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The Consequences of Disposal of Low-Level Radioactive Waste from the Fernald Environmental Management Project: Report of the DOE/Nevada Independent Panel

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The Consequences of Disposal of Low-Level Radioactive Waste from the Fernald Environmental Management Project: Report of the DOE/Nevada Independent Panel

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EXECUTIVE SUMMARY

Multiple investigations followed in the aftermath of a transportation incident involving shipment of low-level radioactive waste from Fernald, Ohio, destined for shallow burial at the Nevada Test Site. Investigators of the incident quickly established that leakage of moisture from in transit waste occurred because of a combination of factors, including stress-fractured shipping containers and development of free liquid (water) from vibration associated with transport. Given these conditions, the logical follow-up questions are

- Does disposing of waste, which contains excess moisture, in stress-fractured metal boxes have a significant impact on the site at which the waste is buried, the Nevada Test Site?
- Is the impact sufficient to endanger public health and safety?

The Nevada Test Site Environmental Management program of the Department of Energy formed a panel of independent primarily local scientists to evaluate these questions. They developed an issues question list and considered the impact of each question on the system performance of the Area 5 radioactive waste site. The following question resolutions were reached unanimously by the Independent Panel:

> ***Question:*** Does reduced container integrity affect performance of the disposal system?
> ***Response:*** No. No credit for container integrity was assumed in the Area 5 performance assessment.
>
> ***Question:*** Does reduced container integrity contribute significantly to subsidence of waste pits?
> ***Response:*** No. Subsidence is driven primarily by void space within and between containers. Stress fractures in containers have a virtually insignificant effect on subsidence.
>
> ***Question:*** Does the presence of excess moisture in waste affect system performance?
> ***Response:*** No. Results of an analysis of all radiological release pathways for both ambient and subsided/flooded conditions (assuming 25% of the waste inventory contains excess moisture, a bounding assumption) indicate that there is no significant performance impact.

To evaluate sensitivity to different percentages of waste inventory with excess moisture, simulation modeling of moisture redistribution in alluvial deposits of the vadose zone was conducted; no significant performance impact was noted for even an unrealistic extreme case of 100% of the waste inventory containing excess moisture. The lack of impact is a result of two independent factors: (1) the extreme conservatism used in assumptions for the Area 5 performance assessment and (2) the arid climate, low-moisture content and considerable depth to the water table for the alluvium-filled valleys of the Nevada Test Site. These features result in an exceptionally viable site for disposal of low-level radioactive waste.

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THE CONSEQUENCES OF DISPOSAL OF LOW-LEVEL RADIOACTIVE WASTE FROM THE FERNALD ENVIRONMENTAL MANAGEMENT PROJECT: REPORT OF THE DOE/NEVADA INDEPENDENT PANEL

by

Bruce Crowe, Wayne Hansen, Robert Waters,
Michael Sully, and Daniel Levitt

Abstract

The Department of Energy (DOE) convened a panel of independent scientists to assess the performance impact of shallow burial of low-level radioactive waste from the Fernald Environmental Management Project, in light of a transportation incident in December 1997 involving this waste stream. The Fernald waste has been transported to the Nevada Test Site and disposed in the Area 5 Radioactive Waste Management Site (RWMS) since 1993. A separate DOE investigation of the incident established that the waste has been buried in stress-fractured metal boxes, and some of the waste contained excess moisture (high-volumetric water contents). The Independent Panel was charged with determining whether disposition of this waste in the Area 5 RWMS has impacted the conclusions of a previously completed performance assessment in which the site was judged to meet required performance objectives.

To assess the performance impact on Area 5, the panel members developed a series of questions. The three areas addressed in these questions were (1) reduced container integrity, (2) the impact of reduced container integrity on subsidence of waste in the disposal pits and (3) excess moisture in the waste.

The panel has concluded that there is no performance impact from reduced container integrity—no performance is allocated to the container in the conservative assumptions used in performance assessment. Similarly, the process controlling post-closure subsidence results primarily from void space within and between containers, and the container is assumed to degrade and collapse within 100 years.

The impact of excess waste moisture on site performance was assessed for all identified pathways for potential release of waste radionuclides. No significant performance impacts were noted for either the base-case scenario (ambient conditions) or a scenario involving subsidence and flooding of the waste cells. Computer simulations of the redistribution of moisture in the vadose zone from the presence of "wet" waste show that the performance of the Area 5 RWMS was not significantly affected even if 100% of the waste contains excess moisture. The panel concluded that combination of an arid climate, low-moisture content of the valley-fill alluvium, and considerable depth of the water table, results in an exceptionally viable site for disposal of low-level radioactive waste. The performance of the site is not significantly affected by disposal of the Fernald waste stream.

1.0 Introduction

The Environmental Management program of the Department of Energy (DOE/EM) convened an Independent Panel to evaluate the performance impact on Area 5 of the Nevada Test Site of disposing of low-level radioactive waste in metal containers. The need for this assessment resulted from a recent transportation incident in which moisture was observed leaking from a truck transporting low-level radioactive waste during a routine shipment from the Fernald Environmental Management Project, Ohio, to the NTS. The free liquid in the waste leaked through stress fractures, which were caused by vibration during transportation. This problem was combined with container design errors and was augmented by storage, handling, and shipping procedures. (DOE Type B Accident Investigation Report, 1998).

The Independent Panel evaluated the performance impact of disposing of stress-fractured metal boxes (white metal boxes) containing low-level radioactive waste with high moisture content. The moisture content of the waste exceeded assumptions used in previous PAs of radioactive waste management sites (RWMS) on the NTS (Shott et al. 1997a). The low-level radioactive waste will be referred to as "Fernald waste stream 006."

The authors use the following phrases to refer to the unique conditions associated with the disposed Fernald waste. The waste containers will be referred to as "stress-fractured containers" or "white metal boxes" (the origin and nature of the container fractures are described in the DOE Type B Accident Investigation Report) (DOE, 1998). Waste with excess moisture or "wet waste" will refer to "waste with volumetric water content," that which exceeds the moisture content of valley-fill alluvium, the surrounding deposits of the sites on the NTS used to dispose low-level radioactive waste (DOE, 1996). The waste with excess moisture was associated with the water-leakage incident during transportation to the NTS in December 1997. Please note, all the Fernald waste does not contain excess moisture, and all the metal boxes do not contain stress fractures.

2.0 Panel Membership

The panel was selected from a list of candidates submitted to DOE/EM, DOE/Headquarters, and representatives of the State of Nevada. The following criteria were used to select candidates for participation on the Independent Panel:

1. Candidate must have a multidisciplinary background with established expertise in one or several of the fields of PA, risk assessment, vadose-zone hydrology, geology of the NTS, engineering, chemistry, and health physics/risk-dose assessment.

2. Candidate must have demonstrated experience and familiarity with risk assessment and performance assessment (PA) studies for disposal of low-level radioactive waste.

3. Candidate must have limited or no current involvement in the ongoing disposal operations or contractor studies of the low-level radioactive waste sites sponsored by the DOE. However, some prior exposure to and understanding of these programs is desirable to avoid delays from the acquisition of background information necessary to conduct the panel studies.

4. Candidate must have knowledge of the hydrologic and geologic setting of the NTS and the alluvial basins of Yucca Flat and Frenchmen Flat.

5. Priority will be given to qualified researchers living in or associated with research institutions located in the state of Nevada.

6. Candidate must be available for required panel activities during an approximate 30-day period.

The following persons were selected for the Independent Panel (resumes on file with DOE/NV; listed in alphabetical order):

Dr. Bruce Crowe, Los Alamos National Laboratory, Las Vegas, Nevada
(geology, risk assessment)

Dr. Wayne Hansen, Los Alamos National Laboratory, Los Alamos, New Mexico
(health physics, environmental dose assessment, PA)

Dr. Anthony Hechanova, Harry Reid Center, University of Nevada, Las Vegas, Nevada
(nuclear engineering, radiological risk assessment)

Dr. Roger Jacobson, Desert Research Institute, Las Vegas, Nevada
(geochemistry, hydrology)

Mr. Charles Voss, Golder Associates, Inc., Redmond, Washington
(geomechanics, risk assessment)

Dr. Robert Waters, Sandia National Laboratory, Albuquerque, New Mexico
(risk assessment, environmental engineering)

Mr. Mike McKinnon of the Nevada Department of Environmental Protection (NDEP), Las Vegas, Nevada, served as an observer of panel activities for the State of Nevada.

Each panel member wrote a summary report, which was submitted to the DOE/EM, that evaluated the performance impacts of container flaws and excess moisture on the Area 5 PA. On March 17, 1998, panel members presented summaries of their reports and briefed the NDEP on how they reached their conclusions. This summary report was prepared by B. Crowe, W. Hansen and R. Waters of Los Alamos National Laboratory and M. Sully and D. Levitt of Bechtel, Nevada. The latter authors were not members of the Independent Panel but they conducted the vadose-zone modeling at the request of the panel. The individual reports of the Independent Panel members will be found in Appendix A.

3.0 Technical Issues: Performance Impacts

The panel identified the following questions as most important for identifying the potential performance impacts of the stress-fractured metal boxes and possible excess moisture in the shipped waste streams:

1. Does the disposal of waste in stress-fractured containers have significant impact on the expected performance of the low-level radioactive waste disposal system at Area 5?

2. Does the disposal of stress-fractured containers have significant impact on subsidence, an issue that was identified in reviews of the PAs for the Area 5-disposal site?

3. Is excess moisture in some waste streams a significant issue with respect to performance objectives for disposal of low-level radioactive waste?

3.1 Background Assumptions used by the Independent Panel

The panel made the following assumptions to facilitate a timely review of this issue.

1. These evaluations will focus on the Fernald waste stream and identified shipping containers. Other implications are considered, but the thrust of the panel investigations is on the performance impacts of disposal of the Fernald waste.

2. Based on information provided by the DOE and DOE-contractors, all the Fernald waste associated with the suspect metal containers has been disposed in the Area 5 RWMS. Accordingly, the panel focused their investigations entirely on performance impacts for this disposal site.

3. The PA for the Area 5 RWMS has been reviewed extensively and accepted using a formal review process (DOE 1996). The panel did not attempt to conduct a repetitive review of the Area 5 PA. Instead, the focus of the activities was on how new information/insight gained from the transportation incident might change any pertinent assumptions or calculations used in the Area 5 PA. Accordingly, the assumptions and calculations used in the existing Area 5 PA study were closely followed and examined with respect to the potential changes caused by disposal of waste with excess moisture in stress-fractured white metal boxes.

4. The topic of inadvertent human intrusion is judged not to be affected by the disposal of the white metal boxes with excess moisture. The panel did not assess this issue.

5. The performance objectives for the Area 5 PA are primarily dose-based. However, the dose-calculations for the PA are derived from analyses of radionuclide releases along multiple pathways. The issues of stress-fractured containers and waste with excess moisture affect the analyses of radionuclide concentrations along pathways from the waste to the atmosphere and the ground water table. The presence of stress-fracture containers and excess moisture affects radionuclide concentrations but not the dose models used in the Area 5 PA. Therefore, the panel focused their evaluations on changes in radionuclide concentrations along identified scenario pathways.

4.0 Information Provided to the Independent Panel

4.1 Briefing Information

The Independent Panel convened several times in early 1998. The DOE and DOE-contractors presented the following briefings to the panel during these meetings:

1. Details of the transportation incident and associated operational activities at the Area 5 RWMS (Bechtel, Nevada).
2. Description of the Fernald waste stream associated with the transportation incident (Bechtel, Nevada).
3. Characteristics of the white metal boxes, stress-fracturing of the boxes, and moisture leakage from the boxes during transportation to the NTS (Bechtel, Nevada).
4. PA studies for the RWMS, Areas 5 and 3 (emphasis on the Area 5 RWMS; Bechtel, Nevada).
5. Conceptual model of the vadose zone used in the PA studies (Bechtel, Nevada).
6. Fernald waste streams, shipping and handling requirements for waste transportation, and database systems maintained on waste generators and waste streams (DOE, Nevada).
7. Results of the Type B Accident Investigation Board Report (DOE, Nevada).
8. Further information on the conceptual model of the vadose zone and modeling capabilities for assessing movement of moisture through closure and operational caps, the waste inventory, and the alluvial sediments of the vadose zone (Bechtel, Nevada).

4.2 Reference Material Provided to the Independent Panel

- Performance Assessment for the Area 5 Radioactive Waste Management Site at the Nevada Test Site (Shott et al. 1997a).
- Performance Assessment /Composite Analysis for the Area 3 Radioactive Waste Management Site at the Nevada Test Site, Nye County, Nevada (Shott et al. 1997b).
- Consequence of Subsidence for the Area 3 and Area 5 Radioactive Waste Management Sites, Nevada Test Site (Working Group Report) (Arnold et al. 1998).
- Second Performance Assessment Iteration of the Greater Confinement Disposal Facility at the Nevada Test Site (Baer et al. 1994).
- Type B Accident Investigation Board Report of the December 15, 1997, Leakage of Waste Containers Near Kingman, Arizona (DOE, 1998).

5.0 Performance Assessment Impacts

5.1 Question List

The following list of questions were developed by the panel with respect to potential performance impacts on the Area 5 RWMS:

1. Are there significant PA impacts from burial of low-level radioactive waste in stress-fractured containers with reduced integrity?

2. Does the disposal of waste in stress-fractured containers have significant impacts on the issue of subsidence?

3. Does the presence of excess moisture in some waste containers have significant impacts on upward pathways and radiological releases of volatile radionuclides?

4. Does the presence of excess moisture in some waste containers have significant PA impacts on upward advection of radionuclides under ambient conditions, under wetter conditions from rainfall events, and on upward diffusion of dissolved solutes?

5. Are there significant impacts on rates of radon transport from excess moisture in some waste containers?

6. Are there significant PA impacts on water movement and radionuclide transport in the vadose zone from the introduction of excess moisture in some waste containers?

7. What are the possibilities for, and are there significant PA impacts with respect to corrosion of waste/containers from the presence of excess moisture?

8. Related to questions 3 and 7, is generation of ^{14}C significant?

9. Related to question 3, is the presence of excess moisture significant with respect to plant and/or insect activity, and could this affect upward pathways and radiological releases?

5.2 Assessments

The PA objectives for shallow-land disposal of low-level radioactive waste are from DOE Order 5820.2A (US DOE, 1988). The performance objectives are dose-specific and encompass five pathway categories including (1) dose through all pathways, (2) dose through atmospheric pathways (excluding radon), (3) radon flux density, (4) ground water resource protection; and (5) the inadvertent human intruder.

The primary goal of a PA is to defensibly evaluate the range and uncertainty in the processes that affect the present and future waste disposal system. This goal is implemented by providing reasonable assurance that the radiological releases to the public do not exceed the performance objectives specified in DOE Order 5820.2A. For the Area 5 PA, reasonable assurance is obtained through the adoption of *conservative* performance calculations. A conservative calculation attempts to bound system performance through assumptions that *overestimate* radiological doses compared to the expected system performance. The difference between the expected doses and the bounded doses constitutes the degree of conservatism built into the calculations. These differences generally cannot be quantified, and the confidence in a conservative PA is dependent on full acceptance that the bounding assumptions are demonstratively conservative. An assessment of the performance impacts of fractured containers with excess moisture for the Area 5 PA requires consideration of whether the changed conditions are or are not encompassed by the bounding conservative assumptions used in the PA.

The potential for changes in the results of the Area 5 PA were evaluated for each identified pathway for both the base-case scenario and a subsidence-case scenario. The subsidence scenario assumed significance subsidence 100 years after closure of a disposal site accompanied by the formation of depressions. The depressions are assumed to pond water from surface run-on resulting in increased infiltration of moisture through the waste inventory of the Area 5 RWMS.

The following assessments summarize the results of the individual assessments by members of the Independent Panel. They are focused on evaluations of the conclusions presented in the Area 5 RWMS with respect to the performance impacts of disposal of waste with excess moisture in stress-fractured white metal boxes.

Question 1: Are there significant PA impacts system from burial of low-level radioactive waste in stress-fractured containers with reduced integrity?

Panel Assessment: The conservative assumption used in the Area 5 PA is that all waste radionuclides are available for uptake and release at closure (Shott et al. 1997a; p. 3-31); essentially, no credit was taken in the Area 5 PA for container integrity. The rationale for this assumption is twofold. First, a range of container types (metal boxes, metal drums, cardboard containers and wooden boxes) have been used for disposal of waste at the Area 5 RWMS (Shott et al. 1997a). Second, there is an absence of information on the expected degradation rates of containers under the prevailing conditions in the vadose zone (Shott et al. 1997a; Arnold et al. 1998). Given considerable uncertainty in container performance, the Area 5 PA simply assumed that the container plays no role in meeting the performance objectives.

Under expected conditions of waste disposal in the vadose zone, the presence of container cracks and excess moisture should lead to more rapid corrosion and degradation of containers relative to similar containers lacking cracks or excessive moisture. These differences would be difficult to quantify numerically and would be expected to be small. However, under the bounding conditions that assume no container integrity, there are no identified performance impacts on the Area 5 PA from disposal of waste in stress-fractured containers.

Question 2: Does the disposal of waste in stress-fractured containers have significant impacts on the issue of subsidence?

Panel Assessment: The conservative assumption used in the Area 5 PA is complete decomposition and collapse of waste packages by the end of the period of institutional control (100 years; Shott et al. 1997; p. 3-31). Container degradation rates are not well known. However, collapse times of 0 to 20 years after burial were estimated for cardboard containers, 20 to 150 years for wooden boxes, and 20 to 1400 years for metal drums and boxes (Arnold et al. 1998). The presence of structural cracks and excess moisture in the white metal boxes shipped from Fernald should accelerate the rate of container degradation. However, this increased degradation rate should not be large, and the expected interval of decomposition and collapse of metal box containers should be considerably longer than the conservative assumption of 100 years used in the Area 5 PA. Subsidence at low-level disposal sites will be driven primarily by void space within containers, decomposition and compression of the waste, void space between containers and trench walls, and compaction of the materials used to construct the closure cap (Arnold et al. 1998). The presence of stress fractures in metal containers will have an extremely small effect on subsidence compared to these other factors. Furthermore, accelerated corrosion could potentially have a positive effect if it promotes subsidence during the interval of institutional control when the effects of subsidence can be mitigated through maintenance of the closure cap.

Three factors lead to a conclusion of no significant performance impacts for the issue of subsidence. First, stress fractures are an insignificant component of factors contributing to subsidence compared to void spaces within and between waste containers. Second, accelerated corrosion and degradation of containers could be a positive factor if these processes occur primarily during the institutional control period of waste disposal cells. Finally, the presence of stress-fractured containers in waste cells is fully bounded in the assumptions used in the Area 5 PA.

Question 3: Does the presence of excess moisture in some waste containers have significant impacts on upward pathways and radiological releases of volatile radionuclides?

Panel Assessment: The Area 5 PA used a simplified, one-dimensional form of Fick's law for modeling diffusion flux and the release to the atmosphere of gaseous radionuclide species

$$Q_j = D_{ej}\left(\frac{C_{oj}}{z}\right)A \qquad (1)$$

where Q_j is release rate in Ci yr^{-1}, D_{e_j} is the effective diffusion coefficient for radionuclide j in pore spaces (m^2 yr^{-1}), C_{oj} is the initial air concentration of radionuclide j in the pore space of the waste (Ci m^{-3}), z is the mean diffusion length (m), and A is the area of the waste cell(s) (m^2). The diffusion flux model used for the Area 5 PA gives maximum release rates and includes multiple conservative assumptions. A key assumption in the Area 5 PA with respect to this report is that the disposed waste has a water content equal to the alluvial deposits (0.09 volumetric water and 36% porosity). The presence of excess moisture in Fernald waste containers would increase locally the volumetric water contents. The key question for assessing performance impacts is what are the effects of higher water contents on release of gasses radionuclides where the identified radionuclides are ^{3}H, ^{14}C, and ^{85}Kr? Examination of equation (1) shows that there are two effects of excess moisture. First, the increased moisture leads to a slight decrease in C_{oj} from dilution assuming a fixed inventory of gaseous radionuclides as established in the Area 5 PA. Second, the equation for the effective diffusion coefficient used in the Area 5 PA is

$$D_{e,H_20} = D_{a,H_20}0.66(\varepsilon - \theta_v) \qquad (2)$$

where $D_{a,H20}$ is the diffusivity of H_20 in air, 0.66 is the tortuosity coefficient, ε is the total porosity and θ_v is the volumetric water content. Equation (2) shows that the net effect of increased moisture is to *reduce* the effective diffusion coefficient, which in turn decreases the diffusive flux of gaseous radionuclides (equation 1).

The excess moisture in waste should result in lower effective diffusion coefficients for gaseous radionuclides in the immediate vicinity of the waste inventory; volumetric moisture contents consistent with the assumptions used in the Area 5 PA should continue to apply above the waste (operational cap and closure cap). Thus, only very small (local) reductions are expected in the release rates of gaseous radionuclides. Additionally, the release rate (Q_j) for the ^{14}C and ^{85}Kr were adjusted conservatively in the PA so that the full inventory of these radionuclides was released in the first year of the PA (Shott et al. 1997a). This is a very conservative assumption compared to the effects of excess moisture.

The primary effect of the subsided case on the release of volatile radionuclides is to reduce z, the mean diffusion length (equation (1)), and to increase the potential for fractures extending through the closure cap. Excess moisture in waste containers would not affect these processes, and the only related effect might be a local increase in the rate of container degradation. The primary effect of excess moisture is a local decrease in the effective diffusion coefficient for gaseous radionuclides and therefore a local reduction in the radiological release rates. Final closure of waste cells requires the addition of a closure cap. This cap would increase z, in equation (1), leading to lower release rates of gaseous radionuclides.

Calculations of the upward release rates of gaseous radionuclides from the Area 5 RWMS meets all performance objectives (Shott et al. 1997a). Excess moisture in waste would locally decrease release rates of gaseous radionuclides. The addition of a closure cap would increase the mean diffusion length of gaseous radionuclides to the atmosphere and decrease gaseous releases. There are no significant impacts on performance from the presence of excess moisture in disposed waste.

Question 4: Does the presence of excess moisture in some waste containers have significant PA impacts on upward advection of radionuclides under ambient conditions, under wetter conditions from rainfall events, and on upward diffusion of dissolved solutes?

Panel Assessment: These pathway processes have been grouped into one question because each process has been dismissed in the Area 5 PA as a significant release pathway. The potential for upward advection of dissolved radionuclides was assessed in the Area 5 PA through estimating the mean travel time for moisture advected upward from the waste inventory to the surface. The assumed travel length was 2.4 meters, the thickness of the operational cap. Matric potentials were assigned for the cap materials using data from a mean smooth profile established for trench and borehole studies. Extremely long travel time estimates for moisture movement from the waste to the surface were calculated. The travel time is sufficiently long to dismiss upward advection as a significant process (Shott et al. 1997a; see also Baer et al. 1994).

The presence of locally higher water contents in the waste inventory from disposal of components of the Fernald waste does not significantly affect the conclusions of no significant impact with respect to upward advection. The primary barrier to advective transport is the low moisture contents of the alluvial sediments of the operational and closure caps above the waste inventory. These low moisture contents lead in turn to low unsaturated hydraulic conductivity. These deposits (soils) should remain largely unaffected from the presence of excess moisture in the waste (see Section 6.0). Similarly, the conclusions of no performance impacts are not significantly changed under wetter conditions. Decreasing the mean travel time for upward advected moisture requires a significant increase in the water contents of the cap materials above the waste. Infiltration modeling used in the Area 5 PA suggest a maximum predicted depth of infiltration of less than 0.3 m, significantly less than the thickness of either the operational cap (2.4 m) or a closure cap constructed above the operational cap (estimated to be about 3 meters). Examination of this predicted maximum depth of infiltration used in the Area 5 PA shows that it is non-conservative. Water-content data measured in Frenchman Flat using time domain reflectometry show that increased water contents from precipitation events have affected infiltration in alluvial deposits to depths of about 1 meter (Shott et al. 1997b; p. A1-6). The conceptual model for the vadose zone developed for the Area 3 PA emphasizes episodic infiltration and evaporation to depths of 1-3 meters (Shott et al. 1997b; see their Fig. 2.21, p. 2-62). Nonetheless, the thickness of the cover provided by the expected combination of the operational and closure caps (> 5 meters) still provides a significant barrier to upward advection of radionuclides to the surface. Of particular significance is the presence of upper soil zones with very low volumetric water contents (< 6 %), an extremely effective barrier to all processes associated with upward advection. While the thickness and water content of this low-conductivity zone will vary with episodic precipitation events, it should be maintained by the high potential evaporation that maintains a moisture deficit state (Shott et al. 1997b).

The issue of upward diffusion of dissolved solutes has been dismissed for multiple reasons. First, the diffusion rates are dependent on the water contents of the alluvial deposits and the concentration gradient (Shott et al. 1997a). The water contents of the upper alluvium deposits are sufficiently low and remain low even with the addition of excess moisture so that the diffusive flux of solutes is inferred to be negligible (see Section 6.0). Second, upward diffusion requires a continuous liquid phase in the pore spaces. The low moisture contents of the near-surface alluvium may be too low to support a continuous liquid phase. The presence of excess moisture in some waste containers will affect local water contents and diffusion rates in the waste inventory but not in the cap materials, and particularly not the near-surface deposits.

There are no significant performance impacts relative to the Area 5 PA on upward advective and diffusive processes, largely because the local excess moisture in waste has limited effects on the overlying materials of the operational and closure caps.

Question 5: Are there significant impacts on rates of radon transport from excess moisture in some waste containers?

Panel Assessment: The radon flux density for the low-level radioactive waste disposal sites are established largely using methods summarized in guidance provided by the Nuclear Regulatory Commission (Shott et al. 1997a,b). The flux density is calculated assuming a combination of gaseous diffusion in the air-filled pore space and advective flow of soil pore gas. Generally, diffusion and advection will be retarded in the water-filled pore space relative to the air-filled pore space. Thus the primary effect of excess moisture will be to decrease the radon flux density. The Area 5 PA shows that the radon flux does not exceed the performance objective (20 pCi $m^{-2}s^{-1}$) throughout the 10,000 year compliance period. The peak doses from radon occur long after the required compliance period (Shott et al. 1997a). The presence of excess moisture in waste has very little impact on these processes Therefore, there are no significant changes from these conclusions presented in the Area 5 PA. The addition of a closure cap will provide an even greater safety margin (total cap thickness) with respect to the radon flux density for the conditions assumed for the Area 5 PA.

Question 6: Are there significant PA impacts on water movement and radionuclide transport in the vadose zone from the introduction of excess moisture in some waste containers?

Panel Assessment: Information provided by Betchel, Nevada (Bechtel Nevada memorandum, L. S. Sygitowicz to B. M. Crowe, March 23, 1998) documented that about 16,720 cubic meters (590,300 cubic feet) of waste from the Fernald waste stream 006 has been shipped and disposed in the Area 5 RWMS. Approximately 11,040 cubic meters (390,000 cubic feet) of waste has been disposed in Pit 4 (about 18% of the pit volume), about 5,660 cubic meters (200,000 cubic feet) has been disposed in Pit 5 (about 36% of the pit volume), and a very small amount of the Fernald waste has been disposed in Pit 6. It is difficult to estimate the volume of the Fernald waste stream that may contain excess moisture. Estimates of these volumes were provided through the generator records at the Fernald site. Based on examination of these records by Fernald personnel, approximately 50% of the Fernald 006 waste stream is estimated to be sludge-type waste that potentially could have excess moisture (Dave Rast, Fernald, Ohio, personal communication, March 1998). Accordingly, about 9% of the waste inventory in Pit 4 and 18% of the inventory in Pit 5 could have excess moisture (excess moisture is defined as volumetric water contents in waste that exceed the ambient conditions for the alluvial deposits of the Area 5 RWMS). Because Pit 5 is still actively receiving waste, the percentage of waste with excess moisture could change dependent on what percentage of future waste shipments are from the Fernald site (waste stream 006).

The performance impact of excess moisture in waste containers was modeled using the computer code VS2DT for simulating isothermal, two-dimensional movement of moisture in the vadose zone. The details and results of this modeling are described in section 6.0 of this report. For one of these simulations (base-case and subsidence/flooding scenario), waste with excess moisture was located in the third of four tiers of waste containers with a disposal geometry similar to Pit 5 of the Area 5 RWMS. This geometry allows 25% of the inventory of Area 5 disposal site to contain excess moisture, an assumption that bounds the *expected* abundance of containers with excess moisture (see above). The waste was assumed to occupy the *full* volume of the white-metal containers and the hydraulic properties of the waste was assumed to be similar to the surrounding alluvial deposits (see Table 1 of Section 6.0). For completeness, simulation modeling was also conducted assuming up to 100% of the waste inventory contained excess moisture (see Section 6.0).

The base-case scenario was dismissed in the Area 5 PA, primarily because of the very long travel times to the ground water table, 240 meters below the surface. The median travel time to the alluvial aquifer in Frenchman Flat was estimated to be about 51,000 years, with greater than a 99 % probability that the travel time exceeds 10,000 years (Shott et al. 1997a). The presence of excess moisture in waste will increase locally the unsaturated hydraulic conductivity and result in a very small decrease in the travel time to the water table. That decrease is insignificant given the long pathways through the vadose zone (240 meters) and the relatively thin zone of increased wetting front velocity from the excess moisture (14 m). The long travel times coupled with radioactive decay of the waste inventory, particularly tritium, means that the base-case scenario continues *not* to be significant even with the presence of waste with excess moisture.

The flooding scenario consisted of filling a subsidence depression formed on an operational waste cover with 2 meters of floodwater that was allowed to infiltrate in the alluvial deposits of the vadose zone. This 200-year flooding event was repeated for three consecutive years, followed by moisture redistribution under ambient weather conditions. Comparison of the simulation results of the Area 5 PA with results obtained in this report assuming 25% wet waste (see section 6.0) shows that there are only small differences between the results for profiles of volumetric water content with depth in the alluvial deposits. After three years, the wetting front for the profile containing waste with excess moisture has moved only about 2 meters deeper than the profile without excess moisture. Shortly after three years, the profiles are virtually indistinguishable. The expected travel time of the wetting front to the ground water table for the condition of 25% of the waste inventory containing excess moisture is about 190 years. This interval is longer than the travel time used in the Area 5 PA because of slightly different modeling assumptions (see Section 6.0).

The resulting conclusion is that the simulations of the flooding scenario with excess moisture are virtually similar to the results without the excess moisture. Therefore, there are no significant performance impacts on the Area 5 PA from excess moisture in waste containers.

Question 7: What are the possibilities for and are there significant PA impacts with respect to corrosion of waste/containers from the presence of excess moisture?

Panel Assessment: This question returns to the issues discussed in the response to Question 1. The presence of container cracks and excess moisture in waste should lead to more rapid corrosion of containers relative to containers that do not contain excess moisture. However, a bounding condition assumed for the Area 5 PA is that no credit is given for container integrity with respect to performance objectives. Further, a second bounding condition of the Area 5 PA is that all radionuclides are immediately available for uptake and release at closure (Shott et al. 1997a). Enhanced corrosion of the waste from the presence of excess moisture does not have any appreciable effect on these conservative assumptions. Therefore, there is no identified impact of accelerated corrosion of waste or waste containers from the presence of excess moisture in the waste containers.

Question 8: Related to questions 3 and 7, is generation of ^{14}C significant?

Panel Assessment: The issue of generation of ^{14}C is bounded in the Area 5 PA by three conservative assumptions. First, ^{14}C release is attributed solely to gaseous $C0_2$ despite the presence of other non-gaseous carbon species that are expected to compete for the available ^{14}C inventory (Shott et al. 1997a; p. 3-41). Second, the entire $^{14}C0_2$ inventory is assumed to be present in the pore space. Third, the ^{14}C flux used in the Area 5 PA results in complete degassing of the full ^{14}C inventory in one year (Shott et al. 1997; p. 6 and p. 3-43). These conservative assumptions fully bound any expected impacts from preferential release of ^{14}C associated with increased container/waste corrosion. Excess moisture will surely contribute to the generation of ^{14}C associated with $C0_2$. However, the relevant assumption in the PA is that all ^{14}C is converted to $C0_2$ and transported away in the first year without identification of a specific mechanism for this release. It is unlikely that any credible transport mechanism associated with increased moisture content would exceed the release rate assumed in the PA.

Question 9: Related to question 3, is the presence of excess moisture significant with respect to plant and/or insect activity and could this affect upward pathways and radiological releases?

Panel Assessment: (Note: The following analysis is based on modifications to the base-case scenario. The subsidence/flooding scenario also analyzed in the PA provides a more direct path to the same conclusion (see Shott et al. 1997a, p. 3-57). Increased moisture in the waste system will provide more opportunity for an increase in plant cover in the case of the 2.4-meter cover system used in Shott et al. (1997a). Examination of the subsidence and flooding scenarios indicates the moisture at depth lasts long enough to influence the growth patterns of plants in the immediate area. Soil moisture appears to decrease over a period of 50 to 90 years before redistribution returns the water content to the original state of the surrounding alluvial deposits (soil). However, the estimates provided by Shott et al. (1997a) rely on diffusion of the water in the soils to the surface. With plants present, there is an active pumping mechanism connected to the atmosphere. Generally, the transpiration of plants will dry the system both faster and to a greater depth than bare soils alone. The system will experience a transient increase in plant populations until the increased plant cover utilizes the water available and the soil returns to the water content common to the area. The plant population will then return to a lower biomass production similar to the current native plant system.

The issue in the Area 5 PA of pathways associated with plant and/or insect activity was assessed by examining mechanisms of moving waste radionuclides from geometrically defined compartments. These compartments consist of a deeper waste compartment, an intermediate-depth subsurface soil compartment, and a shallow soil compartment where the radionuclides can contribute to radiological releases. For both plant and insect activity, empirical equations were developed to define rate coefficients that describe the movement of radionuclides across the compartment. For example, the rate coefficient (K_{r1j}) for plant-root uptake from the waste compartment to the shallow soil compartment is estimated from (Shott et al. 1997a)

$$K_{flj} = B_{jv} x B_p x (1 + \frac{F_{rs}}{B_{ab}}) x F_{rw} x \frac{1}{H_w} x \frac{1}{\rho_b} \tag{3}$$

where

B_{jv} = the plant-soil concentration ration for radionuclide j in $pCig^{-1}$ plant mass per $pCig^{-1}$ dry soil
B_p = annual above-ground perennial shrub biomass productivity in g dry mass m^{-2} yr^{-1}
B_{ab} = ratio of above- to below-ground productivity for shrubs in g yr^{-1} above ground per g yr^{-1} below ground
F_{rs} = fraction of perennial shrub roots in shallow soils compartment, dimensionless
F_{rw} = fraction of perennial shrubs with roots greater than 2.4 m, dimensionless
H_w = depth of waste accessible to roots in meters
ρ_b = dry bulk density of soil in g m^{-3}

The following evaluation uses an estimated time of 50 to 90 years for the soil water content to return to normal after introduction of the wastes. This drying time is long enough to allow a plant response. Biomass production on the surface should increase due to the excess water and be followed by added plant growth due to increased seed germination.

The current PA examined the plant uptake using the conservative assumption that the deepest root penetrations recorded in the literature represented the case at the Area 5 RWMS. Adding water to wastes buried under the 2.4-meter operational cover could, for selected species, encourage more root growth in the direction of a moisture source. Because of the depths to the waste, the roots in the surface soils would not be affected. Doubling the fraction of the vegetation with roots in the waste from 0.05 to 0.1 in equation (3) can represent the changed effect. Availability of water in the system would increase the biomass production. As indicated in the PA, the biomass doubles with a four fold increase in precipitation in Mojave Desert plant communities. For this analysis doubling the fraction of vegetation with roots in waste is represented by doubling the biomass production.

Another factor in equation (3) that may be influenced by the moisture content is the ratio of the above ground biomass to below ground biomass production factor, that is part of the denominator in equation (3). An increase in the parameter indicates the below ground biomass productivity is decreasing. For the purpose of this analysis the below ground productivity is assumed to increase such that more roots are produced in response to more moisture relative to the above ground productivity. The values for this ratio for the Mojave Desert range from 0.6 to 2.3. The result of the use of a value of 0.6 is an increase of plant uptake of radionuclides by a factor of 1.2.

Combining the estimated increases due to the moisture in the wastes results in a factor of 4.8 more radionuclide uptake by plants. Table E.8 of the Area 5 PA indicates the maximum committed effective dose equivalent is 1.1 mrem/year from the milk pathway. This dose could then increase to 5.3 mrem/yr based on the increased plant uptake. This dose still meets the performance objectives. If the milk pathway is not present, the dose decreases to 1.4 mrem/yr from all pathways, still within the performance objectives.

Summarizing, the impact of excess moisture is expected to be small for uptake of radionuclides associated with plant activity for three reasons:

1. Mean root depths of most native plants at the Area 5 RWMS are relatively shallow (probably less than 2 meters), and the majority of roots are not expected to extend into the waste inventory. The uncertainty with this statement is that the maximum root depth for shrub land and some grass species can be greater than 3 meters (Arnold et al. 1998). Therefore, while most shrub roots will not affect the waste inventory, some penetration of the waste inventory at the Area 5 RWMS is expected, an assumption that was allowed for in the calculations used for the Area 5 PA. Modeling of the distribution of excess moisture in alluvium for this report shows that the increased moisture is short-lived and the deposits return to background conditions over intervals of tens of years.

2. Revised dose calculations assuming changes in equation (3) from the presence of excess moisture in waste still remain within required performance objectives.

3. All calculations of root uptake for the Area 5 PA assumed the presence of an operational cap but not a closure cap. The addition of a closure cap will increase the burial depth of waste by approximately 2-3 meters; the actual values will depend on the inventory and design specifications for the closure cap. Any effects of excess moisture on root uptake will be overshadowed in the PA calculations by the presence of the closure cap. The expected effect of adding a closure cap to the PA calculations is a decreased degree of root penetration, even given the presence of excess moisture in some waste containers.

Insects in the area of the waste system may be increased by the increased plant production. Harvester ants were the only contributors to movement of wastes from depth to the surface (Shott et al.1997a), and the Area 5 PA included estimates of the amount of "soil like wastes" brought to the surface. The result was that the amount of contaminated soil brought to the surface dominated the transient occupancy scenario for intrusion with a dose of 9.7 mrem/yr, mostly from ^{226}Ra (Table E.6 of the Area 5 PA). Assuming the number of ant colonies doubles because of the doubling of plant biomass available as food, the increased dose from the moisture in the wastes would be another 9.7 mrem/yr, or a total of 19.4 mrem/yr. The increase is still well within the performance objectives for the waste management system.

Closure plans for the final cover of waste pits of the Area 5 RWMS include the addition of a final cover cap with an assumed thickness of about 2-to-3 meters (Arnold et al. 1998). The addition of cover material reduces the amount of waste volume that is available to animal burrows and would also eliminate the Harvester ants as an important pathway for bringing wastes to the surface. The literature survey by Shott, et al. (1997a) indicated the deep burrows extend to between 2 and 3 meters below the surface. Using only the 2.4-meter operational cover, the conservative approach used in the Area 5 PA was to assume the ants brought wastes to the surface. With an added 3 meters of soil, the distance to the wastes far exceeds the burrow depths of the Harvester ants.

In summary, excess moisture can affect the performance of the Area 5 RWMS for the topic of biointrusion (plant and/or insect). The calculated changes in radiological doses associated with these effects are small, and the resulting doses remain within performance objectives. Reduction of the effects of excess moisture for these topics can be accomplished by accounting for the addition of the closure cap.

6.0 Modeling of the Effects of Excess Moisture

Simulation modeling of downward moisture redistribution in the vadose zone was conducted initially for the conditions of 25% of the inventory of the disposed waste of Pit 5 of the Area 5 RWMS containing waste with excess moisture. This percentage was judged to be adequate to bound the expected conditions of waste disposal at the Area 5 RWMS (see Question 6 in a previous section of this report). On the basis of discussion and questions during the briefing to the State of Nevada on March 17, 1998, a decision was made to further explore the sensitivity of the PA implications for conditions of higher percentages of waste with excess moisture. Simulations were repeated for the base case of soil-water movement assuming ambient weather conditions and the subsidence/flooding scenario. The waste column was assumed to contain waste with respectively, 0, 25, 50, 75 or 100% of the total inventory having excess moisture. These divisions correspond to assuming that zero, one, two, three, or four tiers of a possible total of four tiers of waste containers with volumetric water contents equal to complete saturation of the effective porosity of the waste. The results of model simulations using these conditions are summarized in this section.

Hydraulic properties and initial conditions for the vadose zone modeling were identical to those used for the flooding simulations described in the Area 5 PA (refer to page 3-61). The hydraulic properties are summarized in Table I, and the initial conditions are summarized in Appendix B. Simulations were conducted using the computer code VS2DT, a computer program for simulating isothermal, two-dimensional movement of liquid water in variably saturated porous media (Lappala et al, 1983; Healy, 1990). This code was selected because of its widespread use and its applicability to numerous modeling scenarios. Installation verification was performed by running the verification problems provided with the code. The flow model ODIRE (Lindstom et al., 1991) was used for the flooding scenarios described in the Area 5 PA. ODIRE was not selected for the simulations in this report because of limited use, limited validation and the lack of any experienced operators of this model.

Table I. Hydraulic Parameters

Parameter Description	Value for Simulation
Saturated hydraulic conductivity	0.6390 m d^{-1}
van Genuchten "n" parameter	1.9 m^{-1}
van Genuchten "alpha" parameter	1.831
Residual water content	0.075 m^3 m^{-3}
Saturated water content	0.361 m^3 m^{-3}

6.1 Base-Case Scenario

The base-case scenario consisted of simulating infiltration, redistribution, bare-soil evaporation, and precipitation for a 50-year period at Pit 5 using ambient weather data. The weather data consisted of actual Area 5 RWMS meteorological data from 1995, a year characterized by above-average annual precipitation. Figures 1a and 1b show the results of the model simulations for the base-case scenario with 25, 50, 75 and 100% respectively, of the waste inventory containing excess moisture. The water content of the initially wet packages can be seen at depths that range from 1.2 to 6.7 meters (elongate rectangles of Figures 1a and 1b). Water in these saturated zones

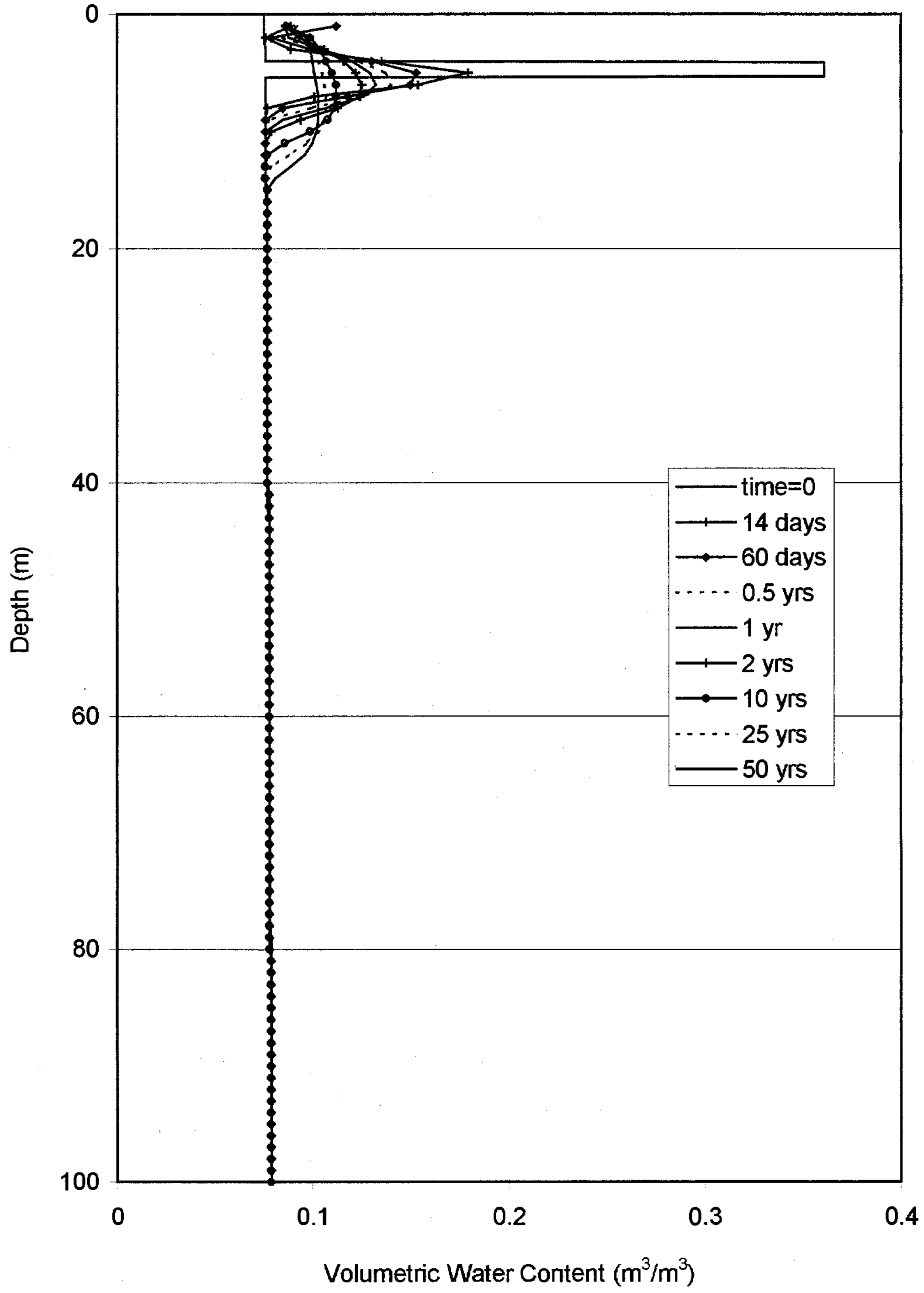

Figure 1a: VS2DT model simulation of the redistribution of moisture in the vadose zone of the Area 5 RWMS for conditions of 25% of the Pit 5 waste inventory containing excess moisture.

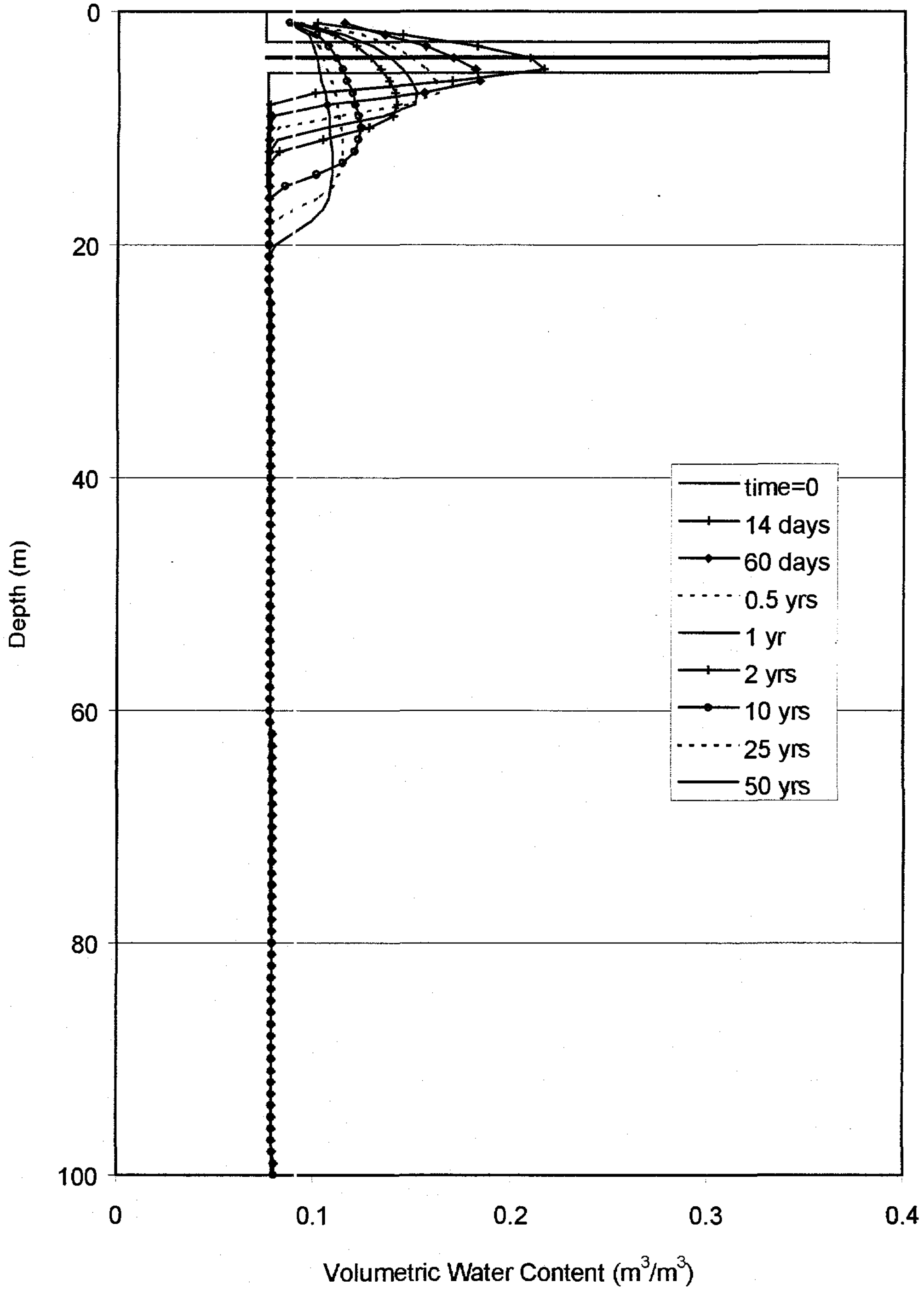

Figure 1b: VS2DT model simulation of the redistribution of moisture in the vadose zone of the Area 5 RWMS for conditions of 50% of the Pit 5 waste inventory containing excess moisture.

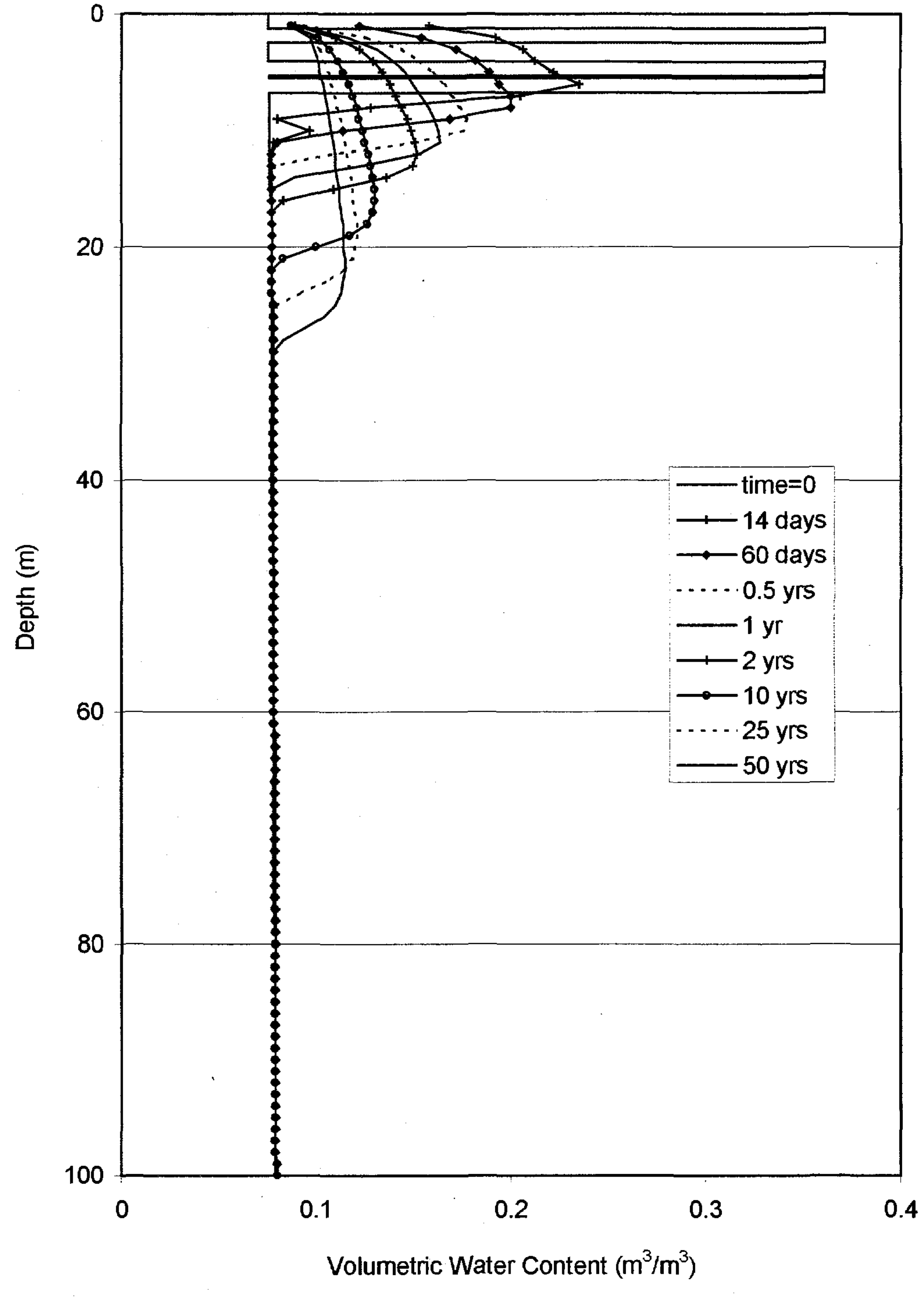

Figure 1c: VS2DT model simulation of the redistribution of moisture in the vadose zone of the Area 5 RWMS for conditions of 75% of the Pit 5 waste inventory containing excess moisture.

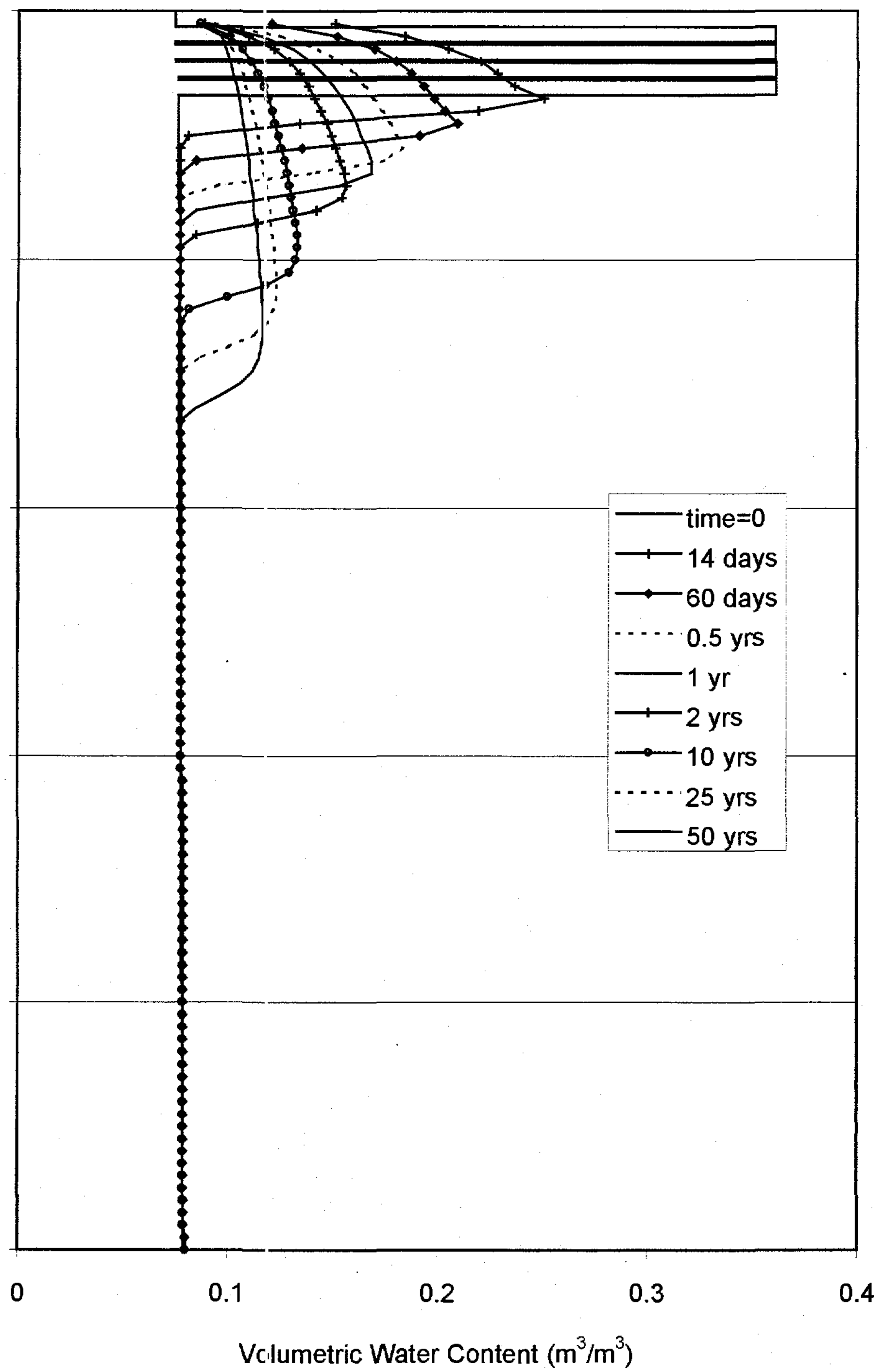

Figure 1d: VS2DT model simulation of the redistribution of moisture in the vadose zone of the Area 5 RWMS for conditions of 100% of the Pit 5 waste inventory containing excess moisture.

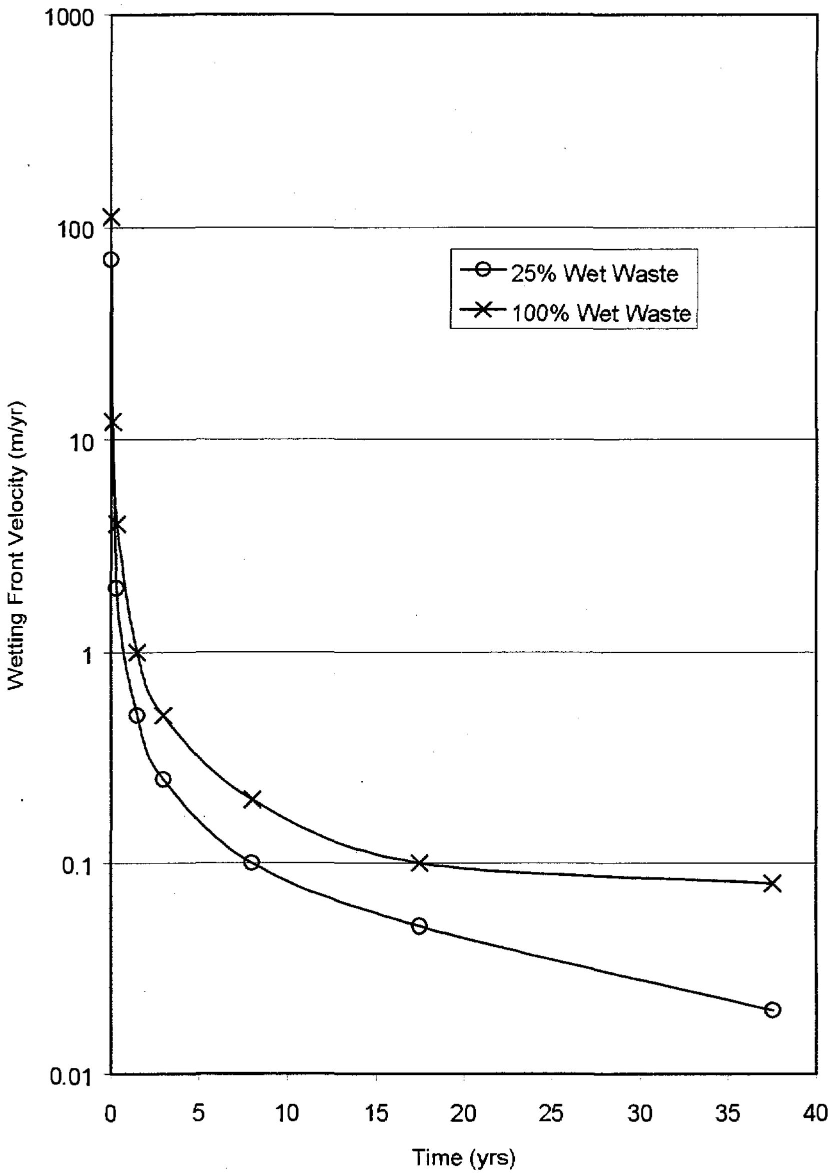

Figure 2. Average velocities of the wetting fronts with time for the base-case scenarios where 25% and 100% respectively, of the waste inventory contains excess moisture.

rapidly redistributes to lower water contents above and below this depth. After 50 years, the wetting fronts from the wet layers of waste and precipitation reach a depth of 14 meters for the 25% wet waste and 33 meters for the 100% wet waste. The average velocities of the wetting fronts are shown in Figure 2 for the 25% and 100% wet-waste scenarios. After about 30 years, the wetting front velocity drops to less than 2 cm per year for the 25% wet-waste scenario and less than 10 cm per year for the 100% wet-waste scenario

The travel times to the water table for the base-case scenario for these conditions were not calculated because of the very long computation times for the modeling runs. The low average velocities of the wetting fronts for these simulations (Figure 2) show that travel time to the water table far exceeds the required compliance period for the Area 5 RWMS. These results are consistent with and extend the conclusions established in the Area 5 PA. The travel times to the water table beneath the Area 5 RWMS are extremely long, and there is effectively no significant recharge beneath the site under current climate conditions.

6.2 Subsidence/Flooding Scenario

The flooding scenario simulations were conducted under the same conditions as those described in the Area 5 PA (page 3-61). In each case, a ponding depth of 2-meters of floodwater was held constant for 24-hours of infiltration. The ponding depth was then allowed to drop as water continued to infiltrate into the soil profile. This flooding event was repeated for three consecutive years, followed by redistribution of water in the soil profile. Results of these simulations are shown in Figure 3a to 3c, where the five profiles are compared. The first profile illustrates soil water distribution within and beneath Pit 5 for a simulation without a layer of waste with excess moisture. The second through fifth profiles illustrate soil water distribution within and beneath Pit 5 for simulations with one to four tiers of waste with excess moisture. After a period of three years, the wetting front for the profile with 25% wet waste reaches approximately 2 meters deeper than the wetting front for the profile without wet waste. Water content after three years in the first profile in Figure 3a is nearly indistinguishable from the profile shown in the Area 5 PA (Figure 3.7, page 3-64), providing confirmation that ODIRE and VS2DT computer codes yield comparable results. Travel times of the wetting front to the ground water table range from 190 years for the dry-waste scenario to 140 years for the 100% wet-waste scenario. The travel time to the ground water table of 146 years reported in the Area 5PA (Shott et al. 1997a) is an extremely conservative calculation because the estimated arrival time of the wetting front was chosen for the capillary fringe located 15 meters above the ground water table. A more realistic travel-time estimation of 190 years is obtained for the subsidence/flooding scenario (no waste with excess moisture) using the revised modeling presented in this report (see Figure 3a). The travel-time estimate, assuming 100% of the inventory contains excess moisture, is 140 years (Figure 3c) and is virtually identical to the travel-time estimate used in the Area 5 PA (Shott et al. 1997a).

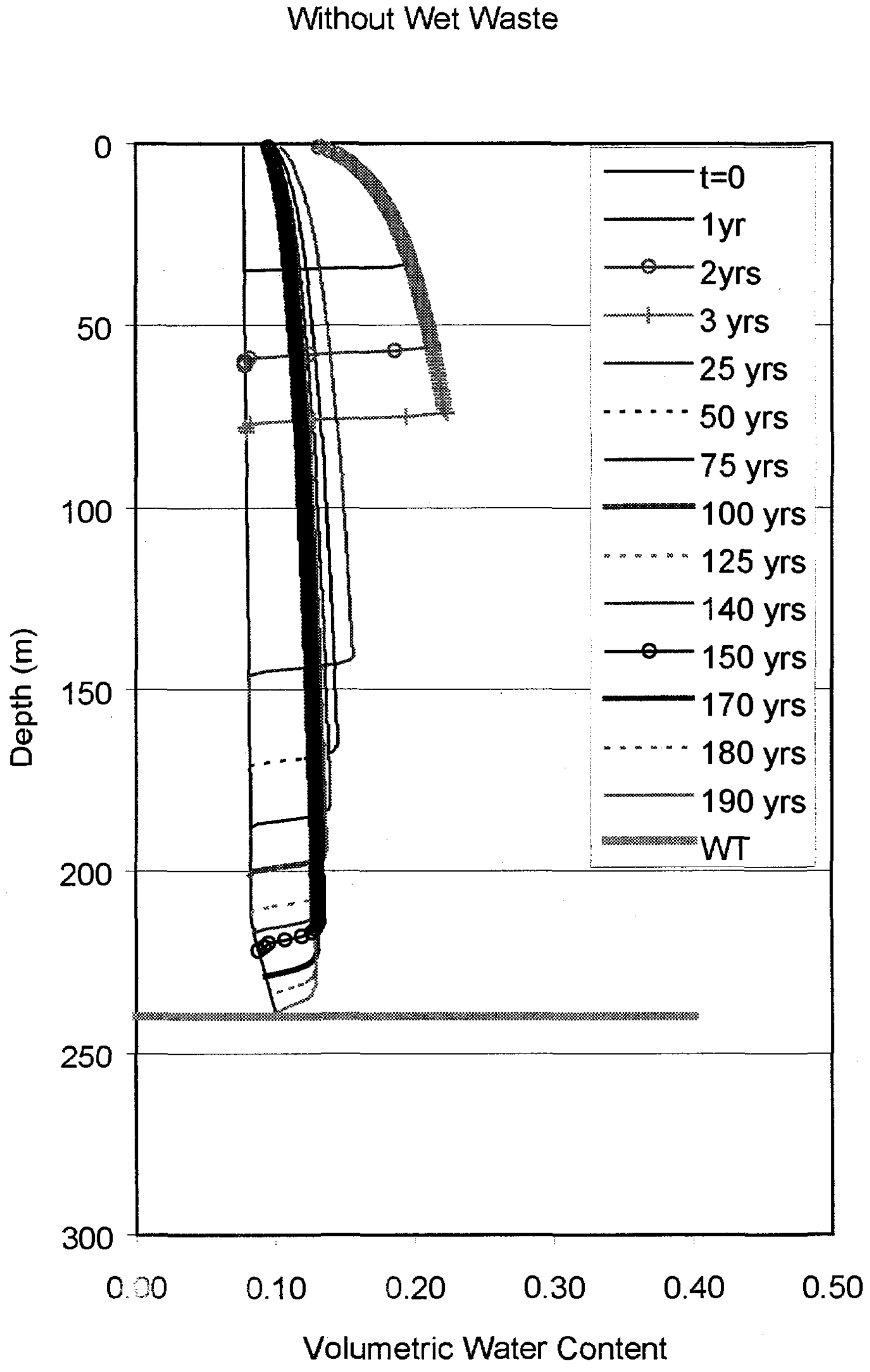

Figure 3a. VS2DT model simulation of moisture redistribution for no wet waste.

With 25% Excess Wet Waste

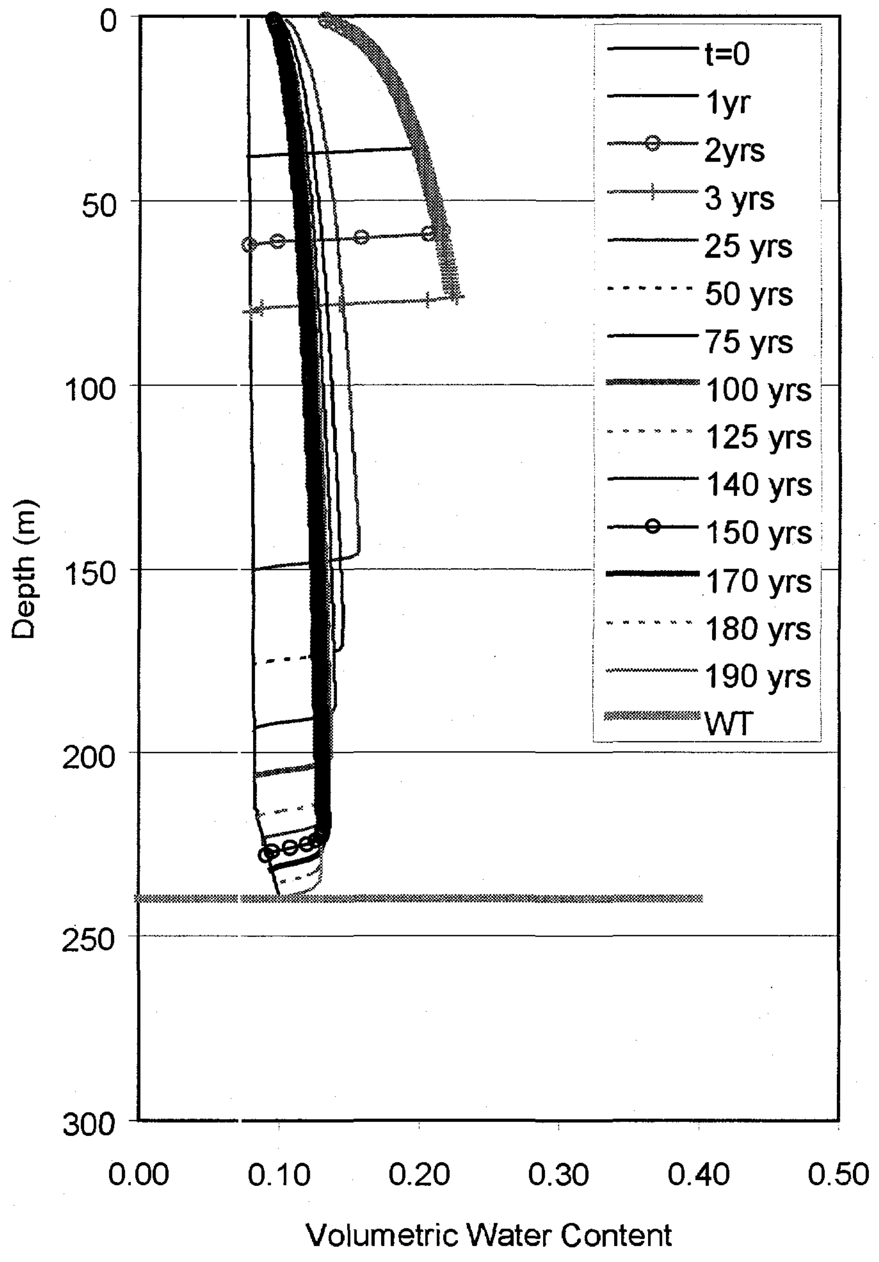

Figure 3b. VS2DT model simulation of moisture redistribution for 25% wet waste.

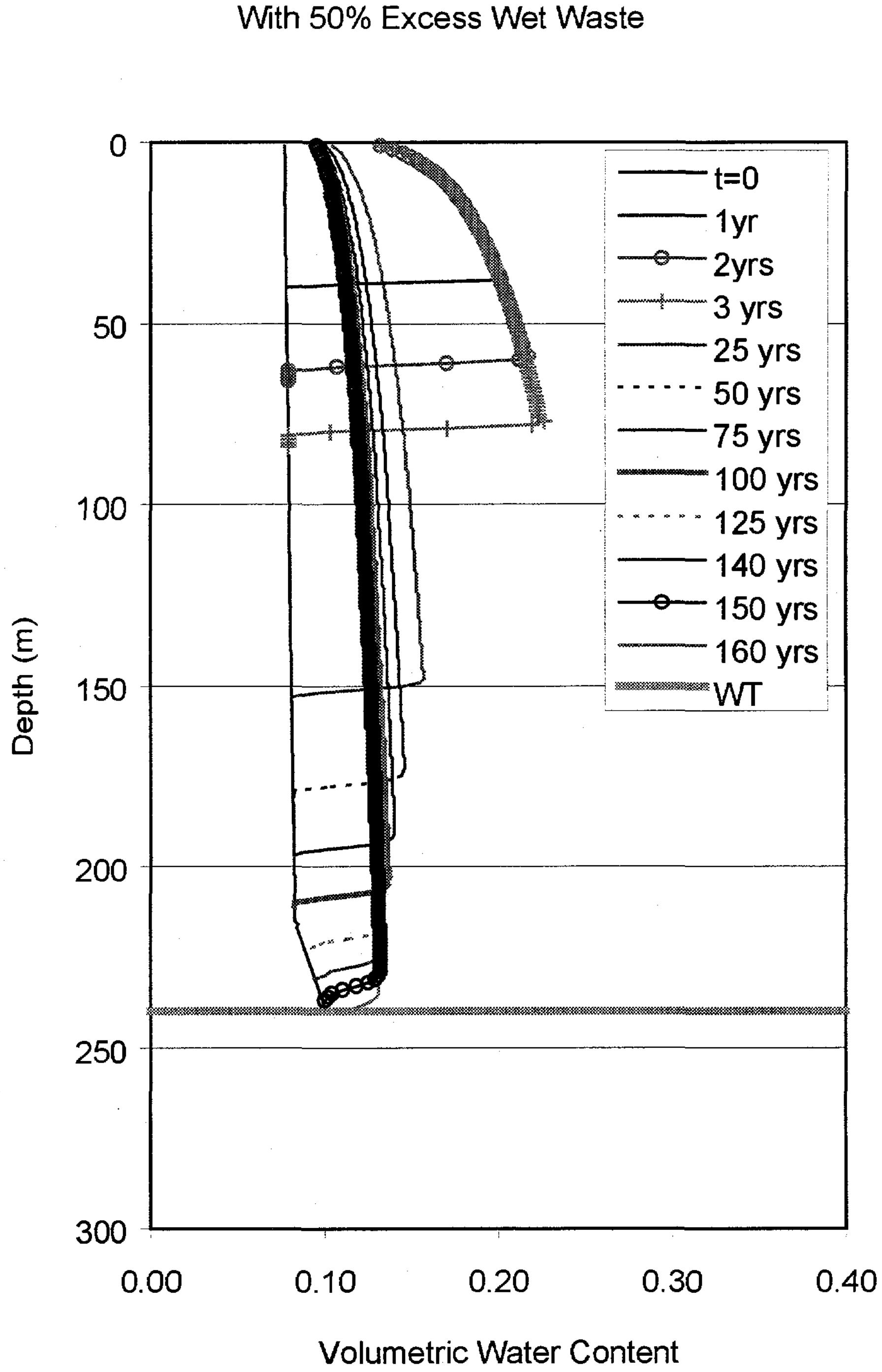

Figure 3c. VS2DT model simulation of moisture redistribution for 50% wet waste.

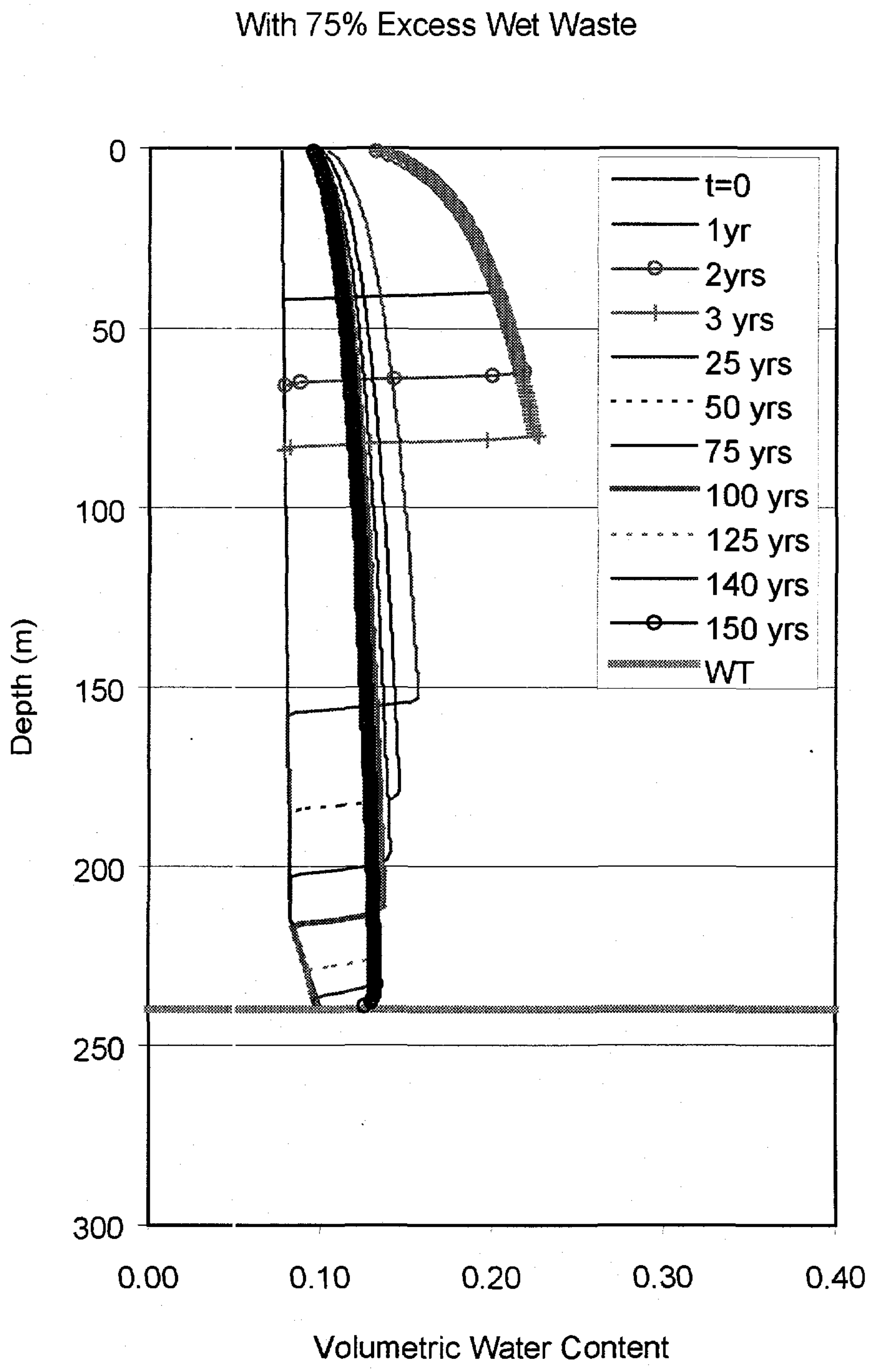

Figure 3d. VS2DT model simulation of moisture redistribution for 75% wet waste.

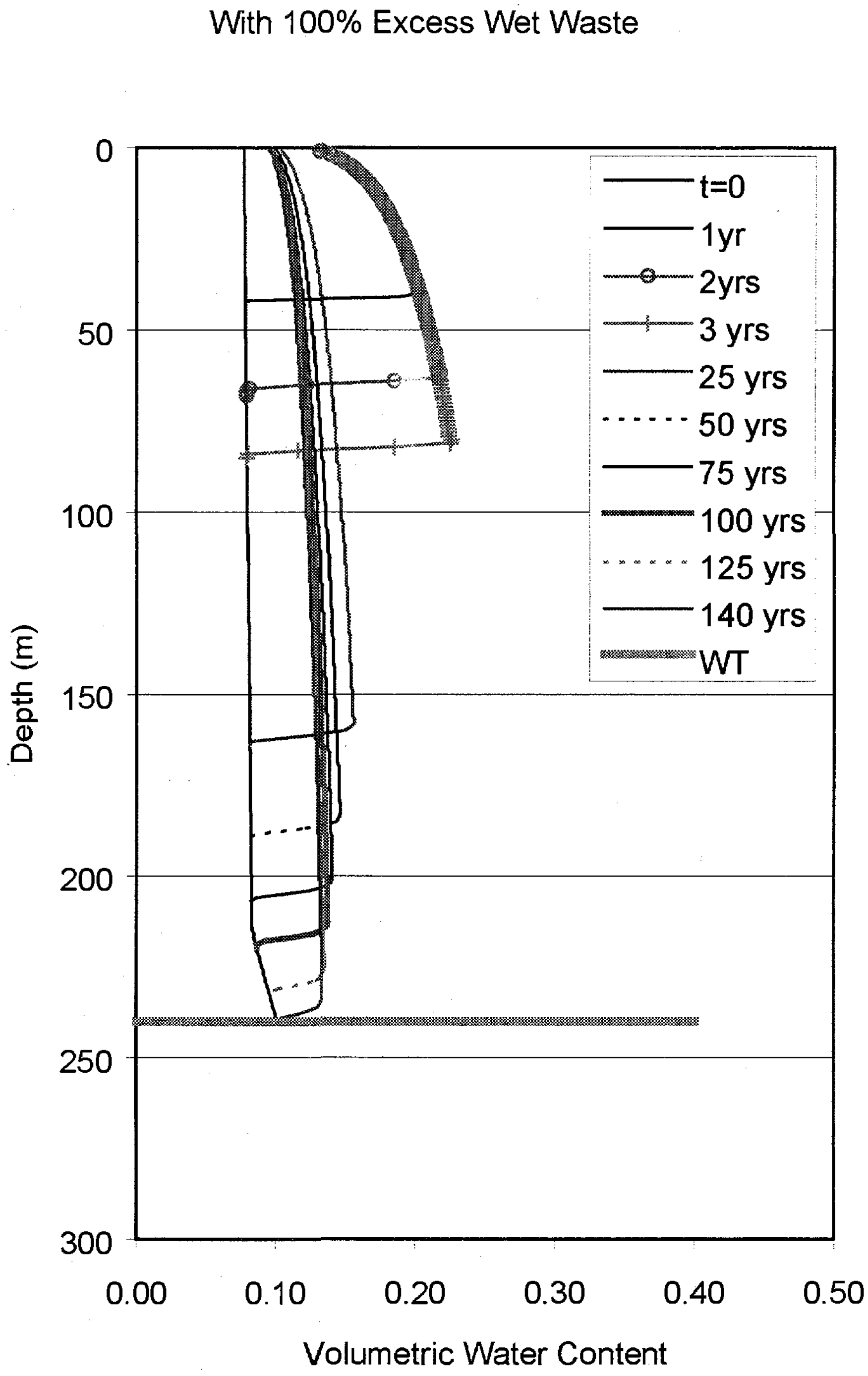

Figure 3e. VS2DT model simulation of moisture redistribution for 100% wet waste.

7.0 Summary and Observations

7.1 Summary

This report presents the results of a systematic examination of the performance effects of disposal of waste with excess moisture in stress-fractured containers (white metal boxes). The approved PA for the Area 5 RWMS was examined for any possible changes that could affect the ability of the PA to meet performance objectives specified in DOE order 5820.2A. No performance or subsidence impacts were identified from disposal of waste in fractured containers. Changes in concentrations of released radionuclides along all potential pathways from the presence of excess moisture in waste were examined, and no significant impacts were noted for each pathway. In all cases, the resulting changes from the PA results presented in the Area 5 report (Shott et al. 1997a) are minimal. Fundamentally, these changes are constrained by the conservative bounding assumptions used in the Area 5-PA. The performance impacts of excess moisture in waste containers were modeled for the base-case scenario and the subsidence scenario using a computer code that simulates isothermal, two-dimensional movement of moisture in the vadose zone. No significant performance impacts were noted for assumptions of 25% of the disposed inventory containing excess moisture, assumptions that are judged to bound the expected occurrence of boxes with excess moisture in the Area 5 RWMS. On the basis of questions raised during a briefing of the results of the panel investigation to representatives of the State of Nevada (NVEP), this modeling was extended in 25% increments up to 100% of the inventory containing excess moisture. No significant impacts were noted for even the extreme cases that are not representative of the inventory disposed in the Area 5 RWMS. The absence of significant impacts is attributed to a combination of the arid climate of Frenchman Flat, the low volumetric moisture contents of alluvial deposits below the Area 5 RWMS, and the considerable depth to the ground water table (~ 240 m).

7.2 Observations

The Independent Panel has four observations. The first two result directly from the panel investigations of PA impacts, and the third and fourth are related but beyond the scope of the panel study.

1. The only significant difference noted with the Area 5 PA is the assumption that the initial moisture content of disposed waste is equal to the ambient moisture content of the alluvial deposits. Some of the disposed waste has considerably higher initial water contents than the native alluvium. There are no performance impacts associated with this difference, primarily because of the overall conservatism used in the Area 5 PA. Moreover, while initially inconsistent, the assumption that waste moisture is equal to alluvium moisture is valid over most of the compliance period. Revised simulation modeling of the vadose zone completed as part of the panel evaluations shows that moisture redistribution occurs over intervals of tens of years, and volumetric water contents then approach initial conditions. Future iterations of PA assessment studies should assume initially higher water contents for some percentage of the waste inventory.

2. One issue that arose during presentation of the panel evaluations to the State of Nevada is identification of the volume of disposed waste that has the potential for including waste streams with high moisture contents. The simulation modeling shows that disposal performance at the Area 5 RWMS will not be significantly affected even if 100% of the disposed waste contains excess moisture. Moreover,

based on discussions with DOE program managers and contractor personnel, it is likely that the volume of disposed "wet" waste at Area 5 is much less than 100% and may be less than 25%. Further clarification of the actual abundance of disposed "wet" waste at the Area 5 RWMS is possible but would be of limited value given no significant performance impacts assuming 100% of the disposed waste inventory contains excess moisture.

3. The shipping and handling requirements for both generators and the NTS environmental management program limit the amount of *free* liquid in waste but do not set specific requirements for the volumetric moisture content of the waste. The routine use of absorbents prior to shipping reduces the potential for free liquids but does not address the issue of high moisture contents. Other approaches to moisture control are possible at the discretion of the generators, including for example, drying of the waste prior to shipment, evaluation of alternative absorbents, and/or using liners in addition to containers to control free liquids during transportation. A preferred approach would be to implement, using the concept of redundant barriers, multiple alternative methods for moisture reduction to decrease the potential for development of free liquids. The key concept is to reduce the moisture content of waste significantly below saturation of the effective porosity to decrease the likelihood of forming free liquid during transportation.

4. Some of the members of the Independent Panel feel that public perception of the transportation incident is a critical element of stakeholder acceptance of the DOE low-level radioactive waste disposal programs at the NTS. The results of the PA for the Area 5 RWMS are judged to be extremely favorable. The site both meets and provides a considerable margin of protection with respect to the performance objectives. This favorable result of the PA could, however, be jeopardized by future transportation incidents. The DOE should take extra precautions to prevent leakage of liquids during transportation to avoid negative impacts on a highly effective waste disposal site.

8.0 Acknowledgments

The participation and full cooperation of all members of the DOE/NV Independent Panel made it possible to complete this evaluation. It is only the result of a procedural technicality that all panel members could not be listed as co-authors of this report. We acknowledge the contributions of the DOE and contractor personnel who presented valuable information to the panel, often on extremely short notice. We gratefully acknowledge the briefing information provided by Wendy Clayton, DOE/Nevada, Joe Ginanni, DOE/Nevada, Runore Wycoff, DOE/Nevada, Bruce Becker, Bechtel/Nevada and Stewart Rawlinson, Bechtel, Nevada. Dave Rast, Fernald, Ohio provided timely information on percentages of sludge-type waste for waste stream 006. Joe Ginanni, DOE/Nevada, Kevin Leary, DOE/Nevada and Stephen Bolivar, Los Alamos National Laboratories provided technical reviews of the report. Susan Klein, Los Alamos National Laboratories served as the editor of this report and provided timely assistance in final preparations for release of the report.

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Appendix A

Reports of Individual Panel Members[1]

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[1] The number of questions and the wording of the question list concerning performance impacts (section 5.1) changed during preparation of the reports by individual panel members. For this reason, there is some variability in the number and content of the questions addressed by panel members. Further, the panel members were provided the option, dependent on their expertise, of not answering selected items on the question list.

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Letter from Dr. Wayne Hanson, Los Alamos National Laboratory

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Los Alamos National Laboratory

Environment, Safety, and Health Division
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Date: April 14, 1998
Refer to:

Carl Gertz
Assistant Manager, Environmental Management
Nevada Operations Office
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Las Vegas, NV 89193-3838

Dear Dr. Gertz:

This letter is to respond to questions related to the effects of saturated wastes in failed containers from Fernald and disposed of in Area 5 of the Nevada Test Site. The information used for the response is an examination of the document entitled "Performance Assessment for the Area 5 Radioactive Waste Management Site at the Nevada Test Site, Nye County, Nevada," by Shott et. al dated January, 1998. Addition information was provided by Bechtel Nevada and DOE personnel at meetings held at your offices.

Since the performance assessment is the analysis that provides the envelope of expected behavior for radioactive materials placed in the waste system, the approach to my review was to examine whether a change in the wastes disposed with added water would exceed the bounds of the scenarios examined in the above document. If so, would the performance objectives be exceeded?

During our meetings at the Nevada Operations Office we formulated a set of questions. My responses to those questions are stated below. I have not responded to every question because others with more expertise in those areas are also preparing responses.

Question 1. What is the impact of the container failure/leakage on the performance assessments of the waste disposal system?

The question above might be rephrased to ask whether or not the existing performance assessments for Area 5 and Area 3 have considered introduction of water to the waste system beyond that normally expected. The Area 5 performance assessment considers subsidence with subsequent flooding. The Area 5 waste area was assumed to subside uniformly and three consecutive years of 2 meters of ponding took place. A second case examined was that of four consecutive years of 1.07 meters of ponding on top the wastes. The amount of water available to move through the wastes in the above flooding scenarios is much greater than the water available from the failed waste containers, even if all were placed in one trench. The flooding events analyzed indicated some migration to the water table. However, the Total Effective Dose Equivalents (TEDE) over a 10,000 year time period was still well below the performance objectives.

Question 2. Do the container flaws have any impact on subsidence?

The performance assessment for Area 5 and Area 3 assume the waste container does not exist after the institutional control period of 100 years. The potential for earlier failure of the containers increases the likely hood of failure within the 100 year period. The container flaws, with the added water in the wastes lead to a potential for more rapid corrosion and underground movement of the wastes. Earlier failure of the containers in the waste system would hasten the subsidence that will take place. Earlier failure in the 100 year institutional control period will provide and opportunity to correct and subsidence areas in the final waste site cover.

Question 5. What is the affect of excess moisture in waste on Radon transport?

Radon migration upward through the cover materials over the wastes in the system are dependent on several factors. Shott, et. al, 1998 performed a sensitivity analysis for the estimated Radon flux at the surface of Area 5. The important factor was the porosity of the materials above the source of Radon and the wastes with all other parameters such as source term concentration and half-life remaining the same. Water added to the waste layers will decrease the porosity of the soil. At the saturated condition Radon fluxes would be negligible from wastes below the cover. As the waste starts to move to partially saturated with water, the low porosity will increase the Radon flux over the base case dry conditions. As the porosity increases with drying, the radon flux will decrease at the surface. In the sensitivity and uncertainty analysis for the performance assessment the porosities of both the waste and cover materials were varied. In no case did the radon flux on the surface exceed the performance objective.

Addition of 3 meters of soil for the final cover of the waste system at Area 5 would reduce the Radon flux to a negligible amount relative to the natural background fluxes of Radon from the soils.

Question 8. What are the possibilities for and the impact of corrosive waters from excess moisture?

Corrosive waters and excess moisture in the waste trench will increase the rate of container failure. Mild steel containers will rust and loose integrity at a more rapid rate. Any wood containers or cardboard containers in the vicinity that have the moisture available will decay at a more rapid rate. Earlier container failure will lead to earlier subsidence of the waste cover. The earlier subsidence will assure the assumption that all subsidence has occurred in the 100 year institutional care period will be met. If subsidence occurs in the 100 year institutional care period, any depressions or cover failure will be maintained and restored to original grade.

Question 10. Related to question 3, is the presence of excess moisture significant with respect to plant and/or insect activity and could this affect upward pathways and radiological releases?

Increased moisture in the waste system will provide more opportunity for plant cover increase in the case of the 2.4 meter cover system examined in Shott, et. al, 1998. Examination of the subsidence and flooding scenarios indicates the moisture at depth lasts long enough to influence the growth patterns of plants in the immediate area. Soil moisture appears to decrease over a period of 50 to 90 years before attaining the original soil water contents. However, the estimates provided by Shott, et. al, 1998 rely on diffusion of the water in the soils to the surface. With plants present there is an active pumping mechanism connected to the atmosphere. The transpiration of plants will dry the system much faster than bare soils alone. The system will experience a transient increase in plant populations until the increased plant cover utilizes the water available and the soil returns to the water content common to the area. The plant population will then return to a lower biomass production similar to the current native plant system.

One means of radionuclide movement upward in soils is by plant uptake. This is highly dependent on the biomass production of the plants and the rooting depths of the plants. The measured rooting depth of the plants common to NTS summarized by Shott, et. al, 1998 are shallow enough that the cover thickness considered for the waste system will strongly influence the amount of root penetration of the wastes. This was considered in the current performance assessment. The following comments examine the affect of changes in plant populations on the rate of radionuclide uptake to the surface by estimating the changes in parameters in equation (3.16) in Shott, et. al, 1998.

The following evaluation uses the estimated time for the soil water content to return to normal after introduction of the wastes. The time for drying is long enough that a plant response could take place. Biomass production on the surface could undergo an increase due to the water and be followed by added plant growth due to increased seed germination.

The current performance assessment examined the plant uptake by using a conservative assumption that the deepest roots penetrations recorded in the literature represented the case at the NTS, Area 5 Waste Management system. Adding water to wastes buried under the 2.4 meter cover could, for selected species, encourage more root growth in the direction of a source of moisture. Because of the depths to the waste, the roots in the surface soils would not be affected. The effect is represented here by doubling the fraction of the vegetation with roots in the waste from 0.05 to 0.1. Availability of water in the system would increase the biomass production. As indicated in the performance assessment the biomass doubles with a four fold increase in precipitation in Mojave Desert plant communities. For this analysis the doubling of the fraction of vegetation with roots in waste will be represented by a doubling of the biomass production.

Another factor in equation 3.16 that may be influenced by the moisture content is the ratio of the above ground biomass to below ground biomass production. This factor is part of the denominator in equation 3.16. An increase in the parameter indicates the below ground biomass productivity is decreasing. For the purpose of this analysis the below ground productivity is assumed to increase such that more roots are produced in response to more moisture relative to the above ground productivity. The values for this ratio for the Mojave Desert range from 0.6 to 2.3. The result of the use of a value of 0.6 is an increase of plant uptake of radionuclides by a factor of 1.2.

Combining the estimated increases due to the moisture in the wastes results in a factor of 4.8 more radionuclide uptake by plants. Table E.8 Maximum Doses for Nonvolatile Radionuclides in the Base Case and Open Range Scenario indicates the maximum Committed Effective Dose Equivalent is 1.1 mrem/year from the milk pathway. This dose could then increase to 5.3 mrem/yr based on the increased plant uptake. This dose still meets the performance objectives. If the milk pathway is not present, the dose decreases to 1.4 mrem/yr from all pathways, still within the performance objectives.

Insects in the area of the waste system may be increased by the increased plant production. Shott, et. al, 1998 examined the depths insects burrow into the soils of the area. Harvester ants were the only contributors to movement of wastes from depth to the surface. Estimates of the amount of "soil like wastes" brought to the surface were made. The result was that the amount of contaminated soil brought to the surface dominated the transient occupancy scenario for intrusion with a dose of 9.7 mrem/yr, mostly from Ra-226 (Table E.6). Assuming the number of ant colonies doubles because of the doubling of plant biomass available as food, the increased dose from the moisture in the wastes would be another 9.7 mrem/yr or a total of 19.4 mrem/yr. The increase is still well within the performance objectives for the waste management system.

Plans for the final cover of the Area 5 waste system include a final cover thickness of 3 meters. The addition of cover material reduces the amount of waste volume that is available to plant roots and animal burrows. With the existing 2.4 meter cover material the plant roots can penetrate up to 2 meters of waste using the deepest root penetrations found in the literature. Addition of 3 meters of cover would remove plant uptake as a means of radionuclide movement to the surface. The addition of 3 meters of soil cover would also eliminate the Harvester ants as an important pathway for bringing wastes to the surface. The literature survey by Shott, et. al, 1998 indicated the deep burrows are between 2 and 3 meters. With the 2.4 meter cover the conservative approach was to assume the ants brought wastes to the surface. With an added 3 meters of soil, the distance to the wastes far exceeds the burrow depths of the Harvester ants.

If you have any questions regarding these comments please contact me at 505 667-4218 or email at hansen_wayne_r@lanl.gov.

Sincerely,

Wayne R. Hansen, Ph.D., CHP
Chief Scientist
Environment, Safety, and Health Division

WH:mv

Cy: Steven Mellington, DOE/AMEM

Letter and paper from Dr. Anthony Hechanova

UNLV
UNIVERSITY OF NEVADA LAS VEGAS

April 13, 1998

Carl Gertz
Assistant Manager, Environmental Management
U.S. Department of Energy, Nevada Operations Office
232 Energy Way
North Las Vegas, NV 89030

Dear Mr. Gertz:

Attached are my final comments regarding my participation in the DOE/NV Independent Panel investigating the implications of Fernald leaking container issues on the Nevada Test Site radioactive waste management site performance assessment. A draft of these comments was provided to Bruce Crowe on March 23, 1998, to aid in the preparation of the Preliminary Draft report entitled "Synthesis Report of the Recommendations of the Independent Panel on the Consequences of Disposal of Stress-Fractured Containers Containing Low-Level Radioactive Waste with Excess Moisture" by Crowe, Hansen, Waters, Sully, and Levitt. I have reviewed the Preliminary Draft and find that it adequately documents the Panel's discussions and observations.

I appreciated the opportunity to participate in the Independent Panel and I trust that the process has been mutually edifying for DOE/NV and the Harry Reid Center's Nevada Risk Assessment/Management Program (NRAMP). I encourage you to continue to seek qualified stakeholder participation which will prove to be the cornerstone of DOE credibility.

Anthony E. Hechanova

Anthony E. Hechanova, Ph.D.
Harry Reid Center for Environmental Studies
University of Nevada, Las Vegas

cc w/ encl.:

Don Baepler, NRAMP PI
Steven Mellington, DOE/AMEM
Runore Wycoff, DOE/WMD
Frank DiSanza, DOE/WMD
Dale Schutte, NTS CAB

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DOE/NV Independent Panel Implications of Fernald Leaking Container Issues on NTS Radioactive Waste Management Site Performance Assessment

Comments from Anthony E. Hechanova, Ph.D.
Harry Reid Center for Environmental Studies
University of Nevada, Las Vegas
April 13, 1998

At least two issues are obvious regarding the December 1997 Fernald Environmental Management Project (FEMP) leaking waste container incidents. First, containment failure occurred and actions are required to correct the problems. The second issue may be less obvious: a waste acceptance criterion was violated at the point of disposal although it may have been acceptable at the point of origin. The Independent Panel was charged to investigate the impact of these issues on the performance assessment of the Nevada Test Site radioactive waste management sites (NTS RWMS). The Panel determined that there are no significant impacts on current NTS RWMS Performance Assessments. The Panel procedures and conclusions are briefly discussed below followed by my opinions which may not reflect those of other Panel members.

Method of Solution

The first step of this process required identification of the scope of the problem, specifically, waste stream characteristics and the location of previously disposed containers. Of all the FEMP Low-Level Radioactive Waste (LLW) streams, only one has been identified that has a potential for saturated waste: Waste Stream 6. Large volumes of this waste stream of concern were disposed in Pits 4 through 6 of the Area 5 RWMS beginning on May 4, 1993. U.S. Department of Energy (DOE) personnel has estimated up to 9 percent of total pit volume in Pit 4 and 18 percent in Pit 5 could potentially contain the sludge waste type (note: Pit 6 contains a small amount of this waste stream and is no longer accepting FEMP shipments until resolution of the problem). Although the Panel was not able to get a precise description for each waste stream from all generators because of the brief time frame of the Independent Panel, it is the opinion of the Panel based on discussion with waste management operators that no other LLW streams probably originated as a sludge. In fact, the Panel decided to confine the investigation to the Area 5 RWMS because the other operating RWMS (in Area 3) was clearly used for disposal of bulk, dry wastes such as bulk debris and contaminated soils from tunnel and surface tests and bulk debris from off-site generators. It is also reasonable to assume that most processes that result in sludge wastes contain solvents and other materials inherent in processing that would classify the waste as Mixed Low-Level Radioactive Waste (MLLW). An example relevant to the NTS is the "pondcrete" from Rocky Flats which originated as a sludge but was solidified and classified as MLLW. Therefore, focusing on FEMP Waste Stream 6 (which is not MLLW) was a reasonable way to bound the scope of the problem.

The second step was to investigate the Area 5 RWMS site characteristics and identify conceivable impacts on performance objectives not only to satisfy the Panel's concerns, but also the critical outsider. This required careful and comprehensive review of the Area 5 Performance Assessment (Shott et al., 1997) from which the Panel developed conceptual impacts in the form of questions, listed in Table I, based on conceivable effects of saturated waste and weakened container integrity on radionuclide migration.

The third step was to investigate the answers to this list of questions to see if a significant effect would be predicted. This step relied on both expert opinion and actual calculations. Panel members concentrated on answering particular questions within their areas of expertise and tasking DOE contractors to rerun certain models using assumptions prescribed by the Panel.

Table I. Issues and Questions Raised and Investigated by the Panel.

Issue	**Question**
Container Integrity	Are there significant performance assessment impacts from burial of low-level radioactive waste in stress-fractured containers with reduced integrity?
Subsidence	Does the disposal of waste in stress-fractured containers have significant impacts on the issue of subsidence?
Upward Pathways (Gaseous)	Does the presence of excess moisture in some waste containers have significant impacts on upward pathways and radiological releases of volatile radionuclides?
Upward Pathways (Advection, Diffusion)	Does the presence of excess moisture in some waste containers have significant performance assessment impacts on upward advection of radionuclides under ambient conditions, under wetter conditions from rainfall events, and on upward diffusion of dissolved solutes?
Radon	Are there significant impacts on rates of Radon transport from excess moisture in some waste containers?
Downward Pathways (Advection)	Are there significant performance assessment impacts on water movement and radionuclide transport in the vadose zone from the introduction of excess moisture in some waste containers?
Corrosion	Are there significant performance assessment impacts with respect to corrosion of waste and/or containers from the presence of excess moisture?
Carbon-14	Are there significant impacts on the rates of ^{14}C transport in the presence of excess moisture?
Biointrusion	Is the presence of excess moisture significant with respect to plant and/or insect activity and could this affect upward pathways and radiological releases?

The final step was to interpret the results of the above investigations and provide conclusions and recommendations to the DOE and other interested parties.

Results and Conclusions

The Panel unanimously concluded that no significant impacts have been identified, based on the information received to date, that would change the conclusions of the current Area 5 Performance Assessment which has shown the site to satisfy the performance objectives in DOE Orders 5820.2A. Each of the nine questions in Table I were investigated and a detailed report providing quantitative results and the reasons for the "no significant impact" judgments will be written by national laboratory scientists Bruce Crowe (Los Alamos), Wayne Hansen (Los Alamos), and Robert Waters (Sandia). I will not reiterate the details of the report. In general, the NTS RWMS Performance Assessments use very conservative assumptions and models. In addition, the site itself is very arid. This combination made it difficult to envision an impact from excess moisture because either the Performance Assessment assumptions already assumed a worst case radionuclide migration scenario rendering the moisture issue a moot point; or, the moisture would soon redistribute itself in all directions and have no conceivable significant impact on the site performance of such an arid locale (in fact, the Panel concluded that the impacts would be considerably less than those evaluated for the Performance Assessment if an appropriate closure cap were considered).

When estimating radionuclide migration, the Performance Assessment assumes that radionuclides are not confined by a container. Therefore there is no conceivable impact from the loss of integrity of any containers, including the FEMP-type containers. However, it is conceivable that a weaker container could bring about surface subsidence sooner than otherwise expected. This would not be a negative effect because it is advantageous to have subsidence occur during the operational time frame so that it can be ameliorated before the closure cap is in place.

I believe the greatest impact of the FEMP container incidents is on DOE credibility. The events have sparked public discontent. Public stakeholders have indicated to me their feelings that (1) some type of waste acceptance criteria verification is required at the disposal point to satisfy public concerns and validate waste characterization assumptions, and (2) some type of independent oversight of the DOE waste management program is needed.

I believe that the Nevada public could perceive the FEMP incidents as an indication that the DOE does not know what they are putting into their radioactive waste management sites. This would greatly diminish the tenuous credibility and trust of the DOE by Nevada stakeholders. Therefore, it is important to convey the reality of the situation: (1) that all waste generation processes are well understood, (2) that waste generators and managers know the characteristics of the waste they are shipping to and disposing in Nevada (at least since the inception of improved databases around 1992, i.e., before Waste Stream 6 was disposed at the NTS), and (3) that the FEMP problem brought to light some glaring errors in container design and waste treatment (these issues are discussed in the Type B Accident Investigation Report (DOE/FEMP, 1998) and by other issue-specific groups established by the DOE). Although mistakes were made, the Panel does not expect them to have any significant impact on the technical performance of waste disposal at the NTS.

Many Nevada stakeholders have for a long time regarded DOE self-regulation and the lack of on-site verification as egregious. The FEMP incidents have given credence to this point of view. A Performance Assessment is only as good as the assumptions upon which it is based and some assumptions were invalid. Although the Panel concluded that there is no significant impact to the NTS RWMS Performance Assessments from these invalid assumptions, problems may exist with other assumptions that are not yet known. A reasonable question on people's mind is: "The DOE has erred on one assumption, could they err on others?" To lend credibility to DOE assumptions in future PAs, I recommend that concepts for verification and independent oversight be investigated to ensure that the assumptions going into a PA are valid.

I would like to conclude these comments with the observation that perception is reality. As a scientist, I perceive the NTS radioactive waste management sites as being DOE's best site for low-level radioactive waste disposal from a purely technical performance point of view. As a local university employee who has been tasked to communicate with Nevada public stakeholders, I observe that citizens are less interested in technical aspects and more interested in their perceptions and visions. The vision left by the FEMP events is one of leaking radioactive waste being trucked across America's highways, through the Las Vegas Valley, and into the Nevada Test Site. The perception is one echoed by Nevada's elected representatives: the NTS contains the nation's dump for deadly radioactive waste that will pose an unfair threat to future generations of Nevadans. Although the Independent Panel of technical experts, of which I am a member, has deemed the impact of the FEMP issues as inconsequential to the RWMS performance assessment, public perceptions and concerns regarding sludge waste types must still be addressed and resolved.

References

DOE/FEMP, *Type B Accident Investigation Board Report of the December 15, 1997, Leakage of Waste Containers Near Kingman, Arizona*, Fernald Environmental Management Project, U.S. Department of Energy, Fernald, OH, February 1998.

Shott, G.J, L.E. Barker, and M.J. Sully, *Performance Assessment for the Area 5 Radioactive Waste Management Site at the Nevada Test Site, Nye County, Nevada*, Revision 2.1, Bechtel Nevada, Las Vegas, NV, February 1997.

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Letter and paper from Dr. Charles F. Voss

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March 23, 1998
U.S. Department of Energy
232 Energy Way
North Las Vegas, NV 89030

ATTN: DR. CARL GERTZ

RE: INDEPENDENT REVIEW PANEL REPORT

Dear Dr. Gertz:

A copy of the report entitled *"Consequences of Failed Containers with Excess Moisture on the Performance of Area 5 Radioactive Waste Management Sites, Nevada Test Site,"* is enclosed. As you know, the Panel members were instructed to provide separate reports concerning their findings. Therefore, the opinions expressed in this report are my own and may not be representative of the other Panel members.

My conclusions can be summarized as follows:

1. The addition of failed containers, saturated waste and free liquid in the Area 5 RWMS is not expected to have a significant impact on the performance of the facility given the assumptions and information used to perform this review. The combination of the arid environment and the RWMS design provides a robust disposal system.

2. The volume of saturated 006 FEMP waste that has been placed in the Area 5 RWMS is inconsistent with the conceptual model used for the Area 5 performance assessment. The models should be modified similar in future performance assessments to account for existing and future sludge disposal at Area 5.

3. The waste acceptance criteria should be modified to account for the potential changes transportation may cause to the waste form. Vibration during transport is a form of "processing" that has been shown to change the physical condition of some forms of the FEMP 006 waste.

4. The practice of disposing of saturated waste is questionable and should be carefully evaluated. The moisture in the sludge introduces a driving force for the potential transport of contaminants. While the performance improvement derived from removing some of the moisture prior to disposal will increase disposal cost, the increase in public confidence may justify the expense.

Thank you for the opportunity to participate in this review. Please contact me if you have any questions or comments on the report.

Sincerely,

GOLDER ASSOCIATES INC.

Charles F. Voss
Principal

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Consequences of Failed Containers with Excess Moisture on the Performance of Area 5 Radioactive Waste Management Sites, Nevada Test Site

by

Charles F. Voss
Golder Associates Inc.
Redmond, Washington

March 1998

Prepared for

U.S. Department of Energy
Nevada Operations Office

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Table of Contents

Introduction

On December 15, 1997, a shipment of low-level radioactive waste from the Department of Energy's (DOE) Fernald Environmental Management Project (FEMP) arrived at the Nevada Test Site destined for disposal in the Area 5 Radioactive Waste Management Site (RWMS) in Frenchman Flats. During the inspection and removal of the waste containers from the trailer, it became apparent that one of the three containers had been breached and some volume of water had leaked from the container. Several hours later, another shipment of FEMP waste was discovered to contain failed containers with significant amounts of free liquids. The trailer was stopped in Kingman, Arizona and inspected. In both cases, radiation from the leaks was below background levels.

The DOE temporarily halted all shipments of waste to the RWMS and initiated several studies to establish the cause of the leaking containers and evaluate the potential performance impacts of disposing of failed containers with excess moisture. This report addresses the latter question. The DOE formed an Independent Review Panel (subsequently referred to as "the Panel") to consider the potential impacts on the long-term performance of the RWMS. The Panel members were instructed to provide independent assessments of the impacts. Hence, the opinion expressed in this report represent those of the author and may not be representative of the other Panel members.

The scope of the Independent Review Panel is described in Section 2. This section also provides background information on the nature and possible cause of the failed containers and the presence of free liquid in the waste. Section 3 summarizes the performance objectives used by the Panel to consider the potential impacts of disposing of failed containers with excess moisture (free liquid) in the RWMS disposal cells. The impacts considered and their likely significance are presented in Section 4. Section 5 contains a summary of the findings and recommendations to the DOE related to this incident.

Background Information

1. Scope of the Independent Review Panel

The DOE initiated two studies in response to the leaking container incidents at the Area 5 RWMS and Kingman, Arizona. A Type B Accident Investigation Board was formed on December 22, 1997 to look into the cause of the container failures and the reason for significant volumes of free liquid being present in the FEMP waste. The Independent Review Panel was convened in late January 1998 to consider the potential consequences of disposing of failed containers with free liquid volumes greater than the waste acceptance criteria. The Panel consisted of seven scientists and engineers with experience in performing safety assessments of radioactive disposal systems. The members of the Panel and their areas of expertise are listed in Table 1.

The scope of the Independent Review Panel was to consider whether disposing of failed (i.e., breached) containers with free liquids was likely to impact the *performance* of the RWMS at Area 5. "Performance" refers to the performance objectives specified in DOE Order 5820.2A, *Radioactive Waste Management* (DOE, 1988) for radioactive waste disposal. The Order requires that a performance assessment be conducted to evaluate the potential risks posed by a waste management system to the public and the environment. The assessment must demonstrate that there is reasonable assurance that a facility will comply with the performance objectives for a period of 10,000 years after closure. While the performance assessment for the Area 5 RWMS (Shott et al., January 1998) indicates the facility will comply with the performance objectives, the assessment was based on the assumption that the moisture content of the waste is the same as the surrounding alluvium. Hence, if a significant percentage of the existing FEMP waste containers in the Area 5 RWMS contain significant (e.g., several times the waste acceptance criterion) volumes of free liquid and saturated waste, the performance of the system could be impacted.

Table 1. Independent Review Panel Members

Name	Affiliation	Technical Area(s)
Dr. Bruce Crowe	Los Alamos National Laboratory	Geology, risk assessment
Dr. Roger Jacobson	Desert Research Institute	Geochemistry, hydrology
Mr. Charles Voss	Golder Associates Inc.	Geomechanics, performance assessment
Dr. Robert Waters	Sandia National Laboratory	Performance assessment, environmental science
Dr. Anthony Hechanova	Harry Reid Center, University of Nevada	Performance assessment, risk assessment
Dr. Wayne Hanson	Los Alamos National Laboratory	Health physics, performance assessment, environmental dose assessment
Mr. Mike McKinnon	Nevada Department of Environmental Protection	

The Panel members conducted their review using the following methodology:

1. Review the performance assessment documents for Area 3 and Area 5 RWMS disposal cells at the Nevada Test Site to consider potential system components and processes that could be impacted;
2. Review the findings of the Accident Investigation Board on the cause and nature of the failed containers and free liquid present in the waste;
3. Consider the potential performance impact(s) of disposing failed containers and free liquids in the RWMS; and
4. Document any conclusions/findings based on the review.

The scope of work was performed over a six week period. The Panel was officially convened on February 10, 1998. Prior to this meeting, the Panel members attended a planning meeting in Las Vegas on January 22 to be briefed on the incident and discuss the technical requirements and scope of the review. Detailed technical discussions were postponed until the second meeting because the panel members had not been formally approved by the DOE and a observer from the State of Nevada had not been identified.

The Panel was provided the following references as part of the review:

- G.J. Shott, L.E. Barker, S.E. Rawlingson, M.J. Scully, and B.A. Moore, *Performance Assessment for the Area 5 Radioactive Waste Management Site at the Nevada Test Site, Nye County, Nevada*, DOE/NV/11718, January 1998.
- G.J. Shott, V. Yucel, M.J. Scully, L.E. Barker, S.E. Rawlingson, and B.A. Moore, *Performance Assessment/Composite Analysis for the Area 3 Radioactive Waste Management Site at the Nevada Test Site, Nye County, Nevada, Revision 2.0*, DOE/NV-491, September 1997.
- W. Arnold et. Al., *Consequences of Subsidence for the Area 3 and Area 5 Radioactive Waste Management Sites, Nevada Test Site (Working Group Report)*, Draft Document, January 1998.
- *Type B Accident Investigation Board Report of the December 15, 1997, Leakage of Waste Containers Near Kingman, Arizona*, February 1998.

The Panel members were instructed to provide separate and independent reports summarizing their conclusions and recommendations. Therefore, this report represents only the opinion of the author and does not necessarily represent the opinion of the other panel members.

2. Nature and Potential Cause of the Leaking Containers

The failure of the waste containers was apparently the result of high shear and tensile stresses at the edge of a center support skid (Type B Accident Investigation Board Report, 1998). The ends of the skid are slightly recessed from the edge of the container resulting in stress concentration in the adjacent container material. The containers are typically stacked during the loading of the shipping trailers. The resulting loads produce high shear and tensile stresses in the container material along the ends of the center skid. All the failed containers at the NTS and at Kingman, Arizona failed at these locations. The small cracks or tears that were formed allowed any free liquid to drain from the container. While the containers are not expected to provide long-term isolation of the waste (i.e., tens to hundreds of years), they are required to provide complete containment of the solids and liquids during transport and handling of the containers.

The waste in the containers with free liquids all came from the same waste stream at FEMP. The waste, referred to as type *006*, is characterized as solid and liquid residues from uranium metal production and includes metals, slurries, filter cake, dust collector residues, raffinate and magnesium fluoride. Because liquids provide for several transport pathways to the accessible environment, the waste specifications for low-level waste disposal require that the waste contain as little free standing liquid as is reasonably achievable. Liquid wastes are required to be solidified or packaged in sufficient absorbent material to absorb twice the volume of the free liquid. The remaining free liquid must not exceed 1 % of the waste volume when the waste is in a disposal container.

The *006* sludge material was generated at the Advanced Waste Water Treatment Plant at FEMP. Prior to shipment, the waste was stored in steel drums. Any free liquid present at the time of shipping was decanted from the waste and a sorbent material, Dicalite, was added to the waste container to sorb any residual moisture. The vibration of the waste during transport apparently caused some of the liquid to be released from the waste form. This was confirmed in one of the containers in the Kingman shipment. Box Number 483004 lost 207 lb (94 kg) of mass during shipment, presumably the result of 25 gal (94 ℓ) of liquid leaking from the breach in the bottom of the container. By the time the container was returned to Fernald, approximately 1 in (2.54 cm) of additional free liquid (approximately 66 ℓ) was observed on top of the waste. Twenty-six samples from the leaking containers and other waste types from FEMP were collected and analyzed. The moisture content was from 7.7% to 65.6%. The 26 samples were subjected to shaking for 15 hours and then allowed to rest for two hours. Sixty-five percent of the samples developed free liquid. The Type B Accident Investigation Board reported that the FEMP operators questioned the effectiveness of the Dicalite sorbent material on high moisture content waste.

The free liquid content in at least one of the containers, Number 483004, exceeded the waste acceptance criterion of 1%. Combining the volume of liquid that leaked from the container and the free water that formed during the return to FEMP, the free liquid volume was in excess of 160 ℓ or 5% of the waste volume. The performance assessment analyses assume the free liquid content in the waste is minimal (< 1% by volume[2]). The question is whether a RWMS containing waste with significantly larger volumes of free liquids would exceed any of the performance objectives specified in DOE Order 5820.2A.

Personnel at Fernald were able to provide some information on the volume of saturated 006 FEMP waste that has been placed in the Area 5 RWMS. A total of 590,332 ft^3 (16,716 m^3) of 006 waste has been disposed of in Pits 4, 5 and 6. FEMP estimates that approximately 50% of the waste is sludge. The pit volumes and the volume of 006 waste in each of the pits is listed in Table 2. Based on the available information, the percentage of high moisture content waste in Pit 5 could be from 18% to 35% of the total volume, the 35% being a maximum value assuming all the 006 waste disposed in Pit 5 was sludge.

Table 2. Pit Volumes and 006 Waste Volumes at Area 5 RWMS

Pit No.	Total Pit Volume (m^3)	006 Waste Volume (m^3)	Percentage of Pit Filled with 006 Waste
4	61,677	11,005	18%
5	16,448	5,702	35%
6	unknown	9	

Potential Impacts Considered

This section summarizes the performance objectives for DOE low-level radioactive waste management systems and the potential performance impacts considered in the Independent Panel Review. The conceptual model of flow and transport processes in a RWMS at the NTS is first summarized and the evolution of the system over time is discussed. The conceptual model and long-term changes in the system are important considerations when evaluating the potential impacts of introducing free liquid in the waste containers. Because the closure cap over a RWMS may have a significant influence on performance, the baseline and alternative closure cap designs are also discussed.

3. Conceptual Model of Flow and Transport Processes

Waste disposal in the Area 5 RWMS consists of a variety of shallow, unlined pits and trenches. High activity radioactive waste has been disposed of in deep shafts. Low level waste in the trenches is disposed of in steel drums and in cardboard, plywood and steel boxes. The waste

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[2] One-percent of the container volume is approximately 8 gallons (30 liters).

containers are stacked closely together from the trench floor to within 4 ft (1.2 m) of the original grade. The thickness of the waste layer ranges from 11 to 44 ft (3.4 to 13.4 m). Soil backfill is placed over the waste layer as disposal advances along the length of the trench. A cover or closure cap system is eventually constructed over the trenches and pits.

The source term for the performance assessment analyses consists of volatile and nonvolatile waste fractions with different release and transport processes. Volatile radionuclides are assumed to be released from the site by gaseous diffusion through the air-filled pores of the soil cap. Nonvolatile radionuclides are assumed to be released by several transport mechanisms including plant uptake, burrowing animals, and advection of solutes in soil pore water.

Desert plants have been observed to have rooting depths down to 13 ft (4 m). Root uptake of radionuclides in the waste could lead to contamination of surface soils as a result of plant biomass becoming detritus. Burrowing animals could also transport waste and contaminated soil to the surface. Burrows from mammals and reptiles have been observed as deep as 10 ft (3 m) below ground surface. The contaminants brought to the surface by these release mechanisms would serve as a source of air contamination and transport to soil and plant surfaces in the area. The likelihood of a release by these mechanisms depends to a large extent on the vertical distance to the waste layer. Hence, the closure cap design is an important component of the RWMS.

The conceptual model of the site hydrology consists of four regions or zones. Moisture movement in these zones is assumed to be primarily vertical. The upper most zone extends from the surface to approximately 115 ft (35 m) depth, depending on soil properties and topography in the area. The magnitude and direction of liquid and vapor flux in the near surface varies seasonally and often daily. Liquid and vapor have a tendency to move upward due to the increasingly negative matric potential towards the surface except following precipitation events when the water content in the soil increases. Most of the water that infiltrates from the surface evaporates or is transpired back to the atmosphere. A "zero flux zone" is thought to lie below the upper zone that extends down to around 295 ft (90 m). Because the waste is emplaced above the zero-flux zone, downward transport to the aquifer is considered to be unlikely. Below the zero flux zone, water flow is considered to be downward. The travel time from the zero-flux zone to the aquifer at approximately 720 ft (220 m) is estimated to be in the order of 51,000 years. The lowest zone is directly above the water table where the water is under capillary fringe condition with relatively static flow conditions.

Several radionuclide transport mechanisms are possible in the hydrologic model described above. Upward advection of water could occur because of the gradient in matric potential. Dissolved solutes in the liquid phase may diffuse upward due to the concentration gradient. Downward advection of water is considered to be unlikely because of the low precipitation and high evaporation rates typical in arid environments.

4. Long-Term Changes to the RWMS

Over the course of several hundred years, the waste packages and waste material in the trenches are expected to decompose, collapse and compress resulting in subsidence of the ground surface. The maximum predicted subsidence above the Area 5 RWMS trenches is approximately 70% of the trench depth or 7 to 21 ft (2.1 to 6.4 m). The magnitude and differential settlement associated with the subsidence will significantly deform the closure cap and could influence the possible modes of radionuclide release. The baseline closure cap design features three layers of materials, a total of 7.5 ft (2.3 m) thick. The lowest layer consists of 1.5 ft (0.5 m) of a soil-cement mixture covered by a 1 ft (0.3 m) soil-bentonite layer and a 5 ft (1.5 m) compacted fill layer.

Differential settlement is likely to result in shearing and cracking of the two rigid, lower cap components resulting in new conditions and potential pathways for release of the volatile and nonvolatile waste components. Examples include direct exposure of the waste at the ground surface, enhanced plant uptake, reduced transport distance to the ground surface and increased waste concentration. The depressions formed by the subsidence could also concentrate surface runoff from precipitation and result in increased infiltration into the disposal unit. As noted above, the arid conditions at the site are expected to result in upward movement of solutes in soil pore water during drying periods between major storms. However, the runoff from very large rainfall events may infiltrate deep enough to not be removed by evaporative processes and proceed downward through the zero-flux zone to the underlying aquifer providing a downward advective transport mechanism for solutes. This scenario was included in the performance assessment of the Area 5 RWMS. However, even when repeated flooding events were considered, the doses and concentrations were within the performance limits (see Section 4.5).

The trenches in Area 5 RWMS are assumed to undergo subsidence at the end of active institutional control (100 years after closure) which may result in reduced cap thickness, increased rooting in buried waste and the collection of water and enhanced infiltration. Alternative closure cap designs are being considered that would reduce the impact differential settlement has on the different transport mechanisms. A recent study (Arnold et al., 1998) recommended that the baseline closure cap design should be replaced by a thick layer of compacted alluvial soil to recreate, to the extent possible, the natural low-infiltration environment of the surrounding natural system. A 10 ft (3 m) thick natural soil cover could theoretically accommodate 16 ft (5 m) of differential settlement) without exposing the waste. This design is being considered by Bechtel Nevada and was incorporated into the performance assessment for the Area 3 RWMS. It is assumed that a similar design will eventually be constructed at the Area 5 RWMS. This is an important assumption since the impact of the free liquid and saturated waste is mitigated by the new closure cover design.

5. Performance Objectives

The basis for assessing the potential impacts from disposing of failed containers with saturated waste and free liquids are the performance objectives required under DOE Order 5820.2A:

- Protect public health and saftey in accordance with the standards;
- The total effective dose equivalent to members of the public should not exceed 25 mrem/year;
- The committed effective dose equivalents to inadvertent human intrusion should not exceed 100 mrem/year chronic, 500 mrem/year acute;
- Ground water resources should be protected consistent with federal, state and local requirements.

The performance assessment must demonstrate with reasonable assurance that the RWMS will be in compliance with the performance objectives for a period of 10,000 years after closure. Based on the conditions assumed in the performance assessment for the Area 5 RWMS, the site will comply. A comparison between the predicted and required performance measures for the base case release and pathway scenarios is shown in Table 3. The analysis included a subsidence scenario with repeated ponding above the disposal area.

Table 3. Comparison between Performance Objectives and Performance Assessment Results for the Area 5 RWMS.

Performance Objective	Performance Assessment Result
25 mrem yr^{-1} from all pathways	0.8 mrem yr^{-1}
10 mrem yr^{-1} from airborne emissions in radon	0.2 mrem yr^{-1}
Average ^{222}Rn flux < 20 pCi m^{-2} s^{-1}	10 pCi m^{-2} s^{-1}
Protect ground water resources ^{226}Ra + ^{228}Ra < 5 pCi L^{-1} Gross alpha < 15 pCi L^{-1} Dose from man-made beta-gamma emitters < 4 mrem yr^{-1}	 0.3 pCi L^{-1} 9 pCi L^{-1} 1 mrem yr^{-1}

6. *Potential Performance Impacts Considered*

The Independent Review Panel considered the following potential impacts as part of their review. Each of the Panel members evaluated the impacts, i.e., no effort was made to develop a common opinion or position for the various issues. The Panel members were instructed to respond to as many of the issues as they felt technically proficient.

1. Are there significant performance assessment impacts on the waste disposal system from burial of low-level radioactive waste in stress-fractured containers?
2. Does the disposal of waste in stress-fractured containers have significant impacts on the issue of subsidence?
3. Does the presence of excess moisture in some waste containers have significant impacts on upward pathways and radiological releases of volatile radionuclides?
4. Does the presence of excess moisture in some waste containers have significant performance assessment impacts on upward advection under ambient conditions, under wetter conditions from rainfall events , and on upward diffusion of dissolved solutes?
5. Are there significant impacts on rates of radon transport from excess moisture in some waste containers?
6. Does the introduction of excess moisture have significant performance assessment impacts on downward advection of waste radionuclides to the ground water table?
7. What are the possibilities for and are there significant performance assessment impacts with respect to corrosion of waste/containers from the presence of excess moisture?
8. Related to questions 5, is generation of 14C significant?
9. Related to question 3, is the presence of excess moisture significant with respect to plant and/or insect activity and could this affect upward pathways and radiological releases?

Issues 1, 2, 3, 4, 6, 7 and 9 are addressed in Section 4. Issues 2 and 7 are treated together. Issues 5 and 8 were not addressed.

Discussion of Potential Impacts

7. *Potential Performance Impact from Stress Fractured Containers*

The presence of failed containers (i.e., containers with small stress fractures) and excess free liquid may increase the rate of corrosion and degradation of containers. However, the performance assessment for the Area 5 RWMS assumed that the entire radionuclide inventory is available for release and transport at the time of closure (Schott et al. 1997). Therefore, the impact of stress fractured containers on system performance is moot. The conceptual model is equivalent to a system in which the waste is placed directly in the disposal cell. This is a reasonable assumption for the purpose of the performance assessment given the uncertainty in the waste properties and the range of containers used (drums, wooden crates, metal boxes, etc.).

8. Impact on Subsidence

As mentioned above, there is considerable uncertainty associated with the degradation behavior of the waste containers. The cardboard containers are assumed to degrade in the first 20 years, wooden boxes in 20 to 150 years and metal drums and boxes in 20 to 1400 years (Arnold et al. 1998). The existence of breached containers and excess free liquids may accelerate corrosion in the steel containers resulting in faster subsidence rates in parts of the disposal cells. The actual rate will depend on many factors and is highly uncertain.

Accelerated corrosion could have a positive impact if the associated subsidence occurs during the active institutional control period. This would allow for the regrading of the closure cap to improve its performance. The performance assessment for the Area 5 RWMS included the subsidence release and pathway scenario. The analysis assumed subsidence, breaching of the closure cap and decreased cap thickness. These events were assumed to occur at the end of institutional control, 100 years after closure. Therefore, any increase in corrosion due to the presence of free liquid is concluded to be minimal given the conservative assumptions in the analysis.

9. Impact of Excess Moisture on Upward Pathways and Releases of Volatile Radionuclides

An increase of the soil moisture content in the vicinity of the waste cell is likely to decrease the release rate of volatile radionuclides. This conclusion is based on Fick's law for a diffusion flux which in one-dimension is given by:

$$Q_j = D_{ej}(\frac{C_{oj}}{z})A$$

where Q_j is the release rate, D_{ej} is the effective diffusion coefficient for a radionuclide j in pore spaces, C_{oj} is the initial air concentration of radionuclide j in the pore space of the waste, z is the mean diffusion length and A is the area of the waste cell. Increasing the moisture content of the soil reduces the release rate since the diffusion coefficient decreases with increasing moisture content.

10. Impact of Excess Moisture on Upward Pathways and Releases of Nonvolatile Radionuclides

Ground water modelers Daniel Levitt and Michael Sully from Bechtel Nevada briefed the Panel on a series of ground water analyses that were performed as part of the performance assessment of Area 5 RWMS. The models were used to simulate soil water movement in the vadose zone under a range of initial and boundary conditions. In order to evaluate the possible impact of introducing free liquids to the subsurface surrounding the waste cell, the Panel requested Levitt and Sully to perform two additional simulations, a base case scenario and a flooding scenario. The simulations assumed that 25% of the waste was saturated. The saturated waste was assumed to be located at the third of four tiers of waste containers (approximately 4 m depth) within Pit 5 of the Area 5 RWMS. The hydraulic properties and initial conditions in the simulations were identical to those used in the subsidence scenario for the performance assessment analyses (Shott et al., 1998).

The base case simulation calculated infiltration, moisture redistribution and bare-soil evaporation for a 50 year period based on ambient weather conditions. Meteorological data for Area 5 RWMS from 1995 were used in the simulation because the year was somewhat wetter than on average. The simulation showed that the moisture in the saturated zone rapidly redistributes to the adjacent soils above and below the moist waste. At the end of the 50 year simulation, the wetting front from the moist area has nearly reached the surface (~1 m depth).

The impact of the upward migration of moisture and the slightly higher moisture content on performance depends on the closure cover design. If the plant roots can reach the impacted soil zone, the slightly wetter conditions could potentially increase releases from plant uptake because of an associated increase in vegetation density. The significance of this impact will depend on a number of other factors including evaporation, plant uptake rates and closure cover thickness which will influence the amount and duration of any increase in the biomass. The relatively small change in moisture content and the conservative assumptions used in the performance assessment suggest the impact will be small to nonexistent, especially if the thick compacted alluvium closure cover is assumed.

11. Impact of Excess Moisture on Downward Pathways and Releases of Nonvolatile Radionuclides

The base case simulation described above in Section 4.4 showed that the moisture in the saturated zone rapidly redistributes to the adjacent soils with lower water contents. At the end of the 50 year simulation, the wetting front from the moist area reached a depth of 14 meters. However, the average wetting front velocity drops to less than 2 cm per year after about 30 years. Assuming the velocity remains constant, the travel time to the water table is approximately 1,000 years.

The flooding scenario simulation used the same conditions as in the Area 5 RWMS performance assessment except for the presence of the saturated waste at a depth of 4 m. A constant head of 2 m was maintained for 24 hours and then allowed to infiltrate into the soil profile. The flooding event was repeated for three consecutive years. The wetting front after three years is approximately 2 m deeper in the case of the excess moisture, i.e., the introduction of the saturated waste has a very small impact on the transport of radionuclides to the ground water and should not impact the performance of the RWMS.

12. Impact of Excess Moisture on Plant Uptake or Radionuclide Releases from Burrowing Animals

The closure cover is expected to be sufficiently thick that a very small percentage of the plant roots will reach the waste, even under conditions of increased moisture content in the waste. The thickness of the soil cover is expected to be greater than the average annual depth of infiltration and plant roots tend to stay within the zone of the infiltration-evaporation front. If the climate becomes wetter, the depth of root penetration may increase and come in contact with the waste. The increased moisture content in the soil around moist waste may support higher plant density and increase the contamination level from plant detritus however the impact on performance is expected to be relatively minor because of the conservative assumptions used in the performance assessment. The slightly higher moisture content in the soil that would result from disposing of waste with excess moisture is not expected to change the behavior of burrowing animals.

Summary and Recommendations

The addition of failed containers, saturated waste and free liquid in the Area 5 RWMS is not expected to have a significant impact on the performance of the facility given the assumptions and information used to perform this review. The combination of the arid environment and the RWMS design provides a robust disposal system. This is demonstrated by the results of the performance assessment analyses which are based on mostly conservative assumptions.

The replacement of the layered closure cap design with the thick layer of compacted alluvial soil is expected to further improve the long-term performance of the RWMS by increasing the depth to the waste layer and minimizing subsidence impacts. The conclusions of this review assume such a closure cap will be used at the Area 5 RWMS.

The volume of saturated 006 FEMP waste that has been placed in the Area 5 RWMS is inconsistent with the conceptual model used for the Area 5 performance assessment. The performance assessment models assume the moisture content of the waste is identical to the alluvium (approximately 9%). However, approximately 50% of the 590,332 ft^3 (590,332 m^3) of 006 waste disposed in Pits 3, 4 and 5 is sludge. The volume of 006 waste in Pit 5 is 201,363 ft^3 (5,702 m^3) or 35% of the pit volume. Assuming half of the waste is saturated, the percentage of saturated waste assumed in the ground water models described in Section 4.4 (25%) appears to be reasonable for a bounding calculation. The percentage may need to be increased in future performance assessments if sludge disposal is continued at the RWMS.

The waste acceptance criteria should be modified to account for the potential changes transportation may cause to the waste form. Vibration during transport is a form of "processing" that has been shown to change the physical condition of some forms of the FEMP 006 waste. Samples of sludge-type wastes should be periodically tested (e.g., laboratory vibration tests) to verify they are stable.

Finally, while a significant volume of sludge has already been disposed of in the Area 5 RWMS, it is the opinion of this author that the practice of disposing of waste with high moisture content is questionable and should be carefully evaluated. Disposing of saturated waste in a facility with the natural low moisture conditions at the NTS introduces a driving force for the potential transport of contaminants. While the performance improvement derived from removing some of the moisture prior to disposal will increase disposal cost, the increase in public confidence may justify the expense.

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Letter from Dr. Bruce Crowe

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The following comments summarize the results of my review of the performance impacts of disposal of low-level radioactive waste in suspect metal box containers shipped from Fernald, Ohio (waste stream 006). The summary is based on my participation on the DOE/Nevada Independent Panel.

Review Assumptions

The following assumptions were made to expedite review of the performance impacts of disposal of low-level radioactive waste from the Fernald waste stream (006):

1. The primary focus of this evaluation is on the Fernald waste stream and identified shipping containers. Other implications of this evaluation are considered, but the thrust of my observations resulting from the panel investigations is on the performance impacts of disposal of the Fernald waste.
2. Based on information provided by the DOE and the DOE-contractors, all the Fernald waste associated with the suspect metal containers has been disposed in the Area 5 RWMS. Accordingly, review comments are directed entirely toward performance impacts for disposed waste at this site.
3. The performance assessment (PA) for the Area 5 RWMS has been reviewed extensively and accepted through a formal review process (DOE Memorandum, August 30, 1996). The comments in this letter are not a review of the Area 5 PA. Instead the focus of the comments is on how new information/insight gained from the transportation incident might change any pertinent assumptions or calculations used in the Area 5 PA. The assumptions and calculations of the performance assessment report (Shott et al. 1997a) were closely followed in this analysis.
4. The issue of inadvertent human intrusion is not affected by the disposal of the white metal boxes with excess moisture and is not evaluated.
5. The performance objectives for the Area 5 PA are primarily dose-based. However, the dose-calculations for the PA are derived from analysis of radionuclide releases along multiple pathways identified in the scenarios and/or conceptual model. The issues of stress-fractured containers and waste with excess moisture affect the analyses of migration of radionuclides along pathways from the waste to the atmosphere and the ground water table. The dose models applied in the Area 5 PA are not changed; the only changes are the concentrations fed into the dose calculations. Therefore, the assessments

summarized in this letter are directed toward changes in radionuclide concentrations along identified scenario pathways.

6. The primary goal of a performance assessment is to defensibly evaluate the range and uncertainty in the processes that affect the present and future hydrogeologic system of a waste disposal site. This goal is implemented in the Area 5 PA primary through the adoption of *conservative* performance calculations. A conservative calculation attempts to bound system performance through assumptions that *overestimate* radiological doses compared to the expected system performance. The difference between the expected doses and the bounded doses constitutes the degree of conservatism built into the calculations. These differences generally cannot be quantified and the confidence in a conservative performance assessment is dependent on full acceptance that the bounding assumptions are demonstratively conservative. An assessment of the performance impacts of fractured containers with excess moisture for the Area 5 PA requires consideration of whether the changed conditions are or are not consistent with the bounding conservative assumptions used in the PA.

Question List: Performance Impacts

The following list of questions was developed by the panel for their assessment of potential performance impacts on the Area 5 RWMS. My comments and observation follow these questions.

1. Are there significant performance assessment impacts from burial of low-level radioactive waste in stress-fractured containers with reduced integrity?
2. Does the disposal of waste in stress-fractured containers have significant impacts on the issue of subsidence?
3. Does the presence of excess moisture in some waste containers have significant impacts on upward pathways and radiological releases of volatile radionuclides?
4. Does the presence of excess moisture in some waste containers have significant performance assessment impacts on upward advection of radionuclides under ambient conditions, under wetter conditions from rainfall events, and on upward diffusion of dissolved solutes?
5. Are there significant impacts on rates of Radon transport from excess moisture in some waste containers?
6. Are there significant performance assessment impacts on water movement and radionuclide transport in the vadose zone from the introduction of excess moisture in some waste containers?
7. What are the possibilities for and are there significant performance assessment impacts with respect to corrosion of waste/containers from the presence of excess moisture?
8. Related to questions 3 and 7, is generation of ^{14}C significant?
9. Related to question 3, is the presence of excess moisture significant with respect to plant and/or insect activity and could this affect upward pathways and radiological releases?

Question 1: Are there significant performance assessment impacts on the waste disposal system from burial of low-level radioactive waste in stress-fractured containers with reduced integrity?

Comment: The conservative assumption used in the Area 5 PA is that all waste radionuclides are available for uptake and release at closure (Schott et al. 1997a; p. 3-31); essentially, no credit was taken in the Area 5 PA for container integrity. The bases for these assumptions are the range of container types (metal boxes, metal drums, cardboard containers and wooden boxes (Shott et al. 1997) and the absence of information on the expected degradation response of the containers under conditions in the vadose zone. Given this uncertainty, the Area 5 PA simply assumed that the container plays no role in meeting the performance objectives of a disposal system.

Under expected conditions of waste disposal in the vadose zone, the presence of container cracks and excess moisture should lead to more rapid corrosion and degradation of containers relative to similar containers lacking cracks or excessive moisture. These differences would be difficult to quantify numerically and would be expected to be small. However, because the bounding conditions assume no container integrity, there are no identified performance impacts from the presence of container cracks and excess moisture.

Question 2: Does the disposal of waste in stress-fractured containers have significant impacts on the issue of subsidence?

Comment: The conservative assumption used in the Area 5 performance assessment is complete decomposition and collapse of waste packages by the end of the period of institutional control (100 years; Shott et al. 1997; p. 3-31). Container degradation rates are not well known. However, collapse rates of 0 to 20 years after burial were estimated for cardboard containers, 20 to 150 years for wooden boxes and 20 to 1400 years for metal drums and boxes (Arnold et al. 1998). The presence of structural cracks and excess moisture in the white metal boxes shipped from Fernald should accelerate the rate of container degradation. However, this increased degradation rate should not be large and the expected interval of decomposition and collapse of metal box containers should be considerably longer than the conservative assumption of 100 years used in the Area 5 PA. Because of this conservatism, no significant performance impacts are identified with respect to subsidence.

Question 3: Does the presence of excess moisture in some waste containers have significant impacts on upward pathways and radiological releases of volatile radionuclides?

Comment: The Area 5 PA used a simplified, one-dimensional form of Fick's law for a modeling diffusion flux and the release to the atmosphere of gaseous radionuclide species

$$Q_j = D_{ej}\left(\frac{C_{oj}}{z}\right)A \qquad (1)$$

where Q_j is release rate in Ci yr^{-1}, D_{ej} is the effective diffusion coefficient for radionuclide j in pore spaces (m^2 yr^{-1}), C_{oj} is the initial air concentration of radionuclide j in the pore space of the waste (Ci m^3), z is the mean diffusion length (m) and A is the area of the waste cell(s) (m^2). The model is a maximum release rate and includes multiple conservative assumptions. A key assumption in the Area 5 PA is the disposed waste has a water content equal to the alluvial deposits (0.086 volumetric water and 36% porosity). The presence of excess moisture in Fernald waste containers is inconsistent with this assumption. Therefore, calculations in the Area 5 PA were repeated assuming the waste in selected containers is fully saturated. The key question for assessing performance impacts is what are the effects of higher water contents on release of gaseous radionuclides?

The primary effect of increased moisture on equation (1) is on D_{ej}, the effective diffusion coefficient for radionuclide j. The equation for the effective diffusion coefficient used in the Area 5 PA is

$$D_{e,H_2O} = D_{a,H_2O} 0.66(\varepsilon - \theta_v) \qquad (2)$$

where $D_{a,H2O}$ is the diffusivity of H_2O in air, 0.66 is the tortuosity coefficient, ε is the total porosity and θ_v is the volumetric water content. Equation (2) shows that the net effect of increased moisture is to *reduce* the effective diffusion coefficient. This equation must be assessed from the perspective of where physically the excess moisture resides in the waste inventory. The excess moisture in waste should result in lower effective diffusion coefficients for gaseous radionuclides in the immediate vicinity of the waste inventory; volumetric moisture contents consistent with the assumptions used in the Area 5 PA should continue to apply above the waste (operational cap and closure cap). Thus only very small (local) reductions are expected in the release rates of gaseous radionulcides. The key conclusion is however, that there is no negative impact on performance relative to the calculations used in the Area 5 PA.

The primary effect of the subsided case on the release of volatile radionuclides is to reduce z, the mean diffusion length (equation (1)) and increase the potential for fractures extending through the closure cap. Excess moisture in waste containers would not affect these processes and the only related effect might be a local increase in the rate of container degradation. The primary effect of excess moisture is a local decrease in the effective diffusion coefficient for gaseous radionuclides and therefore a local reduction in the radiological release rates.

Question 4: Does the presence of excess moisture in some waste containers have significant performance assessment impacts on upward advection of radionuclides under ambient conditions, under wetter conditions from rainfall events, and on upward diffusion of dissolved solutes?

Comment: These pathway processes have been grouped as one question because each process was dismissed in the Area 5 PA as a significant release pathway. The potential for upward advection of dissolved radionuclides was assessed in the Area 5 PA through estimations of the mean travel time for moisture advected upward from the waste inventory to the surface. The assumed travel length was 2.4 meters, the thickness of the operational cap. Matrix potentials were assigned for the cap materials using data from a mean smooth profile established for trench and borehole studies. Extremely long travel time estimates were calculated for moisture movement from the waste to the surface. The travel time is sufficiently long to dismiss upward advection as a significant process (Shott et al. 1997a; see also Baer et al. 1994).

The presence of local higher water contents in the waste inventory from disposal of components of the Fernald waste does not significantly affect the conclusions of no significant impact. The primary barrier to advective transport is the low-conductivity, low moisture alluvial material in the operational and closure caps above the waste and this should remain largely unaffected from the presence of excess moisture in the waste. Similarly, the conclusions of no performance impacts are not significantly changed under wetter conditions. Decreasing the mean travel time for upward advected moisture requires a significant increase in the water contents of the cap materials above the waste. Infiltration modeling used in the Area 5 PA suggest a maximum predicted depth of infiltration of less than 0.3 m, a small length of either the operational cap (2.4 m) or a closure cap constructed above the operational cap (estimated to be about 3 meters). Examination of this predicted maximum depth of infiltration used in the Area 5 PA shows that it is non-conservative. Water-content data measured in Frenchman Flat using time domain reflectometry show that increased water contents from precipitation events have affected infiltration in alluvial deposits to depths of about 1 meter (Shott et al. 1997b; p. A1-6). The conceptual model for the vadose zone developed for the Area 3 PA emphasizes episodic infiltration and evaporation to depths of 1-3 meters (Shott et al. 1977b; see their Fig. 2.21, p. 2-62). Nonetheless, the thickness of the cover provided by the expected combination of the operational and closure caps (> 5 meters) still provides a significant barrier to upward advection of radionuclides to the surface. Of particular significance is the presence of upper soil zones with very low water contents (< 6 %), an extremely effective barrier to all processes associated with upward advection. While the thickness and water content of this low-conductivity zone will vary with episodic precipitation events, it should be maintained by the high potential evaporation of the Area 5 RWMS that maintains a predominantly moisture deficit state (Shott et al. 1997b).

The issue of upward migration of dissolved solutes was dismissed in the Area 5 PA for multiple reasons. First, the diffusion rates are dependent on the water contents of the alluvial deposits and the concentration gradient (Shott et al. 1997a). The water contents of the upper alluvium deposits are sufficiently low that the diffusive flux of solutes is inferred to be negligible. Second, upward diffusion requires a continuous liquid phase in the pore spaces. The moisture contents of the near-surface alluvium are too low to support a continuous liquid phase. The presence of excess moisture in some waste containers will affect local water contents and diffusion rates in the waste inventory but not in the cap materials, and particularly the near-surface deposits.

Question 5: Are there significant impacts on rates of Radon transport from excess moisture in some waste containers?

Comment: The Radon (Rn) flux density for the low-level radioactive waste disposal sites are established largely using methods summarized in guidance provided by the Nuclear Regulatory Commission (Shott 1997a,b). The density is calculated assuming a combination of gaseous diffusion in the air-filled pore space and advective flow of soil pore gas. Generally, diffusion and advection will be retarded in the water-filled pore space relative to the air-filled pore space. Thus the primary effect of excess moisture will be to decrease the Rn flux density. The Area 5 PA shows that the Rn flux does not exceed the performance objective (20 pCi $m^{-2}s^{-1}$) throughout the 10,000 year compliance period. No changes from these conclusions are expected for the case of excess moisture in some waste containers and the addition of a closure cap will provide a greater safety margin (total cap thickness) relative to the conditions assumed for the Area 5 PA.

Question 6: Are there significant performance assessment impacts on downward water movement and radionuclide transport in the vadose zone from the introduction of excess moisture in some waste containers?

Comment: Information provided by Betchel, Nevada shows that about 590,300 cubic feet of waste from the Fernald waste stream 006 has been shipped and disposed in the Area 5 RWMS. Approximately 390,000 cubic feet of waste has been disposed in Pit 4 (about 18% of the pit volume), about 200,000 has been disposed to date in Pit 5 (about 36% of the current pit volume; the pit is still active and receiving waste) and a very small amount of the Fernald waste has been disposed in Pit 6. It is difficult to estimate the volume of the Fernald waste stream that may contain excess moisture. Estimates of these volumes were provided through the generator records at the Fernald site. Based on examination of these records by Fernald personnel, approximately 50% of the Fernald 006 waste stream is estimated to be sludge type waste that potentially could have excess moisture (Dave Rast, Fernald, Ohio, personal communication, March 1998). Accordingly, about 9% of the waste inventory in Pit 4 and 18% of the current inventory in Pit 5 could have excess moisture (excess moisture is defined as volumetric water contents in waste that exceed the ambient conditions for the alluvial deposits of the Area 5 RWMS). Because Pit 5 is still actively receiving waste, the percentage of waste with excess moisture could change dependent on what percentage of future waste shipments are from the Fernald site (waste stream 006).

Betchel, Nevada modeled the performance impact of excess moisture in waste containers as part of studies requested by the DOE/Nevada Independent Panel. They (Betchel, Nevada, unpublished report, 1998) used the computer code VS2DT for simulating isothermal, two-dimensional movement of moisture in the vadose zone. The simulations were modeled for two conditions: the base case and the subsidence/flooding scenarios of the Area 5 PA (Shott et al. 1997a). For each scenario, waste with excess moisture was located in the third of four tiers of waste containers with a disposal geometry similar to Pit 5 of the Area 5 RWMS. This geometry allows 25% of the inventory of Area 5 disposal site to contain excess moisture, an assumption that bounds the expected abundance of containers with excess moisture (see above). The waste is assumed to occupy the *full* volume of the white-metal containers and the hydraulic properties of the waste was assumed to be similar to the surrounding alluvial deposits.

The base case scenario simulates infiltration, moisture redistribution, bare-soil evaporation and precipitation for 50 years using ambient weather data for Pit 5 of the Area 5 RWMS for the calendar year 1995, a year of above-average annual precipitation (Bechtel, Nevada, unpublished report, 1998). The simulation results (Appendix 2, Fig. 3 of the Bechtel, Nevada report) show the development of an initial wet zone with high volumetric water contents derived from the disposal of waste containers with excess moisture. That moisture redistributes to lower water contents with time. The wetting front from the layer of waste with excess moisture reaches a depth of 14 meters in 50 years and the velocity of the wetting front decreases to less than 2 cm yr^{-1} (Bechtel, Nevada, unpublished report, 1998).

The base case scenario was dismissed in the Area 5 PA primarily because of the very long travel times to the ground water table, 240 meters below the surface. The median travel time to the alluvial aquifer in Frenchman Flat was estimated to be about 51,000 years with a > 99 % probability that the travel time exceeds 10,000 years (Shott et al. 1997a). The presence of excess moisture in waste will increase locally the unsaturated hydraulic conductivity and result in a very small decrease in the travel time to the water table. That decrease is insignificant given the long pathways through the vadose zone (240 meters) and the relatively thin zone of increased wetting front velocity from the excess moisture (14 m). The long travel times coupled with radioactive decay of the waste inventory, particularly tritium the nuclide that dominates the waste inventory (Shott et al. 1997a), means that the base case scenario continues to be *insignificant* even with the presence of waste with excess moisture.

The flooding scenario consisted of filling of a continuous 2-m subsidence depression formed on the operational cover with floodwater that subsequently was allowed to infiltrate into the alluvial deposits of the vadose zone. This flooding event was repeated for three consecutive years followed by moisture redistribution under ambient weather conditions. The simulations of the flooding scenario for the panel investigations reproduced the scenarios used in the Area 5 PA with and without a layer of waste containers with excess moisture (see Fig. 5; Betchel, Nevada, unpublished report, 1998). Comparison of the simulation results shows that there are only small differences between the simulated profiles of volumetric water content versus depth in the alluvial deposits. After three years, the wetting front for the profile containing waste with excess moisture has moved only about 2 meters deeper than the profile without excess moisture. Shortly after three years, the profiles are virtually indistinguishable. The resulting conclusion is that the simulations of the flooding scenario with the presence of waste with excess moisture are virtually similar to the results without the excess moisture. Therefore, there are no significant performance impacts on the Area 5 PA from excess moisture in waste containers.

Question 7: What are the possibilities for and are there significant performance assessment impacts with respect to corrosion of waste/containers from the presence of excess moisture?

Comment: This question returns to the issues discussed in the response to Question 1. The presence of container cracks and excess moisture in waste should lead to more rapid corrosion of containers relative to containers that do not contain excess moisture. However, a bounding condition assumed for the Area 5 PA is that no credit is given for container integrity with respect to performance objectives. Further, a second bounding condition of the Area 5 PA is that all radionuclides are immediately available for uptake and release at closure (Shott et al. 1997a). Enhanced corrosion of the waste from the presence of excess moisture does not have any appreciable effect on these conservation assumptions. Therefore, there is no identified impact of accelerated corrosion of waste or waste containers from the presence of excess moisture in the waste containers.

Question 8: Related to questions 3 and 7, is generation of ^{14}C significant?

Comment: The issue of generation of ^{14}C is bounded in the Area 5 PA by two conservative assumptions. First, ^{14}C release is attributed solely to gaseous CO_2 despite the presence of other carbon species that are expected to compete for the available of the ^{14}C inventory. Second, the ^{14}C flux used in the Area 5 PA results in complete degassing of the full ^{14}C inventory in one year (Shott et al. 1997; p. 6 and p. 3-43). These conservative assumptions fully bound any expected impacts from preferential release of ^{14}C associated with increased container/waste corrosion.

Question 9: Related to question 3, is the presence of excess moisture significant with respect to plant and/or insect activity and could this affect upward pathways and radiological releases?

Comment: The issue in the Area 5 PA of pathways associated with plant and/or insect activity was assessed by examining mechanisms of moving waste radionuclides from geometrically defined compartments. These compartments consist of a deeper waste compartment, an intermediate-depth subsurface soil compartment and a shallow soil compartment. Radionuclides moved to the shallow soil compartment can contribute to radiological releases to the atmosphere. For both plant and animal activity, empirical equations were developed to define a rate coefficient that describes the movement of radionuclides across the compartment. For example, the rate coefficient (K_{r1j}) for plant-root uptake from the waste compartment to the shallow soil compartment is estimated from (Shott et al; 1997a)

$$K_{flj} = B_{jv} x B_p x(1 + \frac{F_{rs}}{B_{ab}}) x F_{rw} x \frac{1}{H_w} x \frac{1}{\rho_b} \qquad (3)$$

where

B_{jv} = the plant-soil concentration ration for radionuclide j in pCig^{-1} plant mass per pCig^{-1} dry soil
B_p = annual aboveground perennial shrub biomass productivity in g dry mass m^{-2} yr^{-1}
B_{ab} = ratio of above-to belowground productivity for shrubs in g yr^{-1} aboveground per g yr^{-1} belowground
F_{rs} = fraction of perennial shrub roots in shallow soils compartment, dimensionless
F_{rw} = fraction of perennial shrubs with roots greater than 2.4 m, dimensionless

H_w = depth of waste accessible to roots in meters
ρ_b = dry bulk density of soil in g m^{-3}

The effect of excess moisture in components of the waste inventory can be evaluated through an assessment of the impact of the moisture on individual variables of the equations used for the estimate rate coefficients (equation (3) of this report and other pertinent equations used in the Area 5 PA). The impact of excess moisture is expected to be small for plant activity for two reasons:

1. Mean root depths of most native plants at the Area 5 RWMS are relatively shallow (probably less than 2 meters) and the majority of roots are not expected to extend into the waste inventory. The uncertainty with this statement is that maximum roots for both shrubland and some grass species can be greater than 2 meters (Arnold et al. 1998). Therefore while most shrub roots will not affect the waste inventory, some penetration of the waste inventory at the Area 5 RWMS is expected, an assumption that was allowed for in the calculations used for the Area 5 PA. Modeling of the distribution of excess moisture in alluvium (Betchel, Nevada, unpublished report, 1998) shows that the increased moisture is short-lived and the deposits return to background conditions over intervals of months to years. This observation combined with the relatively deep depth of the disposed waste makes it unlikely that the presence of excess moisture will significantly effect the depth or percentage abundance of penetration of root systems of native vegetation into disposed waste.

2. All calculations of root uptake for the Area 5 PA assumed the presence of an operational cap but not a closure cap. The addition of a closure cap will increase the burial depth of waste by approximately 2-3 meters; the actual depths will depend on the inventory and design specifications for the closure cap. Any effects of excess moisture on root uptake will be overshadowed in the PA calculations by the presence of the closure cap. The expected effect of adding a closure cap to the PA calculations is a decreased degree of root penetration, even given the presence of excess moisture in some waste containers.

Similar conclusions apply to the issue of rate coefficients from burrowing animals. Here the only expected concerns are the effects of burrowing by ants and possibly termites; rodents, while present, are not expected to burrow to the depth of the waste inventory (Shott et al. 1997a). Two arguments suggest that the presence of excess moisture in disposed waste will not have a significant impact on the behavior of burrowing insects and accordingly on the performance of the Area 5 RWMS.

1. None of the variables for the rate coefficient equation that describes the transfer of radionuclides from the waste compartment to the shallow soil compartment (Shott et al.; 1997a) is expected to be affected by the presence excess moisture in waste.
2. The addition of a closure cap to the conditions assumed for the Area 5 PA will increase the depth of burial of waste and decrease the impact of burrowing insects.

Summary and Observations

This letter presents the results of a systematic examination of the radionuclide release pathways from buried waste to the atmosphere and ground water table with respect to disposal of waste with excess moisture in stress-fractured containers. In all cases, the resulting changes from performance assessment studies presented in the Area 5 report (Shott et al. 1998) are minimal and are not a concern. Fundamentally, these changes are contained within and overshadowed by the conservative assumptions used in the PA studies.

Two final observations are provided on the results of the performance review; the first is related directly to the PA studies and the second is beyond the scope of the panel investigations. The latter comment is offered for perspective.

1. The only significant difference that emerges from assessing the container/excess moisture impact relative to the Area 5 PA is the non-conservatism, in the latter, of the assumption that the moisture content of disposed waste is equal to the ambient moisture content of the alluvium deposits. Clearly some of the disposed waste from the Fernald waste stream has considerably higher moisture contents than the native alluvium. There is no impact from this difference primarily because of the conservatism used in the Area 5 PA. Further iterations of the PA studies should assume the presence of some components of waste with higher moisture contents.
2. The generator/shipping requirements for waste disposal address and limit the issue of free liquids in the waste but do not consider the moisture content of the waste. The use of sorbent material in routine processing of waste for shipment is commendable but still does not address the issue of high moisture contents. An independent perspective may need to be brought to this issue. Fundamentally, and separate from the performance impacts, it does not appear to be good operational practice to dispose of wet (saturated or near-saturated) waste. Certainly, public perception of these practices would tend to be negative even given the absence of performance impacts. Attention should be given to consideration of steps that could be taken to restrict the moisture content of waste prior to shipment. These steps may be understandably limited by cost, schedule and/or worker safety. However, if feasible, it would be desirable to "dry" waste prior to shipment. The exact definition of "acceptably dry" will probably prove difficult. The important concept however, is to take steps *not* to ship waste with water contents at or near saturation of the effective porosity.

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Dr. Bruce Crowe
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Letter from Dr. Roger Jacobson

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March 16, 1998

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Dear Mr. Gertz:

Thank you for giving me the opportunity to comment on the series of questions listed below.

1. **Are there significant performance assessment impacts from burial of low-level radioactive waste in stress-fractured containers with reduced integrity?**
There are not significant performance assessment impacts from burial of low-level radioactive waste in stress-fractured containers. The integrity of the container is not an important consideration in the performance calculations currently used.

2. **Does the disposal of waste in stress-fractured containers have significant impacts on the issue of subsidence?**
The change in subsidence related to the very small amount of stress fracturing is truly noise in the system and of no concern. The original calculations were done using containers with no strength and even stress-fractured containers are stronger than that.

3. **Does the presence of excess moisture in some waste containers have significant impacts on upward pathways and radiological releases of volatile radionuclides?**
This change in upward pathways and the release of volatile radionuclides would be very small and should potentially produce an insignificant change in flux at the surface. The additional moisture could transmit a greater amount of volatile radionuclides (Tritium, etc.) because the general moisture gradient is toward the surface. This could be modeled with relative ease and estimate the flux under different water contents. This assumes that the containers are not completely airtight and that vapors can escape.

4. **Does the presence of excess moisture in some waste containers have significant performance assessment impacts on upward advection of radionuclides under ambient conditions, under wetter conditions from rainfall events, and on upward diffusion of dissolved solutes?** There should be little or no impacts under ambient conditions to the upward movement of dissolved radionuclides. The only impact under wetter conditions would be if very significant subsidence had taken place. Under these conditions dissolved radionuclides could conceivably reach the surface, however this is extremely unlikely in the near term. Upward diffusion of dissolved solutes is not

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important under any moisture condition because of the nature of the material above the waste.

5. **Are there significant impacts on rates of Radon transport from excess moisture in some waste containers?** This answer is very similar to the answer to question 3. There should be little or no impacts under ambient conditions to the transport of Radon from excess moisture.

6. **Are there significant performance assessment impacts on water movement and radionuclide transport in the vadose zone from the introduction of excess moisture in some waste containers?** The small amount of additional water in this environment should have no impact on the downward movement of dissolved radionuclides.

7. **What are the possibilities for, and are there significant performance assessment impacts with respect to, corrosion of waste/containers from the presence of excess moisture?** The additional moisture in the unfractured containers will certainly accelerate the corrosion rate under most conditions. The question to be resolved is the rate of corrosion versus the rate of water evaporation from the non-airtight containers. It is assumed that the stress-fractured containers will leak immediately and therefore not contain any excess moisture. It is unclear, however, that any scenario will impact the current performance assessment.

8. **Related to questions 3 and 7, is generation of ^{14}C significant?** Under certain conditions excess moisture could produce additional CO_2 or CH_4 from the decay of organic matter in the containers. If the organic material contained ^{14}C then there could be an additional release. The production rate of these gases under any reasonable conditions would be very low and it is difficult to conceive that the surface flux would change significantly with increased moisture.

9. **Related to question 3, is the presence of excess moisture significant with respect to plant and/or insect activity and could this affect upward pathways and radiological releases?** I do not feel qualified to respond on this question.

Sincerely,

Roger L. Jacobson
Manager for DOE Programs

Cc: Steve Mellington, Deputy Assistant Manager
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Letter from Robert Waters

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March 16, 1998

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Dear Carl,

I have been asked to determine if there are any significant long-term performance impacts resulting from disposal of Fernald waste (some waste in containers having small stress-induced cracks) that exceed the limits for free liquids contained in the Nevada Test Site's (NTS) waste acceptance criteria (WAC). Some of the waste stream of concern, which may contain high moisture levels, has been disposed of at the Area 5 Radioactive Waste Management Site (RWMS) of the NTS. Some of this waste awaits disposal.

My conclusion is that there is no significant impact on long-term disposal at the NTS Area 5 RWMS from waste with excess moisture or from waste in containers with stress-induced cracks. The basis for my conclusion is contained in this report.

To make my determination, I first reviewed the NTS WAC (USDOE 1997). The limit on free liquid in waste of one volume percent of containerized waste specified in the WAC is not derived from results of the site-specific performance assessment. Rather, it is based on generic levels specified in Nuclear Regulatory Commission regulations (10 CFR Part 61.56 (a)(2)) and the DOE Order 5820.2A, Chapter III.3.i (5)(b). Therefore, the NTS WAC was not useful in resolving the subject question.

Next, I reviewed the sensitivity analysis of the performance assessment for the Area 5 RWMS (Shott et al. 1997). Moisture content of waste was not one of the variables evaluated in either the simplified or Monte Carlo sensitivity analyses contained in the Area 5 performance assessment. Therefore, this section of the performance assessment was not useful in resolving the subject question.

Lastly, I reviewed the details of the analysis of performance and the results of analysis of the Area 5 RWMS performance assessment. To guide this review, eight specific questions were addressed:

1. Are there significant performance assessment impacts from burial of low-level radioactive waste in stress-fractured containers with reduced integrity?

2. Does the disposal of waste in stress-fractured containers have significant impacts on the issue of subsidence?
3. Does the presence of excess moisture in some waste containers have significant impacts on upward pathways and radiological releases of volatile radionuclides excluding radon?
4. Does the presence of excess moisture in some waste containers have significant performance assessment impacts on upward transport of nonvolatile radionuclides, including plant and/or burrowing animal activity, under ambient conditions or under wetter conditions from rainfall events?
5. Are there significant impacts on rates of radon transport from excess moisture in some waste containers?
6. Are there significant performance assessment impacts on water movement and radionuclide transport in the vadose zone from the introduction of excess moisture in some waste containers?
7. What are the possibilities for and are there significant performance assessment impacts due to corrosion of waste containers from the presence of excess moisture?
8. Related to questions 3 and 7, is generation of ^{14}C significant?

The remainder of this report provides the results of my review of these eight questions followed by a summary of my findings.

Overview of DOE Performance Assessments

The performance assessment objectives for shallow-land disposal of low-level radioactive waste are contained in DOE Order 5820.2A. The performance objectives are dose-specific and encompass five pathway categories including 1) dose through all pathways; 2) dose through atmospheric pathways (excluding Radon); 3) Radon flux density; 4) ground water resource protection and 5) the inadvertent human intruder. An assessment of the performance impacts of the container/excess moisture issue requires consideration of the approach used in the Area 5 RWMS performance assessment with respect to the required performance objectives.

The primary goal of a performance assessment is to provide reasonable assurance that the engineered and natural features of the disposal facility and surrounding environment are sufficiently adequate to meet the performance objectives. This goal is implemented in the Area 5 PA primary through the adoption of conservative performance calculations. A conservative calculation approach is used in an attempt to bound system performance through assumptions that overestimate radiological doses compared to the actual system performance. The difference between the actual doses and the bounded doses constitutes the degree of conservatism built into calculation.

This difference generally cannot be quantified because the actual future doses, if any, are unknown. Therefore, the confidence in a conservative performance assessment is dependent on the acceptance that bounding assumptions are truly conservative. The results of the performance assessment indicate that all performance measures will be met. Several technical panels established by DOE have reviewed the performance assessment for the Area 5 RWMS and found it to meet the DOE requirements for performance assessments. A review of the adequacy of the performance assessment is therefore not part of this review.

Observations and Assumptions Used in Conducting the Review

The information and data in this section are based on personal communication with Bruce Crow of Los Alamos National Laboratory. Dr. Crow's sources of information are primarily form the DOE Nevada Operations Office and it's operating contractor. Dr. Crow is currently obtaining written documentation for the following statements.

1. The waste of concern is a subset of a waste stream known as Fernald Waste Stream 006.
2. All 590,332 ft^3 of this waste stream have been disposed of in the Area 5 RWMS of the NTS (388,641 ft^3 (18 volume %) in Pit 4; 201,363 ft^3 (35 volume %) in Pit 5; and 327 ft^3 in Pit 6.
3. Waste Stream 006 is comprised of several sub-waste streams. The principal waste sub-stream of concern is a sludge-type waste.
4. Operations staff at Fernald estimated that about 50% of the 006 waste stream shipped to NTS are the sludge sub-stream and therefore potentially wet.
5. Based on statements 2 and 4, the maximum volume percentage of potentially wet waste from Fernald disposed of in Area 5 is approximately 11%.
6. Pit 4 is now closed and Pit 5 continues to be filled. Therefore, there is potential for additional wet wastes to be disposed of in Pit 5.

The effect of high moisture content and fractured containers relative to the assumed intruder scenarios were not expected to be relevant and were not evaluated.

Analysis of Impacts to Long-term Performance

In this section, the eight individual questions listed above are addressed.

1. Are there significant performance assessment impacts from burial of low-level radioactive waste in stress-fractured containers with reduced integrity?

To answer this question, I evaluated the waste container conditions assumed in the performance assessment (Shott et al. 1997) to determine if they bounded the conditions for the stress-fractured containers.

Two cases are analyzed in the performance assessment (1) the base case and (2) the subsided waste case. (The subsided case is discussed with the next question.) The waste form conceptual model for the base case is discussed in Section 3.2.1.6 of the performance assessment:

> Wastes disposed of at the Area 5 RWMS are packaged predominantly in metal drums, metal boxes, and wooden boxes. Little is known about the degradation of these containers under the conditions prevalent at the NTS.
>
> For the base case scenario, waste packages were assumed to completely degrade by the end of institutional control[3]. No credit was taken for the ability of the waste

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[3] The period of active institutional control is 100 years after closure of the disposal facility (Shott et al. 1997, p. 1-2).

> forms to resist release and dispersion. The waste was assumed to have degraded to a material indistinguishable from soil by the end of institutional control.
>
> Under the arid conditions of the NTS, most metal and wood containers and many waste forms are likely to survive intact for a considerable time. However, in the absence of reliable data, it was conservatively assumed for the base case release scenario that all radionuclides were immediately available for uptake and release at closure. (ibid., p. 3-30 and 3-31).

Two factors in the base case demonstrate that the performance assessment calculations bound the situation of reduced container integrity such as stress-fractured containers:

1. No credit was taken for the presence of any waste containers beyond institutional controls and
2. All radionuclides were available for uptake and release at closure.

For this comparison, the first factor is the more important: analysis considering no waste package is more conservative than analysis considering containers with reduced integrity.

Because the base case scenario satisfied the performance objectives and because it bounded the conditions of reduced container integrity, there is no significant long-term performance impact of containers with stress fractures.

2. Does the disposal of waste in stress-fractured containers have significant impacts on the issue of subsidence?

To answer this question, I evaluated the assumptions contained in the performance assessment (Shott et al. 1997) related to the subsided waste scenario to determine if they bounded the conditions for these stress-fractured containers.

The model used to estimate subsidence was necessarily simple due to the many unknown factors associated with this issue. The subsided waste scenario analyzed subsidence due to (ibid., p. 3-31):

- Voids within the container
- Decomposition of the waste within the container
- Compression of the waste material
- Infilling of the initial and subsequently created voids with soil cover material, which is both hastened and exacerbated by:
  - * earthquake ground shaking
  - * induced ground shaking (testing and construction)
  - * flow of water through the soil.

The waste packages evaluated in the subsided waste scenario include metal drums, metal boxes, plywood boxes, cardboard boxes, and wood debris/dunnage and pallets, each with different assumed degradation periods (ibid., p. 3-32).

Two factors in the subsided waste scenario demonstrate that the performance assessment calculations bound the situation of reduced container integrity such as stress-fractured containers:

1. the initial voids surrounding the waste packages and the initial voids within the waste will contribute most to subsidence calculations and
2. steel drums and boxes (even if containing small stress fractures) provide greater structural integrity than wooden or cardboard containers.

For this comparison both factors are important: the initial void space and cardboard and wooden packages are most important factor for subsidence than steel containers with small stress fractures.

Because the subsided waste scenario satisfied the performance objectives and because it bounded the conditions of reduced container integrity, there is no significant long-term performance impact of containers with stress fractures.

3. Does the presence of excess moisture in some waste containers have significant impacts on upward pathways and radiological releases of volatile radionuclides excluding radon?

To answer this question, I evaluated the assumptions contained in the performance assessment (Shott et al. 1997) related to the conceptual model for release of volatile radionuclides, excluding radon to determine if they bounded the conditions for the excess-moisture containers.

Two cases are analyzed in the performance assessment (1) the base case and (2) the subsided waste case. In both of these cases, three radionuclides (^{3}H as tritiated water (HTO), ^{14}C as carbon dioxide, and ^{85}Kr as krypton gas) were evaluated. The release of these vaporous/gaseous species to the air above the RWMC was assumed to be controlled by gaseous diffusion in the air-filled pore space assuming a constant gradient over time (ibid., p. 3-40 and 3-41).

The conceptual model for ^{3}H release is that the concentration of ^{3}H in the pore water is assumed to equal the concentration in water vapor at 100% relative humidity, and this ^{3}H concentration in pore water is diluted by the residual water in the waste. The waste form is assumed to have a porosity (0.36) and volumetric water content (0.086) equal to the values associated with alluvium (ibid., p. 3-41 and 3-42). Increasing the residual water due to excess moisture in the waste serves to provide further dilution of the ^{3}H, resulting in a less conservative analysis than done in the performance assessment. Additionally, the effective diffusion coefficient used in the one-dimensional flux equation is a negative function of volumetric water content, θ_V (ibid., equation 3.6, p. 3-42). Increasing the residual water due to excess moisture in the waste causes the effective diffusion coefficient to decrease, again resulting in a less conservative analysis than done in the performance assessment.

The conceptual models for ^{14}C and ^{85}Kr are similar to that of ^{3}H. The same equation is used to calculate the effective diffusion coefficient and the trend with increasing water content due to excess moisture in the waste is similar. Therefore, increased moisture content in the waste would result in decreased flux from the facility. For both of these radionuclides, the calculated annual releases from this conservative model exceeded their total inventory in the first year. Therefore, the total inventories of these radionuclides were assumed to be released in the first year.

Because the upward diffusion pathway scenario satisfied the performance objectives and because it bounded the conditions of excess moisture in the waste, there is no significant long-term performance impact of containers with excess moisture for this pathway.

4. Does the presence of excess moisture in some waste containers have significant performance assessment impacts on upward transport of nonvolatile radionuclides, including plant and/or burrowing animal activity, under ambient conditions or under wetter conditions from rainfall events?

To answer this question, I evaluated the assumptions contained in the performance assessment (Shott et al. 1997) related to the conceptual model for release of non-volatile radionuclides to determine if they bounded the conditions for the excess moisture containers.

Three pathways are evaluated in the performance assessment for upward transport of non-volatile radionuclides: root uptake, burrowing animals, and resuspension for both the base case and the subsided waste case (ibid., p. 3-50). The subsided waste case is more restrictive because it assumed a reduced thickness of the cap due to erosion and a concomitant increase in plant productivity (ibid., p. 3-57). The moisture content of the waste was not used as an input parameter to any of these three transport models used in the performance assessment. Therefore, results are not expected to be sensitive to changes in this parameter.

Higher moisture content in the waste would seem to imply higher potential for plant productivity. Calculations performed by Bechtel Nevada (Levitt and Sully 1998) for this review indicate that if 25% of the waste were saturated with water (twice the upper bound on the suspected high-moisture waste from Fernald), the overall volumetric moisture content in the disposal zone would return to below 10% within 50 years. The residual soil moisture content is approximately 8%. Therefore, higher moisture content in some wastes will result in only a temporary condition for possible increased plant productivity.

Because the upward transport pathway for non-volatile radionuclides satisfied the performance objectives and because it is only slightly affected by excess moisture content in some wastes, there is no significant long-term performance impact of containers with excess moisture for this pathway.

5. Are there significant impacts on rates of radon transport from excess moisture in some waste containers?

To answer this question, I evaluated the assumptions contained in the performance assessment (Shott et al. 1997) related to the conceptual model for release of radon to determine if they bounded the conditions for the excess moisture containers.

The conceptual model assumes that the fate of radon is governed by molecular diffusion, advection and radioactive decay in the gas phase only. Diffusion and advection of radon will be retarded in the water-filled pore space relative to air-filled pores. Transport will be retarded further by adsorption on radon onto the solid soil matrix (ibid., p. 3-45). Therefore, increased amounts of pore water due to excess moisture in the waste will result in a less conservative analysis than done in the performance assessment.

Additionally, the diffusion coefficient in soil is empirically derived from soil porosity (ibid., p. 3-48), which is likely equation 3.6 or some similar equation. As discussed with question 3, the soil diffusion coefficient is a negative function of moisture content, so that increasing moisture content in the waste would result in lower diffusion rates of radon. Again, this results in a less conservative analysis than done in the performance assessment.

Because the radon transport scenario satisfied the performance objectives and because it bounded the conditions of excess moisture in the waste, there is no significant long-term performance impact of containers with excess moisture for this pathway.

6. Are there significant performance assessment impacts on water movement and radionuclide transport in the vadose zone from the introduction of excess moisture in some waste containers?

To answer this question, I evaluated the assumptions contained in the performance assessment (Shott et al. 1997) related to the conceptual model for infiltration for the subsided case. Additional calculations performed by Bechtel Nevada (Levitt and Sully 1998) to assess the effects of additional moisture on the transport of radionuclides through the vadose zone were also reviewed. These reviews were made to determine if they bounded the conditions for the excess moisture containers.

The performance assessment included two scenarios associated with the subsided waste case in which water was ponded above the disposal facility. The first scenario evaluated two meters of ponding for one day in each of three consecutive years, analogous to three consecutive 200-year floods. The second scenario evaluated one meters of ponding for one day in each of four consecutive years, analogous to four consecutive 50-year floods. The wetting front movement and radionuclide transport were calculated to estimate doses from using ground water (Shott et al 1997, p.3-61 to 3-62). Plots of saturation versus depth were calculated from 3 to 150 years following the flood events (ibid., Figure 3.7, p. 3-64).

Bechtel Nevada modified these calculations to account for 25% of the waste being initially saturated. This is twice the upper bound percentage for the suspect waste from Fernald as described above. The Bechtel Nevada study concluded that, compared to modeling results in the Area 5 performance assessment, there will be little impact on water movement, travel time to the ground water, and therefore radionuclide transport in the vadose zone from the introduction of excess moisture in the waste containers at the Area 5 RWMS.

Because the subsided waste/flooding scenario satisfied the performance objectives and because it was affected only marginally by excess moisture in waste, there is no significant long-term performance impact of containers with excess moisture for this pathway.

7. What are the possibilities for and are there significant performance assessment impacts due to corrosion of waste containers from the presence of excess moisture?

Corrosion is a mechanism of metal container degradation, and additional water in the waste will likely provide an enhancing environment for corrosion. However, as noted in the response to questions 1, the following statements are contained in the performance assessment:

> For the base case scenario, waste packages were assumed to completely degrade by the end of institutional control. No credit was taken for the ability of the waste forms to resist release and dispersion. In the absence of reliable data, it was conservatively assumed for the base case release scenario that all radionuclides were immediately available for uptake and release at closure (Shott et al. 1997, p. 3-30 and 3-31).

While corrosion will likely accelerate degradation of the metal waste containers, it is unlikely that corrosion would cause their complete degradation within the period of institutional controls, particularly in the environmental conditions associated with the NTS. Therefore, the assumptions contained in the performance assessment relative to container integrity appear to bound the possibility of corrosion causing complete degradation for a limited number of metal containers.

Corrosion of metal containers may possibly accelerate the subsidence of the waste. However, as discussed in the response to question 2, the void space between containers and the wooden containers with less structural strength than metal containers are likely the greatest contributors to subsidence. Therefore, it is unlikely that corrosion of metal containers would cause a significant subsidence problem.

Because the assumptions related to performance of the waste containers and subsidence result in analyses that satisfy the performance objectives and because they are not materially affected by the possible effects of corrosion conditions due to excess moisture in the waste, there is no significant long-term performance impact of containers with excess moisture for this pathway.

8. Related to questions 3 and 7, is generation of ^{14}C significant?

To answer this question, I evaluated the assumptions contained in the performance assessment (Shott et al. 1997) related to the conceptual model for formation of ^{14}C to determine if they bounded the conditions for the excess moisture containers.

The transportable form of ^{14}C assumed in the performance assessment is gaseous carbon dioxide (CO_2) in the air-filled pores. This is a conservative assumption because numerous carbon compounds are expected to exist in the waste and subsurface environment, all of which would compete with CO_2 for the available ^{14}C (ibid., p. 3-41). Additionally, the entire inventory (4.12 Ci) of ^{14}C is assumed to be converted to and transported to the ground surface in the first year after closure of the facility (ibid., p.3-43).

Excess moisture will surely contribute to the generation of ^{14}C associated with CO_2. However, the relevant assumption in the performance assessment is that all ^{14}C is converted to CO_2 and transported away in the first year without identification of a specific mechanism. It is unlikely that any credible transport mechanism associated with increased moisture content would exceed the release rate assumed in the performance assessment.

Because the ^{14}C transport scenario satisfied the performance objectives and because it likely bounds any transport scenarios associated with excess moisture in the waste, there is no significant long-term performance impact of containers with excess moisture for this pathway.

Summary

I have been asked to determine if there are any significant long-term performance impacts resulting from inadvertent disposal of Fernald waste containers, some containers having small stress-induced cracks, that exceed the limits for free liquids contained in the site's waste acceptance criteria (WAC).

First I reviewed the NTS WAC. The limit on free liquid in waste of one volume percent of containerized waste specified in the WAC is not derived from results of the Area 5 performance assessment. Rather, it is based on generic levels specified in Nuclear Regulatory Commission regulations (10 CFR Part 61.56 (a)(2)) and the DOE Order 5820.2A, Chapter III.3.i (5)(b). Therefore, there is no site-specific basis for this limit on free liquid in waste at NTS.

Next, I reviewed the sensitivity analysis of the Area 5 performance assessment. Moisture content of waste was not one of the variables evaluated in either the simplified or Monte Carlo sensitivity analyses contained in the Area 5 performance assessment. Therefore, this section of the performance assessment was not useful in resolving the subject question.

Lastly, I reviewed the analysis of performance and results of analysis of the Area 5 performance assessment. To guide this review, eight specific questions were addressed to determine if there were any significant impacts to long-term performance from disposal of some saturated or over-saturated wastes, some in containers containing stress-induced fractures, at the Area 5 RWMS at the NTS. My conclusion to each of these questions was that there are no significant impacts to long-term performance expected from disposal of this waste relative to scenarios evaluated in the site-specific performance assessment. I make this conclusion because the scenarios that were evaluated in the performance assessment and shown to comply with the performance objectives were similar to or more conservative than the scenario involving saturated wastes and fractured containers.

Therefore, my overall conclusion is that there is no significant impact to long-term performance of the Area 5 RWMS at NTS from disposal of these wastes.

I hope you find this report useful. I would be happy to discuss my analysis and conclusions with you at you convenience.

Sincerely,

Dr. Robert Waters

cc: Steve Mellington, DOE/AMEM
Runore Wycoff DOE/WMD

References

Levitt, D. G. and M. J. Sully. Simulation of Soil Water Flow at Pit 5 at the Area 5 RWMC using VS2DT, Bechtel Nevada, March 10, 1998.

Shott, G. J., L. E. Barker, S. E. Rawlinson, M. J. Sully, and B. A. Moore. *Performance Assessment for the Area 5 Radioactive Waste Management Site at the Nevada Test Site, Nye County, Nevada (Rev. 2.1)*, Department of Energy, Nevada Operations Office, Waste Management Division, DOE/NV/11718-176, UC-721, Las Vegas, Nevada, January 1998.

USDOE (U. S. Department of Energy) *Nevada Test Site Waste Acceptance Criteria*, Department of Energy, Nevada Operations Office, Waste Management Division, DOE/NV-235, NTSWAC (Rev. 1), Las Vegas, Nevada, August 1997.

Appendix B

Configurations and assigned initial conditions for simulation modeling of waste with excess moisture in Pit 5.

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Figure B-1. Diagram of Pit 5 at the Area 5 RWMS with the location of containers with fully saturated waste (excess moisture). This configuration corresponds to the case of 25% of the inventory of Pit 5 containing excess moisture.

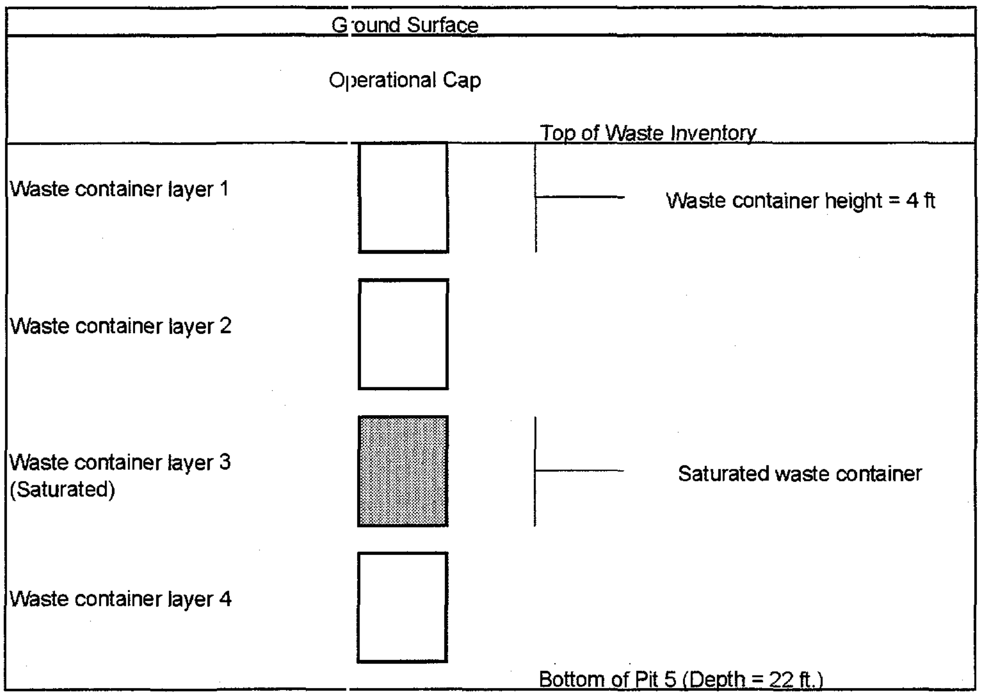


Figure B-2. Figure 1b. Same as Figure 1a but with a configuration that corresponds to the case of 50% of the inventory of Pit 5 containing excess moisture.

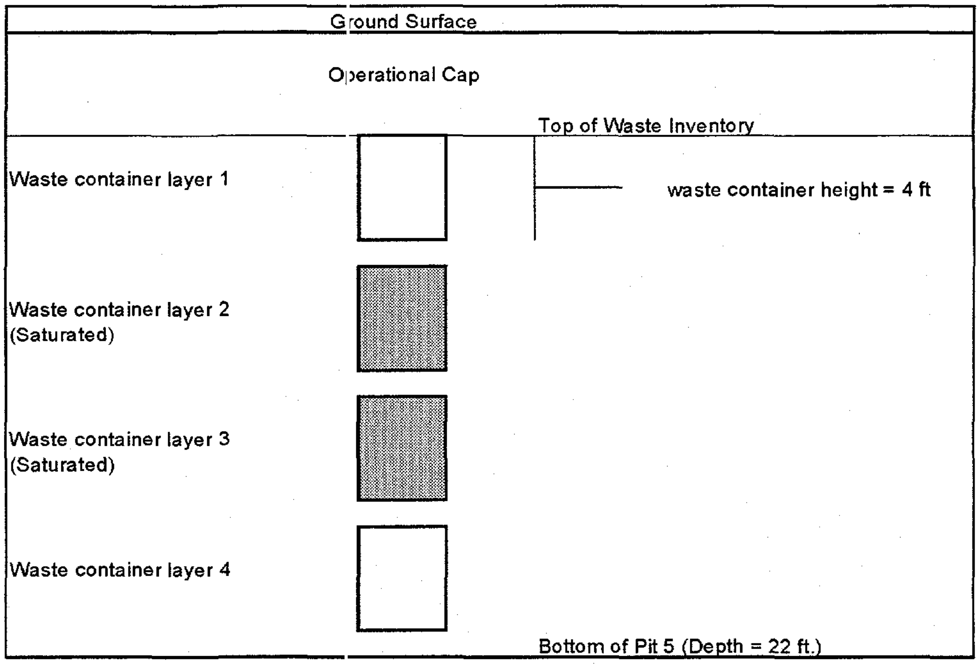


Figure B-3. Same as Figure 1a but with a configuration that corresponds to 75% of the inventory of Pit 5 containing excess moisture.

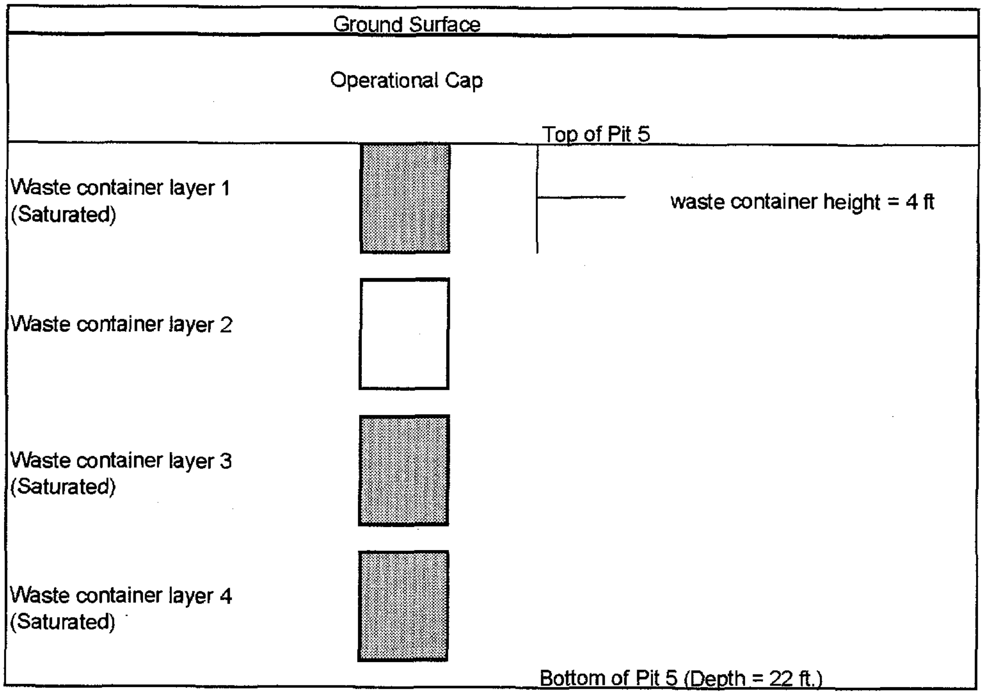
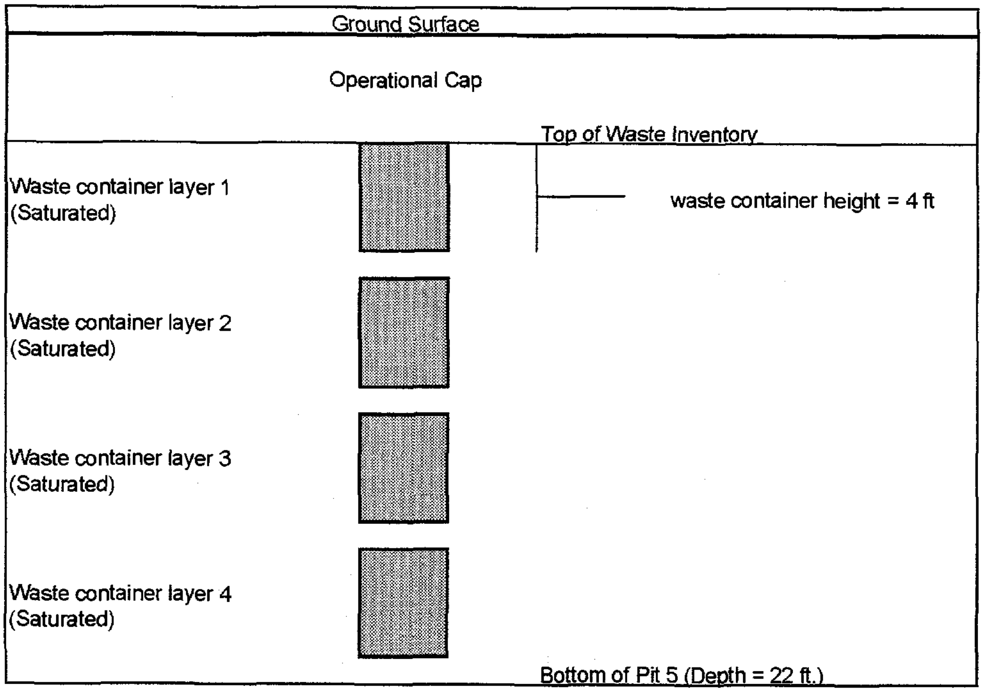


Figure B-4. Same as Figure 1a but with a configuration that corresponds to 100% of the inventory of Pit 5 containing excess moisture.



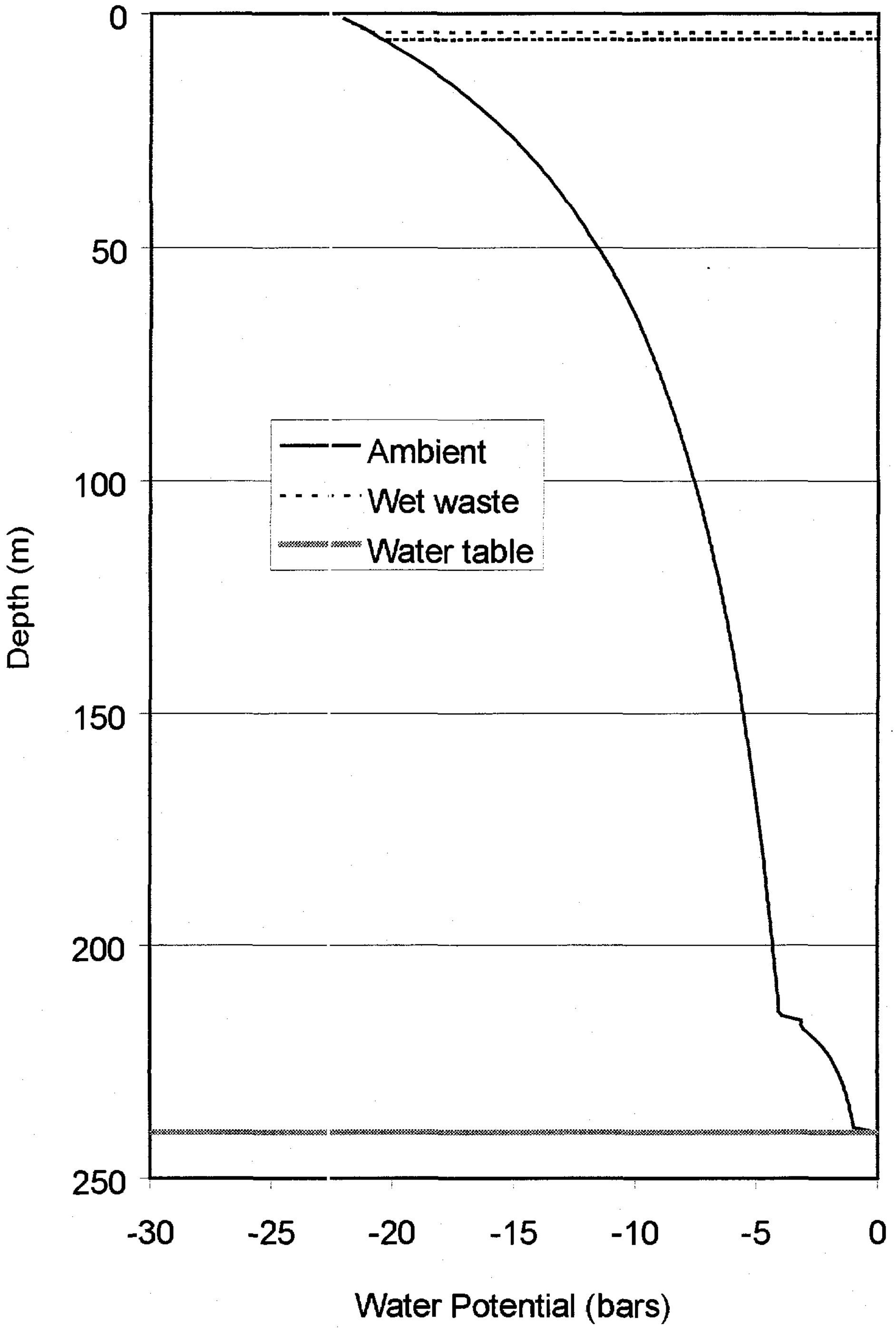


Figure B-5. Initial conditions of soil-water potential for the modeling simulations.

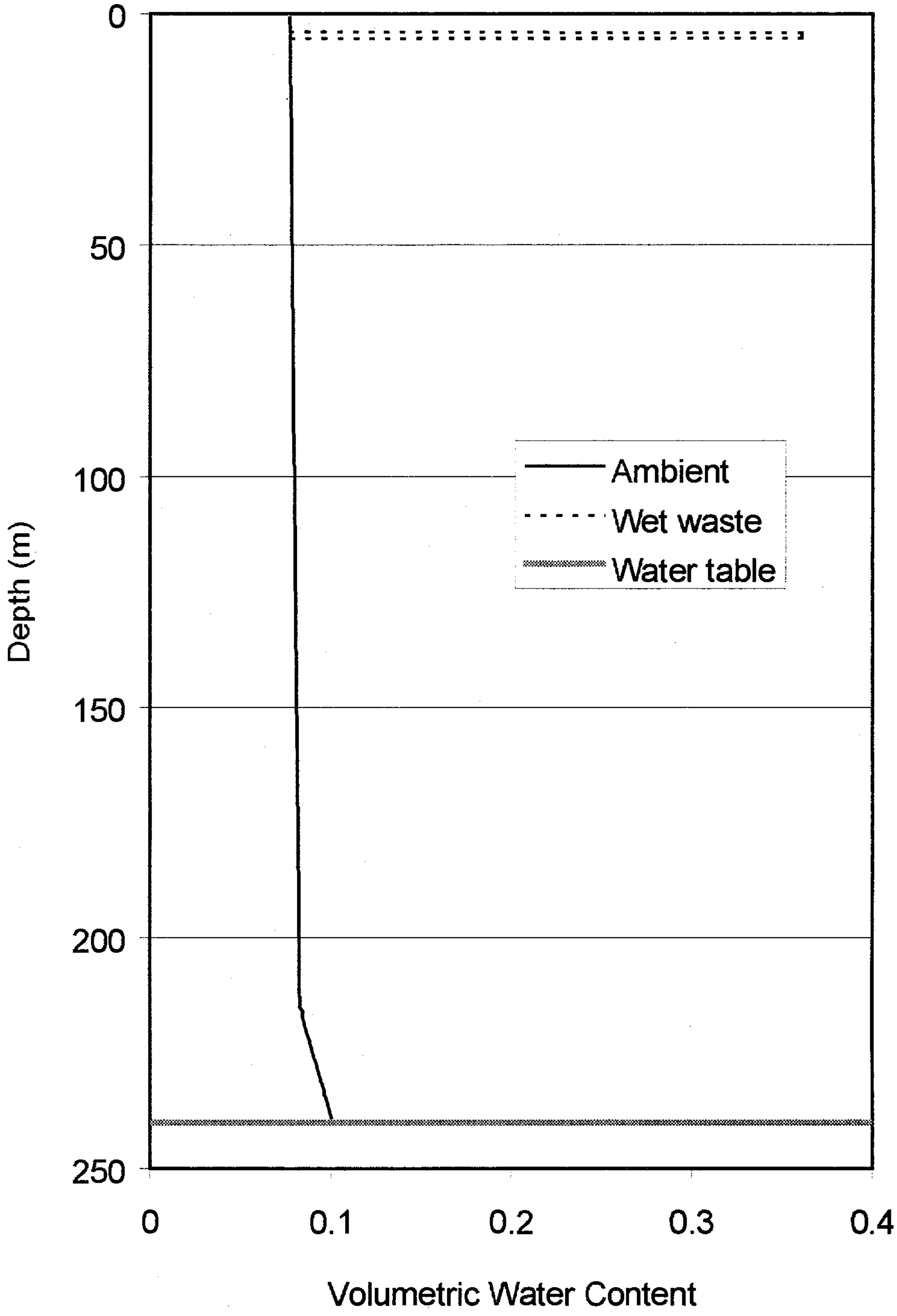


Figure B-6. Initial conditions of soil water content for the modeling simulations.