

THE PERFORMANCE ASSESSMENT IMPACTS OF DISPOSAL OF HIGH-MOISTURE, LOW-LEVEL RADIOACTIVE WASTE AT THE NEVADA TEST SITE

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ABSTRACT

A panel of independent scientists was convened by the Department of Energy to assess the performance impacts of disposal of low-level radioactive waste from the Fernald Environmental Management Project. This waste stream was involved in a transportation incident in December 1997. A resulting outgrowth of investigations of the transportation incident was the recognition that the waste was transported and disposed in stress-fractured metal boxes and that some of the waste contained excess moisture (high volumetric water contents). The panel was charged with determining whether disposal of this waste in the Area 5 radioactive waste management site on the Nevada Test Site has impacted the conclusions of the completed performance assessment. Three questions were developed by the panel to assess performance impacts: 1) What are the performance impacts of reduced container integrity? 2) What is the impact of reduced container integrity on subsidence of waste in the disposal pits? and 3) What are the performance impacts of excess moisture? No performance or subsidence impacts were noted from disposal of the Fernald waste. The impacts of excess moisture were assessed by modeling the movement of moisture in the vadose zone, assuming high water contents ("wet waste") for various percentages of the waste inventory. No performance impacts were noted for either the base-case scenario (ambient conditions) or a scenario involving subsidence and flooding of the waste cells. The absence of performance impacts results

from the extreme conservatism used in the Area 5 performance assessment and the robust nature of the disposal site.

INTRODUCTION

The Environmental Management program of the Department of Energy (DOE/EM) formed an independent panel to evaluate the performance impacts of disposal of low-level radioactive waste in suspect metal containers. The need for this assessment arose from a recent transportation incident in which moisture was observed leaking from a truck transporting white metal boxes containing low-level radioactive waste during a routine shipment from the Fernald Environmental Management Project, Ohio, to the Nevada Test Site (NTS). The container leakage resulted from the development of stress fractures in shipping containers and the presence of free liquid in the waste (1). Both the fractures and the free liquid were produced by a combination of vibration during transportation and container design errors augmented by storage, handling, and shipping procedures. An independent panel was convened to evaluate the performance impacts of disposal of stress-fractured metal boxes (white metal boxes) containing low-level radioactive waste with high moisture content. The moisture content exceeds assumptions used in performance assessments of radioactive waste management sites (RWMS) on the NTS (2). The transportation incident involved shipment of low-level radioactive waste, referred to as Fernald waste stream 006.

In the remainder of this report, we use several phrases to refer to the unique conditions associated with the disposed Fernald waste. The waste containers are 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 (1). Not all of the metal boxes necessarily contain stress fractures. Waste with excess moisture, or *wet waste*, refers to waste with volumetric water content that exceeds the moisture contents of valley-fill alluvium, the surrounding deposits of the sites on the NTS used to dispose low-level radioactive waste (3). Waste with excess moisture was associated with the water-leakage incident during transportation to the NTS in December 1997. Not all of the Fernald waste contains excess moisture.

ASSUMPTIONS USED BY THE PANEL

The primary focus of the panel evaluations is on the Fernald waste stream and the identified shipping containers. Other implications of these evaluations are considered, but the thrust of the panel investigations is on the performance impacts of disposal of the Fernald waste. The following assumptions were used in the study:

1. Based on information provided by the DOE and DOE contractors, all the Fernald waste associated with the suspect metal containers was disposed of in the Area 5 RWMS. Accordingly, the panel focused their investigations entirely on performance impacts at this disposal site.
2. The performance assessment for the Area 5 RWMS has been reviewed extensively and accepted through a formal review process. The focus was on how new information/insight gained from the transportation incident might change any

pertinent assumptions or calculations used in the Area 5 performance assessment. Accordingly, the assumptions and calculations used in the existing Area 5 performance assessment study were closely followed and were examined with respect to the potential changes caused by disposal of waste with excess moisture in stress-fractured white metal boxes.

3. 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 to the ground-water table. The presence of stress-fractured containers and excess moisture affects radionuclide concentrations but does not effect the dose models used in the Area 5 PA. Therefore, the panel focused their evaluations on changes in radionuclide concentrations along identified scenario pathways.

PERFORMANCE ASSESSMENT IMPACTS

The following questions were developed by the panel with respect to potential performance impacts.

1. Are there significant performance assessment impacts from burial of low-level radioactive waste in stress-fractured containers, which have reduced integrity?
2. Does the disposal of waste in stress-fractured containers have significant impact on the issue of subsidence?
3. Does the presence of excess moisture in some waste containers have significant impact 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?

The performance assessment objectives for shallow-land disposal of low-level radioactive waste are drawn from DOE Order 5820.2A (4). They 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) groundwater resource protection, and 5) the inadvertent human intruder.

The primary goal of a performance assessment 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 but unknown 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 encompassed by the bounding conservative assumptions used in the PA.

The potential for changes in the Area 5 PA results was evaluated for each identified pathway, for both the base-case scenario and a subsidence-case scenario. The subsidence scenario assumed significant subsidence 100 years after closure of a disposal site marked by the formation of surface depressions. The depressions were filled repeatedly with water from surface run-on resulting in increased infiltration.

Question 1: Are there significant performance assessment impacts on the 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 (2); 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 (2). Second, there is an absence of information on the expected degradation rates of containers under the conditions in the vadose zone (2,5). 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, containers that are cracked or contain excess moisture should be prone to more rapid corrosion and degradation than would similar containers that lack cracks or excessive moisture. These differences would be difficult to quantify numerically and would be presumably small. However, under the bounding assumption of 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 performance assessment is complete decomposition and collapse of waste packages by the end of the period of institutional control (2). 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 (5). 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 of 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 (5). The presence of stress fractures in metal containers will have an extremely small effect on subsidence compared to these other factors. Further, 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 into the atmosphere of gaseous radionuclide species

$$Q_j = D_{ej} \left(\frac{C_{oj}}{z} \right) A \quad (\text{Eq. 1})$$

where Q_j is release rate in Ci yr^{-1} , D_{ej} is the effective diffusion coefficient for radionuclide j in pore spaces ($\text{m}^2 \text{yr}^{-1}$), 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 (0.086 volumetric water and 36% porosity). The presence of excess moisture in Fernald waste containers would locally increase the volumetric water contents. The key question for assessing performance impacts is: What are the effects of higher water contents on release of gaseous radionuclides where the identified radionuclides are ^3H , ^{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

$$D_{e,H_2O} = D_{a,H_2O} 0.66(\varepsilon - \theta_v) \quad (\text{Eq. 2})$$

where D_{a,H_2O} 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 that in turn decreases the diffusive flux of gaseous radionuclides (Eq. 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. The net effect of excess moisture is to reduce the releases 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 (2). 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 (Eq. 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.

Results of the upward release rates of gaseous radionuclides from the Area 5 RWMS meet all performance objectives (2). 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 performance assessment 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 by estimating the mean travel time for moisture advected upward from the waste inventory to the surface. The assumed travel length was 2.4 m, 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 (2,6).

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-conductivity, low moisture alluvial sediment of the operational and closure caps above the waste inventory. These deposits (soils) 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 suggests 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 m). 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 m (7). The conceptual model for the vadose zone developed for the Area 3 PA emphasizes episodic infiltration and evaporation to depths of 1-3 m (7). Nonetheless, the thickness of the cover provided by the expected combination of the operational and closure caps (> 5 m) 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, they should be maintained by the high potential evaporation that maintains a moisture deficit state (7).

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 (2). 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. 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 in 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 approach used to assess radon flux density for the Area 5 disposal site follows methods summarized in guidance by the Nuclear Regulatory Commission (2,7). 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 radon flux does not exceed the performance objective ($20 \text{ pCi m}^{-2}\text{s}^{-1}$) throughout the 10,000 year compliance period (Note: The Area 5 PA was completed before the compliance period was changed to 1,000 years). The peak doses from radon occur long after the required compliance period (2). 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 Rn flux density for the conditions assumed for the Area 5 PA.

Question 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?

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 m (590,300 cubic feet) of waste from the Fernald waste stream 006 has been shipped and disposed of in the Area 5 RWMS. Approximately 11,040 cubic m (390,000 cubic feet) of waste has been disposed in Pit 4 (about 18% of the pit volume), about 5,660 cubic m (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 (see following section). 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 were assumed similar to the surrounding alluvial deposits (Table 1).

The base-case scenario was dismissed in the Area 5 PA, primarily because of the very long travel times to the groundwater table, 240 m below the surface. The median travel time to the alluvial aquifer in Frenchman Flat was estimated to be about 51,000 years with a greater than 99% probability that the travel time exceeds 10,000 years (2). The presence of excess moisture in waste will locally cause a transient increase in the unsaturated hydraulic conductivity and 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 m) and the relatively thin zone of increased wetting front velocity from the excess moisture (see Figs. 2 and 3). 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 2-m deep subsidence depression formed on an operational cover with flood water 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 shows that there are only small differences between the two 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 m deeper than the profile without excess moisture. Shortly after three years, the profiles are virtually indistinguishable. If 25% of the waste inventory were to contain excess moisture, the expected travel time of the wetting front to the groundwater table would be about 190 years. This interval is longer than the travel time used in the Area 5 PA because of slightly different modeling assumptions.

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 from the Fernald 006 waste stream.

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?

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 taken 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 (2). 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 ^{14}C generation is bounded in the Area 5 PA by three conservative assumptions. First, ^{14}C release is attributed solely to gaseous CO_2 , despite the presence of other non-gaseous carbon species that are expected to compete for the available ^{14}C -inventory (2). Second, the entire $^{14}\text{C}\text{O}_2$ 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 (2). 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 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 for this release. It is unlikely that any credible transport mechanism associated with increased moisture content would exceed the release rate assumed in the performance assessment.

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: Increased moisture in the waste system will provide more opportunity for an increase in plant cover in the case of the 2.4-m cover system used in Shott et al. (2). Examination of the subsidence and flooding scenarios indicates the increased moisture at depth lasts long enough to influence the growth patterns of plants in the immediate area. Soil moisture decreases 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. (2) 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.

The issue of pathways associated with plant and/or insect activity in the Area 5 PA 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 animal activity, empirical equations were developed for 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 (2)

$$K_{r1j} = B_{jv} \times B_p \times \left(1 + \frac{F_{rs}}{B_{ab}}\right) \times F_{rw} \times \frac{1}{H_w} \times \frac{1}{\rho_b} \quad (\text{Eq. 3})$$

where

B_{jv} = the plant-soil concentration ration for radionuclide j in pCi g^{-1} plant mass per pCi g^{-1} dry soil

B_p = annual above ground perennial shrub biomass productivity in $\text{g dry mass m}^{-2} \text{yr}^{-1}$

B_{ab} = ratio of above-to below ground productivity for shrubs in g yr^{-1} aboveground 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 m

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 additional plant growth due to increased seed germination.

The current performance assessment evaluated the effects of 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-m operational cover could encourage, for selected species, more root growth in the direction of a source of moisture. Because of the depth 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 performance assessment, 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, 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 allowing increased root production in response to the waste moisture. The values of this ratio for the Mojave Desert range from 0.6 to 2.3. A value of 0.6 allows an increase in plant uptake of radionuclides by a factor of 1.2.

The combined estimates of the increases due to the moisture in the waste result in a factor of 4.8 more radionuclide uptake by plants. Table E.8 of the Area 5 PA (2) 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.

Insect population 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 (2), 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 in response to the doubling of plant biomass available as food, the increased dose from the moisture in the waste would be another 9.7 mrem/yr, or a total of 19.4 mrem/yr. That increase is still well within the performance objectives for the waste management system.

Closure plans for the final cover of waste pits in the Area 5 RWMS include the addition of a final cover cap with an assumed thickness of about 3 m (5). The addition of cover material reduces the amount of waste volume that is available to burrowing animals. The addition of 3 m 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. (2) indicated the deep burrows extend to between 2 and 3 m below the surface. Using only the 2.4-m operational cover, the conservative approach used in the Area 5 PA assumed the ants brought waste to the surface. With an added 3 m of soil, the depth to the waste far exceeds the burrow depths of the Harvester ants.

In summary, excess moisture can affect the performance of the Area 5 RWMS in the area of biointrusion (plant and/or animal). 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 a closure cap.

MODELING OF THE EFFECTS OF EXCESS MOISTURE

Simulation modeling of downward moisture redistribution in the vadose zone is also conducted for the conditions of 0, 50, 75 or 100% of the total inventory having excess

moisture. These divisions correspond to the assumption that zero, two, three or four tiers of a possible total of four tiers of waste containers have volumetric water contents equal to full saturation of the effective porosity.

Hydraulic properties and initial conditions for the vadose zone modeling were identical to those used for the flooding simulations described in the Area 5 Performance Assessment (2). The hydraulic properties are summarized in Table I.

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

Simulations were conducted using the computer code VS2DT, a program for simulating isothermal, two-dimensional movement of liquid water in variably saturated porous media (8,9). The flow model ODIRE (10) 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.

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 (2). The weather data consisted of actual Area 5 RWMS meteorological data from 1995, a year characterized by above-average annual precipitation. Figure 1 shows the results of the model simulations for the base-case scenario with 25 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 m (elongate rectangles of Figure 1). Water in these saturated zones 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 m for the 25% wet waste and 33 m 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 in 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 conditions.

SUBSIDENCE/FLOODING SCENARIO

The flooding scenario simulations were conducted under the same conditions as those described in the Area 5 PA (2). In each case, a ponding depth of 2 m 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 3, where two profiles are compared. The first profile illustrates soil water distribution within and beneath Pit 5 assuming waste contains 25% excess moisture. The second profile illustrates soil water distribution within and beneath Pit 5 for a simulation with four tiers of waste containing excess moisture. After a period of three years, the wetting front for the profile with 25% wet waste reaches approximately 2 m deeper than the wetting front for the profile without wet waste. Water content after three years in the first profile in Figure 3 (25% wet waste) is nearly indistinguishable from the profile shown in the Area 5 PA (2). Travel times of the wetting front to the groundwater table range from 190 years for the dry-waste scenario to 140 years for the 100% wet-waste scenario. The 140-year travel time to the groundwater table that was reported in the Area 5PA (2) is an extremely conservative calculation, because the estimated arrival time of the wetting front was chosen for the capillary fringe located 15 m above the groundwater 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. The travel-time estimate, assuming 100% of the inventory contains excess moisture, is 140 years (Figure 3) and is virtually identical to the travel-time estimated in the Area 5 PA (2).

SUMMARY AND OBSERVATIONS

This report presents the results of a systematic examination of the performance impacts of disposal of waste with excess moisture in stress-fractured containers (white metal boxes). 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. The performance impacts of excess moisture in waste containers were modeled for the base-case scenario and the subsidence-flooding scenario. No significant performance impacts were noted for assumptions ranging from 25-to-100% of the disposed inventory containing excess moisture. This is attributed

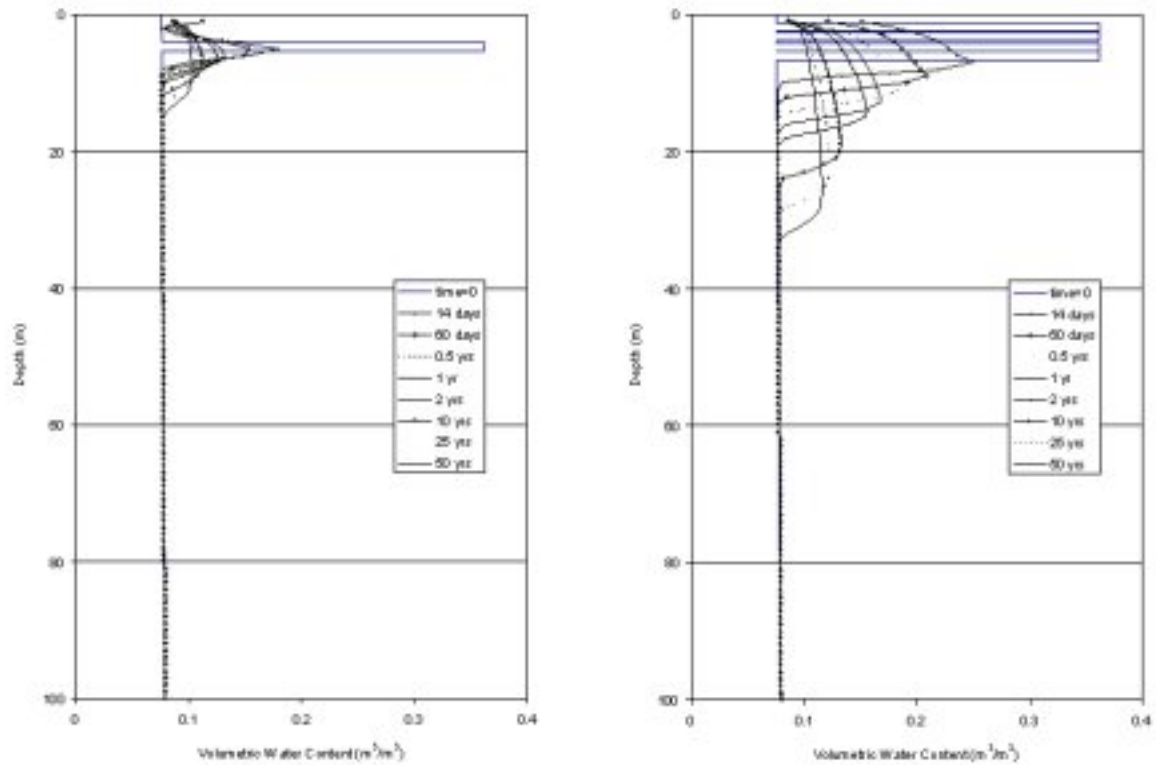


Figure 1. Simulations of the redistribution of moisture in the vadose zone of the Area 5 RWMS for assumed conditions of 25% (left Figure) and 100% (right Figure) of the Pit 5 inventory containing excess moisture.

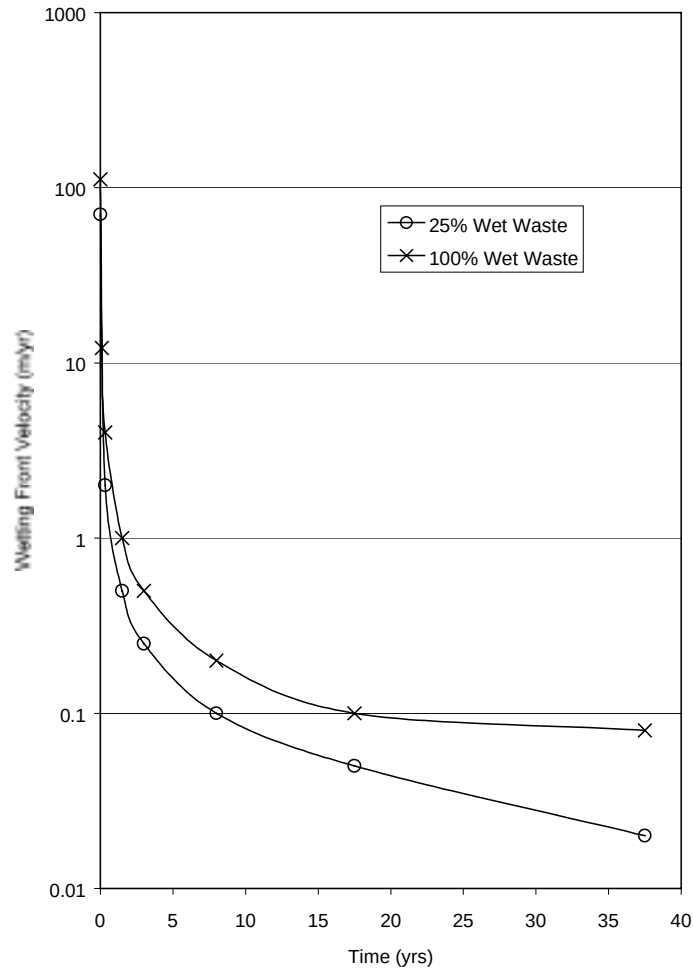


Figure 2. Average velocities of the wetting fronts with time for the base-case scenarios where 25% and 100% respectively, of the waste inventory contains excess moisture.

to two factors. First, the changes to the disposal system are constrained by the conservative bounding assumptions used in the Area 5-performance assessment. Second, the 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) result in an exceptionally viable site for disposal of low-level radioactive waste.

Four observations are provided.

1. The only significant discrepancy with the Area 5 PA (2) is with 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. Revised simulation modeling of the vadose zone shows that moisture redistribution occurs over intervals of tens of years and volumetric water contents then approach initial conditions. Thus, while initially

inconsistent, the assumption that waste moisture is equal to alluvium moisture is valid over most of the compliance period.

2. It is difficult to identify the volume of disposed waste that includes waste streams with high moisture contents. Based on discussions with DOE program managers and contractor personnel, it is likely that the volume of disposed “wet” waste at Area 5 may be less than 25%. Further clarification of the actual abundance of disposed “wet” waste at the Area 5

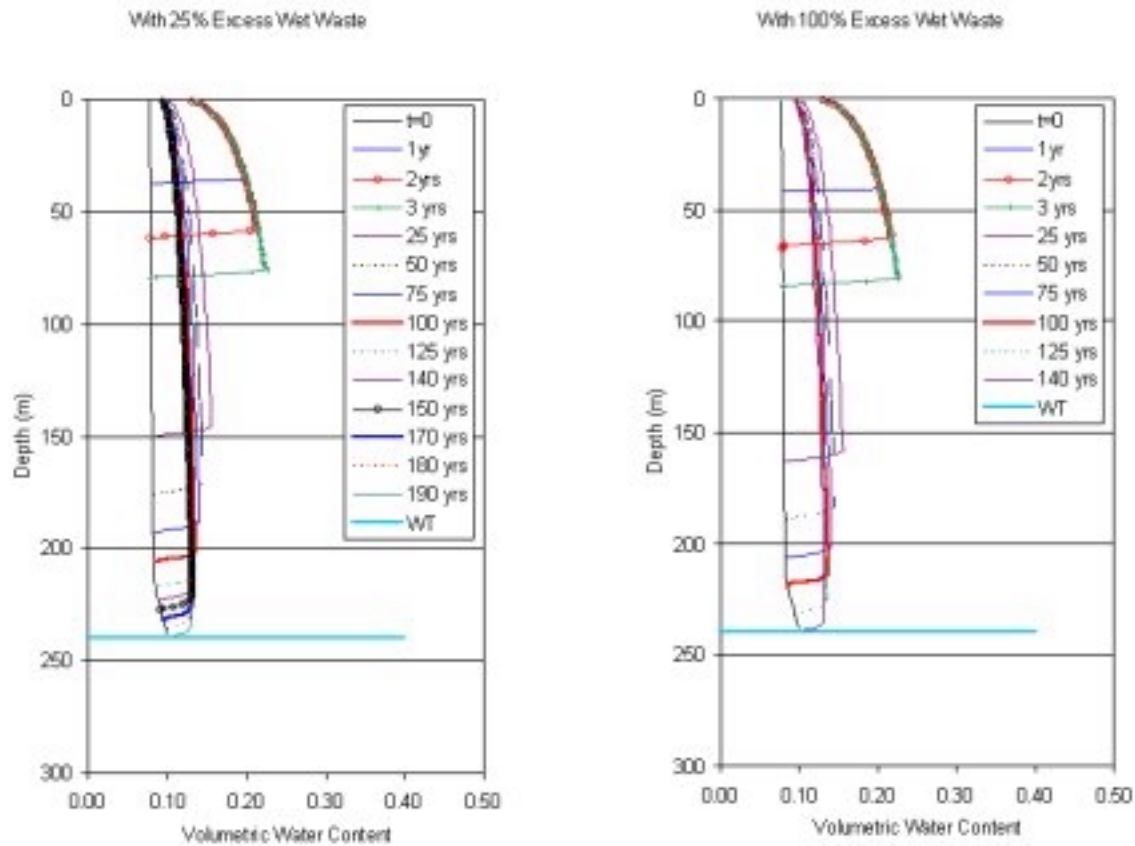


Figure 3. Simulations of moisture redistribution for assumed conditions of 25% wet waste (left Figure) and 100% wet waste (right Figure) for the subsidence/flooding scenario.

RWMS would be of limited value given no significant performance impacts for the assumption that 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, 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. The most logical approach would be to implement, using the concept of redundant barriers, multiple alternative methods for reducing the moisture content of waste significantly below saturation of the effective porosity of the waste. This would greatly decrease the potential for development of free liquids during transportation.

4. Public perception of the Fernald transportation incident is a critical element of stakeholder acceptance of the DOE low-level radioactive waste disposal programs at the NTS. The highly favorable performance assessment of the Area 5 RWMS is an extremely positive attribute. The site both meets and provides a considerable margin of protection with respect to the performance objectives. This positive program could be jeopardized, however by future transportation incidents. The DOE should take extra precautions to prevent leakage of liquids during transportation to avoid negative impacts on an efficient waste disposal program.

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