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PHYSICAL AND HYDRAULIC PROPERTIES OF SEDIMENTS
AND ENGINEERED MATERIALS ASSOCIATED WITH GROUTED
DOUBLE-SHELL TANK WASTE DISPOSAL AT HANFORD

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SUMMARY

Numerical models are used to predict the fate of contaminants in the environment for durations of 10,000 years and more. At the Hanford Site, these models are being used to evaluate the potential health effects and environmental impacts associated with the disposal of double-shell tank waste in grouted vaults. These models require information on the properties of the earthen and manufactured materials that compose the vault system and its surroundings. This report documents the physical and hydraulic properties of the materials associated with burial of grouted double-shell tank waste at the Hanford Site.

A conceptual model of the grout site and engineered structures was used to identify those materials that are, in a first-order sense, dominant controllers of the flow and transport regime. These materials are the Hanford formation sandy sequence, Hanford formation lower gravels, Ringold Formation, backfill soil, gravel, asphalt, concrete, clay cap, and the grouted waste form itself. The published physical and hydraulic data for these materials were identified. If unpublished but available, the data were included in this report. If data were non-existent, estimates were provided along with the rationale for the estimates.

In numerical flow and transport models, the hydraulic properties of porous media are represented by mathematical functions. For the grout performance assessment, the chosen functions were the van Genuchten water retention function and the Mualem hydraulic conductivity function. The parameters in these functions were fitted to the data provided in the Appendix or taken from other publications. For each material in the conceptual model, parameter values were assigned for use in the performance assessment models. For some materials, the number of samples allowed for calculation of means and variances of the parameters. For other materials, the parameters were determined from only one sample. Recommendations are provided for future data collection and parameter estimation. What is needed most is a program dedicated to identifying the important materials, identifying the conditions to which those materials will be subjected, and measuring the properties under

those conditions. Creating a research program now would ensure that the appropriate hydraulic models are identified and parameters for simulations are obtained in a timely fashion.

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1.0 INTRODUCTION

At the Hanford Site in south-central Washington State, numerical models are being used in a performance assessment to evaluate the potential health effects and environmental impacts associated with the disposal of double-shell tank waste in grouted vaults. These models require information on the properties of the earthen and manufactured materials that compose the vault system and its surroundings. The data and parameter estimates contained in this report support the unsaturated flow and contaminant transport modeling studies and sensitivity analyses for the Hanford Grout Technology Program (HGTP) Performance Assessment (PA) Task. This work was conducted for the U.S. Department of Energy by Pacific Northwest Laboratory (PNL)^(a) in collaboration with Westinghouse Hanford Company (WHC).

The two purposes of this report are to identify the significant materials and sediments that govern the movement of water and contaminants in and around the proposed Grout Treatment Facility (GTF) and to estimate the parameters that describe the hydraulic properties of those materials. The data supporting the parameter estimate came from three sources: published reports, laboratory record books, or estimates. The published data and parameters are referenced in this report. All unpublished data and estimated parameters are included in this report as an appendix.

This report is organized as follows. Section 2 describes the grout site and sediment sample locations at Hanford, the general sediment stratigraphy at the grout site, and the operative conceptual model of a buried grout vault. Section 3 describes the methods used to determine physical and hydraulic properties and identifies the data sources (if the data are not reported here). Section 4 describes the parameter estimation procedures and identifies the average hydraulic parameters to be used in the grout PA simulations. Section 5 discusses the data and assumptions to be used for

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unsaturated flow modeling. The Appendix contains the physical and hydraulic property data that have not been reported elsewhere, as well as the hydraulic parameters for all samples used to describe the average hydraulic properties of each material.

2.0 MATERIAL IDENTIFICATION

The purpose of this section is to identify the sediments and engineered materials composing the grout disposal system that are important to the system's performance regarding the release of contaminants. Figure 2.1 shows the position of the GTF within the 200 East Area of the Hanford Site. The hydrogeology of the 200 East Area is summarized by Cushing (1992).

2.1 STRATIGRAPHIC SECTION

The available well logs and sediment sample analyses were reviewed to identify the dominant sediment features at the GTF. Figure 2.1 shows the locations of these wells and sediment samples relative to the GTF. Figure 2.2 shows the stratigraphy at the GTF. Based on that information, a general stratigraphy of the GTF was developed. Underlying the Ringold Formation (Figure 2.2) is the Elephant Mountain Member. The permeability of this basalt member is much lower than that for the overlying sediments and the member was therefore considered to be impermeable. For that reason, the Elephant Mountain Member was not considered part of the hydrologic system at the GTF and was not evaluated for this report.

2.2 CONCEPTUAL MODEL

Figure 2.3 shows the current conceptual model of a grout vault at the GTF. Each material type is briefly described below.

2.2.1 Hanford Formation Sandy Sequence

The sandy sequence of the Hanford formation is a coarse-to-fine-grained sand unit that averages 60-m thick in the 200 East Area. Information representing the sandy sequence was derived from 28 samples collected from well No. 299-E25-234, 5 samples from the 241 AP Tank Farm Facility, 21 samples from the U.S. Ecology site, 3 samples from the 200-BP-1 site, and 3 measurements at the bottom of the existing grout pit (Dames and Moore 1988).

FIGURE 2.1. Relative Locations of the Grout Treatment Facility and Characterization Wells Around the 200 East Area (some sample locations were identified from Connolly et al. 1992b). Sample locations are identified by closed-circle symbols.

FIGURE 2.2. Sediment Stratigraphy in the Vicinity of the Grout Site

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FIGURE 2.3. Conceptual Model of Vertical Cross Section Through a Grout Vault and Underlying Sediment Stratigraphy (MSL = Mean Sea Level)

2.2.2 Hanford Formation Lower Gravels

This material is a pebbly, very coarse sand-to-sandy gravel, about 10 m thick, that overlies the Ringold Formation. Information representing the lower gravels was derived from two samples that were obtained from well No. 299-E25-234, eight samples from the 200-BP-1 site, two samples from B Pond, and two samples from the U.S. Ecology site. Some of the samples were from the upper

gravel sequence of the Hanford formation, which is absent in the vicinity of the GTF. The upper and lower gravel sequences of the Hanford formation are texturally similar and more or less indistinguishable from each other except for stratigraphic position (Connelly et al. 1992a, 1992b).

2.2.3 Ringold Formation

The Ringold Formation averages 30 m thick and consists of well-rounded pebble- to cobble-size gravel with a matrix of sand, silt, and some clay. The Ringold Formation is variably indurated and consolidated, ranging from well-cemented conglomerate to open-work uncemented gravel. Information representing the Ringold Formation was obtained from four samples from B Pond and one sample from the U.S. Ecology site. No samples of the Ringold Formation beneath the GTF were available.

2.2.4 Backfill Soil

During construction, the Hanford formation sandy sequence will be excavated to depths of 20 m. This material will be stockpiled and then used to backfill around the vaults when the vaults are completed. Because the sediments will be somewhat mixed, retaining none of the in situ layering, and because it will be compacted to specifications, the backfill material was considered to be a unique and important material.

The material used to represent the backfill soil was obtained from a stockpile of sand that was excavated during construction of the grout pit. The material was sieved so that only the <2-mm size fraction was used to determine hydraulic properties. The resulting particle size distribution was 91% sand, 3% silt, and 6% clay.

2.2.5 Gravel

Gravel will serve as the drainage layer (not shown in Figure 2.3) in the collection basin beneath the grout. Gravel will also be formed into a sloped capillary barrier above the vault, serving to redirect downward-flowing water to the region beyond the sides of the vault where it can drain freely

without impacting the vault contents. Several gravel sizes will be used as filters and drains. No samples of the actual gravel that will be used were available. As a surrogate for whatever gravel is used, a gravel sample was prepared from 0.5-in.- (1.3-cm-) diameter chipped gravel that was wet sieved through an 8-mm sieve and retained on a 3.962-mm sieve. This procedure left a clean gravel material (i.e., clean in that it was free of fine materials like sands, silts, and clays).

2.2.6 Clay

A compacted clay layer will be used to satisfy the Resource Conservation and Recovery Act (RCRA) requirement for a compacted clay cap over the disposal site. The clay layer will be sloped to divert percolating water away from the vault. The material that was used to represent the RCRA clay cap was a 1:3 mixture of bentonite and Warden silt loam. This silt loam was obtained from the McGee Ranch, which is located on the west side of the Hanford Site, adjacent to the Yakima barricade.

2.2.7 Asphalt

Asphalt will surround the grout vault and, being nearly impermeable, will serve as a barrier to water flow and contaminant diffusion. No samples of asphalt were available for testing.

2.2.8 Concrete

Concrete will be used to create a structure, or vault, into which the contaminant-grout mixture can be poured, cured, and stored. A sample of concrete was obtained by PNL in 1984 from Sandia National Laboratories, who had obtained the concrete from the U.S. Army Waterways Experiment Station. The sample was a cylinder that was 15 cm long and 7.5 cm in diameter. Six subsamples were cut from the original sample and analyzed for hydraulic properties. Because these data were readily available, they were used to represent the hydraulic properties of the concrete used at the GTF.

2.2.9 Grout

Grout is a stabilizing agent used to improve the structural properties or reduce the permeability of earthen materials. For the current grout PA, wastes from the double-shell tanks will be processed into a grout; the resulting mixture is called double-shell slurry feed (DSSF) grout.

On 14 November 1988 a pilot-scale test was conducted to determine physical and chemical characteristics of a single formulation of DSSF grout. That formulation was a blend of (by weight) 47% blast furnace slag, 47% fly ash, and 6% type I/II Portland cement (Lokken et al. 1992a). Core samples were obtained and tested to obtain physical and hydraulic data. Simulated wastes with the same formulation used for the pilot-scale test were generated for durability studies (Lokken et al. 1992b). Information from the durability studies was used to supplement data from the core samples.

3.0 MEASUREMENTS AND ESTIMATES OF PROPERTIES

Measurements of physical and hydraulic properties are needed to determine the hydraulic property parameters for the materials that comprise the conceptual model in Figure 2.3. In lieu of measurements, reasonable estimates of the properties are required. This section summarizes the methods and results.

3.1 METHODS

The methods described below were used to measure or estimate the physical and hydraulic properties reported in the Appendix and by Smoot et al. (1989).

3.1.1 Particle Size Distribution

The distribution of particle sizes is one of the basic (and commonly the only) measures of the physical properties of the sediment. Generally, the sample is sieved to remove those particles greater than 2 mm in diameter before further testing is conducted. The particles removed are categorized as gravel. The percentage of the total sample that is gravel is rarely reported although, for the sediments at the Hanford Site, the percentages can be quite high.

Ideally, the distribution of particle sizes below 2 mm in diameter is not used directly to calculate hydraulic parameters. Rather, the distribution is used to qualitatively classify sediments into categories known as textures, such as clay or sand. If other data are lacking, however, these classifications can be used to infer hydraulic properties based on the hydraulic properties of sediments with similar texture.

The two procedures used to determine particle size distribution were those of the American Society for Testing and Materials (ASTM) (1985) and Gee and Bauder (1986). Approximately 50 g of material that passed a 2-mm sieve was used with the hydrometer method and wet sieving to measure the distribution over the full range of sizes below 2 mm.

3.1.2 Particle Density

The density of particles (ρ_s) was determined using the pycnometer method (Blake and Hartge 1986a). About 10 g of the material less than 2 mm in diameter was used. Although significant gravel percentages were measured in some sediment samples, the density of the gravel was not determined.

3.1.3 Bulk Density

The dry bulk density (ρ_b) of a porous medium is the ratio of its oven-dried mass to its total volume. The bulk densities of the materials described in this report were determined using the method outlined by Blake and Hartge (1986b).

3.1.4 Total Porosity

The total porosity (ϕ_t) of a porous material is a measure of the relative volume of pores capable of filling with water and/or air. Total porosity can be calculated from particle and bulk densities according to the equation (Hillel 1982):

$$\phi_t = 1 - \rho_b/\rho_s \quad (3.1)$$

The total porosity of all the engineered materials described in this report was determined using Equation (3.1).

3.1.5 Water Retention

Four different methods were used to determine water retention data over the full range of matric potentials from fully saturated to residual (irreducible) saturation. In all cases, the measurements were conducted on drained or draining samples. No measurements were made as the samples were wetted, which would have documented the extent of hysteresis.

The methods used were 1) the hanging water column method (Klute 1986), 2) a column method, 3) the pressure-plate extraction method (Klute 1986), and 4) the vapor equilibrium (or thermocouple psychrometer) method (Rawlins and Campbell 1986). When possible, undisturbed samples that retained the in situ structure were obtained. Most of the samples, however, were disturbed (i.e., did not retain their in situ structure); to conduct the tests, these samples were packed to known densities. Water retention varies more between disturbed and undisturbed samples when matric potentials are near zero.

Water retention is the relationship between the water content and the matric potential of a porous medium. The total potential (h_t) of the water in a sample is commonly expressed as the sum of the individual water-potential components as follows (Hillel 1982) :

$$h_t = h_{os} + h + h_g + h_p \quad (3.2)$$

where h_{os} = osmotic potential,

h = matric potential,

h_g = gravitational potential,

h_p = pressure potential.

The osmotic potential represents the attractive forces of water to locations of higher solute concentration. The matric potential represents the capillary and adsorptive forces that attract and bind water to the soil matrix. The gravitational potential is the energy associated with the location of water in the earth's gravitational field, measured with respect to some reference level such as the soil surface or the water table. The pressure potential represents external pressure forces, such as the weight of ponded water.

The application of this total potential concept to soil water equilibrium and transport is not exact because the osmotic potential applies only to the water, and the other components apply to the soil solution (Corey and Klute 1985; Sposito 1986). It is commonly assumed, however, that the

osmotic component of the total water potential has only a negligible effect on the transport of water in soil, especially considering the absence of a differentially permeable membrane in the water flow path (Taylor and Ashcroft 1972; Hillel 1982). Exceptions to the assumption of negligible osmotic potentials for grout and concrete are noted later in this report.

3.1.5.1 Hanging Water Column

Water retention was measured in the 0- to -150-cm range of matric potential using the hanging water column method. Figure 3.1 shows a typical hanging water column apparatus. The soil sample was placed on the porous plate, saturated, then allowed to drain until hydraulic equilibrium was established between the soil water and the water in the reference system. The reference elevation was the soil-plate interface. With that reference, the matric potential of the soil water at the bottom of the sample was equivalent to the negative of the distance (Z_1) between the outflow point and the plate.

Decreasing matric potentials were obtained by increasing the distance Z_1 . After equilibrium was established following a decrease in potential, outflow volumes were measured. After equilibrium was achieved following the final decrease in potential, the final volumetric water content was measured and used to calculate the water contents at the intermediate potentials. If the sample was undisturbed (i.e., not packed), the bulk density was also determined.

3.1.5.2 Column Method

A column method was used to measure retention in the matric potential range from 0 to -100 cm (or more, depending on column length) for the backfill material and the gravel. Two Plexiglass columns, composed of short lengths and taped together, were filled with one of the materials. The columns were saturated and then allowed to drain. Following the cessation of drainage, the columns were sectioned to determine water contents along their length. The matric potentials in each section were ascribed to the negative of the distance from the section midpoint to the drain, assuming the column was in equilibrium with the drain.

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FIGURE 3.1. Schematic of Apparatus Used to Measure Water Retention by the Hanging Water Column Method

3.1.5.3 Pressure-Plate Extraction Method

Water retention was measured in the -310- to -15,300-cm range of matric potential using two variations of the pressure-plate extraction method. Figure 3.2 shows the typical extraction method in which multiple samples are simultaneously subjected to the same pressure force, one pressure increment at a time. The samples and porous plate were saturated, the pressure vessel sealed, the internal pressure raised to a predetermined level, and the samples allowed to equilibrate at the new pressure. After the samples equilibrated, the pressure vessel was opened and the samples were weighed to determine gravimetric water contents. These water contents were converted to volumetric values by multiplying by the bulk density of the material.

FIGURE 3.2. Schematic of Apparatus Used to Measure Water Retention by the Pressure-Plate Method

A variation of the pressure-plate extraction method, the Tempe cell, was used and allowed an individual sample to be subjected to multiple pressures before the vessel was opened. The change in weight between each step increase in pressure determined the water content after the final water content was measured.

3.1.5.4 Vapor Equilibrium Method

Water retention was measured at all matric potentials less than -15,300 cm using the vapor equilibrium method. Water retention was also measured with this method at potentials up to -1,000 cm, although the sensitivity of this method in that potential range is not as great (e.g., relative humidity varies from approximately 1.0 at -1,000 cm to 0.989 at -15,300 cm). The matric potential of water in a porous material can be calculated from measurements of the vapor phase in equilibrium

with the liquid in the pores. When the vapor phase is represented by the relative humidity (p/p^*), the total potential (assuming h_p and h_g are zero) is:

$$h_t = (RT / M) \ln (p/p^*) \quad (3.3)$$

where M = molecular weight of water ($0.01802 \text{ kg mol}^{-1}$),
 R = ideal gas constant ($8.3143 \times 10^{-3} \text{ kg MPa mol}^{-1} \text{ K}^{-1}$),
 T = Kelvin temperature of the liquid phase ($^{\circ}\text{C} + 273.16$),
 p = water vapor pressure in equilibrium with the liquid phase,
 p^* = saturated water vapor pressure at temperature T .

If the osmotic potential is negligible, the matric potential is equivalent to the total potential in Equation (3.3). When the osmotic potential is significant, the matric potential is calculated as the difference between the total and osmotic potentials. The osmotic potential of a solution (outside the porous medium) is calculated by determining the water activity (A_w) based on the total ionic concentration of the solution, and then applying an equation similar to Equation (3.3), where p/p^* and h_t are replaced with A_w and h_{os} , respectively.

The vapor equilibrium tests were conducted using a commercially available instrument (either the SC-10 or CX-1 Water Activity Meter, Decagon Devices, Inc., Pullman, WA 99163) or several saturated salt solutions with known vapor pressures. Because vapor adsorption is relatively independent of bulk density, no attempt was made to pack the samples to a specific density.

The SC-10 uses a thermocouple psychrometer to measure the wet-bulb depression in a closed chamber containing a soil sample. The CX-1 uses a cooled mirror to measure the dewpoint temperature. The saturated salt solutions used were LiCl, MgCl_2 , and $\text{Mg}(\text{NO}_3)_2$. These solutions yielded relative humidities (and corresponding matric potentials in MPa) of 11.3% (-300), 32.8% (-153), and 52.9% (-87.6), respectively, at a temperature of 25°C (Greenspan 1977).

The salt content of the pore water solutions of the sediments in the vicinity of the grout test facility were unknown. Murphy et al. (1991) reported ionic concentrations for six of the major surface soils at the Hanford Site. The low concentrations (e.g., for K^+ , 100 $\mu\text{g/g}$ soil for two different sands) suggested that osmotic potential would not significantly affect the measurement of total potential using the vapor equilibrium method. Therefore, the matric potentials for the sediment samples were assumed to be equal to the measured total potentials.

Total pore solution concentrations of 12 ions in six samples of simulated DSSF grout ranged from 315 to 410 g/L and the solution pH values were greater than 13 (Lokken et al. 1992b). These high salt concentrations suggested that the osmotic potential of this grout was significant. Likewise, data for the aqueous phase of concrete suggested that this material could also have a significant osmotic potential (Bailey and Hampsen 1982; Angus and Glasser 1985; Reardon 1990).

Osmotic potentials for the grout and concrete were calculated from solution chemistry data using the GMIN chemical equilibrium model (Felmy 1990), and Equation (3.3). The GMIN model was used to estimate the activity of water with multiple solutes in the pore waters of the materials. The mathematical algorithm in GMIN is based on a constrained minimization of the Gibbs free energy. The excess free energy in the aqueous phase (as indicated by the activity coefficient) is represented using the equations developed by Pitzer (1973; 1979), and parameters from Harvie et al. (1984) that are valid for solutions with high ionic strengths.

3.1.6 Saturated Hydraulic Conductivity

Laboratory measurements of the saturated hydraulic conductivity (K_s) of a porous medium are based on the application of the Darcy flow equation to a sample of uniform cross-sectional area. Two different methods were used to determine K_s for the materials in this study. For the majority of materials, the falling-head method was used. For the high-permeability materials such as the coarse sands and gravels, a constant head method was used. For the low-permeability materials such as the grout and concrete, a modified constant-head method was used.

3.1.6.1 Falling-Head Method

Figure 3.3 is a schematic representation of the apparatus used for measuring K_s by the falling-head method (Klute and Dirksen 1986). The calculation of K_s is as follows:

$$K_s = (aL/At)\ln(H_1/H_2) \quad (3.4)$$

where a = cross-sectional area of the standpipe,

L = length of the sample,

A = cross-sectional area of the sample,

t = time required for the head difference to decrease from H_1 to H_2 ,

H_1, H_2 = initial and final hydraulic head differences, respectively.

3.1.6.2 Constant Head Method

In the constant head method, the apparatus is similar to that in Figure 3.3. The difference is that the head at the inflow port is held constant at H_2 and the volume of outflow is measured. The calculation of K_s is as follows:

$$K_s = VL / (A t H_2) \quad (3.5)$$

where V = volume of water flowing through the sample,

L = length of sample,

A = cross-sectional area of sample,

t = time,

H_2 = constant hydraulic head difference.

For the clay, concrete, and grout samples, the K_s values were determined using the Ruska permeameter (Model No. 1013-801-00, Ruska Instrument Corp., Houston, Texas). The Ruska permeameter is a constant head device that confines small samples under relatively high pressures.

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FIGURE 3.3. Schematic of Apparatus Used to Measure Saturated Hydraulic Conductivity by the Falling-Head Method

The K_s value of a sample is calculated using Equation (3.5), where the hydraulic head difference (H_2) equals the difference between the applied pressure and atmospheric pressure (Klute and Dirksen 1986).

3.2 RESULTS

This section summarizes the measured and estimated hydraulic properties. If data were reported elsewhere, the reference(s) was cited.

3.2.1 Hanford Formation Sandy Sequence

The water retention and saturated hydraulic conductivity data describing the Hanford sandy sequence were reported by Smoot et al. (1989; 33 samples) and Connelly et al. (1992b; 27 samples). While most of the characterization data for well No. 299-E25-234 at the GTF were reported by Smoot et al. (1989), the particle size distributions were not included. For completeness, those data are included in this report in Table A.1 of the Appendix. All particles greater than 2 mm in diameter were included in the gravel percentage for each sample.

Smoot et al. (1989) reported bulk density values for the samples from well E25-234. Those data are included in Table A.2 of the Appendix to show how bulk density varied as a function of depth and sample size. Also contained in Table A.2 are the average particle density values determined on the less than 2-mm-diameter size fraction. These data were not reported by Smoot et al. (1989).

3.2.2 Hanford Formation Lower Gravels

The water retention and saturated hydraulic conductivity data describing the Hanford gravels were reported by Smoot et al. (1989; two samples) and Connelly et al. (1992b; 12 samples). Of the 14 samples, gravel contents were reported for 10. The gravel contents ranged from 0% to 79%, with an average of approximately 50%. Table A.1 contains the average particle size distribution and Table A.2 the bulk and particle density data for samples from well No. 299-E25-234 (Smoot et al. 1989). Connelly et al. (1992b) reported dry sieve data for 8 of the 12 samples, but did not report bulk or particle density values.

3.2.3 Ringold Formation

The water retention and saturated hydraulic conductivity data describing the Ringold Formation were reported in Connelly et al. (1992b; 5 samples). Particle size distribution and bulk and particle densities were not estimated because the hydraulic parameters were already provided.

3.2.4 Backfill Soil

The water retention properties of backfill were determined between 0 and -100 cm of matric potential using the column method with two Plexiglass columns packed to a bulk density of 1.65 g cm^{-3} . This density represented 90% of the maximum dry density (Dames and Moore 1988). The retention data from the column method were combined with pressure plate and vapor adsorption data to describe the full range of water retention. Particle size distribution and water retention data are contained in Table A.3 of the Appendix. Particle density was assumed to be 2.8 g cm^{-3} .

The saturated hydraulic conductivity was determined with the constant head method using two 30-cm-long columns with an area of 17.65 cm^2 . A 2-cm head was maintained on the surface, resulting in a head gradient of 1.067 across the columns. Four 10-s repetitions of the test on each column yielded average saturated conductivity values of 0.024 and 0.036 cm s^{-1} , for an overall average K_s of 0.030 cm s^{-1} . The source of the retention and conductivity data for the backfill soil was PNL laboratory record book BNW 53071.

3.2.5 Gravel

The water retention properties of gravel were determined between 0 and -10 cm of matric potential using the column method with two Plexiglass columns packed to a bulk density of 1.38 g cm^{-3} . Those data were combined with a vapor adsorption datum and linear interpolation to estimate the full range of water retention. Particle density was assumed to be 2.8 g cm^{-3} . The water retention data are contained in Table A.4 of the Appendix. The only information on particle size distribution is that all particles are between 3.692 mm and 8 mm in diameter.

The saturated hydraulic conductivity was determined with the constant head method using a 10-cm-long column with an area of 17.65 cm². A head gradient of 2.5 cm was maintained across the column. Five 10-second repetitions yielded a range of values from 1.77 to 1.97 cm s⁻¹ and an average value of 1.85 cm s⁻¹. The K_s value (1.85 cm s⁻¹) and the experimental design may have resulted in a Reynolds number in excess of 80, which would indicate turbulence, decreased flow through the sample, and deviation from Darcy's law. Assuming that the effect of the turbulence would be to reduce flow relative to flow under laminar conditions, the actual conductivity value was probably somewhat higher than that reported. In the absence of any other data, however, these hydraulic conductivity estimates were assumed to be reasonable first approximations. The source of the retention and conductivity data for the gravel was PNL laboratory record book BNW 53071.

3.2.6 Clay

The water retention properties of the clay were determined using the pressure plate method (samples were packed to a density of 1.45 g cm⁻³, which represented roughly 90% of the maximum dry density as extrapolated from data in Dames and Moore [1988]) and the vapor adsorption method. Particle density was assumed to be 2.6 g cm⁻³. The water retention data are contained in Table A.5 of the Appendix.

The saturated hydraulic conductivity was determined in triplicate using the constant head method and the Ruska permeameter. The applied pressure difference was 510 cm across a 6.45-cm-long sample with an area of 18.1 cm². The tests were run for about 54 hours and outflow volumes were 8 to 10 cm³. The three conductivity values were 1.23 x 10⁻⁹, 7.75 x 10⁻⁹, and 8.26 x 10⁻⁹ cm s⁻¹, for an average value of 9.4 x 10⁻⁹ cm s⁻¹. After the tests, the conductivity samples remained in the sample cells for 42 days and swelled. The increase in sample length was roughly 30%. The conductivity test was performed again with a pressure difference of 1,020 cm. After about 0.4 hours, the outflow was about 2 cm³. The average calculated K_s value was 1.8 x 10⁻⁷ cm s⁻¹, or approximately 20 times the original value. The source of the retention and conductivity data was PNL laboratory record book BNW 53071.

3.2.7 Asphalt

No data were initially available. Asphalt was assumed to be impermeable to liquid water; hence, hydraulic properties were assigned to satisfy that assumption yet remain compatible with properties of adjacent materials. The assigned values of saturated and residual water contents were 0.162 and 0.0 $\text{cm}^3 \text{ cm}^{-3}$, respectively. The assigned value of saturated conductivity was $10^{-20} \text{ cm s}^{-1}$. After this report was drafted, asphalt data became available. Clemmer et al. (1992) estimated that the total porosity of three samples was 3% to 4%, which was about 1/4 the assumed value of 16.2%. Based on the permeability to N_2 , the asphalt permeability to water was estimated to be $2 \times 10^{-13} \text{ cm s}^{-1}$.

3.2.8 Concrete

Bulk density, particle density, and hydraulic conductivity data are contained in Table A.6 of the Appendix. Saturated hydraulic conductivity was determined using the constant head method and the Ruska permeameter with a pressure difference of 2,068 cm across the samples. The average value, $3.88 \times 10^{-10} \text{ cm s}^{-1}$, was within the range of values reported by Whiting (1988) for seven types of concrete.

Water retention by concrete was determined using only the vapor equilibrium technique because the pressures required to remove water from this material were much greater than those that could be obtained with the other techniques. Water retention data for the concrete are reported in Table A.7 of the Appendix.

Bailey and Hampsen (1982) listed ion concentrations for the aqueous phase of Portland cement before and after complex ion formation. They cited a "typical" molarity for calcium sulfate in the aqueous phase of Portland cement of $0.0258 \text{ mol L}^{-1}$. Using concentrations of sodium, calcium, sulfate, and hydroxide of 15, 57, 58, and 35 mmol L^{-1} , respectively, as reported by Bailey and Hampsen (1982), the GMIN model predicted the activity of water to be 0.99978. Substituting this water activity into Equation (3.3) yielded an estimate of the osmotic potential for cement of

approximately -0.03 MPa (i.e., -306 cm). This value of osmotic potential was considered to be relatively small. Therefore, the total potentials inferred from the thermocouple psychrometer measurements for the Sandia concrete were related directly to matric potential (for calculating retention parameters) without any corrections for osmotic potential. The source of the retention and conductivity data for the concrete was PNL laboratory record books BNW 4042 and BNW 50881.

3.2.9 Grout

Bulk density, particle density, and hydraulic conductivity data are contained in Table A.8 of the Appendix. Saturated hydraulic conductivity was determined using the constant head method and the Ruska permeameter with a pressure difference of 510 cm across the samples. Water retention by grout was determined using only the vapor equilibrium technique because the pressures required to remove water from this material were much greater than those that could be obtained with the other techniques. Water retention data for the DSSF grout are tabulated in Table A.9 in the Appendix.

The data reported by Lokken et al. (1992b) indicated that the molarity of the grout pore water solution was in excess of 4.0 mol L⁻¹. Because of the high molarity, the osmotic potential was calculated to correct the vapor adsorption data. The average concentrations of 6 of the 12 measured constituents (i.e., Na, K, NO₃, NO₂, SO₄, and Cl) from Table 3.1 in Lokken et al. (1992b) were used as input to the GMIN chemical equilibrium model (Felmy 1990) to estimate the activity of water in the DSSF grout pore solutions. The activity of water estimated by the GMIN code was 0.8448. Substituting this water activity into Equation (3.3) yielded an osmotic potential of approximately -23.2 MPa (-232 bar). This value of osmotic potential was subtracted from all total water potential data for the DSSF grouts to estimate the matric potentials reported in Table A.9. Implicit in this osmotic potential correction is the assumption that the osmotic potential of the grout will remain more or less constant and will not change as a function of saturation. The source of the retention and conductivity data for the DSSF grout was PNL laboratory record book BNW 53294.

4.0 HYDRAULIC PARAMETERS

Flow and transport through an unsaturated porous medium is governed by the relationships among water content, matric potential, and hydraulic conductivity. Within numerical models, these relationships can be represented by mathematical functions containing one or more fitted parameters. This section specifies the hydraulic functions used, the parameter fitting procedure, and the corrections for gravel content, and summarizes the average parameters to be used to describe the hydraulic properties of the materials in the conceptual model in Figure 2.3.

4.1 HYDRAULIC FUNCTIONS

The water retention function that was used was proposed by van Genuchten (1980) as follows:

$$\theta(h) = \theta_r + (\theta_s - \theta_r)[1 + (\alpha h)^n]^{-m} \quad (4.1)$$

where $\theta(h)$ = volumetric water content (dimensionless) as a function of h , the matric potential

θ_s = saturated water content (dimensionless)

θ_r = residual water content (dimensionless)

α = reciprocal of air-entry matric potential (cm^{-1})

h = matric potential (cm)

n, m = curve-fitting parameters (dimensionless), with $m=1-1/n$.

Describing water retention with the van Genuchten function enabled calculation of unsaturated hydraulic conductivity, $K(h)$, as follows (van Genuchten 1980):

$$K(h) = K_s \frac{\{1 - (\alpha h)^n [1 + (\alpha h)^n]^{-m}\}^2}{[1 + (\alpha h)^n]^{m/2}} \quad (4.2)$$

using the predictive hydraulic conductivity model of Mualem (1976). In Equation (4.2), the pore interaction term was fixed at a value of 0.5.

4.2 PARAMETER ESTIMATION PROCEDURE

The retention parameters θ_s , θ_r , α , and n from Equation (4.1) were fit to water retention data using the nonlinear, least-squares, curve-fitting program known as RETC (Yates et al. 1992). Generally, the water retention data from the various measurement methods were combined and used to fit the parameters in the van Genuchten water retention function. When data from the pressure plate and hanging water column methods overlapped, the overlapping pressure plate data were omitted during the curve fitting because they were considered less reliable. Smoot et al. (1989) reported fitted parameters for samples from well No. 299-E25-234 in which the retention data from duplicate samples were combined before fitting. For this report, the water retention data from each duplicate subsample were refit individually to obtain fitted parameters. Therefore, the parameter estimates in the Appendix for samples from well No. 299-E25-234 vary somewhat from those reported in Smoot et al. (1989) and Connelly et al. (1992b).

The sandy sequence of the Hanford formation was represented by combining 28 sets of parameters from well No. 299-E25-234, 5 sets of parameters from the 241 AP Tank Farm Facility, 21 sets of parameters from the U.S. Ecology site, 3 sets of parameters from the 200-BP-1 site, and 3 values of in situ saturated hydraulic conductivity determined using a borehole permeameter at the bottom of the existing grout pit (Dames and Moore 1988).

The lower gravel sequence of the Hanford formation was represented by combining two sets of parameters from well No. 299-E25-234, eight sets of parameters from the 200-BP-1 site, two sets of parameters from B Pond, and two sets of parameters from the U.S. Ecology site. Some of the parameter sets were from samples of the upper gravel sequence of the Hanford formation, which is absent in the vicinity of the GTF. However, the upper and lower gravel sequences of the Hanford formation are texturally similar and more or less indistinguishable from each other except for stratigraphic position (Connelly et al. 1992a, 1992b).

The Ringold Formation was represented by combining four sets of parameters from the Ringold Formation near B Pond and one set of parameters from the U.S. Ecology site. No data or sets of parameters were available for the Ringold Formation beneath the GTF.

Parameters for the backfill soil, clay, gravel, concrete, and grout were fitted to the data reported in the Appendix. Given the lack of data on asphalt properties, parameters for the asphalt were estimated. Parameter sets for all of the materials having more than one parameter set are reported in Tables A.10 to A.14 of the Appendix, along with the estimated means and variances.

4.3 CORRECTIONS FOR GRAVEL CONTENT

In a summary of the hydrogeology of the 200 East Area, Cushing (1992) mentioned the presence of gravel throughout portions of the vadose zone. Except for samples collected above the 126-ft (38.4-m) depth from well No. 299-E25-234, all water retention and hydraulic conductivity data used for this report were generated using the less than 2-mm-diameter particle-size fraction.

Bouwer and Rice (1983) proposed a technique for calculating the bulk hydraulic properties of a mixture containing sand and gravel from the hydraulic properties of the sand fraction alone and the volume fraction of the gravel. The water retention of the sand-gravel mixture was determined as follows:

$$\theta_b = (1 - V_r) \theta_s \quad (4.3)$$

where θ_b = volumetric water content of the sand-gravel mixture

θ_s = volumetric water content of the sand fraction

V_r = volume fraction of the gravel.

The bulk saturated hydraulic conductivity, K_b , of the sand-gravel mixture was calculated as

$$K_b = K_s (e_b / e_s) = K_s (\theta_b / \theta_s) (1 - \theta_s) / (1 - \theta_b) \quad (4.4)$$

where K_s = saturated hydraulic conductivity of the sand (less than 2-mm-diameter size fraction)

e_b = void ratio of sand-gravel mixture

e_s = void ratio of sand

and the void ratio is simply the volume of voids divided by the volume of solids. In Equation (4.4), θ_b and θ_s are the saturated values. Bouwer and Rice (1983) suggested that, in practice, the above procedure could be made more accurate if the saturated water content of the sand-gravel mixture was determined in situ. This value could then be used as a matching point when fitting parameters to describe the relationship between K and θ .

Equations (4.3) and (4.4) were used to scale the hydraulic properties of samples 1 and 4 from the 241-AP Tank Farm (Smoot et al. 1989). The scaled hydraulic properties were referenced as sample 1G and 4G, where the "G" indicated that the properties were scaled to account for the gravel fraction. Samples 1G and 4G contained 38% and 10% gravel, respectively. Thus, utilizing Equation (4.3), their effective θ_s values were reduced by 38% and 10%, respectively. Utilizing Equation (4.4), the K_s values were reduced by 51% and 17%, respectively, for samples 1G and 4G. For these calculations, the particle density of the gravel was assumed to equal that of the sediments. Similar corrections for gravel content were not performed for the samples representing the Hanford formation lower gravels.

4.4 PARAMETER SUMMARY

The average parameters for sediments from the Hanford and Ringold Formations and for the other materials comprising the grout waste isolation system are listed in Table 4.1. These parameters were used for the base-case flow and transport simulations for the grout PA. The parameters in Table 4.1 are arithmetic mean values with the exception of the K_s values, which are geometric mean values. Geometric mean values of the saturated hydraulic conductivities were used because saturated hydraulic conductivity has often been shown to be lognormally distributed (Hills and Wierenga 1991; Sudicky 1986).

TABLE 4.1. Average Water Retention Parameters and Vertical Saturated Hydraulic Conductivity Values Used for Grout Vadose Zone Flow and Transport Modeling

<u>Material Type</u>	<u>Water Retention</u>					<u>Unsaturated Hydraulic Conductivity</u>	
	<u>No. of Samples</u>	<u>θ_s</u>	<u>θ_r</u>	<u>$\alpha \text{ cm}^{-1}$</u>	<u>n</u>	<u>No. of Samples</u>	<u>$K_s \text{ cm s}^{-1}$</u>
Hanford Formation^(a)							
Sandy Sequence	57	0.4203	0.0234	0.1943	1.868	45	1.55×10^{-3}
Lower Gravels	14	0.3584	0.0213	0.0290	1.613	13	2.73×10^{-4}
Ringold Formation^(a) (undifferentiated)	5	0.4982	0.0283	0.0176	1.338	5	2.42×10^{-6}
Backfill Soil ^(b)	2	0.3710	0.0450	0.0683	2.080	2	3.00×10^{-2}
Gravel ^(b)	2	0.5180	0.0140	3.5366	2.661	1	1.85
Clay ^(b)	3	0.4480	0.0000	5.39×10^{-4}	1.324	3	9.40×10^{-9}
Asphalt ^(c)	0	0.162	0.0	1.00×10^{-7}	2.0	0	1.0×10^{-20}
Concrete ^(d)	6	0.2258	0.0000	7.61×10^{-6}	1.393	6	3.75×10^{-10}
DSSF Grout ^(e)	9	0.5781	0.0000	1.08×10^{-5}	1.650	3	1.47×10^{-8}

(a) Original data for well No. 299-E25-234 contained in laboratory record book BNW 52457; other data sources were Smoot et al. (1989), Connelly et al. (1992b), and Dames and Moore (1988).

(b) Original data contained in laboratory record book BNW 53071.

(c) Estimated parameters; no available data.

(d) Original data contained in laboratory record books BNW 4042 and BNW 50881.

(e) Original data contained in laboratory record book BNW 53294.

Figures A.1 through A.16 show the retention and conductivity data along with the fitted functions for the samples from well No. 299-E25-234, the backfill soil, gravel, clay, concrete, and grout. Smoot et al. (1989) reported the data and a parameter set for each depth in Well E25-234, but they had lumped the data from individual samples to calculate the parameters. As noted previously in this report, each sample was fitted separately. Connelly et al. (1992b) reported plots of the remaining functions in Tables A.10 to A.12.

The water retention and hydraulic conductivity curves corresponding to the average parameters from Table 4.1 are shown in Figure 4.1. The saturated hydraulic conductivities of the different materials depicted in Figure 4.1 range over 9 to 10 orders of magnitude. Similarly, the air-entry potentials (reciprocal of α) of these materials range over 6 to 7 orders of magnitude. Insufficient data were available to reliably determine representative probability distributions of the parameters for the sediments beneath the GTF. However, means, variances, and minimum and maximum values of the parameters were calculated for this limited number of samples to show the potential ranges of parameter variability.

FIGURE 4.1. Average Water Retention (a) and Hydraulic Conductivity (b) Curves. The parameters used to generate the curves are listed in Table 4.1.

5.0 DISCUSSION

The parameters in Table 4.1 were used in single-phase isothermal flow and transport simulations reported in the grout PA. Summarized here are the assumptions and observations that underlie the generation of those parameters and suggestions for improving the methods used to collect the data and generate new parameters. What is needed most is a program dedicated to identifying the important materials, identifying the conditions to which those materials will be subjected, and measuring the properties under those conditions. Burial of grouted and other defense wastes may eventually require simulations of two-phase nonisothermal flow with reactive transport. The effects of osmotic potential on the flow of water vapor may need to be coupled directly with either isothermal or nonisothermal liquid water flow. Creating a research program now would ensure that the appropriate hydraulic models are identified and parameters for simulations are obtained in a timely fashion.

5.1 METHODS

Overall, the data quality was not consistent. Some sources documented the sample location and reported a range of replicated tests that were well described and referenced; other sources provided only a number. Because the analysis methods have some leeway for interpretation and application, the precise methods used should be documented, along with the sample sizes. Ideally, undisturbed samples should be obtained and analyzed for particle size, particle size distribution (including gravel distribution and clay content), particle density, bulk density, water retention over the entire range of matric potentials, and saturated hydraulic conductivity (and at least one unsaturated conductivity value, if possible). Although not performed on the samples used in this report, chemical tests would reveal useful information such as CaCO_3 content and osmotic potential. All tests should be run in duplicate if not triplicate.

The backfill soil, clay, and asphalt warrant further testing because they are such prominent components of the near-field region of the vaults. The backfill soil was analyzed in duplicate compared to the more than 50 samples used to represent the Hanford sandy sequence. The method used to

measure retention in the backfill (i.e., a column method) remains to be verified by established procedures. The data for the backfill appear to vary significantly from the data for other similar materials; thus, more analyses are needed. For example, the saturated conductivity of the backfill was 10- to 100-fold higher than the values measured for intact cores from the Hanford formation that had almost identical particle size distributions and similar bulk density values. The value was also 100-fold higher than the K_s value for stockpile samples reported by Dames and Moore (1988).

The clay was actually a bentonite/silt mix with the propensity to swell considerably (as demonstrated in the lab). As noted in Section 3.2.6, the K_s of the swelled clay (about $2 \times 10^{-7} \text{ cm s}^{-1}$) was 20 times higher than originally measured. The properties of the clay must be evaluated under the expected conditions, i.e., under a load, under a large temperature cycle as the grout temperature rises and subsides, and under drying. Some test results were reported by Dames and Moore (1988), but the methods and testing ranges must be examined. For the grout PA, the properties used to simulate water behavior in the asphalt barrier were assumed. The properties of the asphalt in its original and degraded states should also be measured and reported.

The properties of the concrete were determined on a sample from Sandia National Laboratories. Some measurements of the properties of the concrete to be used at the GTF must be made to verify the similarity to the Sandia sample. If the properties are not similar, the GTF concrete properties should be evaluated fully.

The properties for DSSF grout were determined for a special formulation. For reasons related to the need to optimize parameters such as leachability and strength, the formulation is subject to revision. Lokken and Martin (1992) discussed DSSF grout formulations in which the ratios of blast furnace slag, cement, fly ash, and limestone flour, and two dilutions of the tank waste, were tested for their effects on properties. As the grout formulation is varied, the resulting grout should be evaluated for the need to conduct physical and hydraulic tests specific to that formulation, as much as two separate soil samples are treated separately or together depending on their similarities.

Measurements of the physical and hydraulic properties of DSSF grout could be affected by changes in the pore solution and grout structure as the samples are dried (e.g., precipitation near surfaces) or water is passed through (e.g., K_s test). The measurement techniques need to be evaluated to determine whether or not such changes have a significant effect on the measurement of properties. During the design life of the GTF, the grout material will experience similar changes or degradation; the results from the evaluation of measurement techniques will be transferable to the evaluation of degradation.

5.2 BULK DENSITY

Table A.2 shows how bulk density varied with depth within the same formation (Smoot et al. 1989). Most of the data used to fit parameter values were derived from samples that were not packed to the in situ bulk densities, which were unknown, the packed samples certainly did not have the structure of the in situ sediment material.

Sample size may have affected the observations of bulk densities. The conductivity cores in Table A.2 were roughly 40 times larger in volume than the water retention cores. Table A.2 shows that the mean bulk density value of the conductivity cores was 0.15 g/cm^3 (i.e., 10%) greater than that of the water retention cores. The difference in bulk density was either the result of the subsampling technique or the indirect method used to calculate the bulk density of the conductivity core.

5.3 HYDRAULIC CONDUCTIVITY

For each material, the predicted hydraulic conductivities reported in the Appendix range from over 3 to 4 orders of magnitude near saturation and more than 10 orders of magnitude near the residual or irreducible water content. However, it should be noted that the unsaturated hydraulic conductivity curves were generated using the saturated hydraulic conductivity as a single matching point. Therefore, there is much more uncertainty in the predicted unsaturated hydraulic conductivity values at lower water contents.

Yates et al. (1992) compared measurements of unsaturated hydraulic conductivity for 23 different soils with predicted values generated using water retention and saturated hydraulic conductivity data with the RETC code and the Mualem model. In general, the predicted unsaturated hydraulic conductivity values were in reasonable agreement with the actual hydraulic conductivity data. Rockhold et al. (1988) compared measured and predicted unsaturated hydraulic conductivities for a sandy soil on the Hanford Site using field and laboratory data. The comparisons indicated differences of up to one order of magnitude between unsaturated hydraulic conductivities predicted using only water retention data and saturated hydraulic conductivity with the Mualem model and the RETC code, and actual unsaturated hydraulic conductivity data generated using the steady-state flux control method in laboratory column experiments (Klute and Dirksen 1986). The lack of unsaturated hydraulic conductivity data for the materials in the grout PA precluded direct comparisons of measured and predicted unsaturated hydraulic conductivities.

5.4 GRAVEL CONTENT

Gravel is a constituent of much of the vadose zone. The percentages of gravel should always be reported. The higher the percentage of gravel, the more important it is to measure the particle density of the gravel fraction. Scaling the hydraulic properties of two samples with high percentages of gravel significantly reduced the values of effective porosity and saturated hydraulic conductivity relative to the values determined using the less than 2-mm particle-size fraction. The accuracy of this method for scaling the hydraulic properties to account for the gravel-size fraction should be verified for the materials in the grout PA. This method or an analogous procedure should, however, be consistently applied to correct the hydraulic properties of all samples containing a measurable gravel content.

5.5 SPATIAL VARIABILITY

The intact sediment cores from well No. 299-E25-234 were lined and did not permit visual examination. Thus, lenses and stratifications noted in the driller's log were not observed in the cores, even though those features may have been present. Two subsamples, one from each end of each

core, were used to represent the entire core. Of 13 intact cores, nine cores yielded retention data for two subsamples that were consistent for each end of the core. In contrast, four cores yielded subsamples with a large degree of variability. For one of those cores (Sample 25), a second set of hanging water column tests was conducted to see if the first set was an anomaly. The results from those tests indicated that, indeed, a significant variation in properties indeed existed within Sample 25 over a distance of 4 cm (Smoot et al. 1989).

Based on the laboratory results, heterogeneity on the scale of the individual conductivity cores (15 cm diameter, 15 cm long) evidently existed. The question of what is the correct scale of measurement necessary to quantify the spatial variability and determine effective flow parameters remains a research topic. However, it may be possible to correlate data obtained from geophysical logging techniques and granulometric (i.e., particle size) data to more clearly delineate lenses and stratifications that control the flow and transport processes.

Insufficient data were available to reliably estimate spatial correlation lengths for the hydraulic properties of the sediments beneath the GTF. If such data were available, conditional simulations could potentially be used to forecast the transport of contaminants from the grout vaults (Journel and Huijbregts 1978; Clifton and Neuman 1982). Conditional simulation allows spatially correlated random hydraulic property fields to be generated with the proper spatial and statistical structures and preserves the values of the field observations at their measurement locations. This type of simulation can be carried out using the Monte Carlo method to generate probabilistic assessments of contaminant migration and fate. Various other techniques for incorporating data and parameter uncertainties into performance assessment models are described by Zimmerman et al. (1990).

5.6 HYSTERESIS

Hysteresis effects were shown to be significant during transient unsaturated flow (Kaluarachchi and Parker 1987; Lenhard and Parker 1987). However, none of the numerical models used for the grout PA simulations accounted for hysteresis in the constitutive relationships describing water

retention or conductivity and no data were collected to support such modeling. Given the burial depth, however, the extent of wetting and drying cycles (when hysteresis is manifested) should be minimal. One or more simulations could be conducted to verify the veracity of this assumption. The analysis is not straightforward, however, because the current simulations do not address the movement of water vapor in response to the temperature pulse and osmotic effects, which are likely to be the two major drivers of water content changes.

5.7 ANISOTROPY

In the groundwater hydrology literature it is common to see references to regional anisotropy, with saturated hydraulic conductivities in the horizontal direction that are 10 or more times greater than those in the vertical direction (Freeze and Cherry 1979). Apparent anisotropy results from the preferred orientation of mineral grains in the horizontal direction and from material heterogeneities (Freeze and Cherry 1979; Marcus and Evenson 1961). Laboratory measurements of saturated hydraulic conductivity generally represent the vertical direction because of the vertical orientation of the samples. Hydraulic conductivities calculated from aquifer test data are more representative of the horizontal direction, and integrate much larger sample volumes. Such tests, however, apply only to the saturated zone of the aquifer and not to the vadose zone.

Graham et al. (1981) reported conductivities in the 200 Area of 0.7 to 3.5 cm s⁻¹ in the Hanford formation, 0.003 to 0.08 in the middle Ringold Formation, and 0.001 to 0.004 in the lower Ringold Formation. They determined an anisotropy ratio in one well that ranged between 16 and 13. Analyses of aquifer test data from the 200 East Area indicated that saturated hydraulic conductivities in the lower gravel sequence of the Hanford formation and the Ringold Formation (gravel unit A) ranged from approximately 0.7 to 6.8 cm s⁻¹ (Newcomer et al. 1992). These values were 4 to 8 orders of magnitude greater than the range of values determined using laboratory methods. This discrepancy was attributed to anisotropy, heterogeneity, and scale differences resulting from different sampling volumes. Also, when collecting split spoon samples, sediments may be compacted during drilling, producing lower saturated hydraulic conductivities. Neither laboratory nor field

measurements of horizontal conductivity values in the vadose zone of the GTF were available. Without supporting field data, the selection of anisotropy ratios for the vadose zone would be arbitrary. Therefore, hydraulic conductivities were assumed to be isotropic for the vadose zone flow and transport simulations that were conducted for this grout PA. To support the use of anisotropy ratios in the vadose zone, measurements of conductivity are needed in both the horizontal and vertical directions on the same undisturbed samples without observable sediment layering or preferred channels. In lieu of measurements, transient flow data are needed that can be used to calibrate flow and transport models with the anisotropy ratio as a calibration parameter.

5.8 TEMPERATURE AND SOLUTE EFFECTS

The testing and analyses reported here did not account for the effects of temperature changes and solutes on the physical and hydraulic properties of the grout and other materials at the GTF. Temperatures in the grout were expected to reach 90°C and above. The solute content of the pore water in DSSF grout was shown to exceed 400 g L⁻¹ (Lokken et al. 1992b). Such high temperatures and solute contents will affect the conductivity of water, the retention of water, the water vapor pressure, and the volume of clays.

The conductivity of water in a porous medium is a function of density and viscosity, which in turn are functions of temperature. Density changes over temperature ranging from 0°C to 100°C are no more than 4% and likely exert a minor effect on predictions of flow and transport. Viscosity changes over the same range, however, are roughly $\pm 75\%$ relative to the viscosity at 20°C. The effect of temperature on viscosity might be accounted for by varying saturated conductivity $\pm 75\%$, although such an analysis would ignore all of the associated effects caused by temperature changes (e.g., vapor pressure changes, solubility changes). Whether the temperature dependence of viscosity explains all of the temperature dependence of unsaturated conductivity is an unresolved issue (Constantz 1982; Hopmans and Dane 1986).

At a constant temperature, the conductivity of water is inversely related to the kinematic viscosity. For a NaNO_3 concentration of 367 g L^{-1} , comparable to those seen by Lokken et al. (1992b), the relative kinematic viscosity would be 1.3, meaning a 23% reduction in conductivity. This reduction appears to be less significant than the changes in viscosity caused by temperature, and certainly smaller than the natural variability of conductivity. For these reasons, viscosity changes were not considered in the grout PA.

Temperature also affects water retention through its dependence on surface tension (between 0°C and 100°C , surface tension varies $\pm 12\%$ from the value at 50°C). The measured effect, however, is much greater; Constantz (1982) reported that retention was reduced 3- to 4-fold more than predicted from surface tension alone as the temperature was increased from 2°C to 25°C to 45°C . Giakoumakis and Tsakiris (1991) saw a similar response in retention between 3°C and 20°C for both drying and wetting experiments.

Vapor flow is affected by osmotic potentials and temperature gradients, both of which will be highest in and around the vaults. Vapor flow resulting from the osmotic potential gradient was estimated and considered in the grout PA. A conservative analysis showed the impact to be much lower than the impact of liquid flow. Vapor flow resulting from a temperature gradient is most likely to be highest during the early years of the GTF and then decrease in importance as the GTF cools. To understand the effect of temperature on vapor flow, consider that the vapor pressure of water approximately doubles as the temperature is raised from 0°C to 10°C , then doubles again at the following temperatures: 21°C , 33°C , 45°C , 60°C , 75°C , and 93°C . Nasser et al. (1992) reported the results of experiments and modeling dealing with the combined effects of heat, water, and solutes in porous media. They looked at temperatures between 9°C and 27°C . Their model performed best at matching the experimental results when the initial water contents were high (0.134 to $0.166 \text{ cm}^3 \text{ cm}^{-3}$) and the initial solute concentration was low ($< 0.1 \text{ mol}$). When the water contents were low, or when the solute concentration was high (i.e., 0.5 mol), the model either underestimated or overestimated water flow. Their results indicate an incomplete understanding of the physics and chemistry of their

system. By implication, their results are likely applicable to the GTF, which could see temperatures near 90°C and solute concentrations above 4.0 mol. An analysis should be conducted to determine whether the experiment-model discrepancies, when scaled to the conditions of the GTF, would have a significant impact on the grout PA.

Clay-size particles have the greatest likelihood for volume changes from flocculation or dispersion caused by the presence of solutes. The volume changes induced in the surrounding sediments by contact with the grout solution is unknown. The clay contents seen in most of the sediment samples were small; for the samples reported in the Appendix, the clay contents were 6% or less. Laboratory tests should be conducted in which the materials (i.e., the concrete, asphalt, and sediments) are subjected to grout pore water and observed for geochemical changes, physical changes, and hydraulic changes.

5.9 GEOCHEMISTRY

The testing and analyses reported here did not account for the effects of geochemical changes in the GTF, particularly within, and in the vicinity of, the grout vaults. These changes will be brought on by precipitation/dissolution reactions as the high-concentration grout pore water interacts with the low-concentration sediment pore water and by the temperature and water content variations experienced by the materials of the GTF over their lifetime. The precipitation/dissolution reactions will cause volume changes that can lead to cracks or the plugging of cracks and pores (e.g., see Lowell et al. [1993] for an example of permeability affected by precipitation). In either case, the physical and hydraulic properties will be changed. Criscenti and Serne (1988) studied the geochemistry of a grouted commercial waste form in contact with soil, but they did not explore the associated physical and hydraulic changes. A literature review and laboratory tests of the actual grout formulations and wastes of the GTF should be conducted to determine the geochemical effects on physical and hydraulic properties.

5.10 DEGRADATION

The testing and analyses reported here did not account for the effects of material degradation, which is defined as any change from the original properties. During the course of compiling the PA, many mechanisms for degradation were proposed that could only be addressed with gross approximations or estimates. Examples include 1) fines infiltrating the gravel and negating the capillary break, 2) concrete spalling and cracking that creates flow pathways within the vault and through the concrete wall, 3) loss of the asphalt to vaporization and biodegradation, leaving only the aggregate mix, and 4) cracking of the asphalt after it becomes brittle from the heat. All proposed degradation mechanisms should be evaluated for validity and impact; those mechanisms that are valid and could significantly affect the PA must be the subject of further tests. An accurate assessment, based on testing, should be made of the rates of degradation and the associated changes in the physical and hydraulic properties.

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APPENDIX

PHYSICAL AND HYDRAULIC PROPERTY DATA

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PHYSICAL AND HYDRAULIC PROPERTY DATA

TABLE A.1. Particle-Size Distribution Data for Sediment Samples from Well No. 299-E25-234. For two samples with gravel contents >10%, 1-kg samples were wet sieved to determine gravel size distribution.

<u>Sample</u>	<u>Particle Size μm</u>	<u>% Less Than</u>	<u>Sample</u>	<u>Particle Size μm</u>	<u>% Less Than</u>
5	2000.00	98.93	19	2000.00	98.23
1% Gravel	1000.00	91.18	2% Gravel	1000.00	95.57
88% Sand	500.00	56.55	62% Sand	500.00	88.01
7% Silt	250.00	25.88	31% Silt	250.00	69.84
4% Clay	106.00	15.15	5% Clay	106.00	47.35
	75.00	12.55		75.00	41.19
	53.00	10.67		53.00	36.33
	48.72	10.13		48.20	21.13
	28.21	8.75		28.11	16.63
	15.48	7.75		15.51	13.25
	8.93	6.88		8.99	9.88
	6.32	5.00		6.36	7.63
	5.15	4.25		5.22	5.25
	4.47	3.63		4.52	5.50
	1.31	3.62		1.32	5.25
25	2000.00	99.74	29	2000.00	99.84
86% Sand	1000.00	97.07	95% Sand	1000.00	98.16
9% Silt	500.00	85.07	2% Silt	500.00	77.67
5% Clay	250.00	51.27	3% Clay	250.00	40.23
	106.00	21.97		106.00	11.83
	75.00	16.98		75.00	7.74
	53.00	13.83		53.00	4.75
	49.19	19.00		49.96	13.38
	28.66	14.88		29.07	9.50
	15.84	10.75		15.97	8.00
	9.19	8.13		9.22	6.75
	6.48	6.00		6.54	2.88
	5.28	6.00		5.33	3.25
	4.58	5.00		4.62	2.63
	1.34	4.63		1.35	2.75

TABLE A.1. (contd)

<u>Sample</u>	<u>Particle Size μm</u>	<u>% Less Than</u>	<u>Sample</u>	<u>Particle Size μm</u>	<u>% Less Than</u>
<u>37</u>	2000.00	98.63	<u>46</u>	2000.00	99.56
1% Gravel	1000.00	92.71	04% Sand	1000.00	97.57
77% Sand	500.00	81.34	4% Silt	500.00	73.37
17% silt	250.00	55.50	3% Clay	250.00	27.39
5% Clay	106.00	32.19		106.00	12.06
	75.00	26.92		75.00	9.78
	53.00	23.24		53.00	8.43
	50.18	21.25		51.33	6.50
	29.21	17.25		29.69	5.38
	16.07	15.38		16.26	4.75
	9.36	10.5		9.38	4.50
	6.62	8.75		6.61	4.25
	5.41	7.00		5.39	3.63
	4.68	6.63		4.66	2.50
	1.37	5.00		1.39	2.75
 <u>54</u>	 2000.00	 99.47	 <u>69</u>	 2000.00	 96.98
1% Gravel	1000.00	96.62	3% Gravel	1000.00	85.03
82% Sand	500.00	81.48	90% Sand	500.00	49.98
11% Silt	250.00	48.28	5% Silt	250.00	26.30
6% Clay	106.22	31.02	2% Clay	106.00	15.97
	75.00	26.75		75.00	13.55
	53.00	23.63		53.00	11.80
	50.11	17.75		50.29	7.00
	29.12	15.75		29.05	6.75
	16.05	12.00		15.92	5.25
	9.30	8.88		9.22	3.25
	6.59	7.88		6.53	2.50
	5.37	7.00		5.33	2.75
	4.65	7.38		4.62	2.00
	1.34	6.00		1.34	2.00

TABLE A.1. (contd)

<u>Sample</u>	<u>Particle Size μm</u>	<u>% Less Than</u>	<u>Sample</u>	<u>Particle Size μm</u>	<u>% Less Than</u>
83	2000.00	95.92	99	2000.00	99.51
4% Gravel	1000.00	79.70	58% Sand	1000.00	97.07
85% Sand	500.00	47.85	40% Silt	500.00	86.13
9% Silt	250.00	26.15	2% Clay	250.00	66.46
2% Clay	106.22	15.36		106.00	49.42
	75.00	12.74		75.00	44.97
	53.00	11.00		53.00	42.31
	49.93	7.13		49.84	8.49
	28.86	6.75		28.98	6.28
	15.85	5.63		15.93	4.76
	9.19	4.00		9.25	2.97
	6.51	3.00		6.55	2.63
	5.32	2.00		5.36	1.87
	4.61	2.00		4.65	1.70
	1.33	2.25		1.34	2.72
110	2000.00	93.82	117	2000.00	96.54
6% Gravel	1000.00	71.65	3% Gravel	1000.00	93.32
81% Sand	500.00	45.45	86% Sand	500.00	59.69
11% Silt	250.00	29.70	8% Silt	250.00	35.33
2% Clay	106.00	16.81	3% Clay	106.00	19.87
	75.00	15.32		75.00	15.98
	53.00	13.32		53.00	13.24
	49.91	8.75		50.49	10.13
	28.89	7.38		29.20	9.00
	15.88	5.88		16.06	6.25
	9.20	4.63		9.27	6.75
	6.52	3.00		6.56	4.50
	5.33	2.00		5.35	4.50
	4.62	1.75		4.64	3.75
	1.34	2.75		1.34	2.63

TABLE A.1. (contd)

<u>Sample</u>	<u>Particle Size μm</u>	<u>% Less Than</u>	<u>Sample</u>	<u>Particle Size μm</u>	<u>% Less Than</u>
<u>126</u>	2.00 (in)	100.00	<u>133</u>	2.00 (in)	100.00
51% Gravel	1.00 (in)	84.19	30% Gravel	1.00 (in)	100.00
39% Sand	0.75 (in)	71.72	48% Sand	0.75 (in)	98.50
9% Silt	0.50 (in)	66.80	19% Silt	0.50 (in)	89.38
1% Clay	4.75 (mm)	58.31	3% Clay	4.75 (mm)	80.70
	2000.00	48.78		2000.00	69.88
	1000.00	36.60		1000.00	57.57
	500.00	22.56		500.00	45.30
	250.00	16.07		250.00	36.77
	106.22	11.84		106.22	28.21
	75.00	10.78		75.00	25.00
	53.00	10.06		53.00	22.24
	50.24	2.13		47.41	15.82
	29.03	2.01		27.68	12.41
	15.90	2.01		15.31	9.79
	9.21	1.22		8.94	5.86
	6.51	1.16		6.35	4.20
	5.33	0.98		5.20	3.41
	4.62	0.55		4.51	3.15
	1.34	0.49		1.30	3.32

TABLE A.2. Bulk and Particle Density Data for Samples from Well No. 299-E25-234. Sample volumes were 68 cm³ for the retention cores and 2600 cm³ for the conductivity cores. Particle density values are the average of three replicates, except for samples 19 and 117, which are averages of two replicates.

Sample	Bulk Density (g cm⁻³) Water Retention Cores	Conductivity Cores	Particle Density (g cm⁻³)
5	1.62, 1.75	1.79	2.82
19	1.45, 1.36	1.61	2.77
25	1.36, 1.31, 1.34, 1.31	1.43	2.72
29	1.53, 1.50	1.83	2.71
37	1.27, 1.29	1.38	2.64
46	1.44, 1.61	1.72	2.68
54	1.47, 1.42	1.66	2.68
69	1.70, 1.62	1.82	2.72
83	1.65, 1.68	1.80	2.73
99	1.71, 1.69	1.84	2.70
110	1.55, 1.58	1.89	2.72
117	1.47, 1.59	1.44	2.71
126	1.80, 1.76	1.82	2.79
133	<u>1.97, 1.96</u>	<u>2.03</u>	<u>2.73</u>
Mean Values ^a	= 1.53	1.68	2.72

(^a) Water retention cores for samples 126 and 133 were packed in the laboratory. Therefore, bulk densities at these two depths were not included in the calculation of mean bulk density.

TABLE A.3. Particle Size Distribution and Water Retention Data for Backfill Soil. Bulk density was 1.65 g cm⁻³. Particle density was assumed to be 2.8 g cm⁻³.

<u>Particle Size Distribution</u>		<u>Matric Potential, -cm</u>	<u>Water Content, cm³ cm⁻³</u>	<u>Method</u>
<u>Diameter</u>	<u>% Less Than</u>			
2000	99.47	0	0.36	Estimated
1000	94.0	5	0.358	Column; mean of 2 reps
500	55.52	15	0.304	"
250	24.0	25	0.181	"
106	15.32	35	0.133	"
75	13.33	45	0.127	"
53	11.73	55	0.116	"
50.1	12.0	65	0.115	"
28.95	12.25	75	0.119	"
15.92	10.0	85	0.113	"
9.213	8.25	95	0.108	"
6.529	7.25	102	0.071	Pressure Plate; mean of 3 reps
5.324	7.25	306	0.068	"
4.611	7.25	1020	0.066	"
1.339	5.5	3060	0.055	"
		31180	0.056	?
		103200	0.05	?
		812600	0.031	?
		1511000	0.023	?
		2483000	0.018	?

TABLE A.4. Water Retention Data for Gravel. Bulk density was 1.38 g cm⁻³. Particle density was assumed to be 2.8 g cm⁻³.

<u>Matric Potential, -cm</u>	<u>Water Content cm³ cm⁻³</u>	<u>Method</u>
0	0.51	Estimated from bulk and particle densities
0.5	0.14	Column; mean of 2 reps
1	0.1	Interpolated from column data at 0.5 and 1.5 cm
1.5	0.075	Column; mean of 2 reps
2.5	0.044	"
5	0.017	Interpolated from column data at 4.5 and 5.5 cm (not shown)
10	0.01	Extrapolated from column data at 8.5 cm (not shown)
100	0.0095	Interpolated between values at 10 and 3.0E6 cm
1000	0.009	"
10000	0.0088	"
100000	0.0083	"
1000000	0.007	"
3000000	0.004	Vapor adsorption

TABLE A.5. Water Retention Data for Clay (i.e., a 1:3 Bentonite/Silt Loam Mix). The bulk density was 1.45 g cm^{-3} . The particle density was assumed to be 2.6 g cm^{-3} .

Matric Potential, cm	Water Content, $\text{cm}^3 \text{ cm}^{-3}$	Method
0	0.442	Estimated from bulk and particle densities
10	0.442	Assumed value
102	0.442	Pressure plate value of 0.66 exceeded porosity; reset to porosity
306	0.442	Pressure plate value of 0.61 exceeded porosity; reset to porosity
1020	0.44	Pressure plate
3060	0.31	"
12400	0.258	Vapor adsorption
23600	0.188	"
291000	0.101	" (average of two samples at different potentials)
1920000	0.028	"

TABLE A.6. Bulk and Particle Density and Saturated Hydraulic Conductivity Data for Concrete. Sample diameters ranged from 1.400 to 1.408 cm. Particle densities estimated from bulk densities and calculated values of saturated water content (Table A.7). Conductivity values for samples D, E, and F were determined in the opposite direction used for samples A, B, and C.

Sample	Sample Length, cm	Sample Volume, cm^3	Bulk Density, g cm^{-3}	Estimated Particle Density, g cm^{-3}	Saturated Conductivity		
					Total Flow, cm^3	Total Time of all Tests, h	Average Test Value, cm s^{-1}
CL-40A	1.155	1.78	2.08	2.57	0.25	72	3.55E-10
CL-40B	1.146	1.78	2.02	2.59	0.25	115	2.19E-10
CL-40C	1.153	1.79	1.93	2.61	0.25	54	4.69E-10
CL-40D	1.155	1.79	1.99	2.61	0.50	102	4.97E-10
CL-40E	1.150	1.79	2.02	2.59	0.50	114	4.43E-10
CL-40F	1.135	1.77	1.90	2.55	0.50	144	3.46E-10
Average			1.99	2.59			3.88E-10

TABLE A.7. Water Retention Data for Concrete. Values at zero matric potential were calculated using weights of supposedly saturated samples.

CL-40A		CL-40B		CL-40C	
Water Potential, -cm	Water Content, cm ³ cm ⁻³	Water Potential, -cm	Water Content, cm ³ cm ⁻³	Water Potential, -cm	Water Content, cm ³ cm ⁻³
0	0.186	0	0.219	0	0.26
2400	0.186	1900	0.219	4100	0.26
10300	0.175	6000	0.213	55000	0.249
30400	0.175	14800	0.207	63100	0.247
43600	0.172	22700	0.204	89700	0.245
55700	0.17	35100	0.198	105500	0.24
61600	0.167	45100	0.196	112700	0.239
86900	0.156	64800	0.194	132600	0.237
90700	0.15	84900	0.188	153000	0.232
105000	0.15	117400	0.182	165300	0.229
128400	0.141	161400	0.173	176200	0.225
166400	0.122	167300	0.154	275700	0.213
205600	0.12	239100	0.143	885100	0.152
885100	0.09	885100	0.112	1164700	0.111
1164700	0.068	1164700	0.087	1468500	0.115
1468500	0.063	1468500	0.081	3077300	0.098
3077300	0.052	3077300	0.068		

CL-40D		CL-40E		CL-40F	
Water Potential, -cm	Water Content, cm ³ cm ⁻³	Water Potential, -cm	Water Content, cm ³ cm ⁻³	Water Potential, -cm	Water Content, cm ³ cm ⁻³
0	0.238	0	0.221	0	0.254
3100	0.238	2700	0.221	3100	0.254
20000	0.227	19700	0.205	44700	0.242
42500	0.222	35100	0.197	65900	0.236
74600	0.217	49100	0.189	71500	0.227
92000	0.214	60700	0.187	94100	0.223
102300	0.211	77600	0.182	102700	0.22
117800	0.209	92200	0.18	117500	0.218
125100	0.207	102500	0.177	132800	0.216
135700	0.206	128300	0.175	202600	0.211
152900	0.198	144100	0.173	277700	0.207
183200	0.192	161900	0.163	885100	0.142
295200	0.188	168100	0.159	1164700	0.112
885100	0.121	211000	0.155	1468500	0.105
1164700	0.098	885100	0.109	3077300	0.087
1468500	0.089	1164700	0.079		
3077300	0.072	1468500	0.079		
		3077300	0.067		

TABLE A.8. Bulk and Particle Density and Saturated Hydraulic Conductivity Data for DSSF Grout Samples from the 14 November 1988 Adiabatic Pilot-Scale Test. Bulk density samples were 10 to 12 cm³. Diameter of conductivity samples was 1.34 cm.

Sample	Maximum Temperature During Curing, °C	Bulk Density, g cm ⁻³	Particle Density, g cm ⁻³	Saturated Conductivity			
				Sample Length, cm	Total Flow, cm ³	Total Time of all Tests, h	Average Value, cm s ⁻¹
A26	85	1.07	-	-	-	-	-
A38	87	1.09	-	-	-	-	-
A73	78	1.06	2.58	-	-	-	-
B06	80	1.15	-	-	-	-	-
B33	94	-	-	-	-	-	-
B52	91	1.09	2.62	-	-	-	-
C16	93	1.12	-	-	-	-	-
C48	99	1.11	-	-	-	-	-
C82	75	1.10	2.63	-	-	-	-
A	-	-	-	2.92	2.1	289	5.52E-9
B	-	-	-	2.95	1.1	257	1.10E-8
C	-	-	-	1.64	6.6	78	5.22E-8
Average		1.10	2.61				2.29E-8

TABLE A.9. Water Retention Data for DSSF Grout (1 bar = 0.1 MPa = 1020 cm).

<u>Sample A26</u>		<u>Sample A38</u>		<u>Sample A73</u>	
<u>Water</u> <u>Potential,</u> <u>-bars</u>	<u>Water</u> <u>Content,</u> <u>100 (g g⁻¹)</u>	<u>Water</u> <u>Potential,</u> <u>-bars</u>	<u>Water</u> <u>Content,</u> <u>100 (g g⁻¹)</u>	<u>Water</u> <u>Potential,</u> <u>-bars</u>	<u>Water</u> <u>Content,</u> <u>100 (g g⁻¹)</u>
249.41	44.18	229.93	45.69	274.53	45.55
275.36	43.18	273.49	45.01	301.05	44.89
290.83	41.16	280.69	43.34	280.69	43.34
293.02	39.62	292.92	41.91	322.57	41.86
316.83	38.75	317.26	41.06	347.49	41.15
333.50	37.56	335.59	40.01	371.48	40.16
344.91	35.47	344.91	38.40	381.33	38.74
375.01	34.50	380.69	37.40	412.00	37.80
393.46	33.14	390.84	36.26	438.08	36.72
393.97	32.32	399.48	35.54	427.92	36.03
455.56	30.63	455.10	33.94	497.97	34.60
459.16	28.84	455.76	32.35	513.48	32.88
472.16	25.81	418.97	29.79	479.95	26.46
504.09	23.16	453.03	27.50	470.85	28.02
709.95	17.89	634.14	22.01	725.06	22.16
749.84	14.43	679.64	17.27	684.39	18.31
758.30	13.30	709.39	15.20	726.31	16.63
882.43	12.31	779.07	14.36	760.60	15.76
1050.27	10.22	985.74	11.40	960.59	12.75
1249.67	8.20	1251.84	8.99	1151.95	10.10

<u>Sample B06</u>		<u>Sample B33</u>		<u>Sample B52</u>	
301.96	42.47	249.16	41.97	247.68	44.37
283.90	41.59	251.90	41.27	264.76	43.65
309.93	39.94	389.24	38.93	299.34	41.88
330.52	38.60	290.74	37.21	299.14	40.54
333.16	37.89	313.59	36.12	318.67	39.77
363.78	36.87	362.71	34.79	333.72	38.70
370.61	35.35	350.69	32.73	343.61	37.05
408.29	34.36	388.09	31.17	386.27	36.01
432.55	33.21	411.11	29.56	394.10	34.87
439.25	32.46	416.41	28.66	399.75	34.08
498.47	30.86	496.32	26.46	464.73	32.47
513.48	29.13	515.67	24.56	463.18	30.73
479.95	26.46	507.39	21.88	416.69	28.31
515.21	24.39	596.40	19.25	472.18	25.53
749.09	19.12	839.59	14.26	679.18	19.62
758.88	15.59	908.04	11.44	749.34	15.37
755.07	13.79	842.92	10.97	754.05	14.05
846.92	13.01	926.72	10.47	877.21	12.64
1024.26	11.25	1081.36	9.59	1027.32	11.01
1203.06	9.10	1309.42	7.92	1270.74	8.59

TABLE A.9. (contd)

Sample C16		Sample C48		Sample C82	
Water Potential, -bars	Water Content, 100 (g g ⁻¹)	Water Potential, -bars	Water Content, 100 (g g ⁻¹)	Water Potential, -bars	Water Content, 100 (g g ⁻¹)
296.41	40.24	234.90	42.00	256.01	44.86
273.77	39.57	240.36	41.11	258.10	44.32
287.74	37.79	284.45	39.18	289.14	42.76
284.16	36.25	285.95	37.55	299.24	41.52
317.15	35.42	294.73	36.67	327.36	40.74
337.46	34.27	329.01	35.48	347.84	39.70
350.93	32.54	333.27	33.55	341.73	38.12
377.20	31.36	372.16	32.34	388.22	37.05
378.34	30.08	387.44	31.34	394.37	35.87
394.23	29.28	375.90	30.16	412.55	35.14
459.71	27.40	442.62	28.14	484.18	33.37
458.45	25.74	463.97	26.13	481.52	31.72
474.58	22.98	458.48	23.12	458.79	29.44
559.41	20.65	550.41	20.42	501.60	26.73
731.20	15.44	746.47	15.36	700.11	21.25
848.06	11.69	856.03	11.81	686.89	17.83
839.57	10.71	840.99	11.04	733.57	16.08
938.70	10.24	920.41	10.44	791.77	14.89
1095.82	9.03	1087.05	9.06	934.32	12.91
1264.66	7.64	1288.62	7.52	1077.55	10.05

TABLE A.10. Water Retention Parameters and Saturated Hydraulic Conductivity Data for the Sandy Sequence of the Hanford Formation. Parameters for location 241-AP are from Smoot et al. (1989). Data for location 88-1 are from Dames and Moore (1988). Parameters for locations 299-E33-38 and MW are from Connolly et al. (1992b).

Well # or Location	Sample	Depth m	θ_s $\text{cm}^3 \text{cm}^{-3}$	θ_r $\text{cm}^3 \text{cm}^{-3}$	α $1/\text{cm}$	n	K_s cm s^{-1}
299-E25-234	5A	1.5	0.4131	0.0188	0.1479	1.3090	5.73E-4
299-E25-234	5B	1.5	0.3367	0.0336	0.0211	1.5364	-
299-E25-234	19A	5.8	0.4700	0.0426	0.1165	1.4816	8.88E-4
299-E25-234	19B	5.8	0.5026	0.0364	0.2728	1.5327	-
299-E25-234	25A	7.6	0.4406	0.0540	0.0473	2.0595	1.80E-3
299-E25-234	25B	7.6	0.5228	0.0345	0.0519	1.3424	-
299-E25-234	25C	7.6	0.5074	0.0282	0.0292	1.3517	-
299-E25-234	25D	7.6	0.5193	0.0000	0.1944	1.3494	-
299-E25-234	29A	8.8	0.4341	0.0000	0.2722	1.1927	2.41E-5
299-E25-234	29B	8.8	0.4387	0.0000	0.1034	1.2240	-
299-E25-234	37A	11.3	0.5114	0.0706	0.0774	1.2924	5.77E-4
299-E25-234	37B	11.3	0.5304	0.0851	0.0894	1.3353	-
299-E25-234	46A	14.0	0.4581	0.0000	0.2923	1.3658	2.99E-4
299-E25-234	46B	14.0	0.3708	0.0000	0.0613	1.4343	-
299-E25-234	54A	16.5	0.4434	0.0278	0.1205	1.4776	1.38E-5
299-E25-234	54B	16.5	0.4543	0.0217	0.1450	1.4421	-
299-E25-234	69A	21.0	0.3722	0.0000	0.3359	1.2658	1.21E-3
299-E25-234	69B	21.0	0.4087	0.0000	0.3553	1.4411	-
299-E25-234	83A	25.3	0.3925	0.0000	0.3198	1.3117	1.78E-4
299-E25-234	83B	25.3	0.3712	0.0011	0.1230	1.3815	-
299-E25-234	99A	30.2	0.3692	0.0000	0.7424	1.2557	2.24E-4
299-E25-234	99B	30.2	0.3774	0.0000	0.4371	1.2961	-
299-E25-234	110A	33.5	0.4293	0.0325	0.1964	1.8193	2.82E-4
299-E25-234	110B	33.5	0.4201	0.0327	0.1991	1.8015	-
299-E25-234	117A	35.7	0.4538	0.0260	0.1114	1.6538	3.63E-3
299-E25-234	117B	35.7	0.3831	0.0012	0.0230	1.5239	-
299-E25-234	126A	38.4	0.3637	0.0000	1.9541	1.2634	1.98E-3
299-E25-234	126B	38.4	0.3747	0.0000	0.8990	1.3152	-
241-AP	1G	-	0.2585	0.0200	0.1008	2.9224	1.24E-3
241-AP	2	-	0.5210	0.0958	0.0309	3.1071	5.97E-4
241-AP	3	-	0.4360	0.0552	0.0494	3.2863	8.10E-4
241-AP	4G	-	0.4086	0.0377	0.0666	2.6751	1.87E-3
241-AP	5	-	0.4280	0.0133	0.0118	1.3945	4.94E-5
88-1	TEST #1	4.8	-	-	-	-	3.01E-2
88-1	TEST #2	9.1	-	-	-	-	5.97E-3
88-1	TEST #3	18.3	-	-	-	-	5.20E-3
299-E33-38	-	15.1	0.2390	0.0000	1.4263	1.2658	5.70E-5
299-E33-38	-	51.0	0.2459	0.0000	0.4612	1.2507	5.00E-4
299-E33-38	-	57.1	0.3714	0.0018	0.0513	1.5057	7.10E-5
MW-10	-	13.7	0.4200	0.0223	0.0640	1.6950	5.31E-3
MW-10	-	26.2	0.4600	0.0253	0.0462	1.9281	1.97E-2

TABLE A.10. (contd)

Well # or Location	Sample	Depth m	θ_s $\text{cm}^3 \text{cm}^{-3}$	θ_r $\text{cm}^3 \text{cm}^{-3}$	α 1/cm	n	K_s cm s^{-1}
MW-10	-	32.0	0.3900	0.0271	0.0460	1.6380	1.73E-3
MW-10	-	38.1	0.4400	0.0214	0.0441	1.7647	4.39E-3
MW-10	-	50.3	0.4600	0.0308	0.0351	2.3036	6.63E-3
MW-10	-	59.4	0.3300	0.0487	0.0267	2.3731	2.65E-3
MW-10	-	62.5	0.3600	0.0214	0.0760	1.6255	6.63E-3
MW-10	-	74.7	0.4400	0.0179	0.0630	1.7787	7.39E-3
MW-10	-	80.8	0.4200	0.0169	0.0386	2.1470	2.65E-3
MW-10	-	86.9	0.4700	0.0168	0.0512	2.0848	3.54E-3
MW-5	-	15.2	0.4400	0.0293	0.0810	1.9709	3.53E-2
MW-5	-	21.3	0.4400	0.0485	0.0144	5.4201	1.57E-3
MW-5	-	27.4	0.4400	0.0218	0.0605	2.4414	2.16E-3
MW-5	-	39.6	0.4700	0.0311	0.0184	3.3059	4.42E-2
MW-5	-	51.8	0.4400	0.0281	0.0278	2.7143	3.81E-3
MW-5	-	57.9	0.4300	0.0242	0.0427	3.0699	5.78E-3
MW-5	-	64.0	0.4300	0.0302	0.1533	2.0330	5.42E-3
MW-5	-	70.1	0.4400	0.0243	0.0427	3.1603	5.31E-3
MW-5	-	82.3	0.4400	0.0000	0.1109	1.3428	5.54E-4
MW-8	-	44.2	0.4200	0.0335	0.0186	2.1503	8.86E-4
MW-8	-	56.5	0.4000	0.0367	0.0764	2.0668	7.19E-3
Number of Samples			57	57	57	57	45
Minimum			0.2390	0.0000	0.0118	1.1927	1.38E-5
Maximum			0.5304	0.0960	1.9541	5.4201	4.42E-2
Mean			0.4203	0.0234	0.1943	1.8680	5.48E-3
Variance			3.86E-3	4.63E-4	0.1142	0.5866	8.90E-5
Geom. Mean			0.4152	-	0.0918	1.7562	1.55E-3

TABLE A.11. Water Retention Parameters and Saturated Hydraulic Conductivity Data for the Upper and Lower Gravel Units of the Hanford Formation. All parameters, except those for Well No. 299-E25-234, are from Connelly et al. (1992b).

Well # or Location	Sample ID	Depth m	θ_s $\text{cm}^3 \text{cm}^{-3}$	θ_r $\text{cm}^3 \text{cm}^{-3}$	α 1/cm	n	K_s cm s^{-1}
299-E25-234	133A	40.5	0.2732	0.0000	0.0182	1.3095	2.76E-5
299-E25-234	133B	40.5	0.2669	0.0000	0.0321	1.2590	-
299-E33-38	-	1.9	0.5256	0.0000	0.0081	1.7389	2.00E-5
299-E33-38	-	57.9	0.4187	0.0000	0.0027	1.5688	2.10E-6
299-E33-38	-	62.3	0.2905	0.0000	0.0101	1.3652	4.20E-3
299-E33-40	-	14.0	0.3021	0.0000	0.1028	1.2734	6.00E-4
216-B-61A	-	4.1	0.3465	0.0352	0.0061	1.5248	1.80E-3
216-B-61A	-	5.8	0.3253	0.0488	0.0060	1.5120	2.80E-3
216-B-61A	-	7.0	0.3430	0.0000	0.0134	1.2816	4.00E-4
216-B-61A	-	8.8	0.2801	0.0201	0.0609	1.2811	1.80E-5
6-43-41H	-	16.6	0.4510	0.1041	0.0165	1.7894	1.10E-5
6-42-41B	-	25.8	0.3550	0.0301	0.0426	1.3900	5.40E-3
MW-8	-	4.6	0.4400	0.0390	0.0440	3.0387	1.70E-3
MW-10	-	93.0	0.4000	0.0205	0.0427	2.2500	4.42E-3
Number of Samples			14	14	14	14	13
Minimum			0.2669	0.0000	0.0027	1.2590	2.10E-6
Maximum			0.5256	0.1041	0.1028	3.0390	5.40E-3
Mean			0.3584	0.0213	0.0290	1.6130	1.65E-3
Variance			6.12E-3	8.75E-4	7.79E-4	0.2348	3.80E-6
Geom. Mean			0.3509	-	0.0184	1.5600	2.73E-4

TABLE A.12. Water Retention Parameters and Saturated Hydraulic Conductivity Data for the Ringold Formation (undifferentiated). Parameters are from Connelly et al. (1992b).

Well # or Location	Sample ID	Depth m	θ_s $\text{cm}^3 \text{cm}^{-3}$	θ_r $\text{cm}^3 \text{cm}^{-3}$	α 1/cm	n	K_s cm s^{-1}
6-42-41B	-	36.1	0.5730	0.0083	0.0132	1.2586	3.00E-8
699-40-40B	-	38.3	0.5680	0.0000	0.0051	1.1732	1.00E-8
699-43-41G	-	50.8	0.5710	0.0941	0.0150	1.4173	1.90E-6
699-43-40	-	39.9	0.3790	0.0387	0.0089	1.4739	1.90E-4
MW-5	-	91.4	0.4000	0.0000	0.0456	1.3661	7.66E-4
Number of Samples			5	5	5	5	5
Minimum			0.3790	0.0000	0.0051	1.1732	1.00E-8
Maximum			0.5730	0.0940	0.0456	1.4739	7.66E-4
Mean			0.4982	0.0283	0.0176	1.3378	1.92E-4
Variance			9.90E-3	1.61E-3	2.61E-4	1.48E-2	1.10E-7
Geom. Mean			0.4897	-	0.0133	1.3333	2.42E-6

TABLE A.13. Water Retention Parameters and Saturated Hydraulic Conductivity Data for Concrete

Sample ID	θ_s cm ³ cm ⁻³	θ_r cm ³ cm ⁻³	α 1/cm	n	K_s cm/s
CL-40A	0.1857	0.0000	1.220E-5	1.3567	3.55E-10
CL-40B	0.2146	0.0000	9.862E-6	1.3409	2.19E-10
CL-40C	0.2593	0.0000	3.826E-6	1.4412	4.69E-10
CL-40D	0.2322	0.0000	4.365E-5	1.4726	4.97E-10
CL-40E	0.2150	0.0000	1.074E-5	1.3396	4.43E-10
CL-40F	0.2480	0.0000	4.669E-6	1.4054	3.46E-10
Number of Samples	6	6	6	6	6
Minimum	0.1857	-	3.826E-6	1.3396	2.19E-10
Maximum	0.2593	-	1.220E-5	1.4726	4.97E-10
Mean	0.2258	-	7.610E-6	1.3927	3.88E-10
Variance	7.012E-4	-	1.389E-11	3.14E-11	1.06E-20
Geom. Mean	0.2245	-	6.822E-6	1.3918	3.75E-10

TABLE A.14. Water Retention Parameters and Saturated Hydraulic Conductivity Data for DSSF Grout

Sample ID	θ_s cm ³ cm ⁻³	θ_r cm ³ cm ⁻³	α 1/cm	n	K_s cm/s
GRT_A26	0.5853	0.0000	1.503E-5	1.5679	5.52E-9
GRT_A38	0.5775	0.0000	9.165E-6	1.6957	-
GRT_A73	0.5891	0.0000	8.804E-6	1.6690	-
GRT_B06	0.5611	0.0000	6.959E-6	1.7719	1.10E-8
GRT_B33	0.5725	0.0000	1.190E-5	1.6304	-
GRT_B52	0.5840	0.0000	1.141E-5	1.6227	-
GRT_C16	0.5741	0.0000	1.574E-5	1.5740	5.22E-8
GRT_C48	0.5779	0.0000	8.946E-6	1.6585	-
GRT_C82	0.5817	0.0000	8.970E-6	1.6565	-
Number of Samples	9	9	9	9	3
Minimum	0.5611	-	6.959E-6	1.5679	5.52E-9
Maximum	0.5891	-	1.574E-5	1.7719	5.22E-8
Mean	0.5781	-	1.077E-5	1.6496	2.29E-8
Variance	6.96E-5	-	9.008E-12	3.884E-3	6.61E-16
Geom. Mean	0.5781	-	1.042E-5	1.6486	1.47E-8

FIGURE A.1. Water Retention and Hydraulic Conductivity Data and Curves for Samples 5A, 5B, 19A, and 19B from Well No. 299-E25-234

FIGURE A.2. Water Retention and Hydraulic Conductivity Data and Curves for Samples 25A, 25B, 25C, and 25D from Well No. 299-E25-234

FIGURE A.3. Water Retention and Hydraulic Conductivity Data and Curves for Samples 29A, 29B, 37A, and 37B from Well No. 299-E25-234

FIGURE A.4. Water Retention and Hydraulic Conductivity Data and Curves for Samples 46A, 46B, 54A, and 54B from Well No. 299-E25-234

FIGURE A.5. Water Retention and Hydraulic Conductivity Data and Curves for Samples 69A, 69B, 83A, and 83B from Well No. 299-E25-234

FIGURE A.6. Water Retention and Hydraulic Conductivity Data and Curves for Samples 99A, 99B, 110A, and 110B from Well No. 299-E25-234

FIGURE A.7. Water Retention and Hydraulic Conductivity Data and Curves for Samples 117A, 117B, 126A, and 126B from Well No. 299-E25-234

FIGURE A.8. Water Retention and Hydraulic Conductivity Data and Curves for Samples 133A and 133B from Well No. 299-E25-234

FIGURE A.9. Water Retention and Hydraulic Conductivity Data and Curves for Backfill Soil

FIGURE A.10. Water Retention and Hydraulic Conductivity Data and Curves for Gravel

FIGURE A.11. Water Retention and Hydraulic Conductivity Data and Curves for RCRA Clay Cap

FIGURE A.12. Water Retention and Hydraulic Conductivity Data and Curves for Concrete Samples CL-40A, CL-40B, CL-40C, and CL-40D

FIGURE A.13. Water Retention and Hydraulic Conductivity Data and Curves for Concrete Samples CL-40E and CL-40F

FIGURE A.14. Water Retention and Hydraulic Conductivity Data and Curves for DSSF GROUT Samples A26, A38, A73, and B06

FIGURE A.15. Water Retention and Hydraulic Conductivity Data and Curves for DSSF GROUT Samples B33, B52, C16, and C48

FIGURE A.16. Water Retention and Hydraulic Conductivity Data and Curves for DSSF Grout Sample C82

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