Natural Groundwater Recharge and Water Balance at the Hanford Site

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**Prepared for the U.S. Department of Energy
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EXECUTIVE SUMMARY

Pacific Northwest Laboratory conducted this study for the U.S. Department of Energy as part of the Hanford Site Performance Assessment (HSPA) project. The objective of this study was to monitor water-balance parameters at three locations of the Hanford Site in FY 1989 as they relate to recharge and contaminant transport.

The Hanford Defense Waste Environmental Impact Statement (USDOE 1987) identified groundwater as the primary pathway for potential exposure to defense-waste contaminants. The HSPA project monitors three locations at the Hanford Site to establish a long-term record of water balance that can be used to predict recharge rates and facilitate computer code development and testing.

The data collected at the three locations in FY 1989 support conclusions reached in earlier status reports that recharge is highly dependent on near-surface, site-specific conditions such as soil type(s), stratigraphy, vegetation type and growing season, and the presence or absence of gravel. Specifically, the data show:

- The presence of vegetation does not ensure zero recharge.
- The year-to-year seasonal distribution of precipitation may determine whether some sites exhibit recharge.
- Recharge estimates based on unit gradient calculations agree reasonably well with measured drainage from lysimeters, but may vary by several orders of magnitude because of uncertainties in soil hydraulic properties and the precision of neutron probe measurements of soil water content.
- At the 200 East Area Lysimeter Site, water contents below the 4.88-m depth in the closed-bottom lysimeter have not changed measurably between 1972 and 1988, implying that significant recharge has not occurred. However, the data are insufficient to conclude whether the presence of a plant community on the lysimeter is the reason for the lack of water increase in the lysimeter over the last 17 years. *or not?*

- Gravel-covered lysimeters designed to simulate tank farm conditions on the 200 Area plateau have drained approximately 4.3 cm of water during the past year, from an initially dry condition. These data are in agreement with previous modeling studies, which show that gravel placed on the soil surface reduces evaporation and facilitates increased drainage.

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1.0 INTRODUCTION

Groundwater recharge (i.e., net infiltration) is the quantity of water from natural precipitation or irrigation that drains through the vadose (unsaturated) zone to the water table. The amount of recharge at the Hanford Site is of considerable interest because recharge provides a mechanism for leaching contaminants from wastes and transporting them to the unconfined aquifer. In the event of leakage or containment failure, the recharge rate can be used to calculate contaminant travel times from the source to the accessible environment (e.g., the Columbia River).

To obtain information on long-term recharge rates, the U.S. Department of Energy commissioned Pacific Northwest Laboratory (PNL) to monitor the water balance at selected locations of the Hanford Site. The information will be used to document site-specific recharge rates and evaluate the capabilities of computer codes for simulating vadose zone water balance and contaminant transport.

The purpose of this report is to present water-balance data collected in 1988 and 1989 from the 300 Area Buried Waste Test Facility (BWTF) and Grass Site, and the 200 East Area closed-bottom lysimeter. This report is an annual update of previous recharge status reports by Gee, Rockhold, and Downs (1989), and Gee (1987). Data from several other lysimeter sites are included for comparison.

The report is organized into six sections. Section 2.0 gives a brief description of the methods used to estimate groundwater recharge. Section 3.0 provides an overview of the water-balance study areas at the Hanford Site, with special reference to the HSPA-funded sites. Section 4.0 summarizes water-balance components and recharge estimates for the HSPA sites. Section 5.0 presents conclusions and discusses implications for contaminant transport. The appendix describes the details of a radionuclide transport study at the BWTF.

2.0 RECHARGE ESTIMATION METHODS

Methods used for estimating the amount of groundwater recharge at the Hanford Site have involved the analysis of water movement downward through the vadose zone. These methods, which are described below, include

- water balance
- lysimetry
- zero-flux plane
- unit gradient or gradient calculation.

Because of the low flux rates at the Hanford Site, methods that infer recharge from water-table changes are not useful for estimating natural groundwater recharge, although they may be appropriate for determining the rates of artificial groundwater recharge in special cases.

A recharge estimation method that has not been previously used at the Hanford Site, involves the use of natural tracers, such as the stable isotopes, ^{18}O and ^2H . Although relatively few studies have used stable isotopes to determine rates of recharge, techniques are available that may enable estimates of local recharge to be made for conditions of low recharge (Allison et al. 1984). These techniques will be reviewed in FY 1990 for use at the Hanford Site.

2.1 WATER BALANCE

The water-balance method is based on quantification of the terms in the following hydrologic cycle equation:

$$\Delta S = P + I - ET - D \pm R \quad (2.1)$$

where ΔS = change in water storage of soil of the plant root zone

P = natural precipitation

I = irrigation or other non-natural water additions

ET = evapotranspiration

D = recharge (also referred to as drainage or net infiltration)

R = net overland flow (i.e., runoff or runon).

These water-balance terms are depicted in Figure 2.1. The water-balance terms are generally expressed as the volume of water per unit area. Therefore, equivalent depth units (cm of H₂O) are used throughout this report.

The water content of soil is measured at the water-balance study sites by a neutron hydroprobe or gravimetry. The technical procedure that is followed for monitoring water content using the neutron hydroprobe is described by Gee, Rockhold, and Downs (1989).

Neutron probe calibration curves are obtained for different soil types by linear regression between measured volumetric water contents and corresponding neutron probe counts or count ratios. Volumetric water contents are generally determined by multiplying gravimetric water contents and soil bulk densities.

According to the manufacturer's published specifications, water contents determined with the neutron probe have a measurement precision of 0.24% at a volumetric water content of 24%. In an analysis of neutron probe data collected from lysimeters at the Hanford Site, Jones (1978) suggested that the neutron probe measurement precision for observed volumetric water contents cannot be expected to be better than 0.5%. Reginato and Nakayama (1988) report average errors in volumetric water content determined using neutron probes in agricultural soils of ± 0.009 and ± 0.010 , depending on the relative soil moisture. A detailed description of the estimation of errors in volumetric

FIGURE 2.1. Water-Balance Components

water-content measurements by the neutron probe and the uncertainties in the associated calibration curve are given by Haverkamp, Vauclin, and Vachaud (1984).

The water storage in soils is calculated for the water-balance study sites using the method of trapezoidal integration of water-content profiles (Green, Ahuja and Chong 1986). In this method, water storage (S) between the soil surface and depth z_1 , can be approximated by

$$S = \int_0^{z_1} \theta \, dz \approx 15\theta_1 + \sum_{i=1}^{n-1} 15(\theta_i + \theta_{i+1})/2 \quad (2.2)$$

where θ_i is the water content of the soil measured at the i^{th} depth in the profile, n is the number of measurement points, and the spacing between successive measurement points is 15 cm. The water content from the soil surface ($z = 0$) to the first depth of measurement is taken as that measured at the first depth. At the BWTF and other lysimeter sites with weighing lysimeters, water-storage changes are also determined from lysimeter weight changes.

Variances associated with water-storage calculations represent the contribution of errors associated with both the neutron probe determinations of water content and the numerical approximation of the storage integral. Haverkamp, Vauclin, and Vachaud (1984) calculated relative errors in water-storage calculations of 1.8 to 2.3% using trapezoidal integration of water-content profiles determined from neutron probes in a 105-cm deep soil profile, with measurements at 10-cm depth intervals.

Precipitation is measured at the study areas using tipping-bucket and standard collection rain gauges. At the BWTF and other weighing lysimeter sites, precipitation can also be calculated from lysimeter weight changes. In addition to these location-specific precipitation measurements, official precipitation records for the Hanford Site are maintained by the Hanford Meteorological Station (HMS) located on the 200 Area plateau. Comparisons are made between precipitation data from the study areas and HMS precipitation records to ensure that data obtained from the field sites are reasonable.

These comparisons also provide a measure of the variability of precipitation across the Hanford Site.

Irrigation is a significant part of several experimental studies of the Hanford Site (Campbell et al. 1989; Freeman and Gee 1989) and in specific areas where artificial recharge occurs (i.e., evaporation ponds, cribs, and trenches). For the time period covered by this report, irrigation did not occur at the HSPA sites and was therefore not included in water-balance calculations in this report.

Evapotranspiration represents the combined processes of plant transpiration and evaporation. Evapotranspiration is determined at the study sites from lysimeter weight changes or from the solution of Equation (2.1) after the other water-balance terms have been measured or calculated. In the absence of plants, only evaporation is considered. Another method for measuring evapotranspiration involves the use of micrometeorological techniques, such as Bowen ratio and eddy correlation. The results of recent studies using these techniques at the BWTF, Grass Site, and Arid Lands Ecology (ALE) sites will be described in a later report.

Evapotranspiration can also be estimated as some fraction of potential evapotranspiration (PET), which is a measure of the maximum amount of water that can be absorbed into the atmosphere given the atmospheric vapor density and radiant energy condition (Jones, Campbell, and Gee 1984). The PET is generally calculated from solar radiation, wind speed, and other climate data using the Penman (1948) equation. These data are collected at the BWTF, Grass site, and ALE water-balance study sites. The PET can be used to empirically estimate actual evaporation and transpiration without describing any controlling physical processes such as diffusion and convection. Descriptions of PET and evaporation models are provided by Jones, Campbell, and Gee (1984). Gee, Rockhold, and Downs (1989) suggest, however, that PET is not a reliable estimate of actual evaporation or evapotranspiration at the Hanford Site.

Runoff, from the standpoint of waste management, is generally considered to be negligible at the Hanford Site. At some locations, however, this water-balance term may be significant when the soil is frozen and when rapid snowmelt occurs, especially on terrain with a significant slope.

Drainage below the root zone represents the recharge term of the water-balance equation. Drainage is usually calculated unless it can be measured directly by lysimeters. Negative drainage indicates upward water flow by capillary imbibition (usually from a water table located near the surface of the soil). This condition is not a factor in water-balance calculations for most of the Hanford Site because the water table is sufficiently deep [10 to 100 m or more below the ground surface (Gee 1987)] to be well below the plant-root zone.

2.2 LYSIMETRY

The weighing lysimeters in the water-balance study areas at the Hanford Site are essentially 1.5-m³ soil-filled containers resting on platform scales that have a 9,090 kg (20,000 lb) capacity. The scales are connected to dataloggers that record voltage changes corresponding to lysimeter weight changes. The design of the weighing lysimeters used at the BWTF and ALE sites is described by Kirkham, Gee, and Jones (1984).

The weighing lysimeters at the BWTF were hand-packed with sediments that were excavated during construction of the facility, as described in Section 3.0 of this report. At the ALE water-balance study sites, 1.5-m³ monoliths of soil were excavated from areas adjacent to the lysimeters and placed in the weighing lysimeters to preserve the natural structure of the soil. Descriptions of additional types of lysimeters used at the Hanford Site are provided by Gee et al. (1989), Freeman and Gee (1989), and Gee and Jones (1985).

Periodic calibration of the weighing lysimeter scales is necessary to ensure that deviations from any measured weight do not exceed the manufacturer's published tolerance of $\pm 0.02\%$ of the loaded value. Therefore, the weighing lysimeter scales at the BWTF and other lysimeter sites are tested each year for sensitivity and hysteresis by the Hanford Engineering Development Laboratory (HEDL). Calibrations based on these tests are then generated and certified to be traceable to national standards (Campbell et al. 1989).

Lysimeter weight changes are calculated using a linear regression of weight-voltage data for the calibration range of each scale. Deviations of calibration weights from the weights determined by regression for the BWTF weighing lysimeter scales are shown in Figure 2.2. At a tolerance of $\pm 0.02\%$

of the loaded value, 15,000 lb should not have deviations greater than $0.0002 \times 15000 = \pm 3$ lb.

Equivalent weight changes expressed in terms of depth units (cm) are determined by dividing the weight change (g) by the area of the lysimeters (cm^2). According to Campbell et al. (1989), the lysimeter scales have a resolution of ± 50 g (0.002 cm). Equivalent weight changes reflect precipitation events, water-storage changes, evapotranspiration, and drainage.

To ensure that measured lysimeter drainage represents recharge, the lysimeters must mimic the natural environment and be sufficiently deep to extend beyond the maximum depth of water withdrawal by plant roots and surface evaporation. Weighing lysimeters at the Field Lysimeter Test Facility (FLTF) have gravel layers at the base to facilitate collection of drainage water. Drainage into the gravel occurs only when the water potential of the soil immediately above the gravel approaches zero. This modification of the natural regime is not significant at the FLTF because the gravel layer comprises a part of the system being represented (e.g., a protective barrier). In the BWTF and ALE weighing lysimeters, suction candles are used to reduce the significance of the modification of the natural regime caused by the

FIGURE 2.2. BWTF Weighing Lysimeter Scale Calibrations, May 18, 1989. NWL and SWL are the North and South weighing lysimeters, respectively. Steps 1-10 = scale loading; steps 11-21 = scale unloading.

impermeable base of the lysimeters. A vacuum is applied to the suction candles to create a potential gradient similar to that in the natural environment. A schematic of the suction-candle vacuum system used in the BWTF weighing lysimeters is provided by Gee, Rockhold, and Downs (1989).

The values of the other terms of the water-balance equation are often used to calculate recharge at the sites where drainage water cannot be measured (i.e., at the Grass Site and 200 East Area closed-bottom lysimeter). The indirect methods of calculating recharge are described in the following sections.

2.3 ZERO-FLUX PLANE

The flux (q) of water through soil is proportional to the hydraulic head gradient (dH/dz). For saturated soils, the flux can be determined with the Darcy flow equation

$$q = -K_s \frac{dH}{dz} \quad (2.3)$$

where K_s is the saturated hydraulic conductivity (i.e., the proportionality factor). For unsaturated soils, the hydraulic conductivity is nonlinearly related to the matric head or water content. Therefore, Equation (2.3) is usually modified to

$$q = -K(\theta) \frac{dH}{dz} \quad (2.4)$$

where K is the flux of water per unit gradient of hydraulic head and θ is the volumetric water content or volume of water per unit bulk volume of soil. To describe transient, vertical flow, Equation (2.4) must be combined with the equation of continuity,

$$\frac{\partial \theta}{\partial t} = -\frac{\partial q}{\partial z} \quad (2.5)$$

where t is time and z is depth. This combination is commonly known as the Richards equation (Richards 1931),

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z} \left[-K(\theta) \frac{\partial H}{\partial z} \right] \quad (2.6)$$

Consideration of the uptake of water by plant roots necessitates the addition of a sink term to Equation (2.6).

The zero-flux-plane method for estimating groundwater recharge relies on determining the location of a plane of zero hydraulic gradient in the soil profile. The location of this plane can be directly determined in the soil by using tensiometers. Recharge for a given duration is calculated by integrating water-content profiles below the zero-flux plane to determine the change in total water stored. A decrease in total storage below this plane over the time period is assumed to be recharge. Unfortunately, this zero-flux plane is not always stationary and the method cannot be used during periods of high infiltration if the hydraulic gradient becomes positive downward throughout the profile.

2.4 UNIT GRADIENT

While studying drainage losses from lysimeters, Black, Gardner, and Thurtell (1969) noted that a "unit gradient" condition often occurred. This condition arises for uniform (homogeneous) soils when the water content is nearly constant with depth, and results in $\partial H / \partial z \approx 1$. For unit gradient conditions, Equation (2.4) reduces to $q = -K(\theta)$ and the flux of water moving through the soil is equal to the hydraulic conductivity. Davidson et al. (1969) rewrote Equation (2.6) in unit gradient form such that

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z} [-K(\theta)] \quad (2.7)$$

Therefore, recharge fluxes can be estimated from soil hydraulic properties and the volumetric water content of the soil below the plant root zone. Unit gradient conditions have been found in drainage lysimeters at the BWTF and

below the 120-cm depth at the Grass Site (Rockhold, Fayer, and Gee 1988; Gee, Rockhold, and Downs 1989).

3.0 WATER-BALANCE STUDY SITES

During the past two decades, a variety of water-balance data have been collected at the locations shown in Figure 3.1. Information about these study sites and the programs that currently sponsor them are summarized in Table 3.1.

This report focuses on the three study sites (i.e., BWTF, Grass Site, and 200 East Area Lysimeter Site) that are funded and managed by the HSPA program. A fourth site, the Small Tube Lysimeter Facility (STLF), contains two gravel-covered lysimeters originally installed as part of the HSPA program. These two lysimeters are now monitored by the Hanford Protective Barriers (HPB) program and the data are reported in Protective Barriers documents (Freeman, Gee, and Relyea 1989; Freeman and Gee 1989). The STLF is referenced as the 622 Area Lysimeter Site in Figure 3.1.

FIGURE 3.1. Water-Balance Study Areas at the Hanford Site

TABLE 3.1. Summary of Soil-Water Balance Study Areas at the Hanford Site

Name	Program	Soil Type	Lysimeter Type and Number			Surface Condition	Waste/Tracer Component
			2	1	5(a)		
BWTF	HSPA	Sand	--	--	--	Nonvegetated, Vegetated	60Co(b), H-3(b)
Grass Site	HSPA	Sandy Loam/Sand	--	--	--	Vegetated	none
200E(c)	HSPA	Sand	--	--	1	Nonvegetated	none
FLTF	HPB	Silt Loam	4	14	--	Nonvegetated, Vegetated, Gravel Admix	none
STLF	HPB	Silt Loam or Sand	100	--	--	Nonvegetated, Vegetated, Gravel Admix, Gravel Layer	none
McGee Ranch	HPB	Silt Loam	--	--	--	Nonvegetated, Vegetated, Gravel Admix	none
ALE(d)	ALE	Silt Loam	4	--	--	Vegetated	none
Lower Snively	ALE	Silt Loam	--	--	--	Vegetated	none
Upper Snively	ALE	Silt Loam	--	--	--	Vegetated	none
CWTF	SWLA	Sand	--	10	--	Nonvegetated	Commercial Waste Forms
GLTF(e)	Grout	Fine Sand/Sand	--	1	1(a)	Nonvegetated	Grout Waste

(a) Originally designed to collect drainage, these lysimeters leak and can only be used to measure water-storage changes.

(b) Tracer no longer present

(c) 200 East Lysimeter Site

(d) ALE Lysimeter Site

(e) Inactive in FY 1989

Data from the two STLF lysimeters will be discussed in the context of how surface conditions affect recharge. A fifth site, the Commercial Waste Test Facility (CWTF), consists of 10 lysimeters adjacent to the BWTF. This site is monitored under the Special Waste-Form Lysimeters Arid (SWLA) Program. Drainage data from the CWTF lysimeters are included for comparison with BWTF drainage data. The following sections briefly describe these study sites.

3.1 300 AREA BURIED WASTE TEST FACILITY

The BWTF is about 6 km northwest of the 300 Area, adjacent to the 300-N Burial Ground. The BWTF was originally designed for field studies of water balance and radionuclide transport (Phillips et al. 1979), but is currently being monitored to document long-term recharge rates and to provide data for testing computer codes that simulate water balance.

The BWTF consists of seven corrugated, galvanized-steel caissons, bolted together in the arrangement shown in Figure 3.2, and two weighing lysimeters. All seven caissons are 7.6 m long. The diameter of the three large caissons is 2.7 m; that of the four small caissons is 0.6 m. The sides of the weighing lysimeters are approximately 1.5 m long and 1.5 m deep.

The BWTF caissons and weighing lysimeters are filled with sediment that was excavated from the area. The fill was passed through a 1.27-cm-mesh screen to ensure uniformity. The resulting backfill consists of approximately 97% sand, 2% silt, and 1% clay. Descriptions of the hydraulic properties of the BWTF sediments are provided by Cass, Campbell, and Jones (1981), and Rockhold, Fayer, and Gee (1988).

A study of bare soil evaporation at the BWTF was made by Jones, Campbell, and Gee (1984). Details of a radionuclide transport study conducted at the BWTF are provided in the appendix to this report.

3.2 300 AREA GRASS SITE

The Grass Site is approximately 3 km southwest of the BWTF located in a broad, shallow topographic depression approximately 900 m wide, several hundred meters long, trending northeast-southwest. This site is being studied

FIGURE 3.2. Plan View and Cross Section of the Buried Waste Test Facility Adjacent to the 300 North Burial Grounds

because of its stratified soil profile and surface conditions (i.e., a vegetative cover of annual grasses) that may be representative of contaminated soil sites after fire or drought conditions. The information being gathered from this site will also be used to estimate long-term recharge rates and to evaluate simulations of water balance.

The soil at the Grass Site is approximately 3.5 m thick and is well drained. The top 0.6 m of soil is classified as a sandy loam, consisting of approximately 74% sand, 21% silt, and 5% clay. From a depth of about 0.6 m to 3.5 m, the soil is classified as a sand, consisting of approximately 91% sand, 6% silt, and 3% clay. A gravel layer that lies below the 3.5-m depth is estimated to be several meters thick based on excavations at adjacent sites. Descriptions of the hydraulic properties of the soils at the Grass Site are provided by Rockhold, Fayer and Gee (1988), and Gee, Rockhold, and Downs (1989).

To document water-storage changes, a network of 25 neutron probe access tubes was installed at the Grass Site in December 1982. The access tubes are arrayed in a 5 by 5 grid, with 6-m spacing between tubes, as shown in Figure 3.3. These access tubes have been monitored on a biweekly to monthly basis since January 1983. A modeling study of the water balance at the Grass Site was conducted by Gee and Kirkham (1984).

FIGURE 3.3. Schematic of Neutron Probe Access Tubes at the Grass Site

3.3 200 EAST AREA LYSIMETER SITE

The 200 East Area Lysimeter Site is approximately 1 km south of the 200 East Area. This facility consists of two 18.5-m deep lysimeters and an instrument room, depicted in Figure 3.4. Constructed in early 1972, this facility contains the oldest lysimeters at the Hanford Site. These lysimeters may also be the deepest in the world.

The facility was designed to test the hypothesis that meteoric water percolates down to the water table beneath the 200 Area plateau. Numerous reports (e.g., Isaacson et al. 1974; Last, Easley, and Brown 1976; Routsen, Fuchs, and Jordan 1988) cite data from this facility as evidence for zero, or nearly zero, recharge. Fayer, Gee, and Jones (1986) suggest that plants growing on the lysimeters (e.g., see the photographs in Gee and Heller 1985, and Gee, Rockhold, and Downs 1989) may have been responsible for the lack of recharge. They further contend that, without the presence of plants, water would have moved deeper into the lysimeters to eventually become recharge.

During the mid-1980s, the facility was not monitored and the open-bottom lysimeter was excavated. In February 1988, vegetation and wind-blown sediments, which had accumulated on the surface of the closed-bottom lysimeter, were removed and an active monitoring program was initiated (Gee, Rockhold, and Downs 1989). The closed-bottom lysimeter, maintained with a bare-soil surface, is currently being monitored to test the hypothesis that plants growing on the lysimeter were the reason that no measurable recharge has occurred during the last 18 years.

Three neutron probe access tubes have been monitored in the closed-bottom lysimeter on a biweekly to monthly basis since February 1988. These replications provide a measure of the water content variability within the lysimeter. Two additional neutron probe access tubes have been monitored at the 200 East Area Lysimeter Site since April 1988. One tube is located southwest of the lysimeter in an area dominated by sagebrush, and the other tube is located directly south of the lysimeter in an area dominated by cheatgrass, as shown in Figure 3.4.

Plan View

Cross Section

FIGURE 3.4. Plan View and Cross Section of the 200 East Area Closed-Bottom Lysimeter

3.4 OTHER SITES

The Commercial Waste Test Facility (CWTF) is located in the 300 Area, approximately 20 m east of the BWTF. This facility was designed to monitor the release of radionuclides from solid wastes. The CWTF was installed in 1984, and is part of the Special Waste Form Lysimeters - Arid Program. Research conducted at this facility is sponsored by the U.S. Department of Energy (DOE) Low-Level Waste Management Program. Details of water balance and radionuclide studies conducted at the CWTF are provided by Jones, Serne, and Toste (1988).

The CWTF consists of 10 lysimeters, each 1.8 m in diameter and 3.1 m deep. The soil in these lysimeters has a texture similar to that at the BWTF, consisting of 92% sand, 6% silt, and 2% clay (Walter, Graham and Gee 1984). All 10 lysimeters at the CWTF have been kept free of vegetation since 1984. Drainage data from these lysimeters are included in Section 4.0 of this report for comparison with BWTF drainage data.

The Small Tube Lysimeter Facility (STLF) is adjacent to the 200 Area Hanford Meteorological Station (HMS) and is identified as the 622 Area Lysimeter Site in Figure 3.1. This facility was constructed to measure the water balance of various barrier configurations, including soils covered with gravels. Details of the lysimeter design and experimental studies at the STLF are provided by Freeman, Gee, and Relyea (1989). Lysimeter monitoring at the STLF began in July 1988. Data collection from these lysimeters is described by Freeman and Gee (1989).

Two gravel-covered lysimeters were initially installed at the STLF as part of the HSPA program. The dimensions of these lysimeters are shown in Figure 3.5. The drainage data from these two lysimeters demonstrate the effect of gravel-covered surfaces on recharge.

FIGURE 3.5. Schematic of Gravel-Covered Lysimeter Used to Simulate Tank Farm Surface Conditions

4.0 WATER-BALANCE CALCULATIONS AND RECHARGE ESTIMATES

Water balance data collected at each of the HSPA sites are presented below. In some cases, data from previous years (although not the entire record) are included to illustrate the seasonal variability of water-balance components. The data include precipitation, soil water content, storage, and drainage.

4.1 BURIED WASTE TEST FACILITY

Water-storage changes (cm) in the North and South weighing lysimeters at the BWTF are shown in Figure 4.1. These data indicate that from July 1, 1988, to June 30, 1989, storage of water within the weighing lysimeters was at a minimum between late October and early November of 1988 and at a maximum in mid-March of 1989. During this period, storage of water in the North weighing lysimeter (NWL) decreased by 0.254 cm, while storage in the South weighing lysimeter (SWL) decreased by 2.860 cm. This difference can be attributed primarily to extraction of water from the soil by plants on the SWL.

The data in Figure 4.1 suggest that there are two periods when vegetation on the SWL was most active in removing water from the soil relative to water loss by evaporation from the NWL. These periods are from late August through early November 1988 and from May 1989 through the end of the reporting period (June 30, 1989). This higher rate of depletion of water from the soil is not continuous during this time because the vegetation was dormant during the winter months (November through February) and senesced during the hot summer months of 1988. This year (1989) has been cooler than normal, with above-average spring precipitation, so that plants on the SWL may remain active throughout the summer and fall.

The differences between maximum storage of water in the soil of the NWL and SWL can be attributed to higher drainage rates from the NWL. During the time from July 1, 1988, to June 30, 1989, 4.0, 0.99, and 4.18 cm of water drained from the NWL, SWL, and South caisson (SC), respectively. The last time before April of 1989 that measurable drainage was collected from the SWL was in July of 1986.

FIGURE 4.1. Water-Storage Changes in the North (NWL) and South (SWL) Weighing Lysimeters at the Buried Waste Test Facility

Cumulative drainage data collected during January 1984 through June 30, 1989, from the NWL, SWL and SC, are compared in Figure 4.2. Drainage from both weighing lysimeters is highly seasonal. For the SWL, the four largest identifiable drainage periods shown in Figure 4.2 occurred from January to March, when plants are usually dormant. For the entire period, cheatgrass and bluegrass covered about 50% of the SWL. In the summer of 1986, a tumbleweed was growing on the SWL, and in the spring of 1987 and 1988, tumble mustard plants were also growing on the SWL (Gee, Rockhold, and Downs 1989). The presence of these plants, which have deeper roots than cheatgrass and bluegrass, may explain the lack of drainage from the SWL between 1986 and 1989. Drainage from the SWL in March and April of 1989 reflects the above-normal precipitation received during February and March, and the lack of plant activity until mid to late April.

Drainage from the NWL tends to occur every year in late winter and early spring. By June of most years, drainage from the NWL has stopped. In contrast to the relatively shallow NWL and SWL, drainage from the SC does not exhibit an on-off behavior. Instead, drainage from the SC is continuous, although it

FIGURE 4.2. Cumulative Drainage from the North (NWL) and South (SWL) Weighing Lysimeters and the South Caisson (SC) at the Buried Waste Test Facility

does show periods of greater and lesser rates that roughly correspond to the seasonal fluxes observed at the NWL. Consequently, the greater depth of soil in the SC serves to buffer the year-to-year drainage, and produces a more constant long-term recharge rate.

Figure 4.3 compares cumulative precipitation measured at the BWTF to precipitation measured at the Hanford Meteorological Station (HMS). During this 3.5-year period (January 1986 through June 30, 1989), the BWTF received approximately 10.6 cm more precipitation than the HMS. The higher cumulative precipitation at the BWTF may be partially attributable to the use of weighing lysimeters to fill gaps in the precipitation record when tipping-bucket rain gauges were inoperative. The tipping-bucket rain gauge at the BWTF has been inoperative occasionally during the winter when its heater malfunctions. The weighing lysimeters, with an exposed surface area of 1.5 m² at the ground surface, may offer a truer measure of precipitation relative to tipping-bucket rain gauges. The differences between measured precipitation at these two locations primarily reflect actual spatial variations between the two areas rather than the effects of different measurement techniques.

FIGURE 4.3. Cumulative Precipitation Measured at the Buried Waste Test Facility (BWTF) and at the Hanford Meteorological Station (HMS)

Using measured storage changes, drainage, and precipitation during the period from July 1988 to June 1989, evaporation and transpiration from the two weighing lysimeters can be calculated using Equation (2.1). The water balance terms of this equation for the BWTF weighing lysimeters are summarized in Table 4.1. These data indicate that a quantity of water evaporated from the NWL that was equivalent to 79% of the precipitation received at the BWTF during this one year period. The combined processes of evaporation and transpiration removed a quantity of water from the vegetated SWL, equivalent to 110% of the precipitation received during this one-year period. Water loss from the SWL was greater than precipitation because of the significant depletion of previously-stored water. In response to the above-average spring precipitation, both weighing lysimeters had drainage.

Total head gradients within the SC at the BWTF were calculated from tensiometer measurements and are shown in Figure 4.4. These head data indicate that unit gradient conditions exist below the 1-m depth within the caisson. Therefore, recharge fluxes within the SC can be estimated from soil hydraulic properties and the volumetric water content within the lysimeter.

Water-content profiles measured within the SC on two dates, using the neutron hydroprobe, are shown in Figure 4.5. The two dates correspond to the periods of minimum and maximum storage of water in the weighing lysimeters, as depicted in Figure 4.1. The spike in the profiles at the 6.2-m depth is caused by a coarse-grained sand layer within the otherwise uniform sand (see Figure 3.2). These data indicate that, except for the coarse-grained sand layer, the volumetric water content below the 2-m depth of the SC remains relatively constant, between 8 and 10.5%. Water content profiles measured within the NWL and SWL on the same dates are shown in Figure 4.6 for relative comparison with the SC.

TABLE 4.1. Terms of the Water-Balance Equation for the Buried Waste Test Facility Weighing Lysimeters for July 1988 through June 1989.

<u>Lysimeter</u>	<u>Surface Condition</u>	<u>P, cm</u>	<u>D, cm</u>	<u>ΔS, cm</u>	<u>ET or E, cm</u>
NWL	Bare	18.01	4.00	-0.25	14.26
SWL	Vegetated	18.01	0.99	-2.86	19.88

FIGURE 4.4. Hydraulic Head Measured Within the South Caisson at the Buried Waste Test Facility

Using the hydraulic properties determined by Rockhold, Fayer, and Gee (1988), and assuming a volumetric water content of 9.5%, a recharge flux of 1.27 cm/yr was calculated for the SC. Assuming a volumetric water content of 10%, this estimated recharge flux increases to 12.07 cm/yr. This order-of-magnitude increase in calculated recharge flux for a 0.5% increase in volumetric water content demonstrates the sensitivity (and relatively high uncertainty) of recharge estimates based on unit gradient calculations. If

FIGURE 4.5. Water-Content Profiles Measured with a Neutron Probe Within the South Caisson at the Buried Waste Test Facility

FIGURE 4.6. Water-Content Profiles Measured with a Neutron Probe Within the North (NWL) and South (SWL) Weighing Lysimeters at the Buried Waste Test Facility

the precision of volumetric water content measurements made with the neutron probe is no better than 0.5% (Jones 1978), then the uncertainty in recharge estimates based on unit gradient calculations is at least one order of magnitude. This uncertainty does not include the uncertainty in soil hydraulic properties (Rockhold, Fayer, and Gee 1988).

Drainage data collected from the BWTF lysimeters during the past four years, from July to June, are shown in Table 4.2. Drainage data from the Commercial Waste Test Facility (CWTF), adjacent to the BWTF, and from the Small Tube Lysimeter Facility (STLF), in the 200 East Area adjacent to the HMS are also provided in Table 4.2 for comparison. Differences in drainage among the lysimeters primarily reflect different soil thicknesses, surface treatments, and the presence (or absence) of vegetation. Differences in drainage from year to year reflect variations in amounts and distribution of annual precipitation.

4.2 GRASS SITE

Cumulative precipitation data collected at the BWTF and Grass Site are compared in Figure 4.7. These data indicate that the cumulative precipitation

TABLE 4.2. Drainage Data for the Buried Waste Test Facility [South Weighing Lysimeter (SWL), North Weighing Lysimeter (NWL), and South Caisson (SC)], the Commercial Waste Test Facility (CWTF), and the Small Tube Lysimeter Facility (STLF).

Year, July-June	Lysimeter Drainage, cm				
	SWL	NWL(a)	SC	CWTF(b)	STLF(c)
1985-1986	10.6	10.0	11.1	12.3 ± 1.4	-
1986-1987	0.1	6.0	10.2	4.9 ± 0.8	-
1987-1988	0.0	3.1	4.0	4.6 ± 0.4	-
1988-1989	1.0	4.0	4.2	5.6 ± 0.6	4.3 ± 0.1(d)

(a) The NWL was temporarily decommissioned from August 1986 to January 1987; hence, no drainage water was collected during this period.

(b) Average of 10 lysimeters.

(c) Average of 2 lysimeters.

(d) The STLF soil was initially dry. Therefore, the potential drainage from these gravel-covered lysimeters is 9.4 cm, which is actual drainage (4.3 cm) plus the increase in storage (5.1 cm).

at these two sites during January 1987 through June 1989 has been nearly identical. For July 1, 1988, to June 30, 1989, 17.69 and 19.45 cm of precipitation were recorded using standard collection gauges at the BWTF and Grass Site, respectively. During this time, 16.84 cm of precipitation was recorded at the HMS using tipping-bucket rain gauges. Although the long-term cumulative precipitation at the BWTF and Grass Site appear to be similar, the short-term differences between the two sites, which are only 3 km apart, can be significant.

Total hydraulic head profiles calculated from tensiometer data at the Grass Site are shown in Figure 4.8 for three dates. These data indicate that near-unit-gradient conditions existed below the 60-cm depth in April 1988 and May 1989. In contrast, the head gradients in November 1988 show a potential for upward movement of water in the soil above the 120-cm depth and downward movement of water in the soil below this depth. These data suggest that, during any given year, the zero-flux plane may be as deep as 120 cm. Therefore, unit gradient or zero-flux plane calculations of recharge should consider water content and storage changes only below the 120-cm soil depth.

FIGURE 4.7. Cumulative Precipitation Measured with Standard Collection Gauges at the Buried Waste Test Facility (BWTF) and Grass Site

FIGURE 4.8. Hydraulic Head Profiles Measured at the Grass Site

Data from 19 of the 25 neutron probe access tubes at the Grass Site were used to calculate the average water storage changes in the soil for July 1986 through June 1989. These data are shown in Figure 4.9. Six of the 25 access tubes were excluded from the averaging process because of specific plot treatments or experiments. From July 1, 1988, to June 30, 1989, the average water storage in the entire profile (0 to 345 cm) increased by 0.29 cm and the average water stored in the lower part of the profile, below the 120-cm depth, decreased by 0.02 cm. Assuming that decreases in storage below the

FIGURE 4.9. Water Storage Calculated with Neutron Probe Data from the Grass Site

120-cm depth represent losses to drainage (i.e., groundwater recharge), the differences between the minimum and maximum average storage values during this period indicate 0.81 cm of recharge. This storage decrease occurred between October 1988 and March 1989, and apparently reflects drainage from the previous winter and spring precipitation.

The data in Figure 4.9 indicate that storage of water in the soil below the 120-cm depth has steadily decreased at the Grass Site since 1986. Slight seasonal increases in storage below this depth correspond to winter and spring precipitation. These slight increases show a 6- to 9-month time lag between the maximum storage in the upper profile (above the 120-cm depth) and the maximum storage in the lower profile (120- to 345-cm depths).

Average water-content profiles for the Grass Site on the dates that correspond to the periods of minimum and maximum storage, between July 1, 1988, and June 30, 1989, are shown in Figure 4.10. These data indicate that the water content below the 120-cm depth remained relatively constant during this period, between 4 and 5% by volume. The error bars in Figure 4.10 correspond to one standard deviation from the mean value of volumetric water content calculated from 19 of the 25 neutron probe access tubes. The relatively constant water content and unit gradient conditions suggest that unit gradient calculations of recharge flux would likely be reasonable.

Using the drying-curve parameters derived from laboratory data for the lower part of the soil profile (Gee, Rockhold, and Downs 1989), the field-measured value of saturated hydraulic conductivity (9.2×10^{-3} cm/s), and the average water content below 120 cm (4.5%), the recharge flux at the Grass Site is estimated to be 0.22 cm/yr. The value of 9.2×10^{-3} cm/s is the average field-measured value of saturated hydraulic conductivity at the 60-cm depth at the Grass Site using a constant-head well permeameter (Rockhold, Fayer, and Gee 1988). Field-measured saturated hydraulic conductivities are often lower than actual saturated hydraulic conductivities because entrapped air reduces the pore space available for flow. Studies by Stephens et al. (1983) suggest, however, that reasonably accurate estimates of actual saturated hydraulic conductivities can be obtained by simply doubling the field-measured saturated hydraulic conductivity. If the average field-measured saturated

FIGURE 4.10. Average Water-Content Profiles Measured with a Neutron Probe at the Grass Site

hydraulic conductivity is doubled to 1.84×10^{-2} cm/s, the calculated recharge flux becomes 0.44 cm/yr.

The effect of neutron probe measurement uncertainty can be evaluated by calculating the recharge flux for water contents that are 0.5% below and above the mean value. Using the saturated hydraulic conductivity value of 1.84×10^{-2} cm/s, the calculated recharge fluxes, for water contents of 4 and 5%, are 0.006 and 2.8 cm/yr, respectively. The variability of these estimates demonstrates the uncertainty of calculations of this type and the importance of neutron probe calibrations and hydraulic property characterization.

The total precipitation from July 1987 to June 1988 at the Grass Site was 11.5 cm (Gee, Rockhold, and Downs 1989). The zero-flux-plane estimate of recharge (0.81 cm/yr) is approximately 7% of the total precipitation that fell during this time period. The total precipitation from July 1988 to June 1989 at the Grass Site was 19.4 cm; this is 69% higher than the previous year. Because of the time lag between seasonal precipitation and subsequent deep drainage or recharge, an evaluation of recharge resulting from the above-average precipitation in the spring of 1989 will not be possible until the spring of 1990.

4.3 200 EAST AREA LYSIMETER SITE

Water storage changes between the soil surface and the 4.88-m depth in the closed-bottom lysimeter and at the sagebrush and bunchgrass sites adjacent to the lysimeter are shown in Figure 4.11 for April 1988 through June 1989. These data indicate that, by late fall or early winter of 1988, the vegetated sites had 3 to 4 cm less water stored above the 4.88-m depth than did the closed-bottom lysimeter. The vegetated sites are undisturbed and have stratified soil profiles; in contrast, the lysimeter is filled with relatively uniform sand (Hsieh, Brownell, and Reisenauer 1973). Therefore, differences in water storage between the lysimeter and the adjacent vegetated sites reflect not only differences in vegetation, but also differences in soil type and stratification.

Water stored above the 4.88-m depth in the closed-bottom lysimeter increased by 9.19 cm, from July 1, 1988, to June 30, 1989. The amount of precipitation recorded at the HMS during this same period was 16.84 cm.

FIGURE 4.11. Water-Storage Changes Calculated from Neutron Probe Data Above the 4.88-m Depth in the Closed-Bottom Lysimeter (Caisson), and in the Sagebrush (Sage) and Cheatgrass (Grass) Plots at the 200 East Area Lysimeter Site

Therefore, assuming that no appreciable amounts of water moved deeper than 4.88 m, approximately 55% of the precipitation recorded for this period was stored within the profile and 45% evaporated.

Average water content profiles in the lysimeter for dates representing the minimum and maximum water storage between July 1988 and June 1989 are shown in Figure 4.12. These profiles show relatively constant volumetric water contents, ranging from about 5 to 6.2% between the 3.05- and 17.37-m depths. The water contents at these depths are nearly identical to those reported elsewhere for various times during the monitoring of the lysimeter (Routson, Fuchs, and Jordan 1988; Last, Easley, and Brown 1976). The error bars for each data point correspond to one standard deviation about the mean value derived from measurements in the three access tubes.

In Figure 4.12, the spike in water content near the 17.6-m depth corresponds to the location of the concrete pad near the bottom of the lysimeter. The shape of this spike has varied considerably over this monitoring period. This variance warranted taking more measurements at smaller spacings in the vicinity of the concrete pad to more clearly define the response of the neutron probe near the pad. On March 1, 1989, neutron probe measurements were taken at 5.08-cm (2-in.) spacings between the 17.22-m and 17.83-m depths. Data from these measurements are shown in Figure 4.13. These more closely spaced measurements will periodically be repeated to determine whether the shape of this profile changes.

Water content as a function of depth and time for the upper 4.88 m of the closed-bottom lysimeter is shown in Figure 4.14. The large mound on the right side of Figure 4.14 represents the wetting front from the above-normal 1989 spring precipitation. On June 30, 1989, the lower fringe of the wetting front was at a depth of approximately 2.74 m (9 ft). During the 1973-74 water year, precipitation percolated to a depth of 4 m (Brownell et al. 1975). During the 1974-75 water year, precipitation percolated to a depth of 2.5 m (Last, Easley, and Brown 1976). All of the wetting fronts in previous years have disappeared, presumably due to upward fluxes caused by evaporation or evapotranspiration.

FIGURE 4.12. Water-Content Profiles Measured with a Neutron Probe Within the 200 East Area Closed-Bottom Lysimeter Site

FIGURE 4.13. Water-Content Profile Measured with a Neutron Probe in the Vicinity of the Concrete Pad at the Base of the 200 East Area Closed-Bottom Lysimeter Site

FIGURE 4.14. Water Content (0-16% by volume) of the Closed-Bottom Lysimeter as a Function of Depth (0 to 4.88 m) and Time (April 1988 to June 1989). Measured with a neutron probe at the 200 East Area lysimeter site.

Water content as a function of depth and time for the access tube located in the sagebrush covered plot, approximately 76 m southwest of the closed-bottom lysimeter, is shown in Figure 4.15. Water content as a function of depth and time from the access tube located in the grass covered plot, approximately 35 m south of the closed-bottom lysimeter, is shown in Figure 4.16. The profile depths and durations shown in Figures 4.15 and 4.16 are the same as those shown in Figure 4.14. Soil stratification is readily apparent by comparing the water-content profiles shown in Figures 4.15 and 4.16 with those shown in Figure 4.14. The 200 East Area closed-bottom lysimeter and adjacent access tubes will continue to be monitored for several

FIGURE 4.15. Water Content (0-16% by volume) in the Sagebrush Plot as a Function of Depth (0 to 4.88 m) and Time (April 1988 to June 1989). Measured with a neutron probe at the 200 East Area lysimeter site.

years to study the redistribution of moisture within the nonvegetated lysimeter compared to that in the adjacent, undisturbed, vegetated areas.

Using the hydraulic property parameters listed by Fayer, Gee, and Jones (1986), and assuming a unit hydraulic gradient and an average volumetric water content of 5.5% results in a calculated recharge flux of 0.71 cm/yr. At volumetric water contents of 5 and 6%, the recharge flux estimates are 0.39 and 1.22 cm/yr, respectively. Again, the variability of these estimates illustrates the uncertainty of recharge flux calculations based on an assumption of a unit gradient.

FIGURE 4.16. Soil Water Content (0-16% by volume) in the Grass Plot as a Function of Depth (0 to 4.88 m) and Time (April 1988 to June 1989). Measured with a neutron probe at the 200 East Area lysimeter site.

A previous study of recharge used data from the 200 East closed-bottom lysimeter as evidence for zero, or near-zero, recharge on the 200 Areas Plateau (Routsen, Fuchs, and Jordan 1988). This study also reported ^{137}Cs activity data from a burial trench in the 200 West Area, and concluded that because there was no measurable ^{137}Cs below the bottom of the trench, the net recharge during the 10-year time of burial was zero. However, data reported by Routsen, Barney, and Smith (1980) show that ^{137}Cs is relatively strongly sorbed by Hanford Site soils. The appendix of this report provides details of a radionuclide transport study conducted at the BWTF. These data indicate that, although there has been considerable drainage (recharge) from the lysimeters

at the BWTF, the ^{60}Co that was emplaced within one of the tracer caissons remained within 30 cm of the depth at which it was emplaced during a 10-year time of burial, because of its sorption onto soil particles.

5.0 CONCLUSIONS AND RECOMMENDATIONS

The data presented in this report support previous conclusions by Gee, Rockhold, and Downs (1989), and Gee (1987), that recharge on the Hanford Site is highly dependent on near-surface conditions, such as soil type(s), stratigraphy, vegetation type and growing season, and the presence or absence of gravel. Each term of the water balance equation for Hanford Site soils must be considered on a site-specific basis to most accurately estimate recharge. Specifically, the data show:

- Drainage from lysimeters in the 300 Area has varied from 0 to over 10 cm/yr during the past 4 years.
- Vegetation has a significant effect in removing water from the soil and limiting or preventing recharge.
- Recharge estimates based on unit gradient calculations agree reasonably well with drainage measured from lysimeters, but may vary by several orders of magnitude because of uncertainties in soil hydraulic properties and the precision of neutron probe measurements of water content.
- Gravel-covered lysimeters designed to simulate tank farm conditions on the 200 Area Plateau have drained approximately 4.3 cm of water during the past year from an initially dry condition. These data are in agreement with previous modeling studies, which show that gravel placed on the soil surface reduces evaporation and facilitates increased drainage.
- Although the vegetative conditions on the 200 East closed-bottom lysimeter between 1972 and 1988 are poorly documented, water contents below the 4.88-m depth have not measurably changed. This finding implies that significant recharge has not occurred within this lysimeter.

The monitoring data and estimates of recharge in this report suggest that continued lysimeter monitoring and further hydraulic property characterization work are needed to provide defensible estimates of groundwater recharge at the Hanford Site. Natural tracer studies that are scheduled to begin in 1990 will provide additional information that will be used to supplement the recharge data and estimates derived from the lysimeter experiments.

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APPENDIX A

DETERMINATION OF COBALT-60 AND WATER-CONTENT PROFILES
IN LYSIMETERS AT THE BURIED WASTE TEST FACILITY

DETERMINATION OF COBALT-60 AND WATER-CONTENT PROFILES
IN LYSIMETERS AT THE BURIED WASTE TEST FACILITY

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INTRODUCTION

In April 1978, the Buried Waste Test Facility (BWTF) was constructed with six lysimeters and an instrument caisson near the 300 North Burial Grounds of the Hanford Site (Phillips et al. 1979). Figure 1 shows the BWTF lysimeter layout. The BWTF was originally designed to provide data on the migration of water and radionuclides through Hanford Site sediments. All lysimeters were kept free of vegetation and were subjected to natural precipitation. The northwest (NW) and northeast (NE) lysimeters were supplied with an additional 70 cm of water via irrigation from April 1979 to July 1981.

In April 1979, the NW and SE lysimeters were spiked with ^{60}Co complexed with ethylenediaminetetraacetic acid (^{60}Co EDTA). The spike was administered by placing a 1-cm soil layer containing ^{60}Co EDTA at a depth of 60 cm below the soil surface. The NE and SW lysimeters were spiked with tritium by the same method of placing contaminated soil at a depth of 60 cm. Laboratory tests (Gee and Campbell 1980) indicated that the complexed ^{60}Co would not be sorbed onto the soil and would migrate at a rate similar to tritium. However, data collected through 1981 (Jones et al. 1983; Jones and Gee 1984) revealed extensive migration of the tritium and essentially no migration of the cobalt. Subsequent, unpublished data revealed the presence of EDTA in leachate water taken from the SE lysimeter, but no cobalt. These data suggest that the ^{60}Co /EDTA complex dissociated and the uncomplexed ^{60}Co was strongly sorbed by the soil.

FIGURE A.1. Diagram of the Lysimeters

In June 1981, the top meter of soil from the SE lysimeter was excavated to determine the distribution of $^{60}\text{Co}/\text{EDTA}$. In August 1988, the NW lysimeter was also excavated to determine the distribution of ^{60}Co . The major objective of these studies was to determine the extent of migration of the $^{60}\text{Co}/\text{EDTA}$ in the lysimeters. A sample of lysimeter soil was taken and laboratory analyses were performed to determine the extent of $^{60}\text{Co}/\text{EDTA}$ migration.

METHODS AND MATERIALS

The techniques for analyzing ^{60}Co had been established in the 1981 excavation of the SE lysimeter. The entire soil layer profile to a depth of 1 m was removed from the lysimeters by excavation. Samples of the excavated material and from sampling ports at depths below 1 m were used to determine the water content of the soil and the concentration of ^{60}Co . These data were then used to determine the rate of migration of $^{60}\text{Co}/\text{EDTA}$.

SAMPLING TECHNIQUES FOR WATER-CONTENT PROFILES

Before excavating the NW lysimeter, volumetric water contents in the NW, SW, and NE lysimeters were measured by neutron probe. Gravimetric water

contents were also determined for soil samples removed from sampling ports on the walls of each lysimeter at 30-cm depth intervals. These gravimetric data were converted to volumetric water content by multiplying them by the bulk density. They were then compared to the volumetric water content measured with the neutron probe. A coring apparatus was inserted into each port, and approximately 50 g of soil was extracted to ensure that a representative sample had been taken at that depth. Because the concentration of ^{60}Co was unknown, all samples were treated as if they were radioactive and all procedures were performed in accordance with Radiation Work Permit (RWP) number HR-5-T. All samples were bagged, taped, and placed in an ice chest for temperature control and safe transport to the laboratory, where they were transferred to a refrigerator for storage.

In the laboratory, duplicate sub-samples were taken from the 50-g sample. Containers and samples were weighed and then dried in an oven at 105°C for 24 hours. The samples were then removed, placed in a desiccator with anhydrous calcium chloride, and allowed to cool. The samples were then reweighed. The water contents were calculated using the equation:

$$\text{Water Content (vol\%)} = \frac{(\text{weight of wet soil}) - (\text{weight of dry soil})}{(\text{weight of dry soil})} \times 100 \quad (1)$$

SAMPLING TECHNIQUE FOR SOIL EXCAVATION

The removal of the top meter of soil from each lysimeter was performed in accordance with RWP HR-5-T, which requires the presence of a Radiation Protection Technologist.

Before sampling of the NW lysimeter was initiated, neutron probe readings were taken and a down-well gamma scan was performed. The counting scan was performed with a 500-volt stabilizer connected to a sodium iodide (NaI) detector. This instrumentation provided a qualitative estimate of the distribution of gamma-emitting radioactive sources in the lysimeter.

The counting scan data were reviewed and a sampling plan prepared. The plan called for the removal of soil in layers whose thickness varied with depth and the relative count rates of the ^{60}Co . The excavation of soil from

the top meter of the lysimeter provided data on the distribution of $^{60}\text{Co}/\text{EDTA}$ within the soil profile.

Excavation and sampling began by locating the rim of the lysimeter and leveling the ground surface using a cement trowel and a level. The trowel was also used to remove the soil in layers. For each layer excavated, an effort was made to remove the proper thickness by measuring with a ruler at several points along the outer edge and in the middle of the lysimeter. As the soil was removed, two samples were taken in small metal cans (the metal can would be used in oven-drying the soil for determination of water content). These samples were taken at the beginning and at the end of excavating each depth interval. The samples were well mixed to ensure homogeneity. These samples were used for both gravimetric determination of water content and gamma analysis to determine ^{60}Co concentration. The remaining excavated soil was double-bagged and taped for transport, and then weighed. These weights (corrected to dry weight by using data from the water content samples) and volumes were used to calculate the dry bulk density within the lysimeter and to quantitatively determine the total mass of ^{60}Co in the lysimeter.

After excavation, the lysimeter was filled with clean soil that had been removed from the same site when the lysimeters were installed. The NW lysimeter now contains no ^{60}Co and is considered to be non-radioactive.

RADIOANALYTICAL TECHNIQUES

Cobalt-60 was measured on duplicate samples from each excavated depth, as well as each depth sampled through the lysimeter access ports. Gamma counting samples were obtained from the dried water-content samples. A radioanalytical system was used in conjunction with a 5 x 5-in. NaI detector for counting and analyzing the spectral data (i.e., at 1.173 and 1.332 MeV) needed for the determination of ^{60}Co . The instrumentation was calibrated using approved techniques and a standard traceable to the National Bureau of Standards.

An important aspect of radioanalysis is that the counting geometry of the sample and the standard be similar for accurate determination of concentration. Thirty-gram soil samples were used in plastic liquid-scintillation vials. The standard consisted of 30 g of aluminum oxide (Al_2O_3) spiked with

a ^{60}Co standard in a plastic liquid-scintillation vial. The Al_2O_3 was chosen because it was similar in density, grain size, and other mineralogical characteristics to the sand in the lysimeters. The combination of the 30-g sample, the geometry of the NaI detector, and varied counting time provided a detection limit of 3.7 pCi/g.

RESULTS AND DISCUSSION

WATER-CONTENT PROFILES

All gravimetric water-content values for the samples taken from the sidewall ports are in Table 1. The volumetric water content was calculated by dividing the product of the gravimetric water content (g/g) and the dry bulk density (B.D., g/cm³) by the density of water (1.0 g/cm³). The calculated dry bulk densities are compiled in Table 2.

In Table 2, the slightly high values for the 54- and 56-cm depths and slightly low value for the 60-cm depth are possibly due to an uneven sampling surface. It is likely that more or less than a 2-cm thickness of soil was collected from these horizons. The overall average dry bulk density of 1.66 g/cm³ was determined using the total dry weight of the soil divided by the

TABLE A.1. Gravimetric and Volumetric Water Contents.

Depth, cm	Gravimetric Water Content, %			Volumetric Water Content, % B.D. = 1.66 g/cm ³		
	NE	NW	SW	NE	NW	SW
30	3.57	3.43	2.85	5.93	5.69	4.73
61	4.48	4.15	4.04	7.44	6.89	6.71
91	5.60	4.25	4.81	9.30	7.06	7.98
122	5.78	5.32	5.02	9.59	8.83	8.33
152	6.04	5.57	6.52	10.03	9.25	10.82
183	5.95	5.43	5.45	9.88	9.01	9.05
213	5.30	5.67	6.05	8.80	9.41	10.04
244	5.64	5.95	5.34	9.36	9.88	8.86
274	5.94	6.27	5.35	9.86	10.41	8.88
305	6.12	6.12	5.26	10.16	10.16	8.73
335	6.07	5.86	5.01	10.08	9.73	8.32
366	6.78	7.01	5.41	11.25	11.64	8.98
396	6.56	6.61	5.39	10.89	10.97	8.95
425	5.44	6.95	6.01	9.03	11.54	9.98
457	5.52	6.51	5.90	9.16	10.81	9.79
488	5.30	6.80	5.78	8.80	11.29	9.59
518	5.74	6.32	5.52	9.53	10.49	9.16
549	6.15	5.83	5.54	10.21	9.68	9.20
579	6.34	6.35	5.42	10.52	10.54	9.00
610	6.08	6.77	5.70	10.09	11.24	9.46
640	0.74	1.96	2.33	1.23	3.25	3.87
671	6.26	5.30	5.22	10.39	8.80	8.67
701	6.30	5.97	5.61	10.46	9.91	9.31
732	3.60	10.13	7.95	5.98	16.82	13.20

TABLE A.2. Dry Bulk Density Determination for the NW (Co-60) Lysimeter

Depth, cm	Wet wt., g	Gravimetric Water Content, %	Total Volume, cm ³	Dry wt., g	Dry Bulk Density, g/cm ³
10	49,902	1.73	29,186	49,054	1.68
20	49,295	3.20	29,186	47,766	1.64
30	49,838	3.56	29,186	48,125	1.65
35	24,931	3.76	14,593	24,028	1.65
40	25,269	3.97	14,593	24,304	1.67
45	25,369	4.04	14,593	24,384	1.67
50	23,358	4.08	14,593	22,442	1.54
52	9,976	4.14	5,837	9,579	1.64
54	15,494	4.23	5,837	14,866	2.55
56	13,470	4.25	5,837	12,921	2.21
58	9,408	4.16	5,837	9,033	1.55
60	7,227	4.33	5,837	6,927	1.19
65	22,466	4.56	14,593	21,486	1.47
70	22,605	4.48	14,593	21,635	1.48
Total					
Average	348,615	3.89	203,097	336,556	1.66

total volume of the section of the lysimeter excavated (i.e., the volume of the lysimeter minus the volume of the neutron probe tubes). This average value was used to compute the volumetric water content of the soil samples.

Figures 2, 3, and 4 compare the measured water contents with those derived from the neutron probe measurements. There is good agreement at all depths, except for the white sand layer at a depth of 6.4 m (21 ft) and at the bottom of the lysimeter at a depth of 7.3 m (24 ft).

COBALT-60 PROFILE

The ⁶⁰Co concentrations for the NW caisson are listed in Table 3. All calculations are based on the caisson dimensions listed in Table 4. Figure 5 shows the concentration profile, by depth, for the upper 90 cm of soil. A

FIGURE A.2. Water-Content Profiles for the NE Caisson

FIGURE A.3. Water-Content Profiles for the NW Caisson

FIGURE A.4. Water-Content Profiles for the SW Caisson

review of the data in Table 3, which lists the ^{60}Co concentration as determined from the sampling ports of the lysimeter, shows that the lower portion of the lysimeter contains no detectable ^{60}Co .

TABLE A.3. Cobalt-60 Concentrations for NW Caisson

<u>Sample Depth, cm</u>	<u>Average, pCi/g</u>	<u>Sample Depth, cm</u>	<u>Average, pCi/g</u>
10	3.7	213	3.7
20	3.7	244	3.7
30	3.7	274	3.7
35	3.7	305	3.7
40	3.7	335	3.7
45	3.7	366	3.7
50	86.0	396	3.7
52	533.0	427	3.7
54	271.0	457	3.7
56	99.9	488	3.7
58	140.0	518	3.7
60	50.5	549	3.7
65	45.2	579	3.7
70	10.4	610	3.7
90	9.6	640	3.7
122	3.7	671	3.7
152	3.7	701	3.7
183	3.7	732	3.7

TABLE A.4. Tracer Caisson Dimensions

Diameter	60.4	cm
Length	731.5	cm
Cross-sectional area	2864.3	cm ²
Total volume	2.1 x 10 ⁶	cm ³

FIGURE A.5. Cobalt-60 Profile for the NW Caisson

SUMMARY

In April 1979, the NW and SE lysimeters at the BWTF were spiked with approximately equal activities of ^{60}Co . A review of the data from the 1981 excavation of the soil from the SE lysimeter showed an activity of approximately $14.1\ \mu\text{Ci}$. The ^{60}Co data collected during August 1988 from the NW lysimeter showed an activity of $15.2\ \mu\text{Ci}$. Both sets of data were adjusted for radioactive decay to the April 1979 spiking date. This agreement is excellent in that both lysimeters received approximately equal activities when the spiked soil was emplaced. The data indicate that very little radionuclide migration has occurred even in the irrigated NW lysimeter.

A review of published information (Swanson 1981, 1983, 1984, and 1985) shows that, for laboratory-scale experiments, $^{60}\text{Co}/\text{EDTA}$ has a relatively low equilibrium distribution coefficient (K_d). Therefore, ^{60}Co would be expected to migrate. However, the data reported here show that all of the ^{60}Co remained within 30 cm of the depth at which it was emplaced. The data from 1981 show a similar distribution. With the recharge rate for these lysimeters averaging approximately 8 cm/yr, a substantial quantity of water has percolated through the layer spiked with $^{60}\text{Co}/\text{EDTA}$.

In the slow percolation of water through the unsaturated zone, the $^{60}\text{Co}/\text{EDTA}$ complex was apparently dissociated by some chemical or biological process. For example, ^{60}Co may have been replaced by calcium or iron in the EDTA molecule. This replacement would allow the ^{60}Co to assume its typical behavior as a cationic species that readily adsorbs onto soil particles. In earlier sampling of drainage water at the bottom of the lysimeter, EDTA was found but ^{60}Co was not; this is another indicator that the ^{60}Co is no longer associated with the EDTA.

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