.942	0
1	.0565	9.21
2	.0017	24.0
3	3.39E-5	38.0

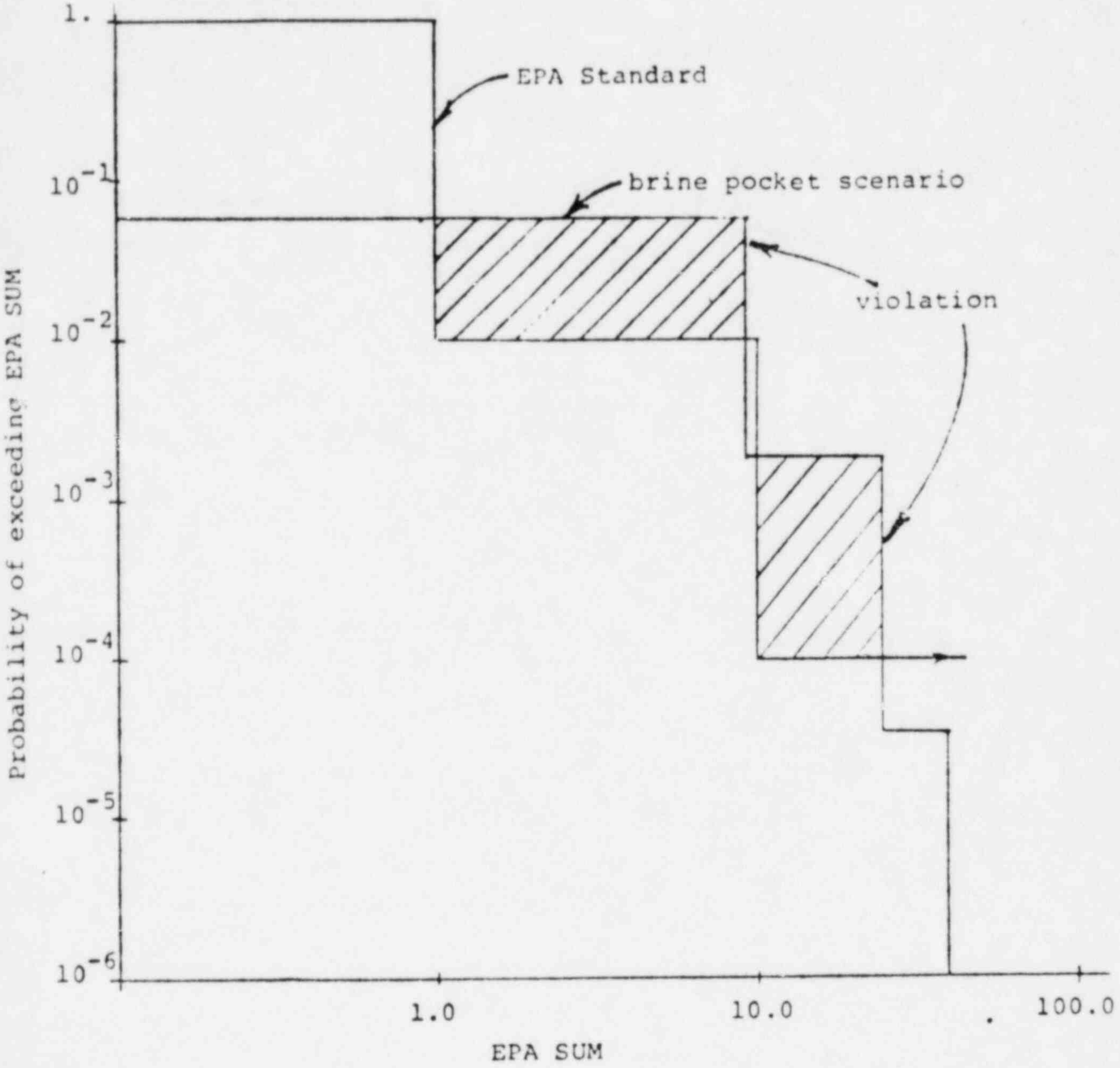


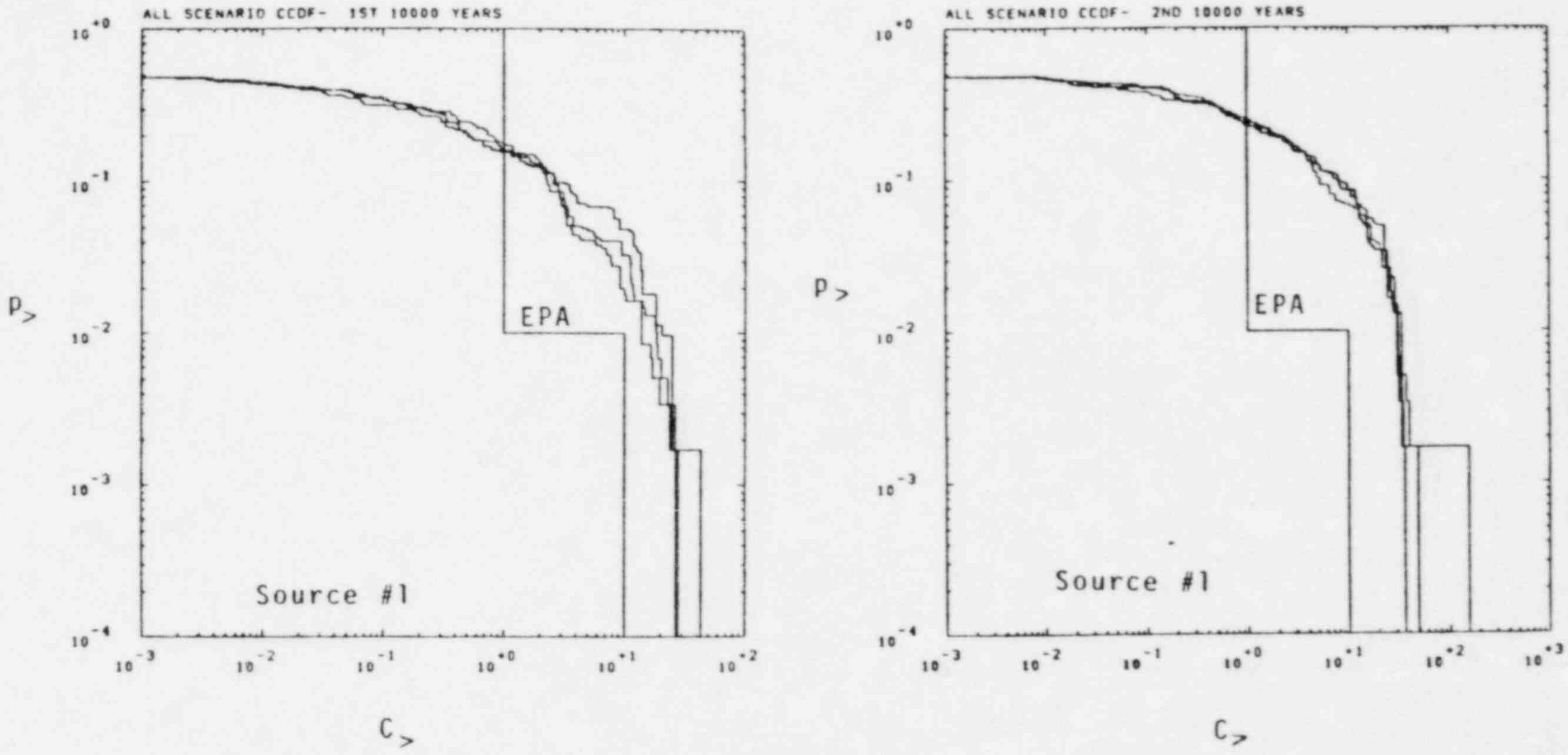
Figure 13. CCDF for the Brine Pocket Penetration Scenario. The Shaded Areas Indicate Violation of the Draft EPA Standard.

The three traces shown in each figure result from evaluation with the three independent samples. The vertical spread in these plots represents an estimate of sampling error associated with the LHS method. As can be seen, the sampling error is small over most of the curve.

All scenarios evaluated with Source #1, (Figure 14) yield large discharges. The results of these calculations indicate violation of the draft EPA Standard in each of the five 10,000 year periods.

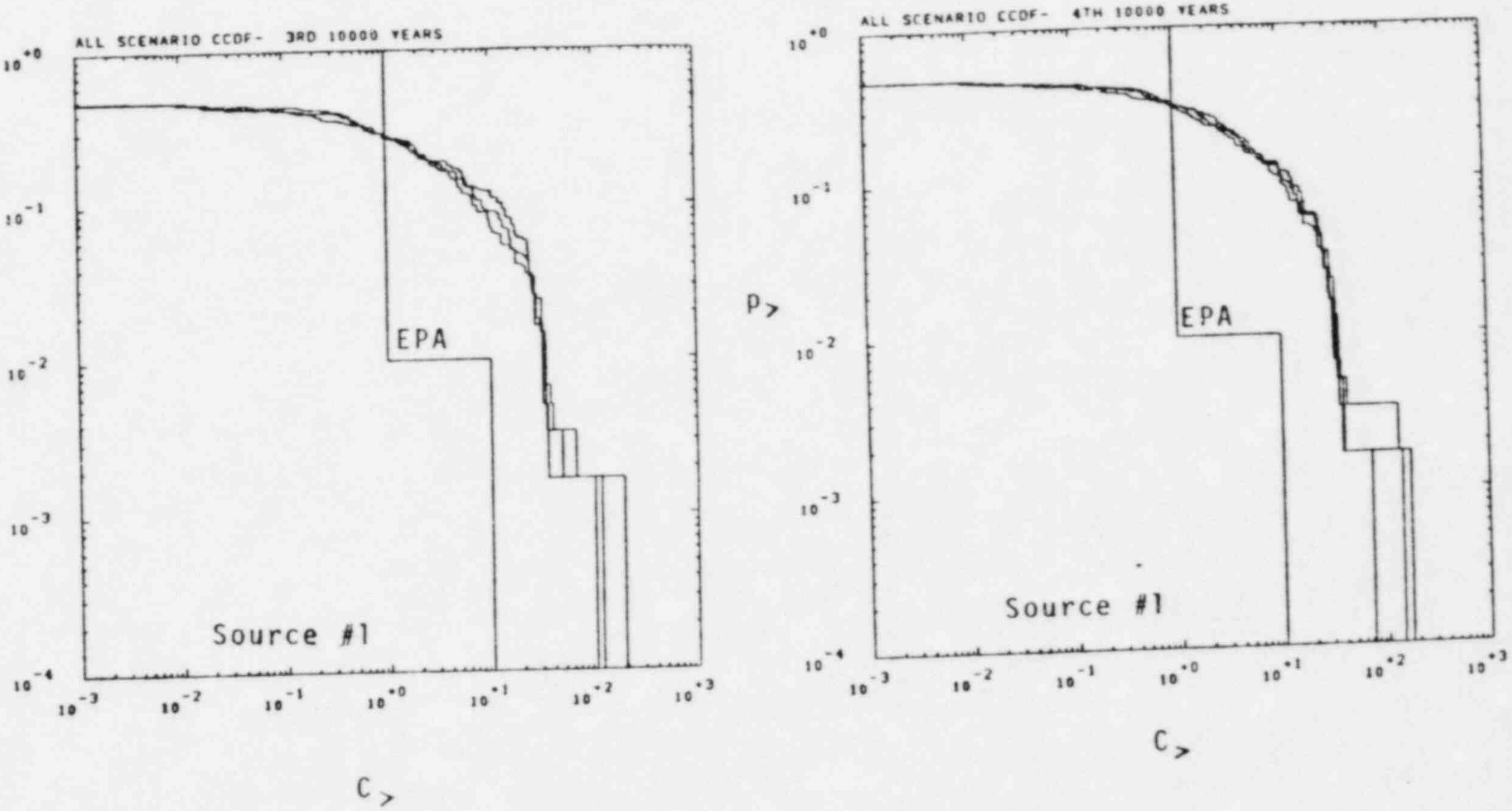
The scenarios evaluated with Source #2 (Figure 15) yield less discharged, indicating that compliance may be achieved during the first 10,000 year period. The results indicate that the standard is violated in the other periods, although the magnitude of the violation is smaller. The results of the disinterment and brine-pocket scenarios should also be considered during the first 10,000 years.

All scenarios evaluated with Source #3 indicate compliance may be achieved if the mixing cell assumption can be justified. As shown in Appendix A, the release rate with this type of source assumption should asymptotically approach that given by the waste form description alone (Table 7). Since we have assumed a less stable waste form, we can infer that the time required to achieve that asymptotic release rate was long compared to the times for which discharges were calculated. The importance of the release rate assumption is indicated by comparing Figures 14, 15, and 16.



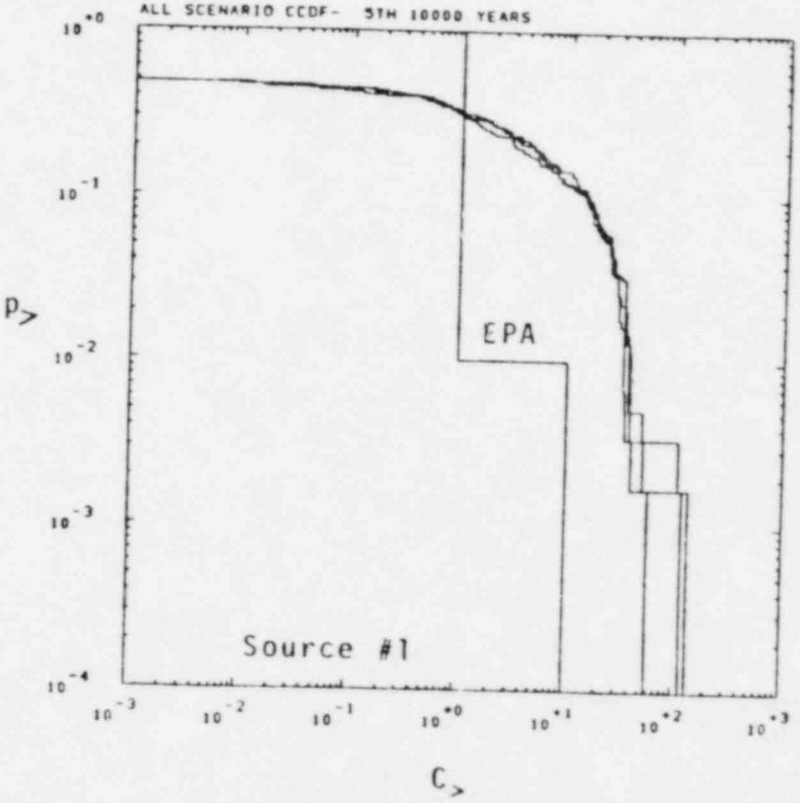
(a) (b)

Figure 14. CCDFs for the Groundwater Transport Scenarios With Source #1.



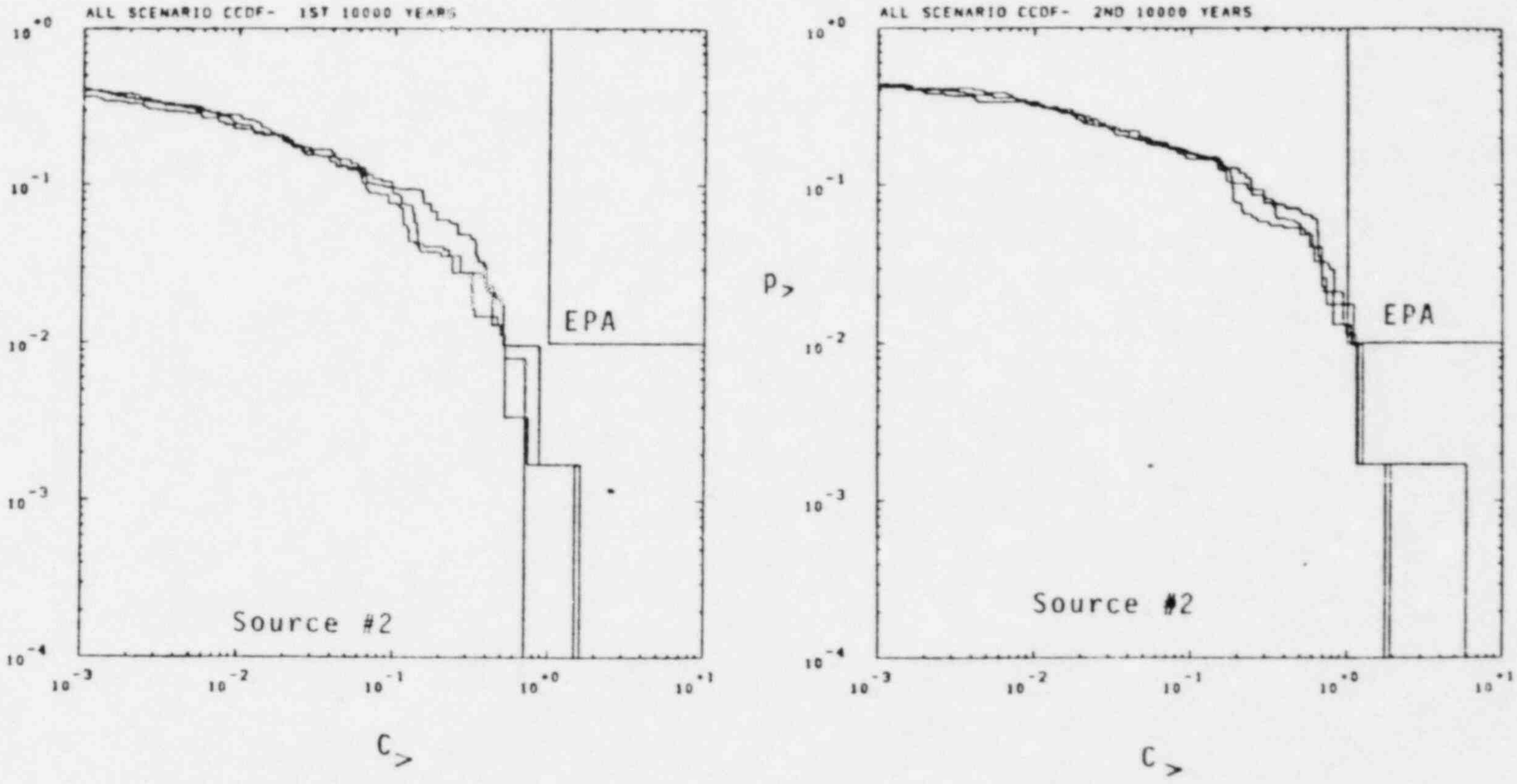
(c) (d)

Figure 14. CCDFs for the Groundwater Transport Scenario With Source #1.



(e)

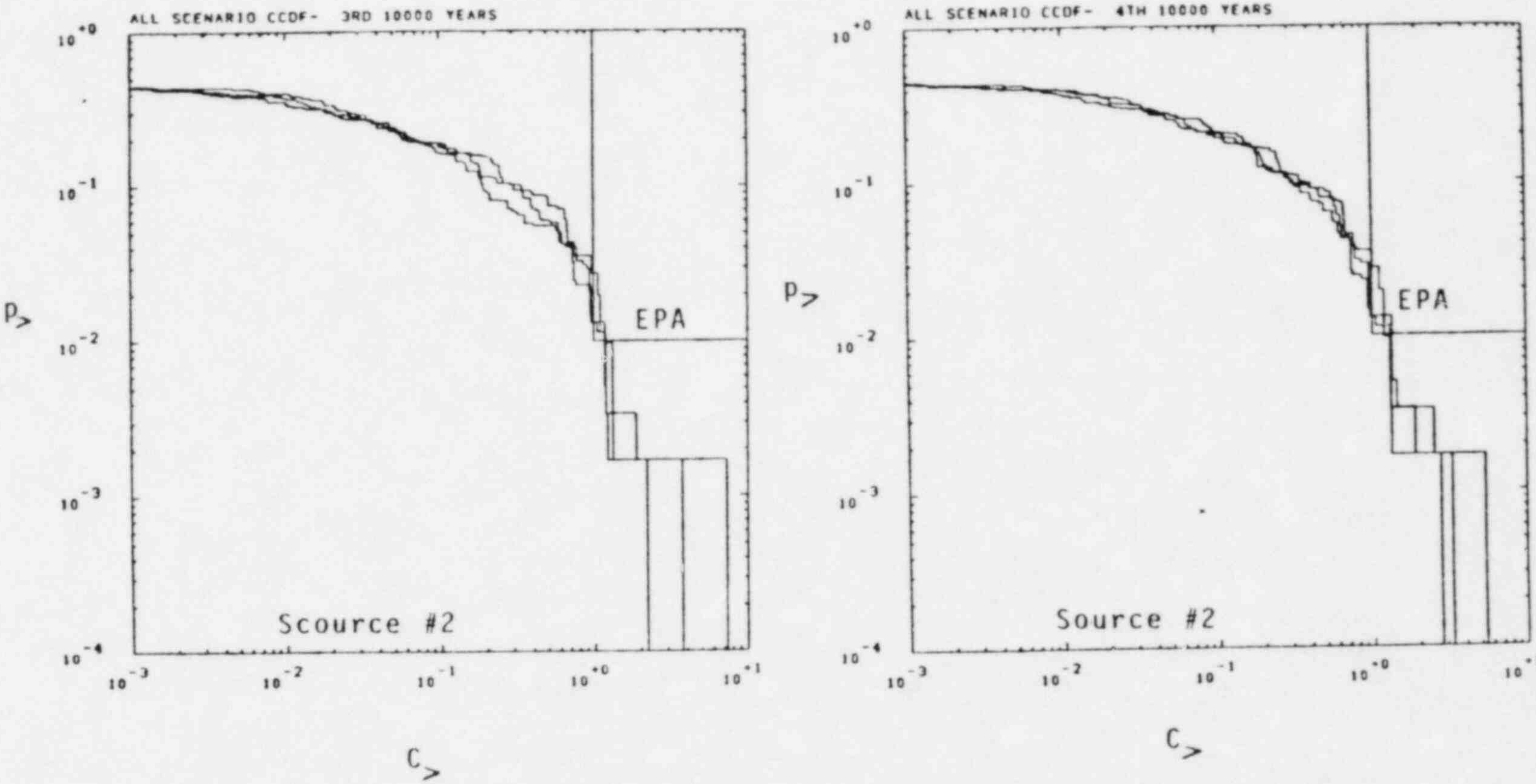
Figure 14. CCDFs for the Groundwater Transport Scenario With Source #1.



(a)

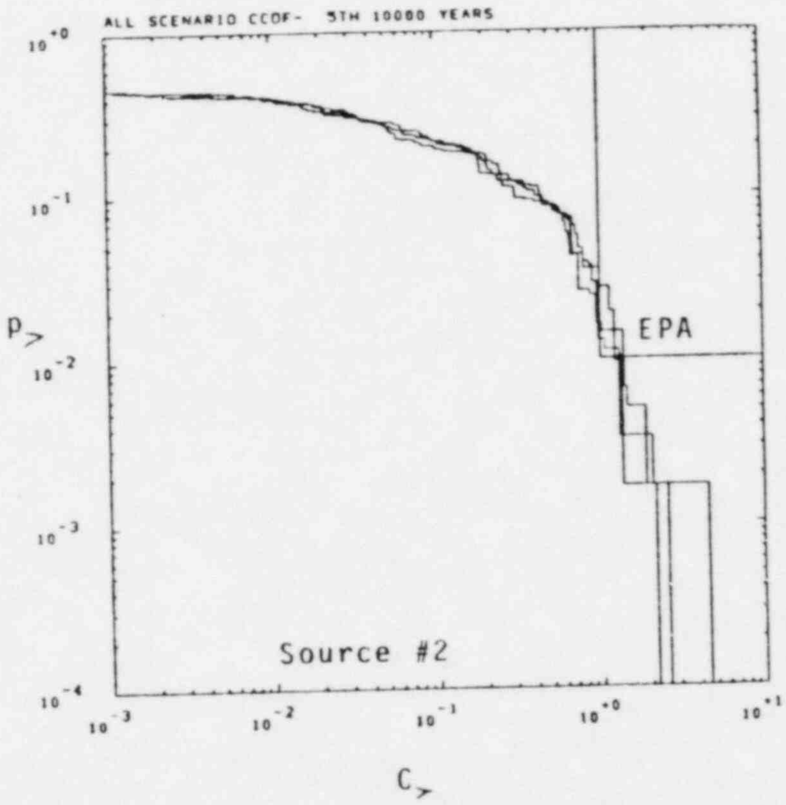
(b)

Figure 15. CCDFs for the Groundwater Transport Scenario With Source #2.



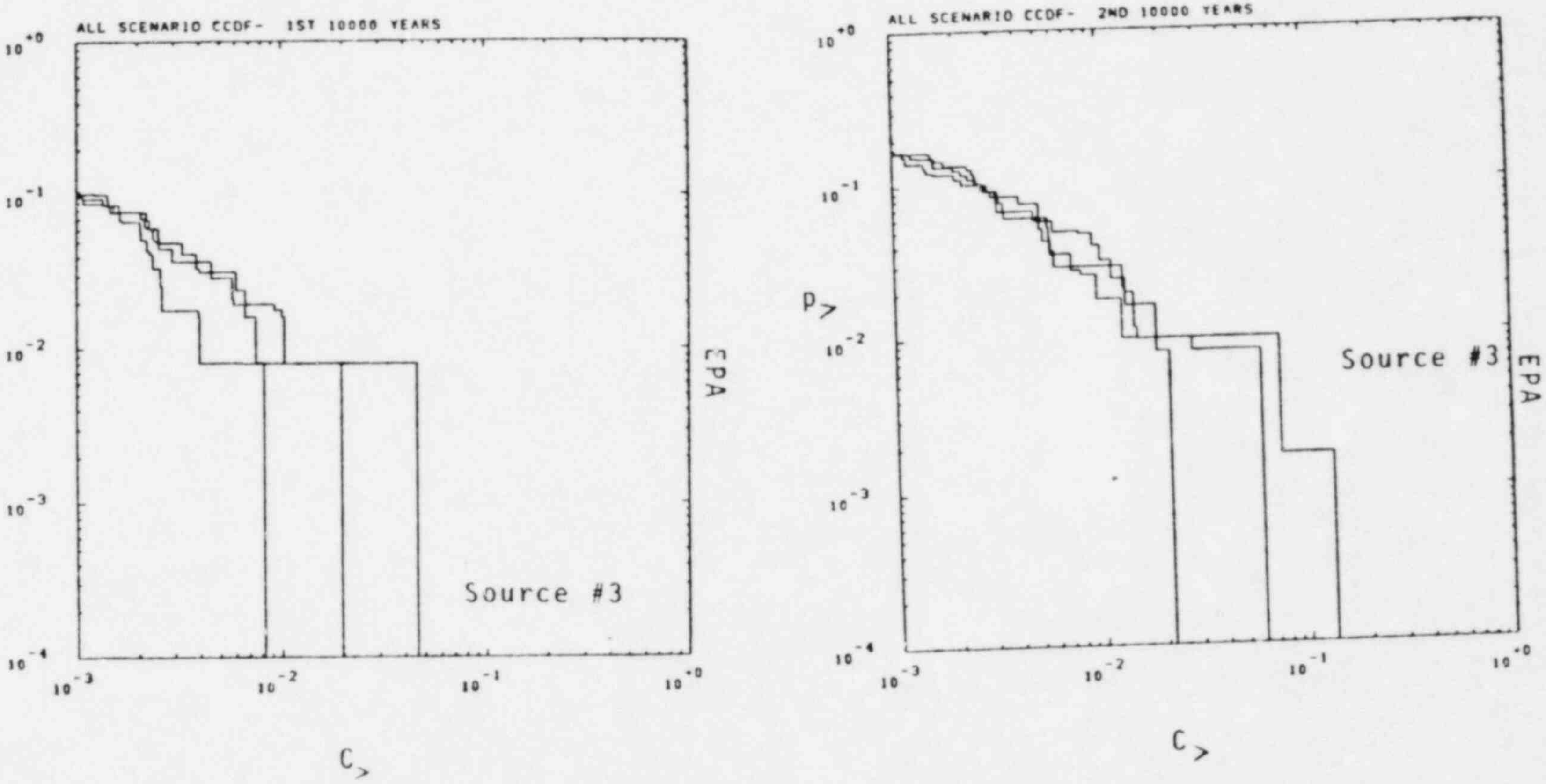
(c) (d)

Figure 15. CCDFs for the Groundwater Transport Scenario With Source #2



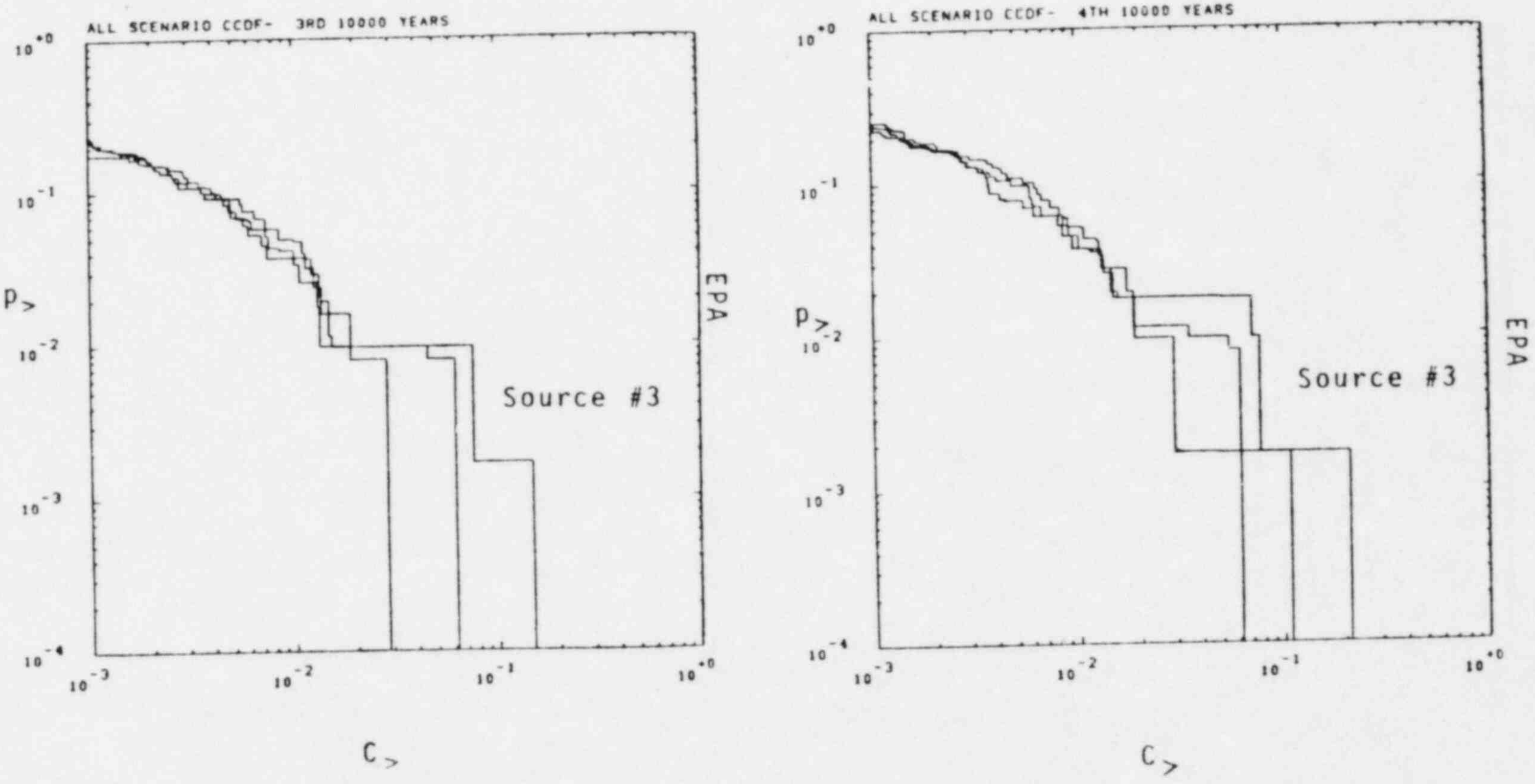
(e)

Figure 15. CCDFs for the Groundwater Transport Scenario With Source #2.



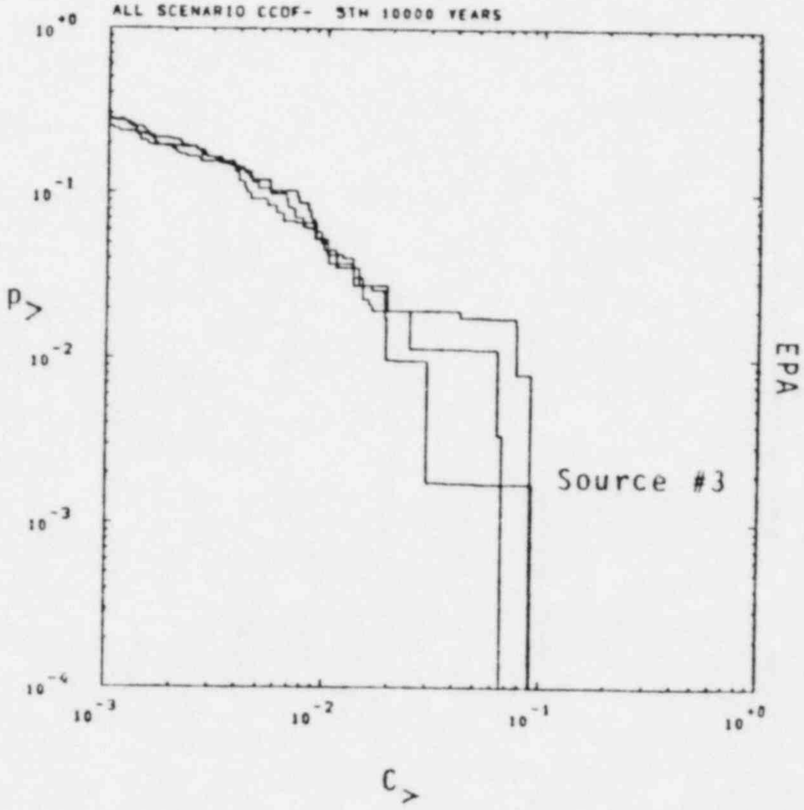
(a) (b)

Figure 16. CCDFs for the Groundwater Transport Scenario With Source #3.



(c) (d)

Figure 16. CCDFs for the Groundwater Transport Scenario With Source #3.



(e)

Figure 16. CCDFs for the Groundwater Transport Scenario With Source #3.

D. Sensitivity Analysis Results

For the groundwater transport scenarios we applied standard sensitivity analysis methods to the calculated discharges as measured by the EPA Sum (Equation 1) [17]. The results of this analysis indicate the relative importance of the various data used in the transport calculations (Tables 6 through 9). The important variables determined by this analysis are tabulated here:

Scenario	Source	
	#1 and #2	#3
1	k_d (U), τ	Cs (U), τ
2	k_d (U), τ	Cs (U), τ
3	k_d (U), τ , K_{ua}	Cs (U), τ
4	k_d (U), τ , K_{ua}	Cs (U), τ

In this table,

$K_d(U)$ = Uranium sorption equilibrium constant (Table 8),

τ = Leach period (reciprocal of Table 7),

Cs(U) = Uranium solubility limit (Table 9),

K_{ua} = Hydraulic conductivity of the upper aquifer, Unit O or D (Table 6).

The variables appearing in the table are those that control the time of first discharge (breakthrough) and the rate of discharge. For slowly varying discharge rates:

$$\begin{pmatrix}\text{Integrated}\\ \text{Discharge}\end{pmatrix} \cong \begin{pmatrix}\text{Discharge}\\ \text{Rate}\end{pmatrix} * \left(T - \begin{matrix}\text{Breakthrough}\\ \text{Time}\end{matrix}\right)$$

where T denotes the end of the period of interest, e.g., T = 10,000 years.

For Source #3 the variables controlling the breakthrough time do not appear to be as important as for Sources #1 and #2. This is likely due to the shape of the leading edge of the discharge pulse. As shown in Appendix A, the mixing cell model gives a release rate (source term for NWFT/DVM) that is initially proportional to the leach rate, τ^{-1}, and increases linearly with time initially. For the leach limited sources, the discharge rate is nearly a step-function. Thus, we expect a larger sensitivity to variables controlling the time of breakthrough for sharply defined breakthroughs than for the slowly increasing breakthroughs typical of Source #3.

Of note is the appearance of Uranium -- specific variables, k_d (U) and Cs (U). Since we calculated discharges for a mixture of radionuclides, the variables influencing all radionuclides may be expected to be most important e.g., τ, K_{ua}. The appearance of element-specific variables indicates the dominance of the element(s) in the mixture.

VII. Conclusions

From the analyses presented here, we can draw several conclusions and make recommendations:

- Drilling in sedimentary basins indicates potentially serious consequences resulting from "direct hits" and we see no practical way to reduce the consequences of this scenario. They are fixed by the canister contents. Therefore, to reduce the seriousness of this scenario, steps would be needed to discourage drilling, perhaps with surface markers indicating the presence of the repository. Also, reducing the cross-sectional area of the canisters, as might be achieved by stacking canisters in storage holes, would reduce the probability of hitting the canisters by vertical drilling. The consequence, however, may be raised.

- Brine pockets in bedded salt may pose a significant problem in complying with the draft EPA Standard. Therefore, site characterization should directly address the question of identifying any brine pockets that may be present. If few brine pockets and low drilling rates can be expected, the probability of this scenario can be kept low.

  Our modeling of this scenario is admittedly simplistic. Impermeable backfills may be expected in actual designs serving to limit the amount of waste that may mix with the flowing brine. Refining the description of this scenario is clearly needed. For example, we assumed (1/40) · 1/106 of the entire waste inventory came into contact with the flowing brine. This fraction represents some 48 canisters distributed over a 100 foot length of the storage room. In fact, one may expect the brine to flow predominantly in the vicinity of the borehole, contacting a much smaller fraction of the waste and reducing the consequences of this scenario. The descriptions of flow along such a borehole and in the backfilled room, as well as the description of brine pocket characteristics require further analysis. One would expect a description in terms of the fraction of the waste contacted and the amount of flow expected; only such a description would be useful in analyzing such scenarios.

- The importance of the groundwater transport scenarios in contributing to estimates of compliance may be great or small, depending on the source model chosen. Since all result from drilling, steps should be taken to keep future drilling rates low. Reducing the consequence may be achieved if the assumptions used in Sources #2 and #3 can be justified. Clearly, the fraction of waste available to flowing groundwater, solubilities, and mixing processes must be understood to estimate the importance of the contribution. Unfortunately, we have not analyzed any processes in the area adjacent to a repository. Such analysis would be needed to make definitive statements on these assumptions.

An important assumption has been made throughout this analysis and should be noted. We have assumed failed shafts and boreholes to remain open throughout the calculation, 50,000 years. In fact they would creep closed unless the groundwater flowing through them dissolved enough salt to keep the conduit open. We have not investigated this assumption in detail. The capability to address it is currently being developed with the DNET Model[12].

In general, we should note that we have not addressed the entire set of scenarios developed in Reference 6. We have addressed a subset of scenarios that we feel may be important. Judging from the results calculated, these scenarios are indeed important for any repository similar to the one we have assumed.

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VIII. Appendix A: The Mixing Cell Source Model

In Source #3 we allow the backfilled regions to be modeled as a mixing cell in which flowing groundwater is assumed to mix with radionuclides in the volume of the mixing cell. The concentration of radionuclides released from the backfilled regions is then given by the uniform concentration in the mixing cell. This model can be calculated analytically for a single stable species.

Let

V = mixing cell volume,

C = radionuclide concentration in water in the mixing cell,

L = rate of radionuclide input into V from waste form leaching,

Q = rate of water flow through V.

In this illustration we will assume the leach rate, L, to be given as a fractional rate, λ_L, of the remaining contaminant in the waste form,

$$L = \lambda_L N_o e^{-\lambda_L t}$$

where N_o is the initial contaminant inventory.

The contaminant concentration in the mixing cell is described by

$$V \frac{dC}{dt} = L - QC \qquad (A.1)$$

If we let

$$\lambda_o \equiv Q/V$$

the solution of A.1 is

$$C(t) = \frac{\lambda_L N_o}{(\lambda_o - \lambda_L)V} \left(e^{-\lambda_L t} - e^{-\lambda_o t} \right) \qquad (A.2)$$

For small t

$$C(t) \cong \frac{\lambda_L N_o}{V} t$$

Thus the concentration of the radionuclide increases linearly from zero.

The asymptotic release rate QC_∞ can be obtained from Equation (A.1) with

$$\frac{dC}{dt} = 0,$$

$$QC_\infty = L$$

Thus, for long times, the release rate approaches a value governed by the rate of waste form leaching. The release rate from the mixing cell is then less than or equal to the release rate given by consideration of the waste form leaching alone.

For decaying radionuclide chains, this model is implemented numerically in NWFT/DVM according to the following compartment model.

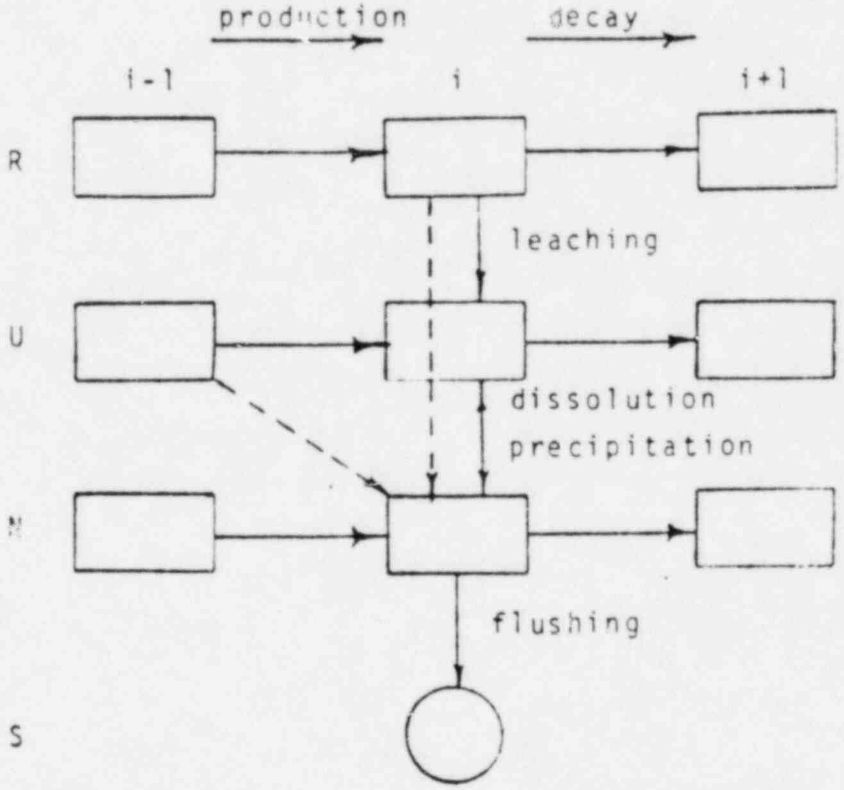

Figure A.1. Implementation of the Mixing Cell Source Model for NWFT/DVM.

Radionuclides remaining in the waste form are represented by Compartments, R. The waste form breakdown rate governs transfer from Compartments R to Compartments U. The inventory in Compartments U is examined along with the water volume in the mixing cell and solubility limits to transfer all or part of that inventory into the mixing cell. The mixing cell inventory is denoted by Compartments N. The mixing cell is flushed constantly to give a release source (S) of

$$S_i = \lambda_0 N_i$$

When solubility limits are applied, radionuclides may be transferred from Compartments N to Compartments U, representing precipitation. For large solubility limits, Compartments U may be empty. Then transfer to Compartments N may occur directly along the dotted paths of Figure A.1.

Horizontal transfer between radionuclides compartment, i, and compartments i + 1 or i - 1 represents decay and production.