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INCORPORATING LONG-TERM CLIMATE CHANGE IN PERFORMANCE ASSESSMENT FOR THE WASTE ISOLATION PILOT PLANT

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ABSTRACT

The United States Department of Energy (DOE) is developing the Waste Isolation Pilot Plant (WIPP) in southeastern New Mexico for the disposal of transuranic wastes generated by defense programs. Applicable regulations (40 CFR 191) require the DOE to evaluate disposal-system performance for 10,000 yr. Climatic changes may affect performance by altering groundwater flow.

Paleoclimatic data from southeastern New Mexico and the surrounding area indicate that the wettest and coolest Quaternary climate at the site can be represented by that at the last glacial maximum, when mean annual precipitation was approximately twice that of the present. The hottest and driest climates have been similar to that of the present. The regularity of global glacial cycles during the late Pleistocene confirms that the climate of the last glacial maximum is suitable for use as a cooler and wetter bound for variability during the next 10,000 yr. Climate variability is incorporated into groundwater-flow modeling for WIPP PA by causing hydraulic head in a portion of the model-domain boundary to rise to the ground surface with hypothetical increases in precipitation during the next 10,000 yr. Variability in modeled disposal-system performance introduced by allowing head values to vary over this range is insignificant compared to variability resulting from other causes, including incomplete understanding of transport processes. Preliminary performance assessments suggest that climate variability will not affect regulatory compliance.

Keywords

climate change, nuclear waste disposal, performance assessment, Waste Isolation Pilot Plant, WIPP

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INTRODUCTION

The Waste Isolation Pilot Plant (WIPP) is planned as a research and development facility to demonstrate the safe disposal of transuranic wastes generated by the United States Department of Energy (DOE). It is located in semiarid rangeland in southeastern New Mexico 42 km east-southeast of the city of Carlsbad (Figure 1), at a surface elevation of 1040 m above mean sea level. Bedded halite of the Late Permian Salado Formation (approximately 255 million yr old) has been selected as the host strata because of its extremely low permeability, long-term geologic stability, and creep properties that facilitate sealing. Excavation of the waste-emplacement panels 655 m below the ground surface is partially complete, and additional panels will be excavated in the future as needed.

No transuranic waste is presently at the WIPP, and before disposing of waste in the facility the DOE must evaluate compliance with applicable long-term regulations of the United States Environmental Protection Agency (EPA). The regulation of interest here is Subpart B of 40 CFR 191 (Environmental Standards for the Management and Disposal of Spent Nuclear Fuel, High-Level and Transuranic Radioactive Wastes, Final Rule [US EPA, 1985]), which requires evaluation of the consequences of future inadvertent intrusion into the repository. As discussed below, climate change will affect performance only if the repository is breached. Compliance with long-term regulations for which human intrusion does not apply, including those implementing the Resource Conservation and Recovery Act (RCRA), will not be affected.

Sandia National Laboratories is performing iterative preliminary performance assessments (PAs) to provide guidance to the WIPP Project while preparing for final evaluations of compliance with applicable long-term regulations. Preliminary PAs for the WIPP have been performed in 1990 (Bertram-Howery et al., 1990; Rechard et al., 1990; Helton et al., 1991), 1991 (WIPP PA Division, 1991 a,b,c; Helton et al., 1992), and 1992 (WIPP PA Department, 1992 a,b; Sandia WIPP Project, 1992; WIPP PA Department 1993 a,b). As stipulated by Congress (Public Law 102-579, 1992), biennial preliminary PAs will continue to be performed for the WIPP until the DOE is prepared to submit a final PA to the EPA (currently scheduled for 1998).

The Containment Requirements of 40 CFR 191 set probabilistic limits on the 10,000-yr cumulative releases of radionuclides at the "accessible environment" boundary, which is the ground surface and, for the WIPP, a vertical plane in the subsurface 2.4 km at its closest point from the waste (WIPP PA Department, 1992a, 1993a). The regulation requires estimating the probability of all releases, and allows larger releases at lower probabilities. "Inadvertent human intrusion" (e.g., by drilling during future exploration for natural resources) must be considered as a possible event.

Preliminary PAs to date indicate that, without human intrusion, the repository will comply with 40 CFR 191 B without difficulty (WIPP PA Department, 1992a, 1993a). Significant quantities of radionuclides from the WIPP will be transported only as solutes in a liquid phase (brine), and all modeling to date indicates that brine will not migrate more than a few tens of meters from the waste in 10,000 yr if the waste-disposal panels are not breached by intrusion (WIPP PA Department, 1993a,b). However, if human intrusion occurs, radionuclides may reach the accessible environment by two paths. First, some material will be brought to the ground surface immediately during drilling. This release may be important for regulatory compliance (WIPP PA Department, 1992a), but will not be affected by climate change and is not discussed further here. Second, additional radionuclides may reach the subsurface boundary of the accessible environment long after the intruding borehole is abandoned, by transport as solutes in brine that migrates up the borehole and laterally away from the repository in an overlying permeable unit (the Culebra Dolomite Member of the Late Permian Rustler Formation). Long-term changes in climate have the potential to affect disposal-system performance by altering flow and transport in this subsurface pathway.

LONG-TERM CLIMATE VARIABILITY

PRESENT CLIMATE

Mean annual precipitation at the WIPP has been estimated to be between 28 and 34 cm/yr (Hunter, 1985). Freshwater pan evaporation in the region is estimated to be 280 cm/yr (US DOE, 1980). At Carlsbad (100 m lower than the WIPP surface elevation), 53 yr (1931-1983) annual means for precipitation and temperature are 32 cm/yr and 17.1°C (University of New Mexico, 1989). Annual precipitation is dominated by a late summer monsoon, when solar warming of the continent creates an atmospheric pressure gradient that draws moist air inland from the Gulf of Mexico (Cole, 1975). Winters are generally cool and dry.

PALEOCLIMATES AND CLIMATIC VARIABILITY

Geologic data from southeastern New Mexico and the surrounding region show repeated alternations of wetter and drier climates throughout the Pleistocene, corresponding to global cycles of glaciation and deglaciation. Data from plant and animal remains and paleo-lake levels permit quantitative climate reconstructions for the region only for the last glacial cycle, and confirm the interpretation that conditions were coolest and wettest during glacial maxima (Swift, 1993). The hottest and driest conditions since the last glaciation have been similar to those of the present. Modeling of global circulation patterns suggests that these changes resulted from the disruption and southward displacement of the winter jet stream by the ice sheet, causing an increase in the frequency and intensity of winter storms throughout the American Southwest (COHMAP Members, 1988). Mean annual precipitation 22,000 to 18,000 yr ago, when the last North American ice sheet reached its southern limit roughly 1500 km north of the WIPP, was approximately twice that of the present (Figure 2). Mean annual temperatures may have been as much as 5°C colder than at present.

Glacial periodicities have been stable for the last 800,000 yr (Milankovitch, 1941; Hays et al., 1976; Imbrie et al., 1984; Imbrie, 1985). Barring anthropogenic changes in the Earth's climate, relatively simple modeling of climatic response to orbital changes in insolation suggests that the next glacial maximum will occur in approximately 60,000 yr (Imbrie and Imbrie, 1980). The extent to which unprecedented anthropogenic climate changes may alter this conclusion is uncertain, but presently available models of climatic response to an enhanced greenhouse effect (e.g., Mitchell, 1989;

Houghton et al., 1990) do not predict changes of a larger magnitude than those of the Pleistocene. Furthermore, published models do not suggest significant increases in precipitation in southeastern New Mexico following global warming (Washington and Meehl, 1984; Wilson and Mitchell, 1987; Schlesinger and Mitchell, 1987; Houghton et al., 1990). Even allowing for anthropogenic change, climate variability at the WIPP can be bounded by Pleistocene extremes (Swift, 1993).

Relatively shorter-term climatic fluctuations have occurred throughout the Pleistocene and Holocene with periodicities on the scale of hundreds to thousands of years (Figure 2). The causes of these nonglacial fluctuations are, in general, unknown, but paleoclimatic data indicate that precipitation may have approached glacial highs at some times during the Holocene (Swift, 1993). Based on the past record, fluctuations of this sort are probable during the next 10,000 yr, and must be included in long-term assessments. The climate-variability model selected for WIPP PA conceptually incorporates uncertainty in both glacial and nonglacial climatic fluctuations by allowing conditions to reach, at a maximum, glacial extremes three times during the next 10,000 yr.

HYDROLOGIC MODELING

WIPP PA models groundwater flow and radionuclide transport in the Culebra Dolomite Member of the Rustler Formation because it is the most transmissive water-saturated unit above the repository (WIPP PA Department 1992b, 1993a). Present groundwater flow is substantially less in other units, and only the Culebra is considered to represent a possible pathway for radionuclide release.

The Culebra is a fractured dolomite approximately 7 m thick, and is present throughout the region of interest at depths typically of 200 m or greater. In most locations, it is bounded above and below by low-permeability mudstones and evaporites (Beauheim and Holt, 1990; Brinster, 1991). WIPP PA modeling treats the Culebra as a perfectly confined aquifer, with flow occurring only in two dimensions in the model domain (Figure 3) (WIPP PA

Department 1992b, 1993a).

No direct evidence exists for the location of either recharge to or discharge from the Culebra. Potentiometric-surface maps constructed from available well data imply inflow to the model domain from the north and outflow to the south. Mercer (1983) suggested that recharge probably occurs 15 to 30 km northwest of the WIPP where the Rustler Formation crops out. Lambert (1991) and Lambert and Carter (1987) have speculated on the basis of isotopic evidence that little if any recharge may be occurring now and that present flow reflects long-term draining from recharge during Pleistocene glacial periods. Preliminary modeling indicates that long-term draining is not incompatible with observed hydraulic properties (Davies, 1989; Corbet and Wallace, 1993). Three-dimensional regional flow modeling in progress will permit additional testing of this hypothesis and provide an improved model for the spatial and temporal variability in vertical flux (Corbet and Wallace, 1993).

For the purposes of PA modeling, the location of recharge is unspecified, but is assumed to occur north of the model domain. The amount of present recharge is not specified, except through the assumption that present hydraulic head values within the model domain reflect steady-state conditions. Changes in recharge are not modeled explicitly because the assumed recharge area is outside the model domain, and are instead approximated by varying head values in a "recharge strip" through which most inflow occurs along the northern edges of the model domain (Figure 3). Heads are not varied along other boundaries, reflecting the belief that all recharge occurs north of the model domain. For the 1991 and 1992 preliminary PAs, climatic variability in recharge to the Culebra has been approximated using the following relationship (Swift, 1991; WIPP PA Division, 1991b,c; Helton et al., 1992):

$$\frac{h_f(t)}{h_p} = \frac{3A+1}{4} - \frac{A-1}{2}\left(\cos\theta t + \frac{1}{2}\cos\phi t - \sin\frac{1}{2}\phi t\right). \qquad (Eq.1)$$

This function defines time-dependent head values in the "recharge strip" where

$h_f(t)$ = head (m) in selected boundary cells in the Culebra at time t,

h_p = estimated head (m) in selected boundary cells in the Culebra now,

A = recharge amplitude factor (dimensionless), as described below,

θ = frequency (Hz) for Pleistocene glaciations,

ϕ = frequency (Hz) for second-order climatic fluctuations, and

t = time (sec) after decommissioning of the WIPP.

Figure 4 shows values of the function at 1000-yr time intervals, as implemented in the 1991 WIPP PA.

This function is not used to predict future climates, but rather is designed to provide a simple way to examine the influence of possible climatic changes during the next 10,000 yr. Variable parameters permit examining sensitivity to both the frequency and amplitude of climatic change.

Periodicity of the function is controlled by two terms, θ and ϕ, that can be adjusted to approximate the periodicities observed in the paleoclimatic record. In preliminary PAs to date, fixed values have been used for these two parameters, yielding a glacial periodicity of 60,000 yr and a second-order periodicity of 3000 yr. If performance is believed to be sensitive to the frequency of climatic change, different values for these parameters can be used in future analyses.

Amplitude of the function is controlled by A, which can be scaled appropriately for the groundwater-flow model parameter to be varied. For the 1991 PA, this parameter was varied from 1 to 1.16. The minimum value, 1, results in no change in boundary head values in the "recharge strip" during the entire 10,000 yr period. The maximum value, 1.16, causes head values to rise from their initial (present) elevation (e.g., 880 m in the northernmost cell) to the elevation of the ground surface (1030 m in the northernmost cell) at the end of the 10,000 period (Figure 4). Geologic evidence suggests that this increase in head may not be unrealistic: fossil spring deposits at lower elevations in the region indicate discharge from a water table at the ground surface during the late Pleistocene (Bachman, 1981; 1987). Relatively low topographic relief in the region precludes head rising significantly above the ground surface.

DISCUSSION

In keeping with the probabilistic requirements of 40 CFR 191, consequence modeling for WIPP PA is performed using a Monte Carlo approach that relies on multiple realizations of system performance using deterministic models of physical processes (WIPP PA Department, 1992a,b). Values for uncertain parameters are selected using a Latin hypercube sampling strategy (McKay et al., 1979) from distributions based on available data, and each realization uses a separate input vector of sampled parameter values. The methodology is well-suited for conducting uncertainty and sensitivity analyses that provide quantitative and qualitative insights about the potential variability in model results caused by uncertainty in specific input data (Helton et al., 1991, 1992; Helton, 1993).

The recharge amplitude factor, A, defined above for Equation 1, was one of 45 parameters sampled for use in 60 realizations in the 1991 preliminary PA (Helton et al., 1992) and one of 49 such parameters used in 70 realizations in the 1992 PA (WIPP PA Department, 1993a). Analyses were performed for scenarios involving a single intruding borehole and two intruding boreholes. In both 1991 and 1992, simulations were repeated using the full suite of realizations for each of several conceptual models for radionuclide transport in the Culebra. The choice of transport model for use in a final PA will be made after additional data are obtained (US DOE, 1993). Cases considered to date include transport in a single-porosity, fracture-only medium and transport in a dual-porosity medium which allowed diffusion into the pore volume of the dolomite matrix. Cases were considered both with and without chemical retardation of radionuclides by sorption. Computational modeling, including discussion of the computer codes used, and the results of these analyses are described in detail elsewhere (WIPP PA Division 1991b, Helton et al., 1992; WIPP PA Department 1992b, WIPP PA Department, 1993a).

Variability in the recharge amplitude factor contributed significantly to variability in total releases only for the conceptual model that included dual-porosity transport without chemical retardation (Helton et al., 1992). Even in this case, regression analysis shows variation in boundary head values to have been a minor contributor to overall variability in model outcomes, ranking below parameters used to describe radionuclide solubility in the source term, permeability of the borehole pathway from the repository to the Culebra, and fracture spacing in the Culebra.

Two analyses were conducted as part of the 1991 PA that specifically examined the importance of boundary head variations by using fixed minimum (1.00) and maximum (1.16) values for the recharge amplitude factor (Helton et al., 1992). The full suite of 60 realizations were repeated for each analysis with sampled values used for all other parameters, resulting in two sets of outcomes which were in all ways comparable except for the value used for A. Results are shown in Figure 5 for both single-porosity and dual-porosity transport with chemical retardation. For all but a few of the single-porosity realizations, using the maximum recharge factor has essentially no effect on total releases. This lack of sensitivity apparently occurs because single-porosity transport is rapid enough that most of the long-lived radionuclides (e.g., U) that enter the Culebra reach the accessible environment within 10,000 yr regardless of the head gradient. For the relatively slower dual-porosity transport, the maximum recharge factor increased releases for essentially all realizations in which subsurface releases occurred.

CONCLUSIONS

For preliminary comparison with requirements of 40 CFR 191, performance estimates are displayed as complementary cumulative distribution functions (CCDFs) that indicate the probability of exceeding various levels of cumulative radionuclide releases to the accessible environment. Because the modeling system and data base are incomplete, no CCDFs presented to date in WIPP PA are suitable for compliance evaluations. Regulatory limits are commonly displayed, however, on preliminary CCDFs to provide guidance to the Project and to assist in identifying those areas in which uncertainty has the potential to affect compliance.

Figure 6 is a composite display of mean CCDFs that shows the relative importance of the recharge factor in the 1991 PA (Helton et al., 1992).

Estimated performance is shown for three alternative cases: transport in a single-porosity medium with chemical retardation and sampled values for the recharge factor, transport in a dual-porosity medium with chemical retardation and the maximum recharge factor used in all realizations, and transport in a dual-porosity medium with chemical retardation and the minimum (i.e., present) recharge factor used in all realizations. Except for those parameters used to describe the alternative transport cases, all parameter values were the same for each case. Results do not include releases at the ground surface during drilling, and therefore are an incomplete measure of overall performance. Limits specified by 40 CFR 191 B are given only for reference.

Single-porosity transport results in the largest releases and the CCDF closest to the EPA limits. Separate curves are not shown for the single-porosity extreme climate cases because, as shown in Figure 5, changing the recharge factor has essentially no effect on the largest releases that determine the location of the mean CCDF. Varying boundary head values within this range does not affect regulatory releases if transport occurs in a single-porosity medium.

The two mean CCDFs shown for dual-porosity transport are significantly further from the EPA limits than the CCDF for the single-porosity case. Allowing boundary head values to rise in response to climatic change does result in an increase in estimated releases, but not sufficiently to affect compliance.

Although all results shown here are conditional on the assumptions used in the analyses, and may change as flow and transport models are improved, the conclusion that climate change is unlikely to affect compliance appears robust. The uncertainty remaining about the correct conceptual models for both climatically-varying recharge and radionuclide transport in the Culebra is substantial, but as long as releases calculated with extreme head elevations and the least favorable transport model considered remain below the EPA limits, climate change alone will not lead to regulatory violations. Defensibility of this conclusion will depend in part on improved understanding of regional flow.

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FIGURE CAPTIONS

Figure 1. Location of the Waste Isolation Pilot Plant

Figure 2. Estimated mean annual precipitation at the WIPP during the late Pleistocene and Holocene (Swift, 1993).

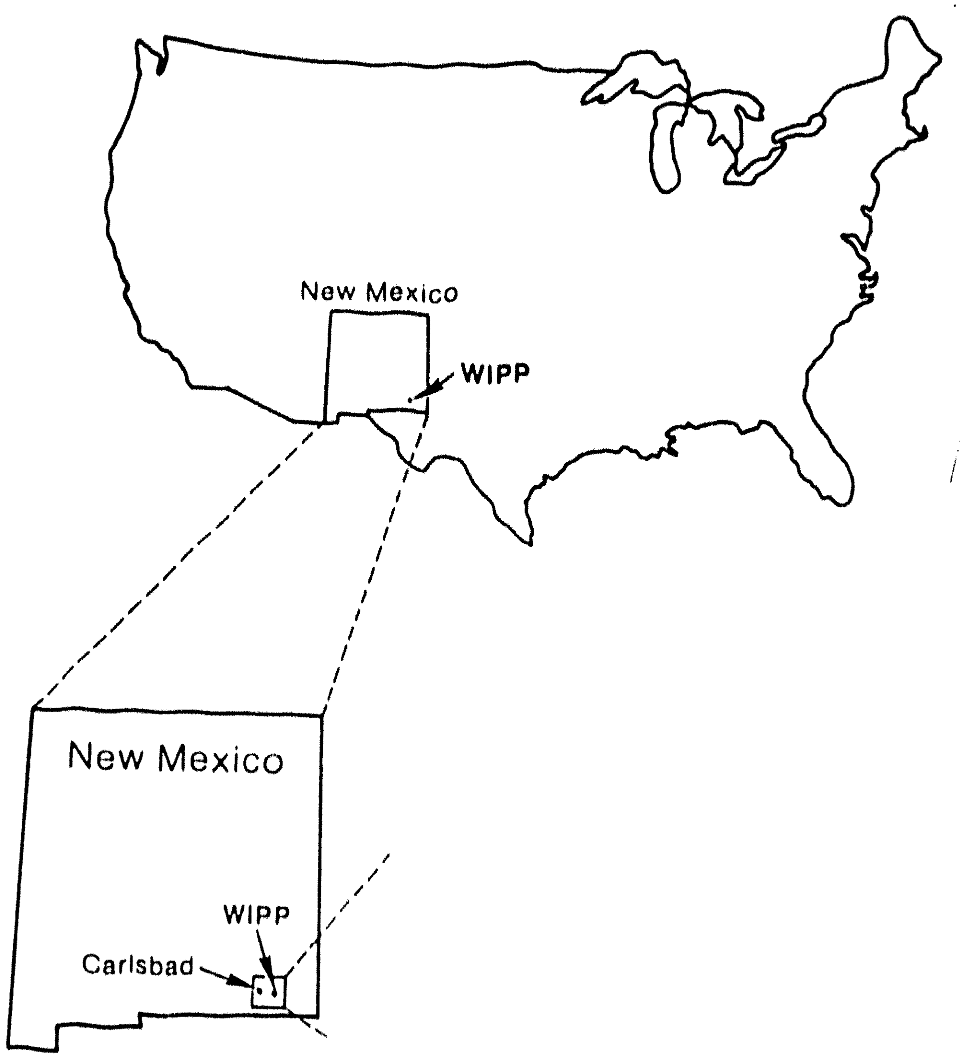
Figure 3. Topographic map of the WIPP area showing the boundaries of the regional groundwater flow model used in the 1991 performance assessment (modified from WIPP PA Division, 1991b).

Figure 4. Boundary head function (Eq. 1) as implemented in the 1991 WIPP performance assessment (WIPP PA Division, 1991b). For this figure, A = 1.16, $\theta = 1.7\times10^{-12}$ Hz, and $\phi = 2\times10^{-10}$ Hz.

Figure 5. Scatterplots showing 10,000-yr cumulative radionuclide releases to the subsurface boundary of the accessible environment 60 for realizations using minimum and maximum values for the recharge amplitude factor (Helton et al., 1992). Releases are normalized to the total inventory, as specified by 40 CFR 191. Releases are shown for single (top) and dual (bottom) porosity conceptual models for radionuclide transport including chemical retardation. Both plots show releases from scenarios involving two intrusions into the same panel 1000 yr after decommissioning (see WIPP PA Division [1991b] for a discussion of scenario definitions). Normalized releases below 10^{-8} (above) and 10^{-12} (below) are plotted at those values.

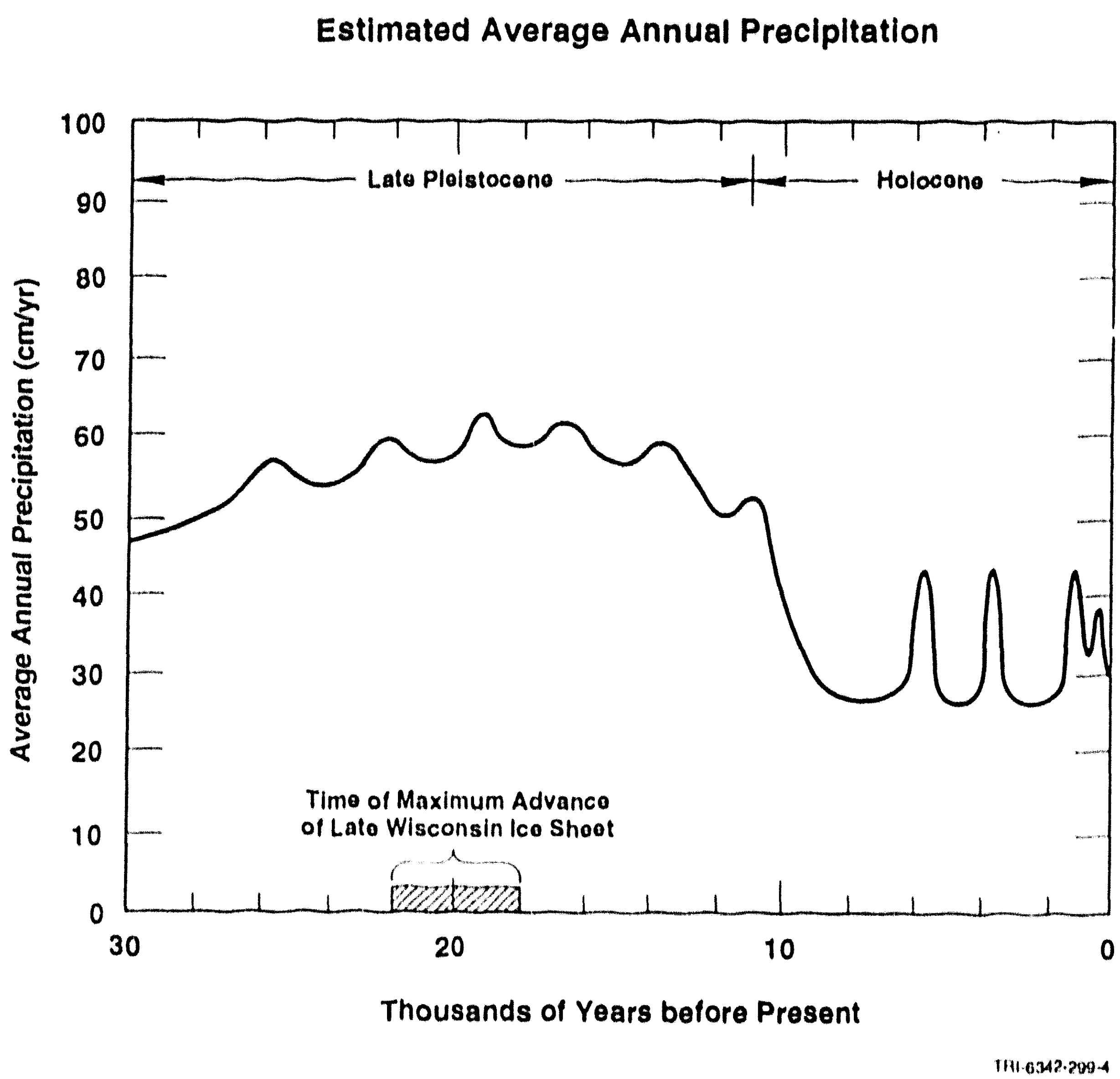
Figure 6. Mean CCDFs showing estimated performance of the WIPP for subsurface

releases only following intrusions at 1000 yr after decommissioning (Helton et al., 1992). Releases are normalized to the total inventory, as specified by 40 CFR 191. Curves are shown for three cases: single-porosity transport with sampled values for the recharge factor, dual-porosity transport with the maximum value for the recharge factor, and dual-porosity transport with the minimum value for the recharge factor. All cases include chemical retardation. EPA limits are shown for reference only. Results here are not suitable for direct comparison to regulatory limits because they are preliminary (i.e., based on an incomplete modeling system and data base) and because they do not include releases at the ground surface during drilling.



Modified From
TRI 6342-1223-1
SAND 92-0700/1
Fig 1-1

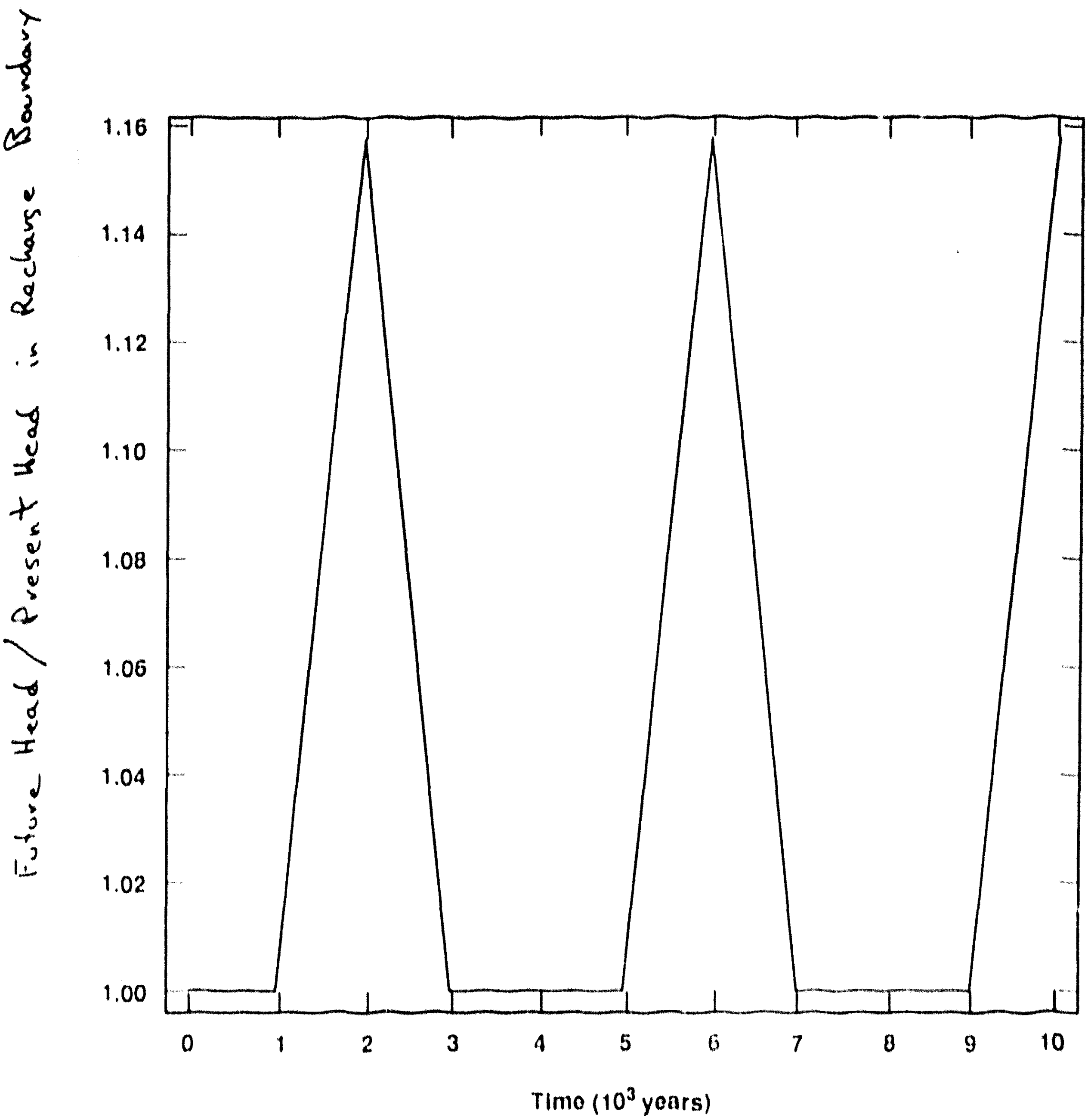
Figure 1



SAND92-0700/2

Fig 2-15

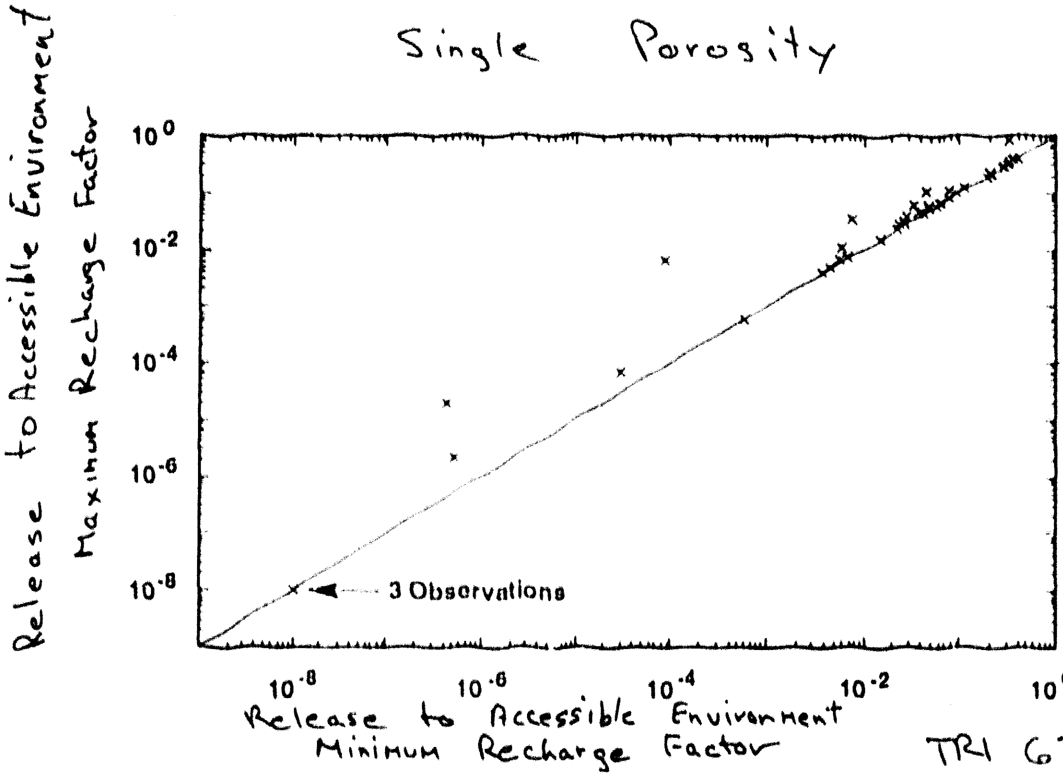
Figure 2



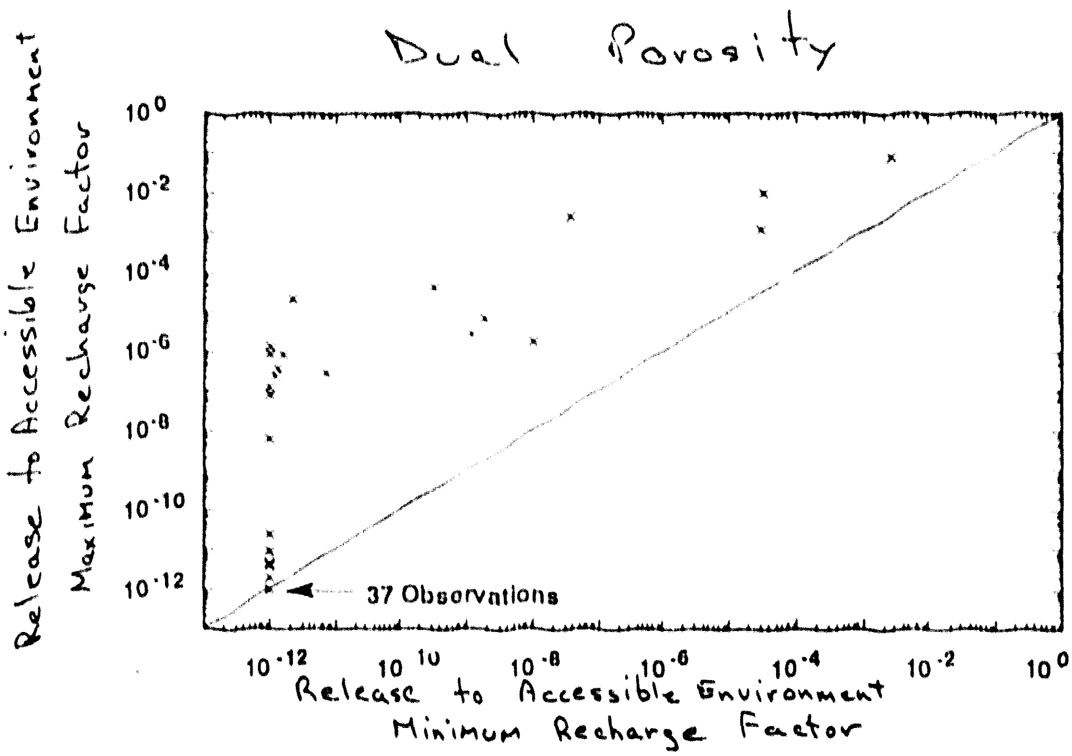
TRI-6342-1361-0

SAND 91-0893/2
Fig 6-6

Figure 4



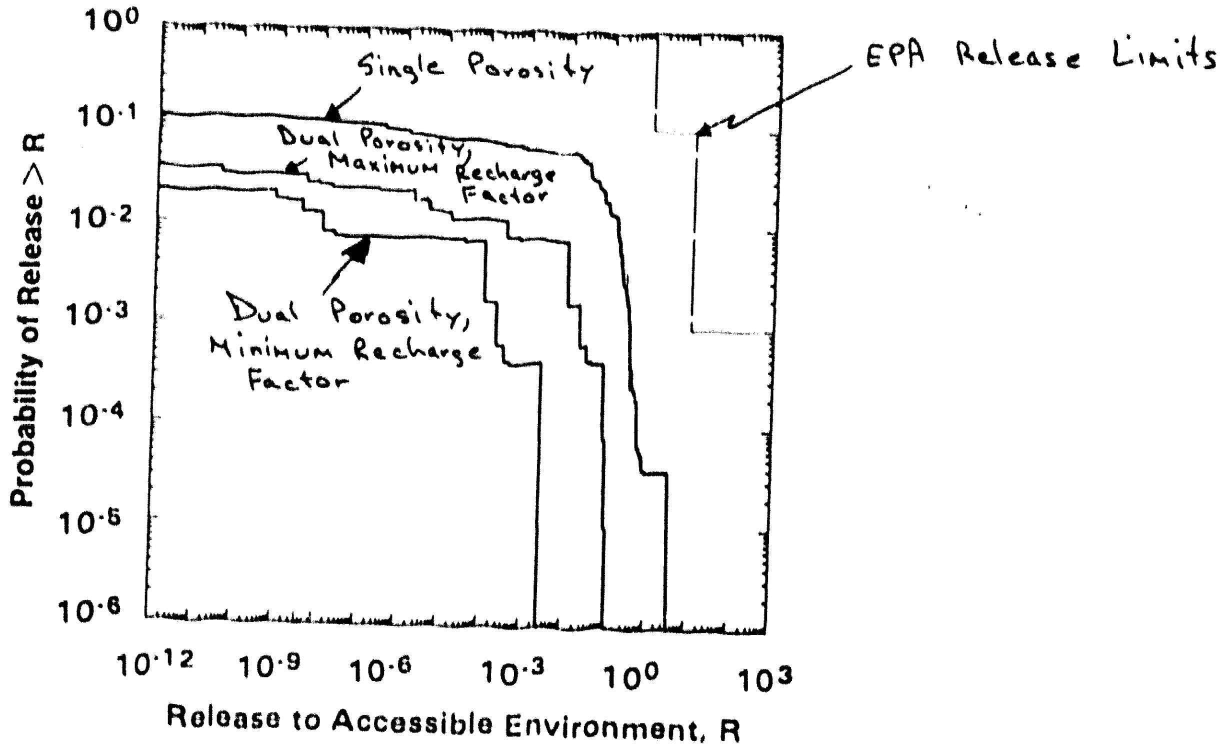
TRI 6342-1649-0



1647-0

Figure 5

SAND91-0893/4
Figs 5.5-1 and 5.5-2



overlay of mean
curves from
TRI 6342 1572-0
1574-0
1579-0

SAND 91-0893/4, Figs 5.5-4
(1991 V.4, + 5.3.3
Helton et al. 1992)

Figure 6

END

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12/22/93