CHAPTER 4

SUBPART D
DESIGN CRITERIA

CHAPTER 4
SUBPART D

TABLE OF CONTENTS

CHAPTER 4
SUBPART D

DESIGN CRITERIA

4.1 INTRODUCTION

New MSWLF facilities and lateral expansions of existing units must comply with either a design standard or a performance standard for landfill design. The Federal Criteria do not require existing units to be retrofitted with liners. The design standard requires a composite liner composed of two feet of soil with a hydraulic conductivity of no more than 1×10^{-7} cm/sec, overlain by a flexible membrane liner (FML) and a leachate collection system. A performance-based design must demonstrate the capability of maintaining contaminant concentrations below maximum contaminant levels (MCLs) at the unit's relevant point of compliance. The performance standard has been established to allow design innovation and consideration of site-specific conditions; approved States may have adopted alternative design standards. Owners/operators are advised to work closely with State permitting agencies to determine the applicable design standard. Owners/operators in unapproved States may use the petition process (§258.40(c)) to allow for use of a performance-based design. This process is discussed in Section 4.5.

The technical considerations discussed in this chapter are intended to identify the key design features and system components for the composite liner and leachate collection system standards, and for the performance standard. The technical considerations include 1) design concepts, 2) design calculations, 3) physical properties, and 4) construction methods for the following:

1) Designs Based on the Performance Standard

   - Leachate characterization and leakage assessment;
   - Leachate migration in the subsurface;
   - Leachate migration models; and
   - Relevant point of compliance assessment.

2) Composite Liners and Leachate Collection Systems

   - Soil liner component (soil properties lab testing, design, construction, and quality assurance/quality control testing);
   - Flexible membrane liners (FML properties, design installation, and quality assurance/quality control testing);
   - Leachate collection systems (strength and compatibility, grading and drainage, clogging potential, and filtration);

- Leachate removal systems (pumps, sumps, and standpipes); and
- Inspections (field observations and field and laboratory testing).

Designs based on the performance standard are described in Section 4.2. Requirements for composite liners are discussed in Section 4.3. These sections address the minimum regulatory requirements that should be considered during the design, construction, and operation of MSWLF units to ensure that they perform in a manner protective of human health and the environment. Additional features or procedures may be used to demonstrate conformance with the regulations or to control leachate release and subsequent effects. For example, during construction of a new MSWLF unit, or a lateral expansion of an existing MSWLF unit, quality control and quality assurance procedures and documentation may be used to ensure that material properties and construction methods meet the design specifications that are intended to achieve the expected level of performance. Section 4.4 presents methods to assess ground-water quality at the relevant point of compliance for performance-based designs. Section 4.5 describes the applicability of the petition process for States wishing to petition to use the performance standard.

4.2 PERFORMANCE-BASED DESIGN 40 CFR §258.40(a)(1)

4.2.1 Statement of Regulation

(a) New MSWLF units and lateral expansions shall be constructed:

(1) In accordance with a design approved by the Director of an approved State or as specified in §258.40(e) for unapproved States. The design must ensure that the concentration values listed in Table 1 will not be exceeded in the uppermost aquifer at the relevant point of compliance as specified by the Director of an approved State under paragraph (d) of this section, or

(2) *(See Statement of Regulation in Section 4.3.1 of this guidance document for the regulatory language for composite liner requirements).*

(b) *(See Statement of Regulation in Section 4.3.1 of this guidance document for the regulatory language for requirements pertaining to composite liner and leachate collection systems).*

(c) When approving a design that complies with paragraph (a)(1) of this section, the Director of an approved State shall consider at least the following factors:

(1) The hydrogeologic characteristics of the facility and surrounding land;

(2) The climatic factors of the area; and

(3) The volume and physical and chemical characteristics of the leachate.

(d) *(See Statement of Regulation in Section 4.4.1 of this guidance document for a discussion of the determination of the relevant point of compliance.)*

TABLE 1
(40 CFR 258.40; 56 FR 51022; October 9, 1991)

Chemical	MCL(mg/l)
Arsenic	0.05
Barium	1.0
Benzene	0.005
Cadmium	0.01
Carbon tetrachloride	0.005
Chromium (hexavalent)	0.05
2,4-Dichlorophenoxy acetic acid	0.1
1,4-Dichlorobenzene	0.075
1,2-Dichloroethane	0.005
1,1-Dichloroethylene	0.007
Endrin	0.0002
Fluoride	4.0
Lindane	0.004
Lead	0.05
Mercury	0.002
Methoxychlor	0.1
Nitrate	10.0
Selenium	0.01
Silver	0.05
Toxaphene	0.005
1,1,1-Trichloroethane	0.2
Trichloroethylene	0.005
2,4,5-Trichlorophenoxy acetic acid	0.01
Vinyl Chloride	0.002

4.2.2 Applicability

The Director of an approved State may approve a performance-based design for new MSWLF units and lateral expansions of existing units (see Section 4.3.2), if it meets the requirements specified in 40 CFR 258.40(a)(1). A performance-based design is an alternative to the design standard (composite liner with a leachate collection system). The composite design is required in unapproved States; however, if EPA does not promulgate procedures for State approval by October 9, 1993, the performance-based design may be available through the petition process (see Section 4.5).

4.2.3 Technical Considerations

Demonstration Requirements

For approval of landfill designs not conforming to the uniform design standard of a composite liner system and a leachate collection system (40 CFR §258.40(a)(2)), the owner or operator of the proposed MSWLF unit must demonstrate to the Director of an approved State that the design will not allow the compounds listed in Table 1 of §258.40 to exceed the MCLs in ground water at the relevant point of compliance. The demonstration should consider an assessment of leachate quality and quantity, leachate leakage to the subsurface, and subsurface transport to the relevant point of compliance. These factors are governed by site hydrogeology, waste characteristics, and climatic conditions.

The nature of the demonstration is essentially an assessment of the potential for leachate production and leakage from the landfill to ground water, and the anticipated fate and transport of constituents listed in Table 1 to the proposed relevant point of compliance at the facility. Inherent in this approach is the need to evaluate whether contaminants in ground water at the relevant point of compliance will exceed the concentration values listed in Table 1. If so, then the owner or operator needs to obtain sufficient site-specific data to adequately characterize the existing ground-

water quality and the existing ground-water flow regime (e.g., flow direction, horizontal and vertical gradients, hydraulic conductivity, stratigraphy, and aquifer thickness).

An assessment should be made of the effect MSWLF facility construction will have on site hydrogeology. The assessment should focus on the reduced infiltration over the landfill area and altered surface water run-off patterns. Reduction of ground-water recharge and changes in surface water patterns resulting from landfill construction may affect ground-water gradients in some cases and may result in changes in lateral flow directions. One example of a hypothetical performance-based demonstration follows.

It is possible that a MSWLF unit located in an arid climatic zone would not produce leachate from sources of water (e.g., precipitation) other than that existing within the waste at the time of disposal. In such an environment, an owner or operator may demonstrate that significant quantities of leachate would not be produced. The demonstration should be supported by evaluating historic precipitation and evaporation data and the likelihood that the unit could be flooded as the result of heavy rains, surface run-off, or high water tables. It may be possible, through operational controls, to avoid exposing waste to precipitation or infiltration of water through overlying materials. If significant leachate production would not be expected, the regulatory authority, when reviewing the demonstration, should consider the hydrogeologic characteristics of the facility and the surrounding area, in addition to the expected volume of leachate and climatic factors.

Assuming leachate is produced, the demonstration should evaluate whether constituents listed in Table 1 can be expected to be present at concentrations greater than the MCLs. If such a demonstration is possible, it must address the hydrogeologic characteristics of the facility and the surrounding land to comply with §258.40(d). The following sections describe the various parts of a demonstration in greater detail.

Leachate Characterization

Leachate characterization should include an assessment and demonstration of the quantity and composition of leachate anticipated at the proposed facility. Discussion of this assessment follows.

Estimates of volumetric production rates of leachate are important in evaluating the fate and transport of the constituents listed in Table 1. Leachate production rates depend on rainfall, run-on, run-off, evapotranspiration, water table elevation relative to the bottom of the landfill unit, in-place moisture content of waste, and the prevention of liquid disposal at the site. Run-on, run-off, and water table factors can be managed traditionally through design and operational controls. The MSWLF Criteria prohibit bulk or containerized liquid disposal. Incident precipitation and evapotranspiration can be evaluated using models (e.g., HELP) or other methods of estimating site-specific leachate production (e.g., local historical meteorologic data).

If leachate composition data that are representative of the proposed facility are not available, then leachate data with a similar expected composition should be presented. Landfill leachate composition is influenced by:

(1) The annual infiltration of precipitation and rate of leaching;

(2) The type and relative amounts of materials in the waste stream; and

(3) The age and the biological maturity of the landfill unit, which may affect the types of organic and inorganic acids generated, oxidation/reduction potential (Eh), and pH conditions.

An existing landfill unit in the same region, with similar waste stream characteristics, may provide information that will allow the owner or operator to anticipate leachate composition of the proposed landfill unit. A review of existing literature also may be required to assess anticipated leachate composition if actual data are unavailable (see U.S. EPA, 1987b). A wide range of leachate concentrations are reported in the literature with higher concentrations of specific constituents typically reported for the initial leachate from laboratory or field experimental test fills or test cells. These "batch" one-day landfill tests do not account for the long-term climatic and meteorological influences on a full-scale landfill operation. Such high initial concentrations are not typical of full-scale operations (which are subject to the dilution effects of incidental rainfall on unused portions of the unit).

Assessment of Leakage Through Liners

An assessment of leakage (the volumetric release of leachate from the proposed performance-based design) should be based on analytical approaches supported by empirical data from other existing operational facilities of similar design, particularly those that have leak detection monitoring systems (see U.S. EPA, 1990b). In lieu of the existence or availability of such information, conservative analytical assumptions may be used to estimate anticipated leakage rates.

The transport of fluids and waste constituents through geomembranes differs in principle from transport through soil liner materials. The dominant mode of leachate transport through liner components is flow through holes and penetrations of the geomembrane, and Darcian flow through soil components. Transport through geomembranes where tears, punctures, imperfections, or seam failures are not involved is dominated by molecular diffusion. Diffusion occurs in response to a concentration gradient and is governed by Fick's first law. Diffusion rates through geomembranes are very low in comparison to hydraulic flow rates in soil liners, including compacted clays. For synthetic liners, the most significant factor influencing liner performance is penetration of the liner, including imperfect seams or pinholes caused by construction defects in the geomembrane (U.S. EPA, 1989).

A relatively new product now being used in liner systems is the geosynthetic clay liner (GCL). GCLs consist of a layer of pure bentonite clay backed by one or two geotextiles. GCLs exhibit properties of both soil liners and geomembranes, and have successfully substituted for the soil component in composite liner designs. GCLs are believed to transport fluids primarily through diffusion according to their low hydraulic conductivities (i.e., 1×10^{-9} cm/sec reported by manufacturers). Applications for GCLs are discussed further in the sections that follow.

Several researchers have studied the flow of fluids through imperfections in single

geomembrane and composite liner systems. Further discussion of liner leakage rates can be found in Section 4.3.3 below. For empirical data and analytical methods the reader is referred to Jayawickrama et al. (1988), Kastman (1984), Haxo (1983), Haxo et al. (1984), Radian (1987), Giroud and Bonaparte (1989, Parts I and II), and Giroud et al. (1989). Leakage assessments also may be conducted with the use of the HELP model (U.S. EPA, 1988). Version 3.0 of the model is under revision and will include an updated method to assess leakage that is based on recent research and data compiled by Giroud and Bonaparte.

Leachate Migration in the Subsurface

Leachate that escapes from a landfill unit may migrate through the unsaturated zone and eventually reach the uppermost aquifer. In some instances, however, the water table may be located above the base of the landfill unit, so that only saturated flow and transport from the landfill unit need to be considered. Once leachate reaches the water table, contaminants may be transported through the saturated zone to a point of discharge (i.e., a pumping well, a stream, a lake, etc.).

The migration of leachate in the subsurface depends on factors such as the volume of the liquid component of the waste, the chemical and physical properties of the leachate constituents, the loading rate, climate, and the chemical and physical properties of the subsurface (saturated and unsaturated zones). A number of physical, chemical, and biological processes also may influence migration. Complex interactions between these processes may result in specific contaminants being transported through the subsurface at different rates. Certain processes result in the attenuation and degradation of contaminants. The degree of attenuation is dependent on the time that the contaminant is in contact with the subsurface material, the physical and chemical characteristics of the subsurface material, the distance that the contaminant has traveled, and the volume and characteristics of the leachate. Some of the key processes affecting leachate migration are discussed briefly here. The information is based on a summary in Travers and Sharp-Hansen (1991), who in turn relied largely on Aller et al. (1987), Keely (1987), Keely (1989), Lu et al. (1985), and U.S. EPA (1988a).

Physical Processes Controlling Contaminant Transport in the Subsurface

Physical processes that control the transport of contaminants in the subsurface include advection, mixing and dilution as a result of dispersion and diffusion, mechanical filtration, physical sorption, multi-phase fluid flow, and fracture flow. These processes, in turn, are affected by hydrogeologic characteristics, such as hydraulic conductivity and porosity, and by chemical processes.

<u>Advection</u> is the process by which solute contaminants are transported by the overall motion of flowing ground water. A non-reactive solute will be transported at the same rate and in the same direction as ground water flow (Freeze and Cherry, 1979). Advective transport is chiefly a function of the subsurface hydraulic conductivity distribution, porosity, and hydraulic gradients.

<u>Hydrodynamic dispersion</u> is a non-steady, irreversible mixing process by which a contaminant plume spreads as it is transported through the subsurface. Dispersion results from the effects of two

components operating at the microscopic level: mechanical dispersion and molecular diffusion. Mechanical dispersion results from variations in pore velocities within the soil or aquifer and may be more significant than molecular diffusion in environments where the flow rates are moderate to high. Molecular diffusion occurs as a result of contaminant concentration gradients; chemicals move from high concentrations to low concentrations. At very slow ground-water velocities, as occur in clays and silts, diffusion can be an important transport mechanism.

Mechanical filtration removes from ground water contaminants that are larger than the pore spaces of the soil. Thus, the effects of mechanical filtration increase with decreasing pore size within a medium. Filtration occurs over a wide range of particle sizes. The retention of larger particles may effectively reduce the permeability of the soil or aquifer.

Physical sorption is a function of Van der Waals forces, and the hydrodynamic and electrokinetic properties of soil particles. Sorption is the process by which contaminants are removed from solution in ground water and adhere or cling to a solid surface. The distribution of a contaminant between the solution and the solid phase is called partitioning.

Multiphase fluid flow occurs because many solvents and oils are highly insoluble in water and may migrate in the subsurface as a separate liquid phase. If the viscosity and density of a fluid differ from that of water, the fluid may flow at a different rate and direction than the ground water. If the fluid is more dense than water it may reach the bottom of the aquifer (top of an aquitard) and alter its flow direction to conform to the shape and slope of the aquitard surface.

Hydraulic conductivity is a measure of the ability of geologic media to transmit fluids (USGS, 1987). It is a function of the size and arrangement of water-transmitting openings (pores and fractures) in the media and of the characteristics of the fluids (density, viscosity, etc.). Spatial variations in hydraulic conductivity are referred to as heterogeneities. A variation in hydraulic conductivity with the direction of measurement is referred to as anisotropy.

Variable hydraulic conductivity of the geologic formation may cause ground-water flow velocities to vary spatially. Variations in the rate of advection may result in non-uniform plume spreading. The changes in aquifer properties that lead to this variability in hydraulic conductivity may be three-dimensional. If the geologic medium is relatively homogeneous, it may be appropriate, in some instances, to assume that the aquifer properties also are homogeneous.

Secondary porosity in rock may be caused by the dissolution of rock or by regional fracturing; in soils, secondary porosity may be caused by desiccation cracks or fissures. Fractures or macropores respond quickly to rainfall events and other fluid inputs and can transmit water rapidly along unexpected pathways. Secondary porosity can result in localized high concentrations of contaminants at significant distances from the facility. The relative importance of secondary porosity to hydraulic conductivity of the subsurface depends on the ratio of fracture hydraulic conductivity to intergranular hydraulic conductivity (Kincaid et al., 1984a). For scenarios in which fracture flow is dominant, the relationships

used to describe porous flow (Darcy's Law) do not apply.

Chemical Processes Controlling Contaminant Transport in the Subsurface

Chemical processes that are important in controlling subsurface transport include precipitation/dissolution, chemical sorption, redox reactions, hydrolysis, ion exchange, and complexation. In general, these processes, except for hydrolysis, are reversible. The reversible processes tend to retard transport, but do not permanently remove a contaminant from the system. Sorption and precipitation are generally the dominant mechanisms retarding contaminant transport in the saturated zone.

Precipitation/dissolution reactions can control contaminant concentration levels. The solubility of a solid controls the equilibrium state of a chemical. When the soluble concentration of a contaminant in leachate is higher than that of the equilibrium state, precipitation occurs. When the soluble concentration is lower than the equilibrium value, the contaminant exists in solution. The precipitation of a dissolved substance may be initiated by changes in pressure, temperature, pH, concentration, or redox potential (Aller et al., 1987). Precipitation of contaminants in the pore space of an aquifer can decrease aquifer porosity. Precipitation and dissolution reactions are especially important processes for trace metal migration in soils.

Chemical adsorption/desorption is the most common mechanism affecting contaminant migration in soils. Solutes become attached to the solid phase by means of adsorption. Like precipitation/dissolution, adsorption/desorption is a reversible process. However, adsorption/desorption generally occurs at a relatively rapid rate compared to precipitation reactions.

The dominant mechanism of organic sorption is the hydrophobic attraction between a chemical and natural organic matter that exists in some aquifers. The organic carbon content of the porous medium, and the solubility of the contaminant, are important factors for this type of sorption.

There is a direct relationship between the quantity of a substance sorbed on a particle surface and the quantity of the substance suspended in solution. Predictions about the sorption of contaminants often make use of sorption isotherms, which relate the amount of contaminant in solution to the amount adsorbed to the solids. For organic contaminants, these isotherms are usually assumed to be linear and the reaction is assumed to be instantaneous and reversible. The linear equilibrium approach to sorption may not be adequate for all situations.

Oxidation and reduction (redox) reactions involve the transfer of electrons and occur when the redox potential in leachate is different from that of the soil or aquifer environment. Redox reactions are important processes for inorganic compounds and metallic elements. Together with pH, redox reactions affect the solubility, complexing capacity, and sorptive behavior of constituents, and thus control the presence and mobility of many substances in water. Microorganisms are responsible for a large proportion of redox reactions that occur in ground water. The redox state of an aquifer, and the identity and quantity of redox-active reactants, are difficult to determine.

Hydrolysis is the chemical breakdown of carbon bonds in organic substances by water and its ionic species H^+ and OH^-. Hydrolysis is dependent on pH and Eh and is most significant at high temperatures, low pH, and low redox potential. For many biodegradable contaminants, hydrolysis is slow compared to biodegradation.

Ion exchange originates primarily from exchange sites on layered silicate clays and organic matter that have a permanent negative charge. Cation exchange balances negative charges in order to maintain neutrality. The capacity of soils to exchange cations is called the cation exchange capacity (CEC). CEC is affected by the type and quantity of clay mineral present, the amount of organic matter present, and the pH of the soil. Major cations in leachate (Ca, Mg, K, Na) usually dominate the CEC sites, resulting in little attenuation in soils of trace metals in the leachate.

A smaller ion exchange effect for anions is associated with hydrous oxides. Soils typically have more negatively charged clay particles than positively charged hydrous oxides. Therefore, the transport of cations is attenuated more than the transport of anions.

Complexation involves reactions of metal ions with inorganic anions or organic ligands. The metal and the ligand bind together to form a new soluble species called a complex. Complexation can either increase the concentration of a constituent in solution by forming soluble complex ions or decrease the concentration by forming a soluble ion complex with a solid. It is often difficult to distinguish among sorption, solid-liquid complexation, and ion exchange. Therefore, these processes are usually grouped together as one mechanism.

Biological Processes Controlling Contaminant Transport in the Subsurface

Biodegradation of contaminants may result from the enzyme-catalyzed transformation of organic compounds by microbes. Contaminants can be degraded to harmless byproducts or to more mobile and/or toxic products through one or more of several biological processes. Biodegradation of a compound depends on environmental factors such as redox potential, dissolved oxygen concentration, pH, temperature, presence of other compounds and nutrients, salinity, depth below land surface, competition among different types of organisms, and concentrations of compounds and organisms. The transformations that occur in a subsurface system are difficult to predict because of the complexity of the chemical and biological reactions that may occur. Quantitative predictions of the fate of biologically reactive substances are subject to a high degree of uncertainty, in part, because little information is available on biodegradation rates in soil systems or ground water. First-order decay constants are often used instead.

The operation of Subtitle D facilities can introduce bacteria and viruses into the subsurface. The fate and transport of bacteria and viruses in the subsurface is an important consideration in the evaluation of the effects of MSWLF units on human health and the environment. A large number of biological, chemical, and physical processes are known to influence virus and bacterial survival and transport in the subsurface. Unfortunately, knowledge of the processes and the available data are insufficient to develop models that can

simulate a wide variety of site-specific conditions.

Leachate Migration Models

After reviewing the hydrogeologic characteristics of the site, the nature of liner leakage, and the leachate characteristics, it may be appropriate to use a mathematical model to simulate the expected fate and transport of the constituents listed in Table 1 to the relevant point of compliance. Solute transport and ground-water modeling efforts should be conducted by a qualified ground-water scientist (see Section 5.5). It is necessary to consider several factors when selecting and applying a model to a site. Travers and Sharp-Hansen (1991) provide a thorough review of these issues. The text provided below is a summary of their review.

Overview of the Modeling Process

A number of factors can influence leachate migration from MSWLF units. These include, but are not limited to, climatic effects, the hydrogeologic setting, and the nature of the disposed waste. Each facility is different, and no one generic model will be appropriate in all situations. To develop a model for a site, the modeling needs and the objectives of the study should be determined first. Next, it will be necessary to collect data to characterize the hydrological, geological, chemical, and biological conditions of the system. These data are used to assist in the development of a conceptual model of the system, including spatial and temporal characteristics and boundary conditions. The conceptual model and data are then used to select a mathematical model that accurately represents the conceptual model. The model selected should have been tested and evaluated by qualified investigators, should adequately simulate the significant processes present in the actual system, and should be consistent with the complexity of the study area, amount of available data, and objectives of the study.

First, an evaluation of the need for modeling should be made (Figure 4-1). When selecting a model to evaluate the potential for soil and ground-water contamination (Boutwell et al., 1986), three basic determinations must be made (Figure 4-2). Not all studies require the use of a mathematical model. This decision should be made at the beginning of the study, since modeling may require a substantial amount of resources and effort. Next, the level of model complexity required for a specific study should be determined (Figure 4-3). Boutwell et al. (1986) classify models as Level I (simple/analytical) and Level II (complex/numerical) models. A flowchart for determining the level of model complexity required is shown in Figure 4-3. Finally, the model capabilities necessary to represent a particular system should be considered (Figure 4-4). Several models may be equally suitable for a particular study. In some cases, it may be necessary to link or couple two or more computer models to accurately represent the processes at the site. In the section that follows, specific issues that should be considered when developing a scenario and selecting a model are described.

Models are a simplified representation of the real system, and as such, cannot fully reproduce or predict all site characteristics. Errors are introduced as a result of: 1) simplifying assumptions; 2) a lack of data; 3) uncertainty in existing data; 4) a poor understanding of the processes influencing the fate and transport of contaminants; and

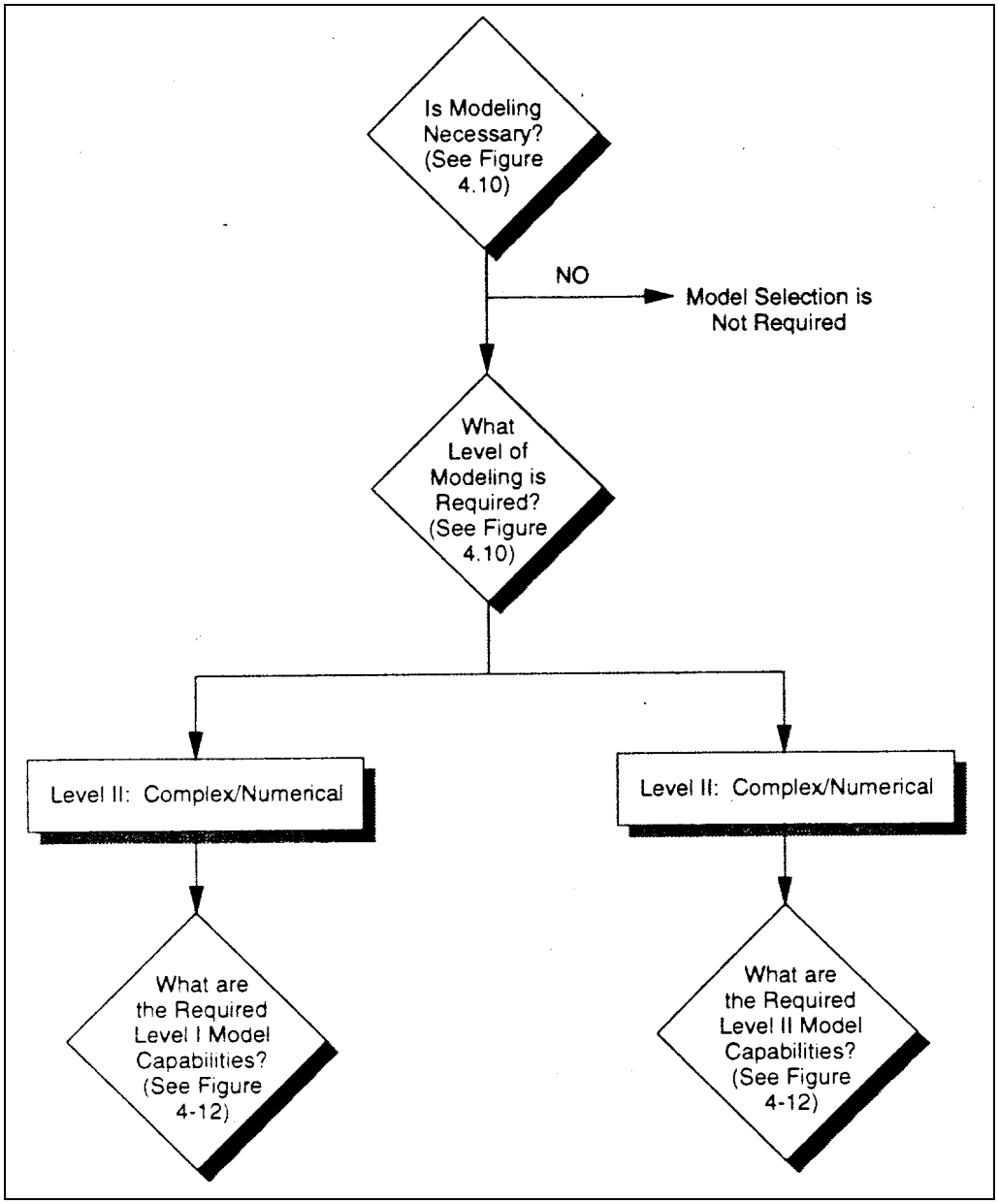


Figure 4-1
Three Basic Decisions in Model Selection
(Boutwell et. al., 1986)

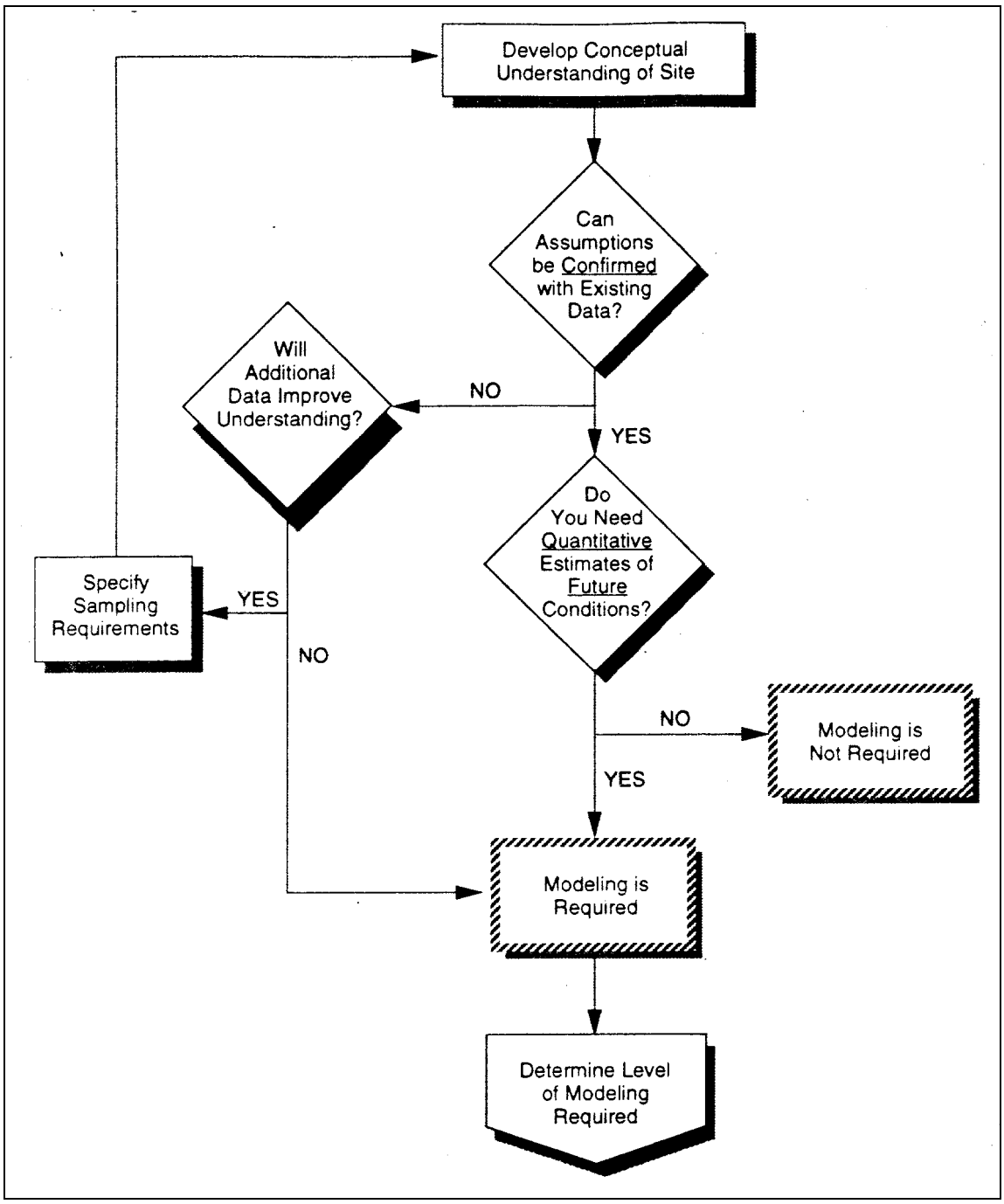


Figure 4-2
Flow Chart to Determine if Modeling is Required
(Boutwell et. al., 1986)

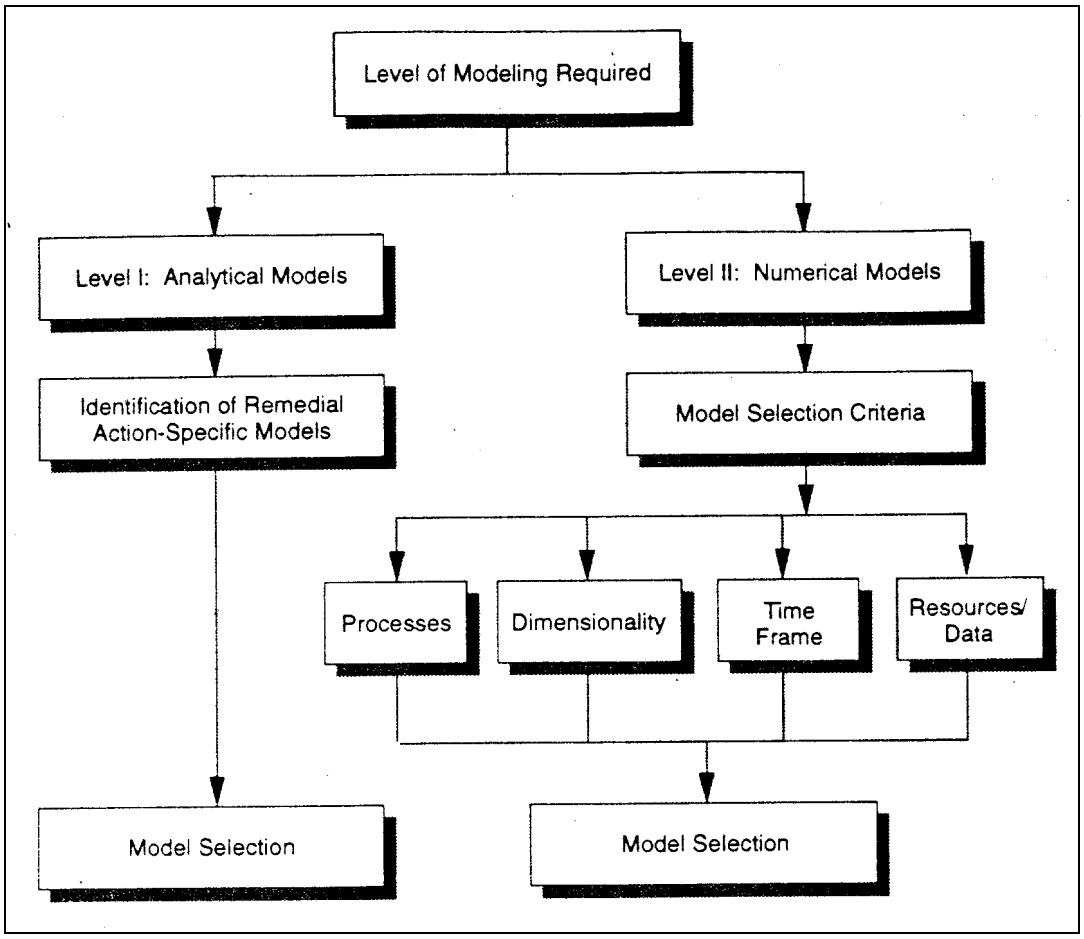


Figure 4-3
Flow Chart to Determine the Level of Modeling Required for Soil and Groundwater Systems
(Boutwell et. al., 1986)

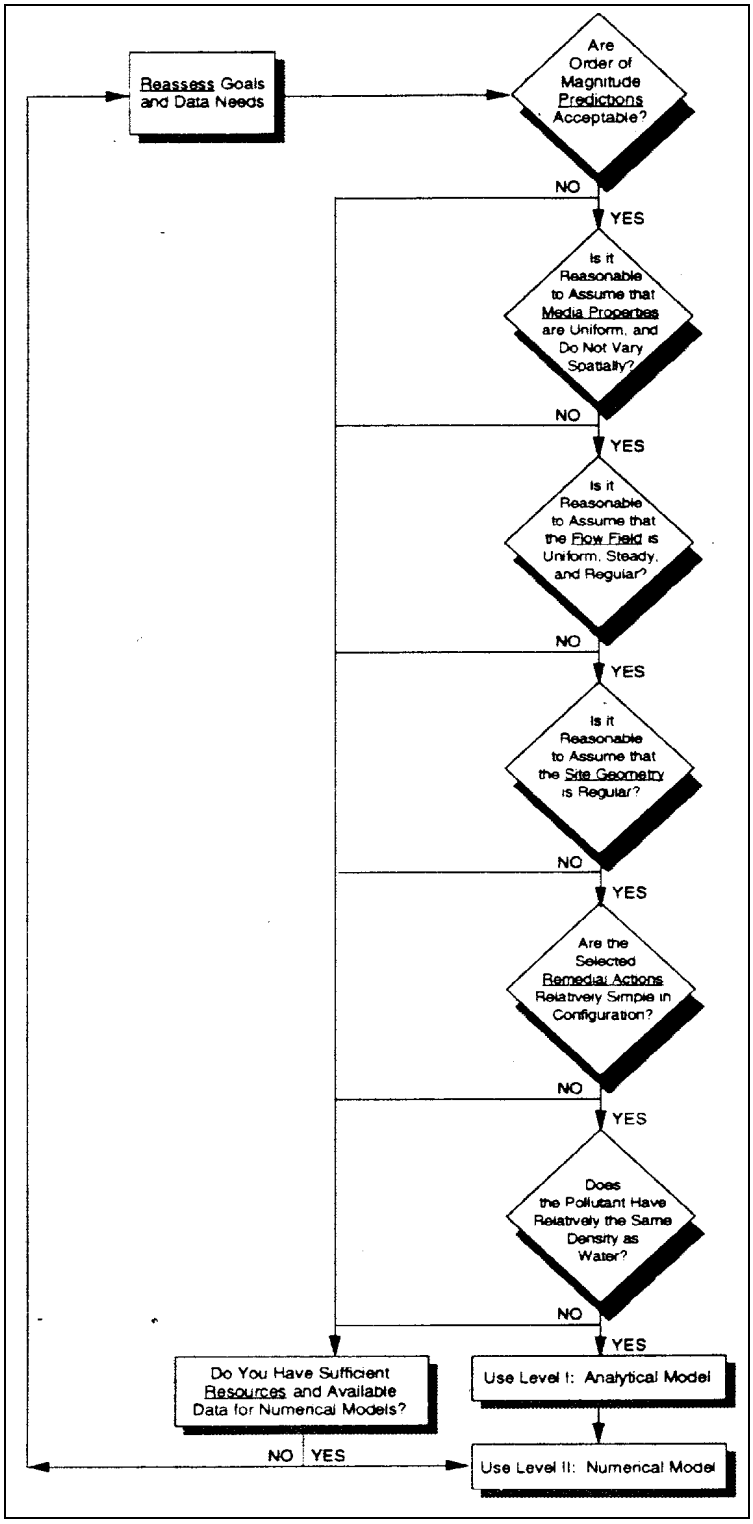


Figure 4-4
Flow Chart for Required Model Capabilities for Soil and Groundwater Systems (Boutwell et. al., 1986)

5) limitations of the model itself. Therefore, model results should be interpreted as estimates of ground-water flow and contaminant transport. Bond and Hwang (1988) recommend that models be used for comparing various scenarios, since all scenarios would be subject to the same limitations and simplifications.

The quality of model results can depend to a large extent on the experience and judgement of the modeler, and on the quality of the data used to develop model input. The process of applying the model may highlight data deficiencies that may require additional data collection. The model results should be calibrated to obtain the best fit to the observed data. The accuracy of the results obtained from modeling efforts should then be validated. Model validation, which is the comparison of model results with experimental data or environmental data, is a critical aspect of model application, and is particularly important for site-specific evaluations.

Several recent reports present detailed discussions of the issues associated with model selection, application, and validation. Donigian and Rao (1990) address each of these issues, and present several options for developing a framework for model validation. EPA's Exposure Assessment Group has developed suggested recommendations and guidance on model validation (Versar Inc., 1987). A recent report by the National Research Council (1990) discusses the issues related to model application and validation, and provides recommendations for the proper use of ground-water models. Weaver et al. (1989) discuss options for selection and field validation of mathematical models.

Model Selection

Ground-water flow and solute transport models range from simple, analytical calculations to sophisticated computer programs that use numerical solutions to solve mathematical equations describing flow and transport. A sophisticated model may not yield an exact estimate of water quality at the relevant point of compliance for a given set of site conditions, but it may allow an estimate of the effects of complex physical and chemical processes. Depending on the complexity of site conditions and the appropriateness of the simplifying assumptions, a fairly sophisticated numerical model may provide useful estimates of water quality at the relevant point of compliance.

The following considerations should be addressed when selecting a model.

Analytical Versus Numerical Models

Mathematical models use either analytical, semi-analytical, or numerical solutions for ground-water flow and transport equations. Each technique has advantages and disadvantages. Analytical solutions are computationally more efficient than numerical simulations and are more conducive to uncertainty analysis (i.e., Monte Carlo techniques). Typically, input data for analytical models are simple and do not require detailed familiarity with the computer model or extensive modeling experience. Analytical solutions are typically used when data necessary for characterization of the site are sparse and simplifying assumptions are appropriate (Javandel et al., 1984). The limited data available in most field situations may not justify the use of a detailed numerical model; in some cases, results from simple analytical models may be appropriate

(Huyakorn et al., 1986). Analytical models require simplifying assumptions about the system. Therefore, complex interactions involving several fate and transport processes cannot be addressed in detail. Analytical models generally require a limited number of parameters that are often assumed to be constant in space and time (van der Heijde and Beljin, 1988).

Semi-analytical models approximate complex analytical solutions using numerical techniques (van der Heijde and Beljin, 1988). Semi-analytical methods allow for more complex site conditions than those that can be simulated with a purely analytical solution. Semi-analytical solution methods can consider multiple sources or recharging and discharging wells. However, they still require simplifying assumptions about the dimensionality and homogeneity of the system.

Numerical models are able to evaluate more complex site conditions than either analytical or semi-analytical models. Numerical models provide the user with a large amount of flexibility; irregular boundaries and spatial and temporal variations in the system can be considered. Numerical models require significantly more data than analytical models, and are typically more computationally intensive. Use of a numerical model requires an experienced modeler, and can involve a larger amount of computer time than simulations using an analytical or semi-analytical method.

To select an appropriate model, the complexity of the site hydrology and the availability of data should be considered. If data are insufficient, a highly sophisticated and complex model should not be used. In some situations, it is beneficial to use an analytical or semi-analytical model as a "screening level" model to define the range of possible values, and to use a numerical model when there are sufficient data.

A highly complex hydrogeologic system cannot be accurately represented with a simple analytical model. Heterogeneous or anisotropic aquifer properties, multiple aquifers, and complicated boundary conditions can be simulated using numerical models. In addition, sophisticated numerical models are available that can simulate processes such as fracture flow. Because each site is unique, the modeler should determine which conditions and processes are important at a specific site, and then select a suitable model.

Spatial Characteristics of the System

Although actual landfill units and hydrogeologic systems are three-dimensional, it is often desirable to reduce the number of dimensions simulated in a mathematical model to one or two. Two- and three-dimensional models are generally more complex and computationally expensive than one-dimensional models, and therefore require more data. In some instances, a one-dimensional model may adequately represent the system; the available data may not warrant the use of a multi-dimensional model. However, modeling a truly three-dimensional system using a two-dimensional model may produce results without adequate spatial detail. The choice of the number of dimensions in the model should be made for a specific site, based on the complexity of the site and the availability of data.

Steady-State Versus Transient Models

Models can simulate either steady-state or transient flow conditions. It may be

appropriate to assume that some ground-water flow systems have reached approximate "steady-state" conditions, which implies that the system has reached equilibrium and no significant changes are occurring over time. The assumption of steady-state conditions generally simplifies the mathematical equations used to describe flow processes, and reduces the amount of input data required.

However, assuming steady-state conditions in a system that exhibits transient behavior may produce inaccurate results. For example, climatic variables, such as precipitation, vary over time and may have strong seasonal components. In such settings, the assumption of constant recharge of the ground-water system would be incorrect. Steady-state models also may not be appropriate for evaluating the transport of chemicals which sorb or transform significantly (Mulkey et al., 1989). The choice of simulating steady-state or transient conditions should be based on the degree of temporal variability in the system.

Boundary and Initial Conditions

The solution of differential equations describing flow and transport processes requires that initial and boundary conditions be specified. The initial conditions describe the conditions present in the system at the beginning of the simulation. In many ground-water flow and transport models, these conditions are related to the initial hydraulic conditions in the aquifer and the initial concentration of contaminants. Boundary conditions define the conditions present on the borders of the system, which may be steady-state or temporally variable. The initial and boundary conditions chosen to represent a site can significantly affect the results of the simulation.

One of the most significant boundary conditions in solute transport models is the introduction of a contaminant to the system. A source of ground-water contamination should be described in terms of its spatial, chemical, and physical characteristics, and its temporal behavior. Spatially, a source may be classified as a point source, line source, a distributed source of limited areal or three-dimensional extent, or as a non-point source of unlimited extent (van der Hjeide et al., 1988). Typically, temporal descriptions of the source term boundary conditions for models with analytical solutions are constant, constant pulse, and/or exponential decay (Mulkey et al., 1989). Numerical models typically handle a much wider range of source boundary conditions, allowing for a wide range of contaminant loading scenarios.

Homogeneous Versus Heterogeneous Aquifer/Soil Properties

The extent of the spatial variability of the properties of each aquifer will significantly affect the selection of a mathematical model. Many models assume uniform aquifer properties, which simplifies the governing equations and improves computational efficiency. For example, a constant value of hydraulic conductivity may be assumed at every point in the aquifer. However, this assumption may ignore the heterogeneity in the hydrogeologic system. Bond and Hwang (1988) present guidelines for determining whether the assumption of uniform aquifer properties is justified at a particular site. They state that the error associated with using an average value versus a spatial distribution is site-specific and extremely difficult to determine.

When site-specific data are limited, it is common to assume homogeneous and

isotropic aquifer properties, and to develop a "reasonable worst-case" scenario for contaminant migration in the subsurface. However, as Auerbach (1984) points out, the assumption of homogeneous and isotropic aquifers often will not provide a "worst-case" scenario. For example, a continuous zone of higher hydraulic conductivity in the direction of ground-water flow can result in much higher rates of contaminant movement than would be predicted in a completely homogeneous aquifer. To develop a true "worst-case" model, information on the probable heterogeneity and anisotropy of the site should be collected.

The number of aquifers in the hydrogeologic system also will affect the selection of a mathematical model. Some systems include only a single unconfined or confined aquifer, which is hydraulically isolated from the surrounding layers. Some mathematical models, and in particular those with analytical solutions, can simulate only single layers. In other cases, the upper aquifer may be hydraulically connected to underlying aquifers. The MSWLF Criteria specify that MCLs not be exceeded at the relevant point of compliance within the uppermost aquifer. The uppermost aquifer includes not only the aquifer that is nearest the ground surface, but also all lower aquifers that are hydraulically connected to the uppermost aquifer within the vicinity of the facility.

Availability of Data

Although computer models can be used to make predictions about leachate generation and migration, these predictions are highly dependent on the quantity and quality of the available data. One of the most common limitations to modeling is insufficient data. Uncertainty in model predictions results from the inability to characterize a site in terms of the boundary conditions or the key parameters describing the significant flow and transport processes (National Research Council, 1990). The application of a mathematical model to a site typically requires a large amount of data. Inexperienced modelers may attempt to apply a model with insufficient data and, as a result, produce model results that are inconclusive.

To obtain accurate model results, it is essential to use data that are appropriate for the particular site being modeled. Models that include generic parameters, based on average values for similar sites, can be used to provide initial guidance and general information about the behavior of a system, but it is inappropriate to apply generic parameters to a specific hydrogeologic system. An excellent summary of the data required to model saturated and unsaturated flow, surface water flow, and solute transport is presented in Mercer et al. (1983). This report provides definitions and possible ranges of values for source terms, dependent variables, boundary conditions, and initial conditions.

Summary of Available Models

Several detailed reviews of ground-water models are available in the literature. A number of ground-water models, including saturated flow, solute transport, heat transport, fracture flow, and multiphase flow models, are summarized in van der Heijde et al. (1988). A report by van der Heijde and Beljin (1988) provides detailed descriptions of 64 ground-water flow and solute transport models that were selected for use in determining wellhead protection areas. A review of ground-water flow and

transport models for the unsaturated zone is presented in Oster (1982). A large number of ground-water flow and transport models are summarized by Bond and Hwang (1988). Finally, Travers and Sharp-Hansen (1991) summarize models that may be applicable to problems of leachate generation and migration from MSWLF units. (See References supplied in Section 4.6.)

Table 4-1 (adapted from Travers and Sharp-Hansen (1991)) provides information on select leachate generation models. Tables 4-1a, b, and c list some of the available models that can be used to predict contaminant transport. The factors used to select these models include availability, documentation, uniqueness, and the size of the user community. These models are categorized by the techniques used to solve flow and transport equations. Table 4-1a lists analytical and semi-analytical models, and Tables 4-1b and 4-1c list numerical models that are solved by the finite-difference and the finite-element method, respectively.

The types of models that are available for application to the evaluation of MSWLF designs include leachate generation models and saturated and unsaturated zone flow and transport models. The level of sophistication of each of these types of models is based on the complexity of the processes being modeled. The majority of the models consider flow and transport based on advection dispersion equations. More complex models consider physical and chemical transformation processes, fracture flow, and multiphase fluid flow.

Leachate generation models predict the quantity and characteristics of leachate that is released from the bottom of a landfill. These models are used to estimate contaminant source terms and the releases of contaminants to the subsurface. Flow and transport models simulate the transport of contaminants released from the source to the unsaturated and saturated zones. Geochemical models are available that consider chemical processes that may be active in the subsurface such as adsorption, precipitation, oxidation/reduction, aqueous speciation, and kinetics.

Complex flow models have been developed to simulate the effects of nearby pumping and discharging wells, fracture flow, conduit flow in karst terrane, and multiphase flow for fluids that are less dense or more dense than water. However, the use of the more complex models requires additional data based on a thorough investigation of the subsurface characteristics at a site as well as well-trained users to apply the model correctly.

Most of the ground-water flow and solute transport models are deterministic. However, the use of stochastic models, which allow for characterization of spatial and temporal variability in systems, is increasing. A few of the models include a Monte Carlo capability for addressing the uncertainty inherent in the input parameters.

The EPA Multimedia Exposure Assessment Model (MULTIMED)

EPA has developed a modeling package to meet the needs of a large percentage of MSWLF unit owners and operators who will require fate and transport modeling as part of the performance-based design demonstration. This model, the Multimedia Exposure Assessment Model (MULTIMED), is intended for use at sites where certain simplifying assumptions can be made. MULTIMED can be used in

Table 4-1. Models for Application to Leachate Generation Problems (adapted from Travers and Sharp-Hansen, 1991)

Model Reference	Model Dimensions	Flow Conditions	Aquifer Conditions	Model Processes	Chemical Species	Additional Information
Bonazountas and Wagner (1984); SESOIL	1D/FD	Ss,Unsat	L,Hom,Iso	Ppt,Inf, RO,ET, Adv,Dif, Ads,Vol, Dec	single	Seasonal Soil Compartment Model. Simulates transport of water, sediment, and contaminants in soils. Includes affects of capillary rise, biological transformation, hydrolysis, cation exchange, complexation chemistry (metals by organic ligands). Hydrology based on generalized annual water balance dynamics model.
Carsel et al. (1984) PRZM	1D/FD	Usat,Ss,Tr	L,Hom,Iso	Adv,Dis, Dif,Dec, Rxn,ET, Vol,Inf	1,2, or 3	Pesticide Root Zone Model. Also includes plant uptake, leaching, runoff, management practices, and foliar washoff. Hydrologic flow solved by water routing scheme, chemical transport solved by finite difference scheme. Requires meteorological data. Water balance model.
EPRI (1981) UNSAT1D	1D/FD	Sat,Usat, Ss,Tr	Het,Hom,L Iso	Ppt,Inf, RO,ET	flow only	Solves one-dimensional Richard's equation. Accounts for capillary and gravitational effects. Requires landfill design data.
Knisel et al. (1989) GLEAMS	1D/FD	Usat,Tr,Ss	Hom,Iso,L	Inf,Dec,R O,ET,Ads	single	Groundwater Loading Effects of Agricultural Systems model. Developed by modifying CREAMS (Knisel, 1980) to add capability to estimate groundwater loadings. Simulates erosion. Water balance computations.
Schroeder et al. (1984) HELP	quasi-2D FD	Tr,Sat,Usat	L,Homo, Iso	ET,Ppt,In f,Dra,RO	flow only	A quasi-two-dimensional, deterministic water budget for landfills. Requires landfill design data. Model may be applied to open, partially open, and closed landfills. Requires meteorological data.

1D = One-dimensional
2D = Two-dimensional
3D = Three-dimensional
H = Horizontal
V = Vertical
Ss = Steady-State
Tr = Transient

Sat = Saturated
Usat = Unsaturated
Hom = Homogeneous
Het = Heterogeneous
Iso = Isotropic
An = Anisotropic
C = Confined Aquifer

Uc = Unconfined aquifer
Adv = Advection
Dis = Decay
Dif = Diffusion
Dec = Decay
Ads = Adsorption
Ret = Retardation

In = Infiltration
ET = Evapotranspiration
Ppt = Precipitation
RO = Runoff
Rxn = Reaction
W = Discharge or pumping wells
L = Layers

Table 4-1a. Analytical and Semi-Analytical Models for Application to Leachate Migration Problems (adapted from Travers and Sharp-Hansen, 1991)

Model Reference	Model Dimensions	Flow Conditions	Aquifer Conditions	Model Processes	Chemical Species	Additional Information
Beljin (1983) SOLUTE	1D(H), 2D(H) or 3D	Ss, Sat	C, Hom, Iso	Adv, Dis, Ads, Dec	single	A package of 8 analytical models for solute transport in groundwater. Also includes a program for unit conversion and error and function calculation.
Domenico and Palciauakes (1982) VHS	1D advection 2D dispersion	Ss, Sat	C, Hom, Iso	Adv, Dis	single	Model for Vertical and Horizontal Spreading. Assumes infinite aquifer thickness. EPA considers VHS to be a conservative model since retardation, sorptions, precipitation, aquifer recharge not considered. Source is continuous constant strip source.
Domenico and Robbins (1985)	3D (transport)	Ss, Sat	C, Hom, Iso	Adv, Dis	single	Contaminant transport from a finite or continuous source in a continuous flow regimen. Assumes infinite thickness.
Huyakorn et al. (1987)	3D	Ss, Sat	C, Uc, Hom, Iso, An	Adv, Dis, Ads, Dec	single	Model allows for estimation of maximum concentration distribution along center line of a leachate plume. Gaussian vertical strip source.
Javandel et al. (1984) RESSQ	2D(H)	Ss, Sat	C, Hom, Iso	Adv, Ads	single	Calculate transport by advection and adsorption in a homogeneous, isotropic, uniform-thickness, confined aquifer. Uses semi-analytical solution methods.
Lindstrom and Boerams (1989) CXPHPH	1D(H)	Ss, Sat	C, Hom, Iso	Adv, Dis, Dec, Ads, Rxn	single	Analytical solutions of the general one-dimensional transport equation for confined aquifers, with several different initial and boundary conditions.
Nelson and Schur (1983) PATHS	2D(H)	Ss, Tr, Sat	C, Hom, Iso	Adv, Ads	single	Groundwater flow equations solved analytically, characteristic pathlines solved by Ruage-Kulls method.
Ostendorf et al. (1984)	1D(H,V)	Ss, Sat	Uc, Hom, Iso	Adv, Ads, Dec	single	Assumes transport of a simply reactive contaminant through a landfill and initially pure, underlying, shallow, aquifer with plane, sloping bottom.
Prakash (1984)	1D, 2D or 3D	Ss, Sat	C, Hom, Iso	Adv, Dis, Ads, Dec	single	Source boundary condition: instantaneous or finite-time release of contaminants from a point, line, plane, or parallel piped source.

Table 4-1a. Analytical and Semi-Analytical Models for Application to Leachate Migration Problems (adapted from Travers and Sharp-Hansen, 1991) (continued)

Model Reference	Model Dimensions	Flow Conditions	Aquifer Conditions	Model Processes	Chemical Species	Additional Information
Salhotre et al. (1990) MULTIMED	1D(vadose zone), 3D (transport in saturated zone)	Ss, Sat, Usat	Uc, Hom, Iso, L (Usat)	Adv, Dis, Ads, Dec, Vol	single	Model simulates movement of contaminants in saturated and unsaturated groundwater zones. In surface water and emissions to air. Includes Monte Carlo capability. Unsaturated zone transport solution is analytical, saturated zone is semi-analytical. Gaussian or patch source boundary condition.
Unge et al. (1986); Summers et al. (1989) MYGRT (Version 1.0, 2.0)	1,2(H,V)	Ss, Sat	Uc, Hom, Iso	Adv, Dis, Ret, Dec	single	Simulates migration of organic and inorganic solutes. Constant pulse source boundary condition. Proprietary code.
van Genuchten and Alves (1982)	1D(H,V)	Ss, Sat	C, Hom, Iso	Adv, Dis, Dif, Ads	single	Three types of source boundary conditions are considered: constant, exponential decay, and pulse step function.
Yeh (1981) AT123D	1D, 2D or 3D	Tr, Sat	C, Uc, Hom, Iso, An	Adv, Dis, Dif, Ads, Dec	single	Analytical, semi-analytical, solution techniques based on Green's function. Source boundary conditions include: constant, instantaneous pulse, or finite-time release from a point, line, area, or volume source

1D	=	One-dimensional	Sat	=	Saturated	Uc	=	Unconfined aquifer	Inf	=	Infiltration
2D	=	Two-dimensional	Usat	=	Unsaturated	Adv	=	Advection	ET	=	Evapotranspiration
3D	=	Three-dimensional	Hom	=	Homogeneous	Dis	=	Dispersion	Ppt	=	Precipitation
H	=	Horizontal	Het	=	Heterogeneous	Dif	=	Diffusion	RO	=	Run-off
V	=	Vertical	Iso	=	Isotropic	Dec	=	Decay	Rxn	=	Reaction
Ss	=	Steady-state	An	=	Anisotropic	Ads	=	Adsorption	W	=	Discharge or pumping wells
Tr	=	Transient	C	=	Confined aquifer	Ret	=	Retardation	L	=	Layers

Table 4-1b. Finite-Difference Models for Application to Leachate Migration Problems (adapted from Travers and Sharp-Hansen, 1991)

Model Reference	Model Dimensions	Flow Conditions	Aquifer Conditions	Model Processes	Chemical Species	Additional Information
Abriele and Pinder (1983)	1D	Ss, Tr, Sat, Usat	Uc, Iso, Hom	Dis, Dif	multiphase	Multiphase model for modeling aquifer contamination by organic compounds. Simulates simultaneous transport of contaminant in a nonaqueous phase, aqueous phase and as a mobile fraction of gas phase. Effects of capillarity, interphase mass transfer, diffusion, and dispersion considered.
Dillion et al. (1981; 1986) SWIFT/ SWIFT II	3D	Ss, Tr, Sat	C, Hom, Het, Iso, An	Adv, Dis, Dif, Dec, Rxn, W	single	Coupled groundwater flow, and heat or solute transport. Includes fracture flow, ion exchange, salt dissolution, in confined aquifer. SWIFT-II includes dual porosity for fractured media.
Erdogen and Heufeld (1983)	1D	Tr, Sat	Hom, Iso	Adv, Dis, Ads, Ppt	single	Model describes the desorption process using intraparticle and external file diffusion resistances as rate controlling mechanism (considers fluid velocity and particle size). Predicts leachate concentration profiles at the boundary of the landfill. Simulates precipitation with interrupted flow conditions.
GeoTrans (1985); Faust et al. (1989) SWAN-FLOW	3D	Ss, Tr, Sat, Usat	Uc, Hom, Het, Iso, An		multiphase	Faust (1989) extends SWANFLOW to include a solution technique which takes advantage of parallel computer processing.
Kipp (1987) NST3D	3D	Tr, Sat	C, Uc, Hom, Het, Iso, An	Adv, Dis, Dif, Ads, Dec, W	single	Simulates coupled density dependent groundwater flow and heat or mass transport in an anisotropic, heterogeneous aquifer.
Konikow and Bradshoeft (1985) USGS-NOC	2D (H,V)	Ss, Tr, Sat	C, Uc, Hom, Het, Iso, An	Adv, Dis, Dif, Ads, Dec, ET, W	single	Groundwater flow solved by finite difference, solute transport by the method of characteristics.

Table 4-1b. Finite-Difference Models for Application to Leachate Migration Problems (adapted from Travers and Sharp-Hansen, 1991) (continued)

Model Reference	Model Dimensions	Flow Conditions	Aquifer Conditions	Model Processes	Chemical Species	Additional Information
Harasimhan et al. (1986) DYNAMIX	3D	Ss, Tr, Sat	C, Uc, Hom, Het, Iso, An	Adv, Dis, Dif, Dec	multiple	Model couples a chemical specification model PHREEQE (Parkhurst et al, 1980) with a modified form of the transport code TRUMP (Edwards, 1969, 1972). Considers equilibrium reactions (see geochemical codes).
Prickett et al. (1981) RANDOM WALK or TRANS	1D or 2D(H)	Ss, Tr, Sat	C, Uc, Hom, Het, Iso, An, L	Adv, Dis, Ads, Dec, ET, W	single	Finite difference solution to groundwater flow, random walk approach used to simulate dispersion. Simulates random movement. Aquifer properties vary spatially and temporally.
Ruachel (1985) PORFLOW-II and III	2D(H,V) or 3D	Ss, Tr, Sat	C, Uc, Hom, Het, Iso, An, L	Adv, Dis, Dif, Ads, Dec, Rxn, W	single	Simulates density dependent flow, heat and mass transport. Aquifer and fluid properties may be spatially and temporally variable. Integrated finite difference solution. Includes phase change.
Travis (1984) TRACR3D	3D	Ss, Tr, Sat, Usat	C, Hom, Het, Iso, An	Adv, Dis, Dif, Ads, Dec	two-phase, multiple	Simulates transient two-phase flow and multi-component transport in deformable, heterogeneous, reactive, porous media.
Walton (1984) 35 Micro-computer Programs	1D, 2D(H) or 3D (radial, cyl)	Ss, Tr, Sat	C, Uc, Hom, Het, L	Adv, Dis, Ret	single	A series of analytical and simple numerical programs to analyze flow and transport of solutes in aquifers with simple geometry.

1D	=	One-dimensional	Sat	=	Saturated	Uc	=	Unconfined aquifer	Inf	=	Infiltration
2D	=	Two-dimensional	Usat	=	Unsaturated	Adv	=	Advection	ET	=	Evapotranspiration
3D	=	Three-dimensional	Hom	=	Homogeneous	Dis	=	Dispersion	Ppt	=	Precipitation
H	=	Horizontal	Het	=	Heterogeneous	Dif	=	Diffusion	RO	=	Run-off
V	=	Vertical	Iso	=	Isotropic	Dec	=	Decay	Rxn	=	Reaction
Ss	=	Steady-state	An	=	Anisotropic	Ads	=	Adsorption	W	=	Discharge or pumping wells
Tr	=	Transient	C	=	Confined aquifer	Ret	=	Retardation	L	=	Layers

Table 4-1c. Finite-Element Models for Application to Leachate Migration Problems (adapted from Travers and Sharp-Hansen, 1991)

Model Reference	Model Dimensions	Flow Conditions	Aquifer Conditions	Model Processes	Chemical Species	Additional Information
Cederberg et al. (1985) TRANQL	1 D, radial	Ss, Sat	C, Uc, Hom	Adv, Dis, Dif, Ads, Dec	multiple	Multicomponent transport model which links chemical equilibrium code MICROQL (Westfall, 1976) and transport code ISOQUAD (Pinder, unpublished manuscript, 1976). Includes a complexation in aqueous phase.
Dean et al. (1989) RUSTIC	1D(root zone, vadose zone); 2DH,V, radial (saturated zone)	Ss, Tr, Usat, Sat	C, Uc, Hom, Het, Iso, An, L	Adv, Dis, Ads, Dif, Dec, ET, W, Ppt, RO, Ret	1, 2, or 3	Simulates fate and transport of chemicals through three linked modules: root, values, and saturated zone. Includes PRZN (Carsel et al., 1984). RUSTIC is in Beta-testing phase. Includes Monte Carlo capability PRZN solution by finite difference.
Gupta et al. (1982) CFEST	2D(H,V) or 3D	Ss, Tr, Sat	C, Uc, Hom, Het, Iso, An, L	Adv, Dis, Dif, Ads, Dec, W	single	Solves coupled groundwater flow, solute and heat transport equations. Fluid may be heterogeneous.
Gureghian et al. (1980)	2D	Ss, Sat	C, Uc, Iso, An	Adv, Dis, Ads, Dec	single	Source boundary condition: Gaussian distributed source. Transport only.
Guvanssen (1986) NOTIF	1D, 2D, or 3D	Ss, Tr, Sat, Usat	C, Uc, Hom, Het, Iso, An	Adv, Dis, Dif, Ads, Dec	single	Groundwater flow and solute transport in fractured porous media.
Haji-Djafari and Wells (1982) GEOFLOW	3D	Ss, Tr, Sat	C, Uc, Hom, Het, Iso, An, L	Adv, Dis, Dif, Dec, Rxn, Ret, W	single	Simulation of areal configuration only. Proprietary code.
Huyakorn et al. (1984) SEFTRAN	1D or 2D(H,V)	Ss, Tr, Sat	C, Uc, Hom, Het, Iso, An, L	Adv, Dis, Dif, Ads, Dec, W	single	Proprietary code.
Huyakorn et al. (1986) TRAFRAP	2D(H,V)	Ss, Tr, Sat	C, Uc, Hom, Het, Iso, An	Adv, Dis, Dif, Ads, Dec, Rxn, W	single	Simulates groundwater flow and solute transport in fractured porous media. Includes precipitation.
Osborne and Sykes (1986) WSTIF	2D	Tr, Sat, Usat	Uc, Hom, Het, Iso, An, L		two-phase	Model simulates transport of immiscible organics in groundwater. Assumes no mass transport between phases.

Table 4-1c. Finite-Element Models for Application to Leachate Migration Problems (adapted from Travers and Sharp-Hansen, 1991) (continued)

Model Reference	Model Dimensions	Flow Conditions	Aquifer Conditions	Model Processes	Chemical Species	Additional Information
Theis et al. (1982) FIESTA	1D	Sat	Hom, Iso	Adv, Dis, Ads, Dec	multiple	Combinations of a component transport model, FEAP, and the chemical equilibrium speciation model NINEQL (Westfall et al. 1976). Simulates up to 6 chemical components, including all solution and sorbed phase complexes.
van Genuchten (1978) SUMATRA-I	1D(V)	Tr, Sat, Usat	C, Uc, Hom, Het, Iso, L	Adv, Dis, Ads, Dec, Ret	single	Simulates simultaneous flow of water and solutes in a one-dimensional, vertical soil profile.
Voss (1984) SUTRA	2D(H,V)	Ss, Tr, Sat, Usat	C, Uc, Hom, Het, Iso, An	Adv, Dis, Dif, Ads, Dec, Rxn, W	single	Fluid may be heterogeneous (density-dependent groundwater flow).
Yeh and Ward (1981) FEMWATER FEMWASTE	2D(H,V)	Ss, Tr, Sat, Usat	Uc, Hom, Het, Iso, An	Adv, Dis, Ads, Dec, Ppt, W	single	FEMWATER simulates groundwater flow. FEMWASTE simulates waste transport through saturated-unsaturated porous media. Simulates capillarity, infiltration, and recharge/discharge sources (e.g., lakes, reservoirs, and streams).
Yeh (1990) LEWASTE, 3DLEWASTE	2D/3D	Ss, Tr, Sat, Usat	Uc, C, Hom, Het, Iso, An	Adv, Dis, Ads, Dec, W	single	Transport codes based on the Lagrangian-Eulerian approach, can be applied to Peciet Numbers from 0 to infinity. LEWASTE is intended to simulate 2D local flow systems. 3DLEWASTE can simulate regional or local flow systems. The LEWASTE series replaces the FEMWASTE models.

1D	=	One-dimensional	Sat	=	Saturated	Uc	=	Unconfined aquifer	Inf	=	Infiltration
2D	=	Two-dimensional	Usat	=	Unsaturated	Adv	=	Advection	ET	=	Evapotranspiration
3D	=	Three-dimensional	Hom	=	Homogeneous	Dis	=	Dispersion	Ppt	=	Precipitation
H	=	Horizontal	Het	=	Heterogeneous	Dif	=	Diffusion	RO	=	Run-off
V	=	Vertical	Iso	=	Isotropic	Dec	=	Decay	Rxn	=	Reaction
Ss	=	Steady-state	An	=	Anisotropic	Ads	=	Adsorption	W	=	Discharge or pumping wells
Tr	=	Transient	C	=	Confined aquifer	Ret	=	Retardation	L	=	Layers

conjunction with a separate leachate source model, such as HELP (Schroeder et al., 1984). Output from HELP is then used in MULTIMED to demonstrate that either a landfill design or the specific hydrogeologic conditions present at a site will prevent contaminant concentrations in ground water from exceeding the concentrations listed in Table 1 of §258.40. (Refer to pp. 4-53 and 6-8 for further discussion of HELP.) A description of MULTIMED follows with guidance for determining if its use is appropriate for a given site.

[NOTE: Version 3.0 of the HELP model will be available during the fall of 1993. To obtain a copy, call EPA's Office of Research and Development (ORD) in Cincinnati at (513) 569-7871.]

Overview of the Model

The MULTIMED model consists of modules that estimate contaminant releases to air, soil, ground water, or surface water. General information about the model and its theory is provided in Salhotra *et al.* (1990). Additionally, information about the application of MULTIMED to MSWLF units (developed by Sharp-Hansen *et al.* [1990]) is summarized here. In MULTIMED, a steady-state, one-dimensional, semi-analytical module simulates flow in the unsaturated zone. The output from this module, which is water saturation as a function of depth, is used as input to the unsaturated zone transport module. The latter simulates transient, one-dimensional (vertical) transport in the unsaturated zone and includes the effects of dispersion, linear adsorption, and first-order decay. Output from the unsaturated zone modules is used as input to the semi-analytical saturated zone transport module. The latter considers three-dimensional flow because the effects of lateral or vertical dispersion may significantly affect the model results.

Therefore, reducing the dimensions to one in this module would produce inaccurate results. The saturated zone transport module also considers linear adsorption, first-order decay, and dilution as a result of ground-water recharge. In addition, MULTIMED has the capability to assess the impact of uncertainty in the model inputs on the model output (contaminant concentration at a specified point), using the Monte Carlo simulation technique.

The simplifying assumptions required to obtain the analytical solutions limit the complexity of the systems that can be evaluated with MULTIMED. The model does not account for site-specific spatial variability (e.g., aquifer heterogeneities), the shape of the land disposal facility, site-specific boundary conditions, or multiple aquifers and pumping wells. Nor can MULTIMED simulate processes, such as flow in fractures and chemical reactions between contaminants, that may have a significant effect on the concentration of contaminants at a site. In more complex systems, it may be beneficial to use MULTIMED as a "screening level" model to allow the user to obtain an understanding of the system. A more complex model could then be used if there are sufficient data.

Application of MULTIMED to MSWLF Units

Procedures have been developed for the application of MULTIMED to the design of MSWLF units. They are explained in Sharp-Hansen et al. (1990) and are briefly summarized here. The procedures are:

- Collect site-specific hydrogeologic data, including amount of leachate generated (see Section 4.3.3);

- Identify the contaminant(s) to be simulated and the point of compliance;

- Propose a landfill design and determine the corresponding infiltration rate; then

- Run MULTIMED and calculate the dilution attenuation factor (DAF) (i.e., the factor by which the concentration is expected to decrease between the landfill unit and the point of compliance); and

- Multiply the initial contaminant concentration by the DAF and compare the resulting concentration to the MCLs to determine if the design will meet the standard.

At this time, only contaminant transport in the unsaturated and/or saturated zones can be modeled, because the other options (i.e., surface water, air) have not yet been thoroughly tested. In addition, only steady-state transport simulations are allowed. No decay of the contaminant source term is permitted; the concentration of contaminants entering the aquifer system is assumed to be constant over time. The receptor (e.g., a drinking water well) is located directly downgradient of the facility and intercepts the contaminant plume; also, the contaminant concentration is calculated at the top of the aquifer.

The user should bear in mind that MULTIMED may not be an appropriate model for some sites. Some of the issues that should be considered before modeling efforts proceed are summarized in Table 4-2. A "no" answer to any of the questions in Table 4-2 may indicate that MULTIMED is not the most appropriate model to use. As stated above, MULTIMED utilizes analytical and semi-analytical solution techniques to solve the mathematical equations describing flow and transport. As a result, the representation of a system simulated by the model is simple, and little or no spatial or temporal variability is allowed for the parameters in the system. Thus, a highly complex hydrogeologic system cannot be accurately represented with MULTIMED.

The spatial characteristics assumed in MULTIMED should be considered when applying MULTIMED to a site. The assumption of vertical, one-dimensional unsaturated flow may be valid for facilities that receive uniform areal recharge. However, this assumption may not be valid for facilities where surface soils (covers or daily backfill) or surface slopes result in an increase of run-off in certain areas of the facility, and ponding of precipitation in others. In addition, the simulation of one-dimensional, horizontal flow in the saturated zone requires several simplifying assumptions. The saturated zone is treated as a single, horizontal aquifer with uniform properties (e.g., hydraulic conductivity). The effects of pumping or discharging wells on the ground-water flow system cannot be addressed with the MULTIMED model.

The MULTIMED model assumes steady-state flow in all applications. Some ground-water flow systems are in an approximate "steady-state," in which the amount of water entering the flow system equals the amount of water leaving the system. However, assuming steady-state conditions in a system that exhibits transient behavior may produce inaccurate results.

TABLE 4-2
ISSUES TO BE CONSIDERED
BEFORE APPLYING MULTIMED
(from Sharp-Hansen et al., 1990)

Objectives of the Study

- Is a "screening level" approach appropriate?
- Is modeling a "worst-case scenario" acceptable?

Significant Processes Affecting Contaminant Transport

- Does MULTIMED simulate all the significant processes occurring at the site?
- Is the contaminant soluble in water and of the same density as water?

Accuracy and Availability of the Data

- Have sufficient data been collected to obtain reliable results?
- What is the level of uncertainty associated with the data?
- Would a Monte Carlo simulation be useful? If so, are the cumulative probability distributions for the parameters with uncertain values known?

Complexity of the Hydrogeologic System

- Are the hydrogeologic properties of the system uniform?
- Is the flow in the aquifer uniform and steady?
- Is the site geometry regular?
- Does the source boundary condition require a transient or steady-state solution?

MULTIMED may be run in either a deterministic or a Monte Carlo mode. The Monte Carlo method provides a means of estimating the uncertainty in the results of a model, if the uncertainty of the input variables is known or can be estimated. However, it may be difficult to determine the cumulative probability distribution for a given parameter. Assuming a parameter probability distribution when the distribution is unknown does not help reduce uncertainty. Furthermore, to obtain a valid estimate of the uncertainty in the output, the model must be run numerous times (typically several hundred times), which can be time-consuming. These issues should be considered before utilizing the Monte Carlo technique.

4.3 COMPOSITE LINER AND LEACHATE COLLECTION SYSTEM 40 CFR §258.40

4.3.1 Statement of Regulation

(a) New MSWLF units and lateral expansions shall be constructed:

(1) *See Statement of Regulation in Section 4.2.1 of this guidance document for performance-based design requirements.*

(2) With a composite liner, as defined in paragraph (b) of this section and a leachate collection system that is designed and constructed to maintain less than a 30-cm depth of leachate over the liner,

(b) For purposes of this section, composite liner means a system consisting of two components; the upper component must consist of a minimum 30-mil flexible

membrane liner (FML), and the lower component must consist of at least a two-foot layer of compacted soil with a hydraulic conductivity of no more than 1 x 10^{-7} cm/sec. FML components consisting of high density polyethylene (HDPE) shall be at least 60-mil thick. The FML component must be installed in direct and uniform contact with the compacted soil component.

4.3.2 Applicability

New MSWLF units and expansions of existing MSWLF units in States without approved programs must be constructed with a composite liner and a leachate collection system (LCS) that is designed to maintain a depth of leachate less than 30 cm (12 in.) above the liner. A composite liner consists of a flexible membrane liner (FML) installed on top of, and in direct and uniform contact with, two feet of compacted soil. The FML must be at least 30-mil thick unless the FML is made of HDPE, which must be 60-mil thick. The compacted soil liner must be at least two feet thick and must have a hydraulic conductivity of no more than 1 x 10^{-7} cm/sec.

Owners and operators of MSWLF units located in approved States have the option of proposing a performance-based design provided that certain criteria can be met (see Section 4.2.2).

4.3.3 Technical Considerations

This section provides information on the components of composite liner systems including soils, geomembranes, and leachate collection systems.

Standard Composite Liner Systems

The composite liner system is an effective hydraulic barrier because it combines the complementary properties of two different materials into one system: 1) compacted soil with a low hydraulic conductivity; and
2) a FML (FMLs are also referred to as geomembranes). Geomembranes may contain defects including tears, improperly bonded seams, and pinholes. In the absence of an underlying low-permeability soil liner, flow through a defect in a geomembrane is essentially unrestrained. The presence of a low-permeability soil liner beneath a defect in the geomembrane reduces leakage by limiting the flow rate through the defect.

Flow through the soil component of the liner is controlled by the size of the defect in the geomembrane, the available air space between the two liners into which leachate can flow, the hydraulic conductivity of the soil component, and the hydraulic head. Fluid flow through soil liners is calculated by Darcy's Law, where discharge (Q) is proportional to the head loss through the soil (dh/dl) for a given cross-sectional flow area (A) and hydraulic conductivity (K) where:

$$Q = KA(dh/dl)$$

Leakage through a geomembrane without defects is controlled by Fick's first law, which describes the process of liquid diffusion through the membrane liner. The diffusion process is similar to flow governed by Darcy's law for soil liners except that diffusion is driven by concentration gradients and not by hydraulic head. Although diffusion rates in geomembranes are several orders of magnitude lower than comparable hydraulic flow rates in low-permeability soil liners, construction of a completely impermeable geomembrane is

difficult. The factor that most strongly influences geomembrane performance is the presence of imperfections such as improperly bonded seams, punctures and pinholes. A detailed discussion of leakage through geomembranes and composite liners can be found in Giroud and Bonaparte (1989 (Part I and Part II)). A geomembrane installed with excellent control over defects may yield the equivalent of a one-centimeter-diameter hole per acre of liner installed (Giroud and Bonaparte, 1989 (Part I and Part II)). If the geomembrane were to be placed over sand, this size imperfection under one foot of constant hydraulic head could be expected to account for as much as 3,300 gal/acre/day (31,000 liters/hectare/ day) of leakage. Based upon measurements of actual leakage through liners at facilities that have been built under rigorous control, Bonaparte and Gross (1990) have estimated an actual leakage rate, under one foot of constant head, of 200 liters/hectare/day or about 21 gallons/acre/day for landfill units.

The uniformity of the contact between the geomembrane and the soil liner is extremely important in controlling the effective flow area of leachate through the soil liner. Porous material, such as drainage sand, filter fabric, or other geofabric, should not be placed between the geomembrane and the low permeability soil liner. Porous materials will create a layer of higher hydraulic conductivity, which will increase the amount of leakage below an imperfection in the geomembrane. Construction practices during the installation of the soil and the geomembrane affect the uniformity of the geomembrane/soil interface, and strongly influence the performance of the composite liner system.

Soil Liner

The following subsections discuss soil liner construction practices including thickness requirements, lift placement, bonding of lifts, test methods, prerequisite soil properties, quality control, and quality assurance activities.

Thickness

Two feet of soil is generally considered the minimum thickness needed to obtain adequate compaction to meet the hydraulic conductivity requirement. This thickness is considered necessary to minimize the number of cracks or imperfections through the entire liner thickness that could allow leachate migration. Both lateral and vertical imperfections may exist in a compacted soil. The two-foot minimum thickness is believed to be sufficient to inhibit hydraulic short-circuiting of the entire layer.

Lift Thickness

Soil liners should be constructed in a series of compacted lifts. Determination of appropriate lift thickness is dependent on the soil characteristics, compaction equipment, firmness of the foundation materials, and the anticipated compactive effort needed to achieve the required soil hydraulic conductivity. Soil liner lifts should be thin enough to allow adequate compactive effort to reach the lower portions of the lift. Thinner lifts also provide greater assurance that sufficient compaction can be achieved to provide good, homogeneous bonding between subsequent lifts. Adequate compaction of lift thickness between five and ten inches is possible if appropriate equipment is used (USEPA, 1988). Nine-inch loose lift thicknesses that will yield a 6-

inch soil layer also have been recommended prior to compaction (USEPA, 1990a).

Soil liners usually are designed to be of uniform thickness with smooth slopes over the entire facility. Thicker areas may be considered wherever recessed areas for leachate collection pipes or collection sumps are located. Extra thickness and compactive efforts near edges of the side slopes may enhance bonding between the side slopes and the bottom liner. In smaller facilities, a soil liner may be designed for installation over the entire area, but in larger or multi-cell facilities, liners may be designed in segments. If this is the case, the design should address how the old and new liner segments will be bonded together (U.S. EPA, 1988).

Bonding Between Lifts

It is not possible to construct soil liners without some microscopic and/or macroscopic zones of higher and lower hydraulic conductivity. Within individual lifts, these preferential pathways for fluid migration are truncated by the bonded zone between the lifts. If good bonding between the lifts is not achieved during construction, the vertical pathways may become connected by horizontal pathways at the lift interface, thereby diminishing the performance of the hydraulic barrier.

Two methods may be used to ensure proper bonding between lifts. Kneading or blending a thinner, new lift with the previously compacted lift may be achieved by using a footed roller with long feet that can fully penetrate a loose lift of soil. If the protruding rods or feet of a sheepsfoot roller are sufficient in length to penetrate the top lift and knead the previous lift, good bonding may be achieved. Another method includes scarifying (roughening), and possibly wetting, the top inch or so of the last lift placed with a disc harrow or other similar equipment before placing the next lift.

Placement of Soil Liners on Slopes

The method used to place the soil liner on side slopes depends on the angle and length of the slope. Gradual inclines from the toe of the slope enable continuous placement of the lifts up the slopes and provide better continuity between the bottom and sidewalls of the soil liner. When steep slopes are encountered, however, lifts may need to be placed and compacted horizontally due to the difficulties of operating heavy compaction equipment on steeper slopes.

When sidewalls are compacted horizontally, it is important to tie in the edges with the bottom of the soil liner to reduce the probability of seepage planes (USEPA, 1988). A significant amount of additional soil liner material will be required to construct the horizontal lifts since the width of the lifts has to be wide enough to accommodate the compaction equipment. After the soil liner is constructed on the side slopes using this method, it can be trimmed back to the required thickness. The trimmed surface of the soil liner should be sealed by a smooth-drum roller. The trimmed excess materials can be reused provided that they meet the specified moisture-density requirements.

Hydraulic Conductivity

Achieving the hydraulic conductivity standard depends on the degree of compaction, compaction method, type of clay, soil moisture content, and density of the soil during liner construction. Hydraulic

conductivity is the key design parameter when evaluating the acceptability of the constructed soil liner. The hydraulic conductivity of a soil depends, in part, on the viscosity and density of the fluid flowing through it. While water and leachate can cause different test results, water is an acceptable fluid for testing the compacted soil liner and source materials. The effective porosity of the soil is a function of size, shape, and area of the conduits through which the liquid flows. The hydraulic conductivity of a partially saturated soil is less than the hydraulic conductivity of the same soil when saturated. Because invading water only flows through water-filled voids (and not air-filled voids), the dryness of a soil tends to lower permeability. Hydraulic conductivity testing should be conducted on samples that are fully saturated to attempt to measure the highest possible hydraulic conductivity.

EPA has published Method 9100 in publication SW-846 (Test Methods for Evaluating Solid Waste) to measure the hydraulic conductivity of soil samples. Other methods appear in the U.S. Army Corps of Engineers Engineering Manual 1110-2-1906 (COE, 1970) and the newly published "Measurement of Hydraulic Conductivity of Saturated Porous Materials Using a Flexible Wall Permeameter" (ASTM D-5084). To verify full saturation of the sample, this latter method may be performed with back pressure saturation and electronic pore pressure measurement.

Soil Properties

Soils typically possess a range of physical characteristics, including particle size, gradation, and plasticity, that affect their ability to achieve a hydraulic conductivity of 1×10^{-7} cm/sec. Testing methods used to characterize proposed liner soils should include grain size distribution (ASTM D-422), Atterberg limits (ASTM D-4318), and compaction curves depicting moisture and density relationships using the standard or modified Proctor (ASTM D-698 or ASTM D-1557), whichever is appropriate for the compaction equipment used and the degree of firmness of the foundation materials.

Liner soils usually have at least 30 percent fines (fine silt- and clay-sized particles). Some soils with less than 30 percent fines may be worked to obtain hydraulic conductivities below 1×10^{-7} cm/sec, but use of these soils requires greater control of construction practices and conditions.

The soil plasticity index (PI), which is determined from the Atterberg limits (defined by the liquid limit minus the plastic limit), should generally be greater than 10 percent. However, soils with very high PI, (greater than 30 percent), are cohesive and sticky and become difficult to work with in the field. When high PI soils are too dry during placement, they tend to form hard clumps (clods) that are difficult to break down during compaction. Preferential flow paths may be created around the clods allowing leachate to migrate at a relatively high rate.

Soil particles or rock fragments also can create preferential flow paths. For this reason, soil particles or rock fragments should be less than 3 inches in diameter so as not to affect the overall hydraulic performance of the soil liner (USEPA, 1989).

The maximum density of a soil will be achieved at the optimum water content, but this point generally does not correspond to the point at which minimum hydraulic

conductivity is achieved. Wet soils, however, have low shear strength and high potential for desiccation cracking. Care should be taken not to compromise other engineering properties such as shear strengths of the soil liner by excessively wetting the soil liner. Depending on the specific soil characteristics, compaction equipment and compactive effort, the hydraulic conductivity criterion may be achieved at moisture values of 1 to 7 percent above the optimum moisture content.

Although the soil may possess the required properties for successful liner construction, the soil liner may not meet the hydraulic conductivity criterion if the construction practices used to install the liner are not appropriate and carefully controlled. Construction quality control and quality assurance will be discussed in a later section.

Amended Soils

If locally available soils do not possess properties to achieve the specified hydraulic conductivity, soil additives can be used. Soil additives, such as bentonite or other clay materials, can decrease the hydraulic conductivity of the native soil (USEPA, 1988b).

Bentonite may be obtained in a dry, powdered form that is relatively easy to blend with on-site soils. Bentonite is a clay mineral (sodium-montmorillonite) that expands when it comes into contact with water (hydration), by absorbing the water within the mineral matrix. This property allows relatively small amounts of bentonite (5 to 10 percent) to be added to a noncohesive soil (sand) to make it more cohesive (U.S. EPA, 1988b). Thorough mixing of additives to cohesive soils (clay) is difficult and may lead to inconsistent results with respect to complying with the hydraulic conductivity criterion.

The most common additive used to amend soils is sodium bentonite. The disadvantage of using sodium bentonite includes its vulnerability to degradation as a result of contact with chemicals and waste leachates (U.S. EPA, 1989).

Calcium bentonite, although more permeable than sodium bentonite, also is used as a soil amendment. Approximately twice as much calcium bentonite typically is needed to achieve a hydraulic conductivity comparable to that of sodium bentonite.

Soil/bentonite mixtures generally require central plant mixing by means of a pugmill, cement mixer, or other mixing equipment where water can be added during the process. Water, bentonite content, and particle size distribution must be controlled during mixing and placement. Spreading of the soil/bentonite mixture may be accomplished in the same manner as the spreading of natural soil liners, by using scrapers, graders, bulldozers, or a continuous asphalt paving machine (U.S. EPA, 1988).

Materials other than bentonite, including lime, cement, and other clay minerals such as atapulgite, may be used as soil additives (U.S. EPA, 1989). For more information concerning soil admixtures, the reader is referred to the technical resource document on the design and construction of clay liners (U.S. EPA, 1988).

Testing

Prior to construction of a soil liner, the relationship between water content, density,

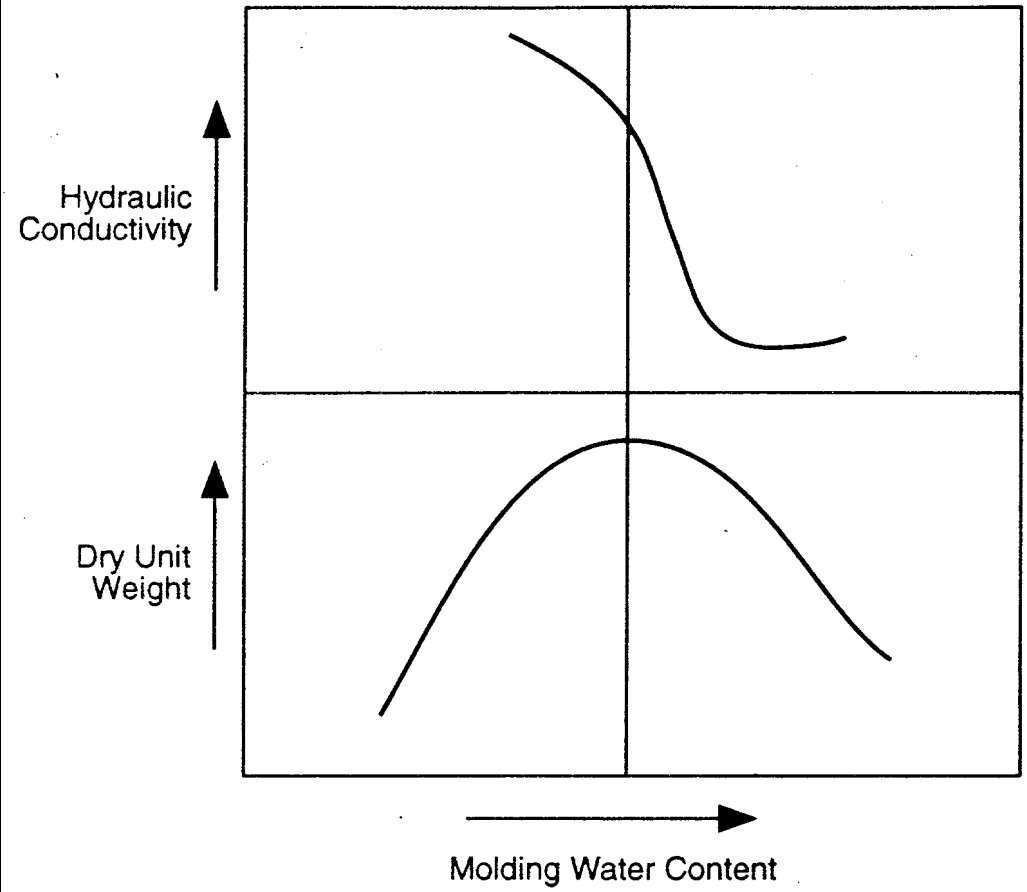
and hydraulic conductivity for a particular soil should be established in the laboratory. Figure 4-5 shows the influence of molding water content (moisture content of the soil at the time of compaction) on hydraulic conductivity of the soil. The lower half of the diagram is a compaction curve and shows the relationship between dry unit weight, or dry density of the soil, and water content of the soil. The optimum moisture content of the soil is related to a peak value of dry density known as maximum dry density. Maximum dry density is achieved at the optimum moisture content.

The lowest hydraulic conductivity of compacted clay soil is achieved when the soil is compacted at a moisture content slightly higher than the optimum moisture content, generally in the range of 1 to 7 percent (U.S. EPA, 1989). When compacting clay, water content and compactive effort are the two factors that should be controlled to meet the maximum hydraulic conductivity criterion.

It is impractical to specify and construct a clay liner to a specific moisture content and a specific compaction (e.g., 5 percent wet of optimum and 95 percent modified Proctor density). Moisture content can be difficult to control in the field during construction; therefore, it may be more appropriate to specify a range of moisture contents and corresponding soil densities (percent compaction) that are considered appropriate to achieve the required hydraulic conductivity. Benson and Daniel (U.S. EPA, 1990) propose water content and density criteria for the construction of clay liners in which the moisture-density criteria ranges are established based on hydraulic conductivity test results. This type of approach is recommended because of the flexibility and guidance it provides to the construction contractor during soil placement. Figure 4-6 presents compaction data as a function of dry unit weight and molding water content for the construction of clay liners. The amount of soil testing required to determine these construction parameters is dependent on the degree of natural variability of the source material.

Quality assurance and quality control of soil liner materials involve both laboratory and field testing. Quality control tests are performed to ascertain compaction requirements and the moisture content of material delivered to the site. Field tests for quality assurance provide an opportunity to check representative areas of the liner for conformance to compaction specifications, including density and moisture content. Quality assurance laboratory testing is usually conducted on field samples for determination of hydraulic conductivity of the in-place liner. Laboratory testing allows full saturation of the soil samples and simulates the effects of large overburden stress on the soil, which cannot be done conveniently in the field (U.S. EPA, 1989).

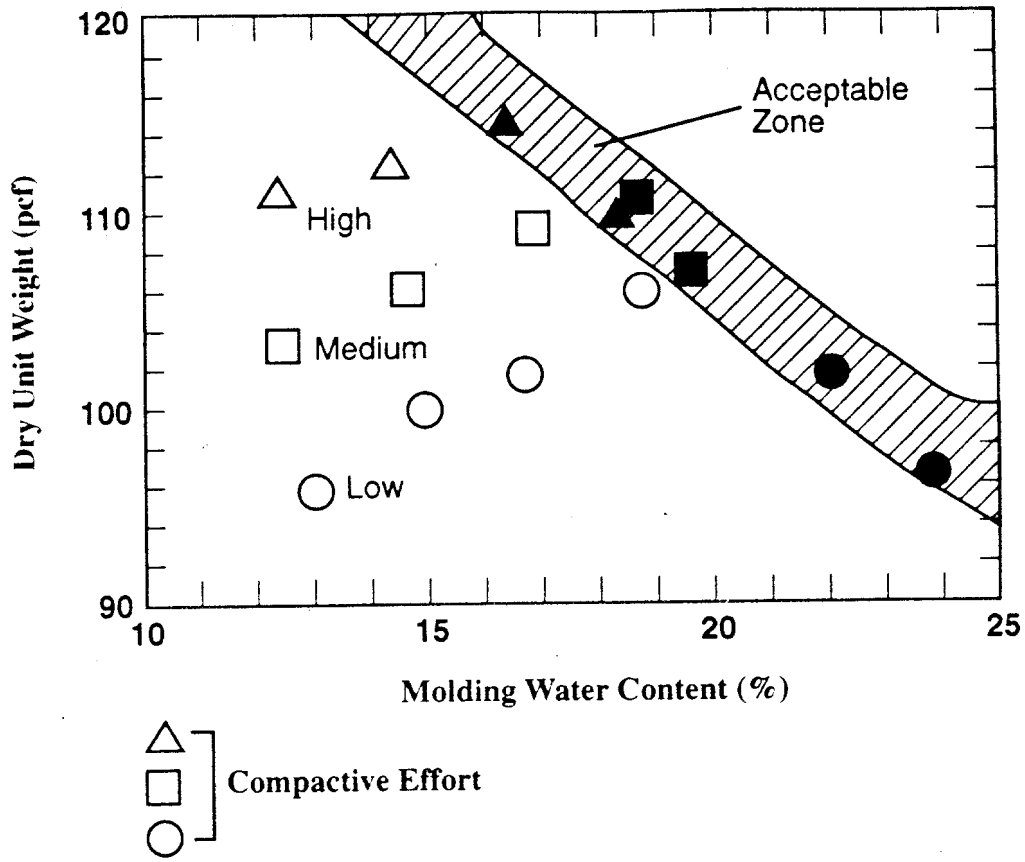
Differences between laboratory and field conditions (e.g., uniformity of material, control of water content, compactive effort, compaction equipment) may make it unlikely that minimum hydraulic conductivity values measured in the laboratory on remolded, pre-construction borrow source samples are the same as the values achieved during actual liner construction. Laboratory testing on remolded soil specimens does not account for operational problems that may result in desiccation, cracking, poor bonding of lifts, and inconsistent degree of compaction on sidewalls (U.S. EPA, 1988b). The relationship between field and laboratory hydraulic conductivity testing has been investigated by the U.S. Environmental



Source: U.S. EPA, 1989.

Note: The optimum moisture content occurs at the point at which maximum density is achieved. The lowest hydraulic conductivity generally occurs at water contents higher than optimum.

Figure 4-5
Hydraulic Conductivity and Dry Unit Weight as a Function of Molding Water Content



Compaction Data for a Silty Clay (from Mitchell et al., 1965). Solid symbols represent specimens with a hydraulic conductivity ≤ 1 x 10^{-7} cm/s and open symbols represent specimens with hydraulic conductivity > 1 x 10^{-7} cm/s.

Source: CERI 90-50 (USEPA, 1990)

Figure 4-6. Compaction Data for Silty Clay

Protection Agency using field case studies (U.S. EPA, 1990c).

In situ, or field, hydraulic conductivity testing operates on the assumption that by testing larger masses of soil in the field, one can obtain more realistic results. Four types of *in situ* hydraulic conductivity tests generally are used: borehole tests, porous probes, infiltrometer tests, and underdrain tests. A borehole test is conducted by drilling a hole, then filling the hole with water, and measuring the rate at which water percolates into the borehole. In the borehole test, water also can percolate through the sidewalls of the borehole. As a result, the measured hydraulic conductivity is usually higher than that measured by other one-dimensional field testings.

The second type of test involves driving or pushing a porous probe into the soil and pouring water through the probe into the soil. With this method, however, the advantage of testing directly in the field is somewhat offset by the limitations of testing such a small volume of soil.

A third method of testing involves a device called an infiltrometer. This device is embedded into the surface of the soil liner such that the rate of flow of a liquid into the liner can be measured. The two types of infiltrometers most widely used are open and sealed. Open rings are less desirable because, with a hydraulic conductivity of 10^{-7} cm/sec, it is difficult to detect a 0.002 inch per day drop in water level of the pond from evaporation and other losses.

With sealed rings, very low rates of flow can be measured. However, single-ring infiltrometers allow lateral flow beneath the ring, which can complicate the interpretation of test results. Single rings are also susceptible to the effects of temperature variation; as the water temperature increases, the entire system expands. As it cools down, the system contracts. This situation could lead to erroneous measurements when the rate of flow is small.

The sealed double-ring infiltrometer has proven to be the most successful method and is the one currently used. The outer ring forces infiltration from the inner ring to be more or less one-dimensional. Covering the inner ring with water insulates it substantially from temperature variation.

Underdrains, the fourth type of in situ test, are the most accurate in situ permeability testing device because they measure exactly what migrates from the bottom of the liner. However, under-drains are slow to generate data for low permeability liners, because of the length of time required to accumulate measurable flow. Also, underdrains must be installed during construction, so fewer underdrains are used than other kinds of testing devices.

Field hydraulic conductivity tests are not usually performed on the completed liner because the tests may take several weeks to complete (during which time the liner may be damaged by desiccation or freezing temperatures) and because large penetrations must be made into the liner. If field conductivity tests are performed, they are usually conducted on a test pad. The test pad should be constructed using the materials and methods to be used for the actual soil liner. The width of a test pad is usually the width of three to four construction vehicles, and the length is one to two times the width. Thickness is usually two to three feet. Test pads can be used as a means for verifying that the proposed

materials and construction procedures will meet performance objectives. If a test pad is constructed, if tests verify that performance objectives have been met, and if the actual soil liner is constructed to standards that equal or exceed those used in building the test pad (as verified through quality assurance), then the actual soil liner should meet or exceed performance objectives.

Other than the four types of field hydraulic conductivity tests described earlier, ASTM D 2937 "Standard Test Method for Density of Soil in Place by the Drive-Cylinder Method" may be used to obtain in-place hydraulic conductivity of the soil liner. This test method uses a U.S. Army Corps of Engineers surface soil sampler to drive a thin-walled cylinder (typically 3-inch by 3-inch) into a completed lift of the soil liner to obtain relatively undisturbed samples for laboratory density and hydraulic conductivity testings. This test can provide useful correlation to other field and quality assurance testing results (e.g, Atterberg limits, gradation, in-place moisture and density of the soil liner) to evaluate the in-place hydraulic conductivity of the soil liner.

Soil Liner Construction

Standard compaction procedures are usually employed when constructing soil liners. The following factors influence the degree and quality of compaction:

- Lift thickness;
- Full scale or segmented lift placement;
- Number of equipment passes;
- Scarification between lifts;
- Soil water content; and
- The type of equipment and compactive effort.

The method used to compact the soil liner is an important factor in achieving the required minimum hydraulic conductivity. Higher degrees of compactive effort increase soil density and lower the soil hydraulic conductivity for a given water content. The results of laboratory compaction tests do not necessarily correlate directly with the amount of compaction that can be achieved during construction.

Heavy compaction equipment (greater than 25,000 lbs or 11,300 kg) is typically used when building the soil liner to maximize compactive effort (U.S. EPA, 1989). The preferred field compaction equipment is a sheepsfoot roller with long feet that fully penetrates loose lifts of soil and provides higher compaction while kneading the clay particles together. The shape and depth of the feet are important; narrow, rod-like feet with a minimum length of about seven inches provide the best results. A progressive change from the rod-like feet to a broader foot may be necessary in some soils after initial compaction, to allow the roller to walk out of the compacted soil. The sheepsfoot feet also aid in breaking up dry clods (see *Soil Properties* in this section). Mechanical road reclaimers, which are typically used to strip and re-pave asphalt, can be extremely effective in reducing soil clod size prior to compaction and in scarifying soil surfaces between lifts. Other equipment that has been used to compact soil includes discs and rototillers.

To achieve adequate compaction, the lift thickness (usually five to nine inches) may be decreased or the number of passes over

the lift may be increased. Generally, compaction equipment should pass over the soil liner five to twenty times to attain the compaction needed to comply with the minimum hydraulic conductivity criterion (U.S. EPA, 1989).

Efforts made to reduce clod size during excavation and placement of the soil for the liner should improve the chances for achieving low hydraulic conductivity in several ways. Keeping clods in the soil liner material small will facilitate a more uniform water content. Macropores between clod remnants can result in unacceptably high field hydraulic conductivity.

Opinions differ on acceptable clod sizes in the uncompacted soil. Some suggest a maximum of one to three inches in diameter, or no larger than one-half the lift thickness. The main objective is to remold all clods in the compaction process to keep hydraulic conductivity values consistent throughout the soil liner (U.S. EPA, 1988).

Geomembranes

Geomembranes are relatively thin sheets of flexible thermoplastic or thermoset polymeric materials that are manufactured and prefabricated at a factory and transported to the site. Because of their inherent impermeability, use of geomembranes in landfill unit construction has increased. The design of the side slope, specifically the friction between natural soils and geosynthetics, is critical and requires careful review.

Material Types and Thicknesses

Geomembranes are made of one or more polymers along with a variety of other ingredients such as carbon black, pigments, fillers, plasticizers, processing aids, crosslinking chemicals, anti-degradants, and biocides. The polymers used to manufacture geomembranes include a wide range of plastics and rubbers differing in properties such as chemical resistance and basic composition (U.S. EPA, 1983 and U.S. EPA, 1988e). The polymeric materials may be categorized as follows:

- Thermoplastics such as polyvinyl chloride (PVC);
- Crystalline thermoplastics such as high density polyethylene (HDPE), very low density polyethylene (VLDPE), and linear low density polyethylene (LLDPE); and
- Thermoplastic elastomers such as chlorinated polyethylene (CPE) and chlorosulfonated polyethylene (CSPE).

The polymeric materials used most frequently as geomembranes are HDPE, PVC, CSPE, and CPE. The thicknesses of geomembranes range from 20 to 120 mil (1 mil = 0.001 inch) (U.S. EPA, 1983 and U.S. EPA, 1988e). The recommended minimum thickness for all geomembranes is 30 mil, with the exception of HDPE, which must be at least 60 mil to allow for proper seam welding. Some geomembranes can be manufactured by a calendering process with fabric reinforcement, called scrim, to provide additional tensile strength and dimensional stability.

Chemical and Physical Stress Resistance

The design of the landfill unit should consider stresses imposed on the liner by the design configuration. These stresses include the following:

- Differential settlement in foundation soils;
- Strain requirements at the anchor trench; and
- Strain requirements over long, steep side slopes.

An extensive body of literature has been developed by manufacturers and independent researchers on the physical properties of liners. Geosynthetic design equations are presented in several publications including Kastman (1984), Koerner (1990), and U.S. EPA (1988e).

The chemical resistance of a geomembrane to leachate has traditionally been considered a critical issue for Subtitle C (hazardous waste) facilities where highly concentrated solvents may be encountered. Chemical resistance testing of geomembranes may not be required for MSWLF units containing only municipal solid waste; EPA's data base has shown that leachate from MSWLF units is not aggressive to these types of materials. Testing for chemical resistance may be warranted considering the waste type, volumes, characteristics, and amounts of small quantity generator waste or other industrial waste present in the waste stream. The following guidance is provided in the event such testing is of interest to the owner or operator.

EPA's Method 9090 in SW-846 is the established test procedure used to evaluate degradation of geomembranes when exposed to hazardous waste leachate. In the procedure, the geomembrane is immersed in the site-specific chemical environment for at least 120 days at two different temperatures. Physical and mechanical properties of the tested material are then compared to those of the original material every thirty days. A software system entitled Flexible Liner Evaluation Expert (FLEX), designed to assist in the hazardous waste permitting process, may aid in interpreting EPA Method 9090 test data (U.S. EPA, 1989). A detailed discussion of both Method 9090 and FLEX is available from EPA.

It is imperative that a geomembrane liner maintain its integrity during exposure to short-term and long-term mechanical stresses. Short-term mechanical stresses include equipment traffic during the installation of a liner system, as well as thermal expansion and shrinkage of the geomembrane during the construction and operation of the MSWLF unit. Long-term mechanical stresses result from the placement of waste on top of the liner system and from subsequent differential settlement of the subgrade (U.S. EPA, 1988a).

Long-term success of the liner requires adequate friction between the components of a liner system, particularly the soil subgrade and the geomembrane, and between geosynthetic components, so that slippage or sloughing does not occur on the slopes of the unit. Specifically, the foundation slopes and the subgrade materials must be considered in design equations to evaluate:

- The ability of a geomembrane to support its own weight on the side slopes;
- The ability of a geomembrane to withstand down-dragging during and after waste placement;
- The best anchorage configuration for the geomembrane;

- The stability of a soil cover on top of a geomembrane; and
- The stability of other geosynthetic components such as geotextile or geonet on top of a geomembrane.

These requirements may affect the choice of geomembrane material, including polymer type, fabric reinforcement, thickness, and texture (e.g., smooth or textured for HDPE) (U.S. EPA, 1988). PVC also can be obtained in a roughened or file finish to increase the friction angle.

Design specifications should indicate the type of raw polymer and manufactured sheet to be used as well as the requirements for the delivery, storage, installation, and sampling of the geomembrane. Material properties can be obtained from the manufacturer-supplied average physical property values, which are published in the Geotechnical Fabrics Report's Specifier's Guide and updated annually. The minimum tensile properties of the geomembrane must be sufficient to satisfy the stresses anticipated during the service life of the geomembrane. Specific raw polymer and manufactured sheet specifications and test procedures include (U.S. EPA, 1988e, and Koerner, 1990):

Raw Polymer Specifications

- Density (ASTM D-1505);
- Melt index (ASTM D-1238);
- Carbon black (ASTM D-1603); and
- Thermogravimetric analysis (TGA) or differential scanning calorimetry (DSC).

Manufactured Sheet Specifications

- Thickness (ASTM D-1593);
- Tensile properties (ASTM D-638);
- Tear resistance (ASTM D-1004);
- Carbon black content (ASTM D-1603);
- Carbon black dispersion (ASTM D-3015);
- Dimensional stability (ASTM D-1204); and
- Stress crack resistance (ASTM D-1693).

Geomembranes may have different physical characteristics, depending on the type of polymer and the manufacturing process used, that can affect the design of a liner system. When reviewing manufacturers' literature, it is important to remember that each manufacturer may use more than one polymer or resin type for each grade of geomembrane and that the material specifications may be generalized to represent several grades of material.

Installation

Installation specifications should address installation procedures specific to the properties of the liner installed. The coefficient of thermal expansion of the geomembrane sheet can affect its installation and its service performance. The geomembrane should lie flat on the underlying soil. However, shrinkage and expansion of the sheeting, due to changes in temperature during installation, may result in excessive wrinkling or tension in the

geomembrane. Wrinkles on the geomembrane surface will affect the uniformity of the soil-geomembrane interface and may result in leakage through imperfections. Excessive tautness of the geomembrane may affect its ability to resist rupture from localized stresses on the seams or at the toe of slopes where bridging over the subgrade may occur during installation. In addition to thermal expansion and contraction of the geomembrane, residual stresses from manufacturing remain in some geomembranes and can cause non-uniform expansion and contraction during construction. Some flexibility is needed in the specifications for geomembrane selection to allow for anticipated dimensional changes resulting from thermal expansion and contraction (U.S. EPA, 1988).

Technical specifications for geomembranes also should include: information for protection of the material during shipping, storage and handling; quality control certifications provided by the manufacturer or fabricator (if panels are constructed); and quality control testing by the contractor, installer, or a construction quality assurance (CQA) agent. Installation procedures addressed by the technical specifications include a geomembrane layout plan, deployment of the geomembrane at the construction site, seam preparation, seaming methods, seaming temperature constraints, detailed procedures for repairing and documenting construction defects, and sealing of the geomembrane to appurtenances, both adjoining and penetrating the liner. The performance of inspection activities, including both non-destructive and destructive quality control field testing of the sheets and seams during installation of the geomembrane, should be addressed in the technical specifications. Construction quality assurance is addressed in an EPA guidance document (USEPA, 1992).

The geomembrane sheeting is shipped in rolls or panels from the supplier, manufacturer, or fabricator to the construction site. Each roll or panel may be labeled according to its position on the geomembrane layout plan to facilitate installation. Upon delivery, the geomembrane sheeting should be inspected to check for damage that may have occurred during shipping. (U.S. EPA, 1992).

Proper storage of the rolls or panels prior to installation is essential to the final performance of the geomembrane. Some geomembrane materials are sensitive to ultraviolet exposure and should not be stored in direct sunlight prior to installation. Others, such as CSPE and CPE, are sensitive to moisture and heat and can partially crosslink or block (stick together) under improper storage conditions. Adhesives or welding materials, which are used to join geomembrane panels, also should be stored appropriately (U.S. EPA, 1992).

Visual inspection and acceptance of the soil liner subgrade should be conducted prior to installing the geomembrane. The surface of the subgrade should meet design specifications with regard to lack of protruding objects, grades, and thickness. Once these inspections are conducted and complete, the geomembrane may be installed on top of the soil liner. If necessary, other means should be employed to protect the subgrade from precipitation and erosion, and to prevent desiccation, moisture loss, and erosion from the soil liner prior to geomembrane placement. Such methods may include placing a plastic tarp on top of completed portions of the soil liner

(USEPA, 1992). In addition, scheduling soil liner construction slightly ahead of the geomembrane and drainage layer placement can reduce the exposure of the soil liner to the elements.

Deployment, or placement, of the geomembrane panels or rolls should be described in the geomembrane layout plan. Rolls of sheeting, such as HDPE, generally can be deployed by placing a shaft through the core of the roll, which is supported and deployed using a front-end loader or a winch. Panels composed of extremely flexible liner material such as PVC are usually folded on pallets, requiring workers to manually unfold and place the geomembrane. Placement of the geomembrane goes hand-in-hand with the seaming process; no more than the amount of sheeting that can be seamed during a shift or work day should be deployed at any one time (USEPA, 1988). Panels should be weighted with sand bags if wind uplift of the membrane or excessive movement from thermal expansion is a potential problem. Proper stormwater control measurements should be employed during construction to prevent erosion of the soil liner underneath the geomembrane and the washing away of the geomembrane.

Once deployment of a section of the geomembrane is complete and each section has been visually inspected for imperfections and tested to ensure that it is the specified thickness, seaming of the geomembrane may begin. Quality control/quality assurance monitoring of the seaming process should be implemented to detect inferior seams. Seaming can be conducted either in the factory or in the field. Factory seams are made in a controlled environment and are generally of high quality, but the entire seam length (100 percent) still should be tested non-destructively (U.S. EPA, 1988). Destructive testing should be done at regular intervals along the seam (see page 4-66).

Consistent quality in fabricating field seams is critical to liner performance, and conditions that may affect seaming should be monitored and controlled during installation. An inspection should be conducted in accordance with a construction quality assurance plan to document the integrity of field seams. Factors affecting the seaming process include (U.S. EPA, 1988):

- Ambient temperature at which the seams are made;
- Relative humidity;
- Control of panel lift-up by wind;
- The effect of clouds on the geomembrane temperature;
- Water content of the subsurface beneath the geomembrane;
- The supporting surface on which the seaming is bonded;
- The skill of the seaming crew;
- Quality and consistency of the chemical or welding material;
- Proper preparation of the liner surfaces to be joined;
- Moisture on the seam interface; and
- Cleanliness of the seam interface (e.g., the amount of airborne dust and debris present).

Depending on the type of geomembrane, several bonding systems are available for the construction of both factory and field seams. Bonding methods include solvents, heat seals, heat guns, dielectric seaming, extrusion welding, and hot wedge techniques. To ensure the integrity of the seams, a geomembrane should be seamed using the bonding system recommended by the manufacturer (U.S. EPA, 1988). EPA has developed a field seaming manual for all types of geomembranes (U.S. EPA, 1991a).

Thermal methods of seaming require cleanliness of the bonding surfaces, heat, pressure, and dwell time to produce high quality seams. The requirements for adhesive systems are the same as those for thermal systems, except that the adhesive takes the place of the heat. Sealing the geomembrane to appurtenances and penetrating structures should be performed in accordance with detailed drawings included in the design plans and approved specifications.

An anchor trench along the perimeter of the cell generally is used to secure the geomembrane during construction (to prevent sloughing or slipping down the interior side slopes). Run out calculations (Koerner, 1990) are available to determine the depth of burial at a trench necessary to hold a specified length of membrane, or combination of membrane and geofabric or geotextile. If forces larger than the tensile strength of the membrane are inadvertently developed, then the membrane could tear. For this reason, the geomembrane should be allowed to slip or give in the trench after construction to prevent such tearing. However, during construction, the geomembrane should be anchored according to the detailed drawings provided in the design plans and specifications (USEPA, 1988).

Geomembranes that are subject to damage from exposure to weather and work activities should be covered with a layer of soil as soon as possible after quality assurance activities associated with geomembrane testing are completed. Soil should be placed without driving construction vehicles directly on the geomembrane. Light ground pressure bulldozers may be used to push material out in front over the liner, but the operator must not attempt to push a large pile of soil forward in a continuous manner over the membrane. Such methods can cause localized wrinkles to develop and overturn in the direction of movement. Overturned wrinkles create sharp creases and localized stresses in the geomembrane that could lead to premature failure. Instead, the operator should continually place smaller amounts of soil or drainage material working outward over the toe of the previously placed material. Alternatively, large backhoes can be used to place soil over the geomembrane that can later be spread with a bulldozer or similar equipment. Although such methods may sound tedious and slow, in the long run they will be faster and more cost-effective than placing too much material too fast and having to remobilize the liner installer to repair damaged sections of the geomembrane. The QA activities conducted during construction also should include monitoring the contractor's activities on top of the liner to avoid damage to installed and accepted geomembranes.

Leachate Collection Systems

Leachate refers to liquid that has passed through or emerged from solid waste and contains dissolved, suspended, or immiscible

materials removed from the solid waste. At MSWLF units, leachate is typically aqueous with limited, if any, immiscible fluids or dissolved solvents. The primary function of the leachate collection system is to collect and convey leachate out of the landfill unit and to control the depth of the leachate above the liner. The leachate collection system (LCS) should be designed to meet the regulatory performance standard of maintaining less than 30 cm (12 inches) depth of leachate, or "head," above the liner. The 30-cm head allowance is a design standard and the Agency recognizes that this design standard may be exceeded for relatively short periods of time during the active life of the unit. Flow of leachate through imperfections in the liner system increases with an increase in leachate head above the liner. Maintaining a low leachate level above the liner helps to improve the performance of the composite liner.

Leachate is generally collected from the landfill through sand drainage layers, synthetic drainage nets, or granular drainage layers with perforated plastic collection pipes, and is then removed through sumps or gravity drain carrier pipes. LCS's should consist of the following components (U.S. EPA, 1988):

- A low-permeability base (in this case a composite liner);
- A high-permeability drainage layer, constructed of either natural granular materials (sand and gravel) or synthetic drainage material (e.g., geonet) placed directly on the FML, or on a protective bedding layer (e.g., geofabric) directly overlying the liner;
- Perforated leachate collection pipes within the high-permeability drainage layer to collect leachate and carry it rapidly to a sump or collection header pipe;
- A protective filter layer over the high permeability drainage material, if necessary, to prevent physical clogging of the material by fine-grained material; and
- Leachate collection sumps or header pipe system where leachate can be removed.

The design, construction, and operation of the LCS should maintain a maximum height of leachate above the composite liner of 30 cm (12 in). Design guidance for calculating the maximum leachate depth over a liner for granular drainage systems materials is provided in the reference U.S. EPA (1989). The leachate head in the layer is a function of the liquid impingement rate, bottom slope, pipe spacing, and drainage layer hydraulic conductivity. The impingement rate is estimated using a complex liquid routing procedure. If the maximum leachate depth exceeds 30 cm for the system, except for short-term occurrences, the design should be modified to improve its efficiency by increasing grade, decreasing pipe spacing, or increasing the hydraulic conductivity (transmissivity) of the drainage layer (U.S. EPA, 1988).

Grading of Low-Permeability Base

The typical bottom liner slope is a minimum of two percent after allowances for settlement at all points in each system. A slope is necessary for effective gravity drainage through the entire operating and post-closure period. Settlement estimates of the foundation soils should set this two-

percent grade as a post-settlement design objective (U.S. EPA, 1991b).

High-Permeability Drainage Layer

The high-permeability drainage layer is placed directly over the liner or its protective bedding layer at a slope of at least two percent (the same slope necessary for the composite liner). Often the selection of a drainage material is based on the on-site availability of natural granular materials. In some regions of the country, hauling costs may be very high for sand and gravel, or appropriate materials may be unavailable; therefore, the designer may elect to use geosynthetic drainage nets (geonets) or synthetic drainage materials as an alternative. Frequently, geonets are substituted for granular materials on steep sidewalls because maintaining sand on the slope during construction and operation of the landfill unit is more difficult (U.S. EPA, 1988).

Soil Drainage Layers

If the drainage layer of the leachate collection system is constructed of granular soil materials (e.g., sand and gravel), then it should be demonstrated that this granular drainage layer has sufficient bearing strength to support expected loads. This demonstration will be similar to that required for the foundations and soil liner (U.S. EPA, 1988).

If the landfill unit is designed on moderate-to-steep (15 percent) grades, the landfill design should include calculations demonstrating that the selected granular drainage materials will be stable on the most critical slopes (e.g., usually the steepest slope) in the design. The calculations and assumptions should be shown, especially the friction angle between the geomembrane and soil, and if possible, supported by laboratory and/or field testing (USEPA, 1988).

Generally, gravel soil with a group designation of GW or GP on the Unified Soils Classification Chart can be expected to have a hydraulic conductivity of greater than 0.01 cm/sec, while sands identified as SW or SP can be expected to have a coefficient of permeability greater than 0.001 cm/sec. The sand or gravel drains leachate that enters the drainage layer to prevent 30 cm (12 in) or more accumulation on top of the liner during the active life of the MSWLF unit LCS. The design of a LCS frequently uses a drainage material with a hydraulic conductivity of 1 x 10^{-2} cm/sec or higher. Drainage materials with hydraulic conductivities in this order of magnitude should be evaluated for biological and particulate clogging (USEPA, 1988). Alternatively, if a geonet is used, the design is based on the transmissivity of the geonet.

If a filter layer (soil or geosynthetic) is constructed on top of a drainage layer to protect it from clogging, and the LCS is designed and operated to avoid drastic changes in the oxidation reduction potential of the leachate (thereby avoiding formation of precipitates within the LCS), then there is no conceptual basis to anticipate that conductivity will decrease over time. Where conductivity is expected to decrease over time, the change in impingement rate also should be evaluated over the same time period because the reduced impingement rate and hydraulic conductivity may still comply with the 30 cm criterion.

Unless alternative provisions are made to control incident precipitation and resulting surface run-off, the impingement rate during the operating period of the MSWLF unit is

usually at least an order of magnitude greater than the impingement rate after final closure. The critical design condition for meeting the 30 cm (12 in) criterion can therefore be expected during the operating life. The designer may evaluate the sensitivity of a design to meet the 30 cm (12 in) criterion as a result of changes in impingement rates, hydraulic conductivity, pipe spacing, and grades. Such sensitivity analysis may indicate which element of the design should be emphasized during construction quality monitoring or whether the design can be altered to comply with the 30 cm (12 in) criterion in a more cost-effective manner.

The soil material used for the drainage layer should be investigated at the borrow pit prior to use at the landfill. Typical borrow pit characterization testing would include laboratory hydraulic conductivity and grain size distribution. If grain size distribution information from the borrow pit characterization program can be correlated to the hydraulic conductivity data, then the grain size test, which can be conducted in a short time in the field, may be a useful construction quality control parameter. Compliance with this parameter would then be indicative that the hydraulic conductivity design criterion was achieved in the constructed drainage layer. This information could be incorporated into construction documents after the borrow pit has been characterized. If a correlation cannot be made between hydraulic conductivity and grain size distribution, then construction documents may rely on direct field or laboratory measurements to demonstrate that the hydraulic conductivity design criterion was met in the drainage layer.

Granular materials are generally placed using conventional earthmoving equipment, including trucks, scrapers, bulldozers, and front-end loaders. Vehicles should not be driven directly over the geosynthetic membrane when it is being covered. (U.S. EPA, 1988a).

Coarse granular drainage materials, unlike low-permeability soils, can be placed dry and do not need to be heavily compacted. Compacting granular soils tends to grind the soil particles together, which increases the fine material and reduces hydraulic conductivity. To minimize settlement following material placement, the granular material may be compacted with a vibratory roller. The final thickness of the drainage layer should be checked by optical survey measurements or by direct test pit measurements (U.S. EPA, 1988).

Geosynthetic Drainage Nets

Geosynthetic drainage nets (geonets) may be substituted for the granular layers of the LCRs on the bottom and sidewalls of the landfill cells. Geonets require less space than perforated pipe or gravel and also promote rapid transmission of liquids. They do, however, require geotextile filters above them and can experience problems with creep and intrusion. Long-term operating and performance experience of geonets is limited because the material and its application are relatively new (U.S. EPA, 1989).

If a geonet is used in place of a granular drainage layer, it must provide the same level of performance (maintaining less than 30 cm of leachate head above the liner). An explanation of the calculation used to compute the capacity of a geonet may be found in U.S. EPA (1987a). The

transmissivity of a geonet can be reduced significantly by intrusion of the soil or a geotextile. A protective geotextile between the soil and geonet will help alleviate this concern. If laboratory transmissivity tests are performed, they should be done under conditions, loads, and configurations that closely replicate the actual field conditions. It is important that the transmissivity value used in the leachate collection system design calculations be selected based upon those loaded conditions (U.S. EPA, 1988). It is also important to ensure that appropriate factors of safety are used (Koerner, 1990).

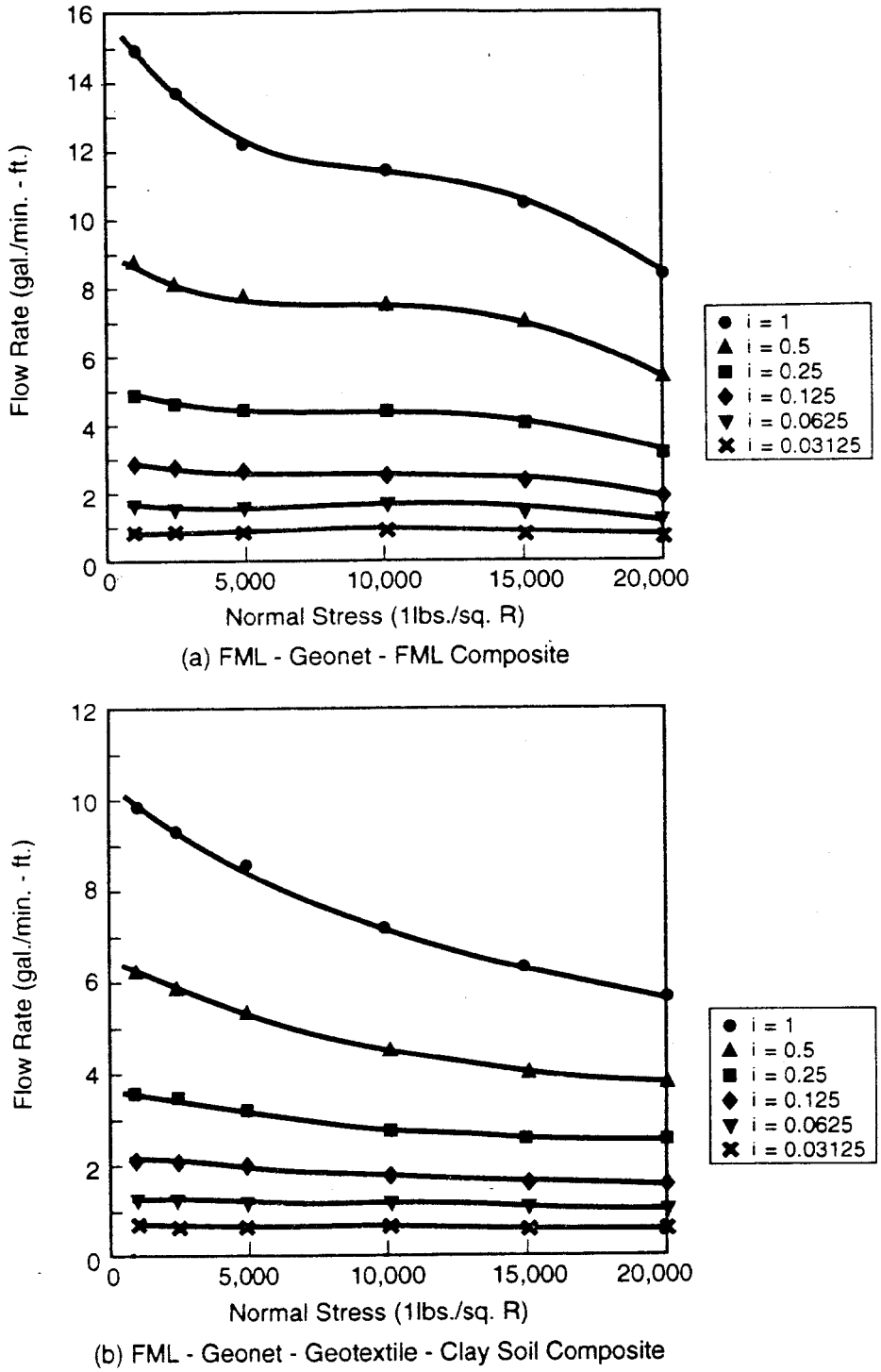
The flow rate or transmissivity of geonets may be evaluated by ASTM D-4716. This flow rate may then be compared to design-by-function equations presented in U.S. EPA (1989). In the ASTM D-4716 flow test, the proposed collector cross section should be modeled as closely as possible to actual field conditions (U.S. EPA, 1989).

Figure 4-7 shows the flow rate "signatures" of a geonet between two geomembranes (upper curves) and the same geonet between a layer of clay soil and a geomembrane (lower curves). The differences between the two sets of curves represent intrusion of the geotextile/clay into the apertures of the geonet. The curves are used to obtain a flow rate for the particular geonet being designed (U.S. EPA, 1989). Equations to determine the design flow rate or transmissivity are also presented in U.S. EPA (1989), Giroud (1982), Carroll (1987), Koerner (1990), and FHWA (1987).

Generally, geonets perform well and result in high factors of safety or performance design ratios, unless creep (elongation under constant stress) becomes a problem or adjacent materials intrude into apertures (U.S. EPA, 1989). For geonets, the most critical specification is the ability to transmit fluids under load. The specifications also should include a minimum transmissivity under expected landfill operating (dynamic) or completion (static) loads. The specifications for thickness and types of material should be identified on the drawings or in the materials section of the specifications, and should be consistent with the design calculations (U.S. EPA, 1988).

Geonets are often used on the sidewalls of landfills because of their ease of installation. They should be placed with the top ends in a secure anchor trench with the strongest longitudinal length extending down the slope. The geonets need not be seamed to each other on the slopes, only tied at the edges, butted, or overlapped. They should be placed in a loose condition, not stretched or placed in a configuration where they are bearing their own weight in tension. The construction specifications should contain appropriate installation requirements as described above or the requirements of the geonet manufacturer. All geonets need to be protected by a filter layer or geotextile to prevent clogging (U.S. EPA, 1988).

The friction factors against sliding for geotextiles, geonets, and geomembranes often can be estimated using manufacturers data because these materials do not exhibit the range of characteristics as seen in soil materials. However, it is important that the designer perform the actual tests using site materials and that the sliding stability calculations accurately represent the actual design configuration, site conditions, and the specified material characteristics (U.S. EPA, 1988).



Source: U.S. EPA. 1989.

Figure 4-7. Flow Rate Curves for Geonets in Two Composite Liner Configurations

Leachate Collection Pipes

All components of the leachate collection system must have sufficient strength to support the weight of the overlying waste, cover system, and post-closure loadings, as well as the stresses from operating equipment. The component that is most vulnerable to compressive strength failure is the drainage layer piping. Leachate collection system piping can fail by excessive deflection, which may lead to buckling or collapse (USEPA, 1988). Pipe strength calculations should include resistance to wall crushing, pipe deflection, and critical buckling pressure. Design equations and information for most pipe types can be obtained from the major pipe manufacturers. For more information regarding pipe structural strength, refer to U.S. EPA (1988).

Perforated drainage pipes can provide good long-term performance. These pipes have been shown to transmit fluids rapidly and to maintain good service lives. The depth of the drainage layer around the pipe should be deeper than the diameter of the pipe. The pipes can be placed in trenches to provide the extra depth. In addition, the trench serves as a sump (low point) for leachate collection. Pipes can be susceptible to particulate and biological clogging similar to the drainage layer material. Furthermore, pipes also can be susceptible to deflection. Proper maintenance and design of pipe systems can mitigate these effects and provide systems that function properly. Acceptable pipe deflections should be evaluated for the pipe material to be used (USEPA, 1989).

The design of perforated collection pipes should consider the following factors:

- The required flow using known percolation impingement rates and pipe spacing;
- Pipe size using required flow and maximum slope; and
- The structural strength of the pipe.

The pipe spacing may be determined by the Mound Model. In the Mound Model (see Figure 4-8), the maximum height of fluid between two parallel perforated drainage pipes is equal to (U.S. EPA, 1989):

$$h_{max} = \frac{L\sqrt{c}}{2}\left[\frac{\tan^2\alpha}{c} + 1 - \frac{\tan\alpha}{c}\sqrt{\tan^2\alpha + c}\right]$$

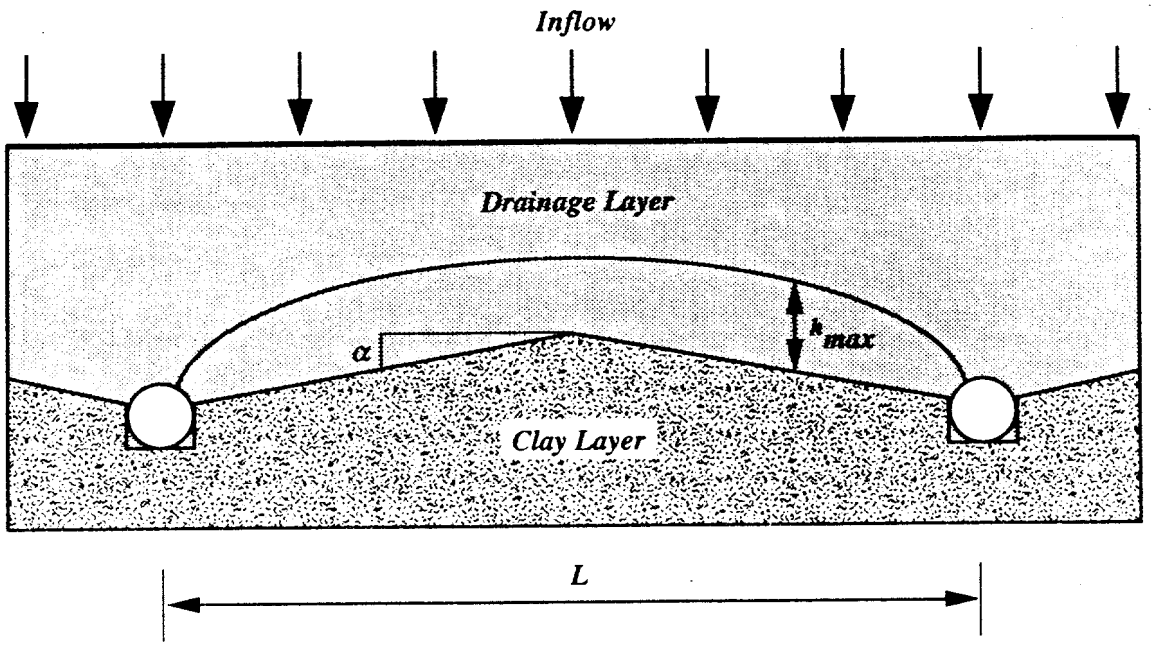
where c = q/k
k = permeability
q = inflow rate
α = slope.

The two unknowns in the equation are:

L = distance between the pipes; and
c = amount of leachate.

Using a maximum allowable head, h_{max}, of 30 cm (12 in), the equation is usually solved for "L" (U.S. EPA, 1989).

The amount of leachate, "c", can be estimated in a variety of ways including the Water Balance Method (U.S. EPA, 1989) and the computer model Hydrologic Evaluation of Landfill Performance (HELP). The HELP Model is a quasi-two-dimensional hydrologic model of water movement across, into, through, and out of landfills. The model uses climatologic, soil, and landfill design data and incorporates a solution technique that accounts for the effects of surface storage, run-off, infiltration, percolation, soil-moisture



Source: U.S. EPA, 1989

Figure 4-8. Definition of Terms for Mound Model Flow Rate Calculations

storage, evapotranspiration, and lateral drainage. The program estimates run-off drainage and leachate that are expected to result from a wide variety of landfill conditions, including open, partially open, and closed landfill cells. The model also may be used to estimate the depth of leachate above the bottom liner of the landfill unit. The results may be used to compare designs or to aid in the design of leachate collection systems (U.S. EPA, 1988).

Once the percolation and pipe spacing are known, the design flow rate can be obtained using the curve in Figure 4-9. The amount of leachate percolation at the particular site is located on the x-axis.

The required flow rate is the point at which this value intersects with the pipe spacing value determined from the Mound Model. Using this value of flow rate and the bottom slope of the site, the required diameter for the pipe can be determined (see Figure 4-10). Finally, the graphs in Figures 4-11 and 4-12 show two ways to determine whether the strength of the pipe is adequate for the landfill design. In Figure 4-11, the vertical soil pressure is located on the y-axis. The density of the backfill material around the pipe is not governed by strength, so it will deform under pressure rather than break. Ten percent is the absolute limiting deflection value for plastic pipe. Using Figure 4-11, the applied pressure on the pipe is located and traced to the trench geometry, and then the pipe deflection value is checked for its adequacy (U.S. EPA, 1989).

The LCS specifications should include (U.S. EPA, 1988):

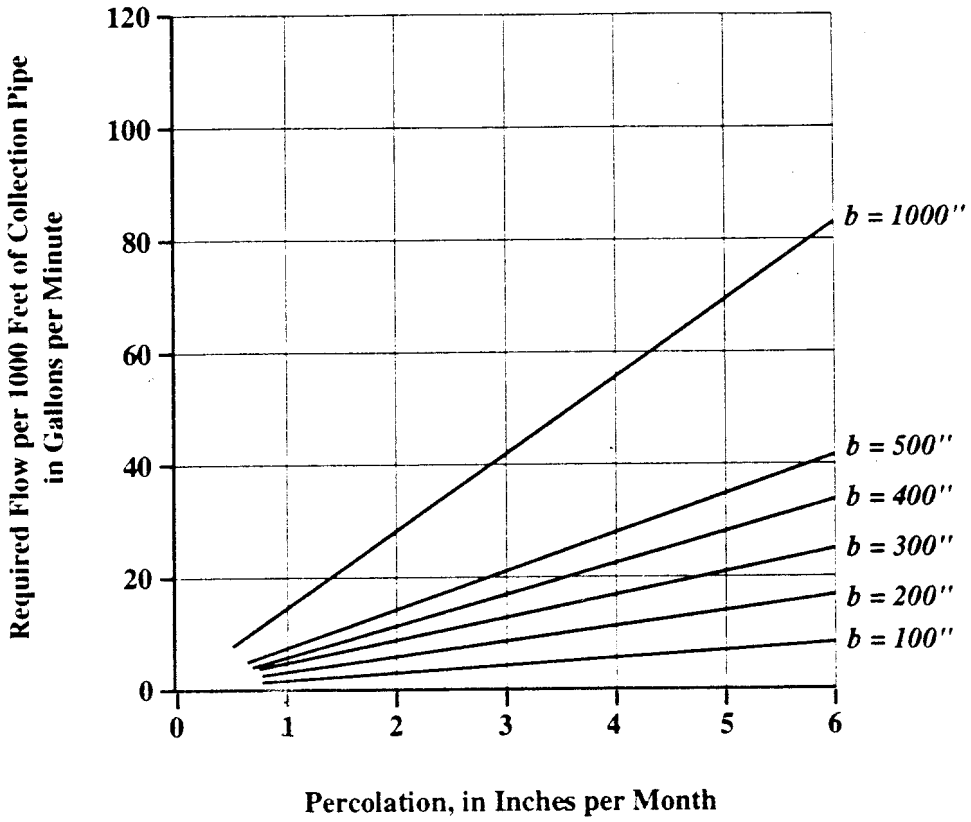
- Type of piping material;
- Diameter and wall thickness;
- Size and distribution of slots and perforations;
- Type of coatings (if any) used in the pipe manufacturing; and
- Type of pipe bedding material and required compaction used to support the pipes.

The construction drawings and specifications should clearly indicate the type of bedding to be used under the pipes and the dimensions of any trenches. The specifications should indicate how the pipe lengths are joined. The drawings should show how the pipes are placed with respect to the perforations. To maintain the lowest possible leachate head, there should be perforations near the pipe invert, but not directly at the invert. The pipe invert itself should be solid to allow for efficient pipe flow at low volumes (U.S. EPA, 1988).

When drainage pipe systems are embedded in filter and drainage layers, no unplugged ends should be allowed. The filter materials in contact with the pipes should be appropriately sized to prevent migration of the material into the pipe. The filter media, drainage layer, and pipe network should be compatible and should represent an integrated design.

Protection of Leachate Collection Pipes

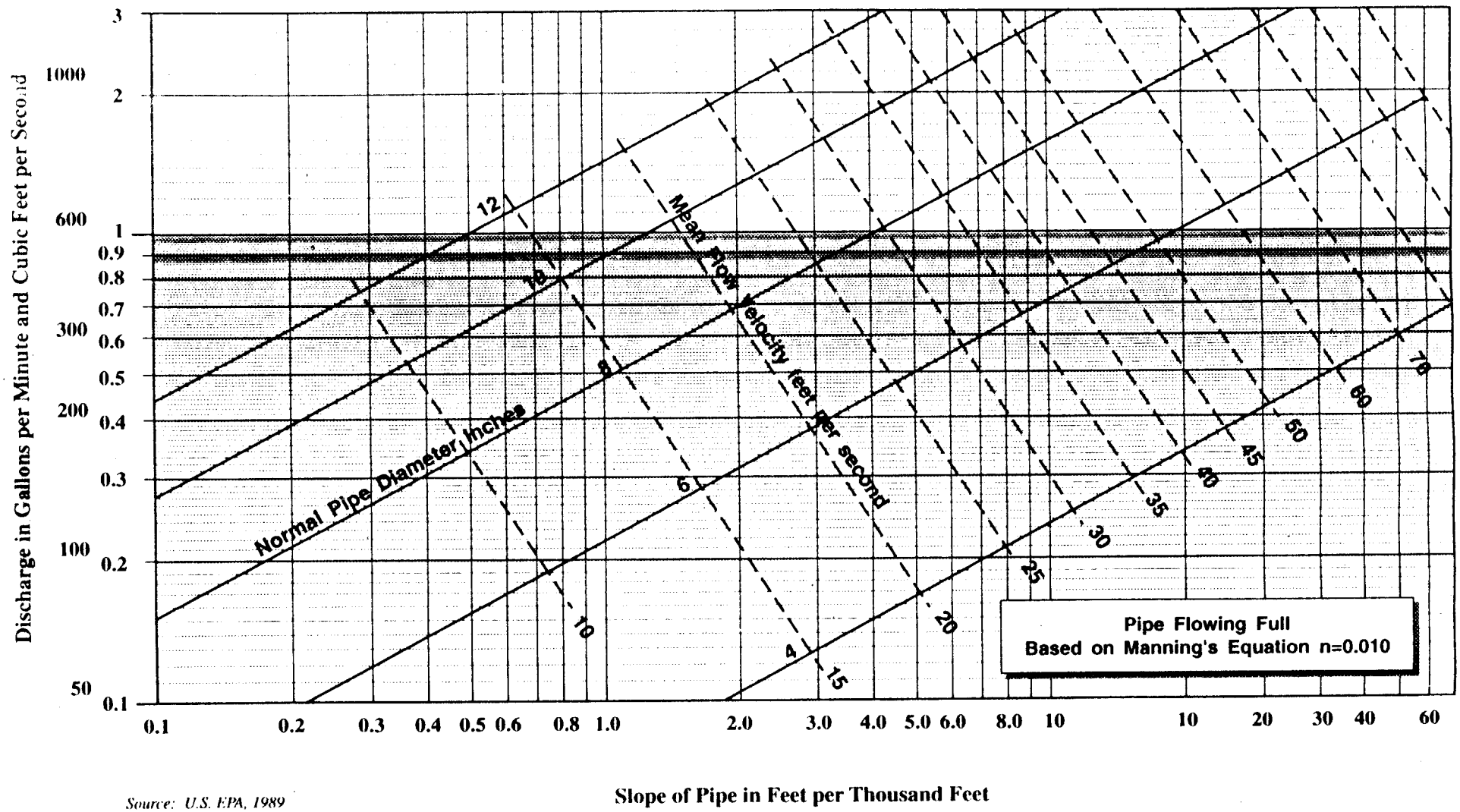
The long-term performance of the LCS depends on the design used to protect pipes from physical clogging (sedimentation) by the granular drainage materials. Use of a graded material around the pipes is most effective if accompanied by proper sizing of pipe perforations. The Army Corps of



*Where b = width of area contributing to leachate collection pipe

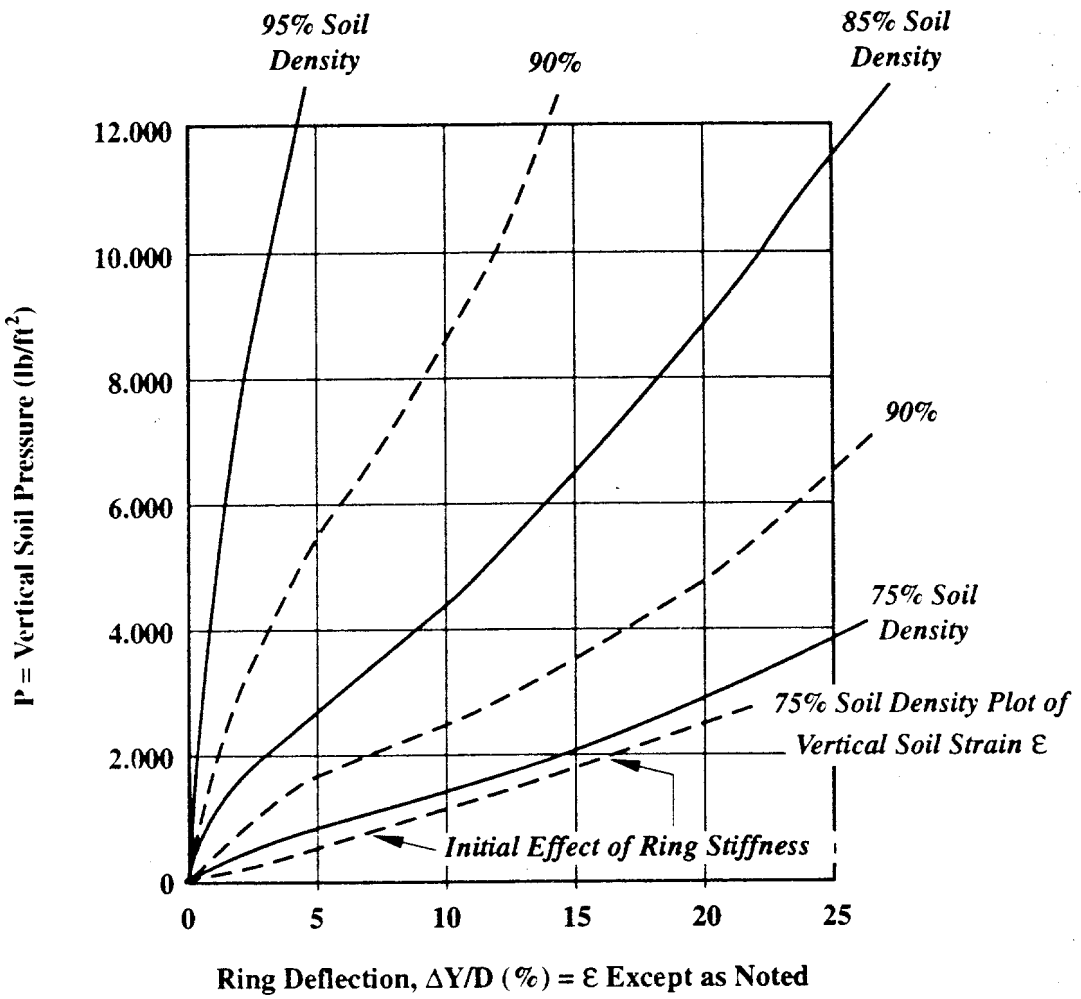
Source: U.S. EPA, 1989

Figure 4-9. Required Capacity of Leachate Collection Pipe



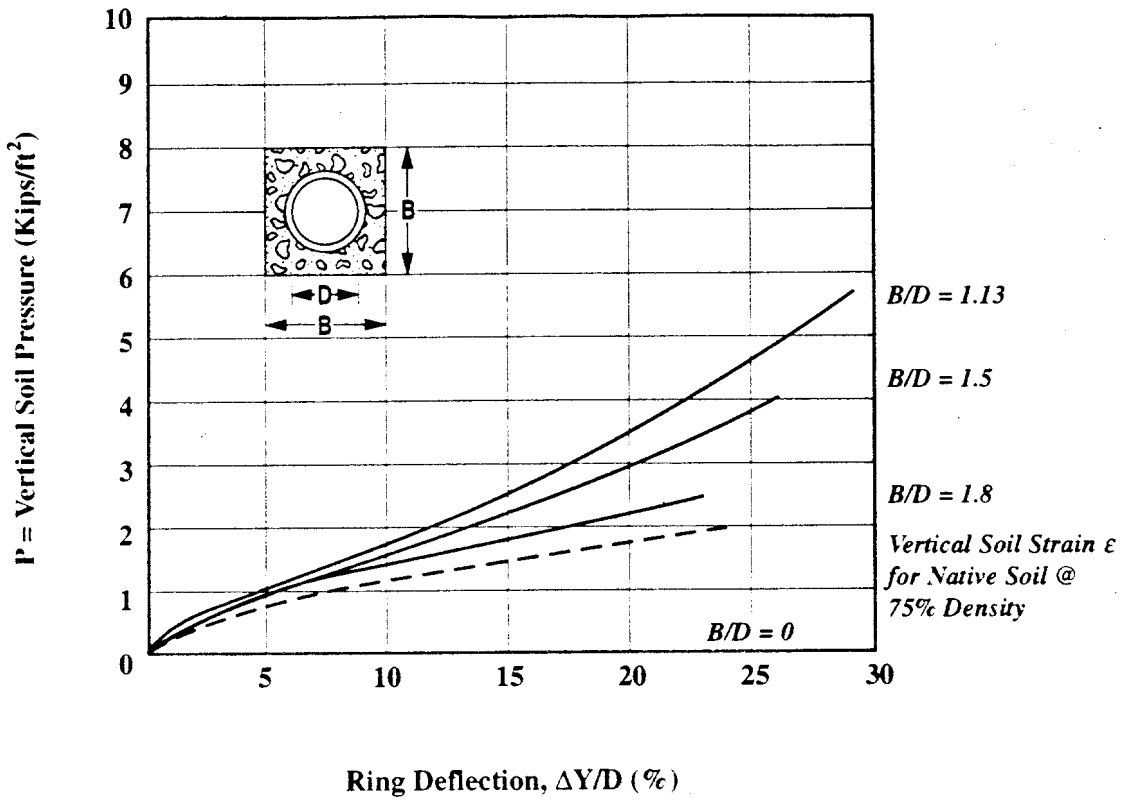
Source: U.S. EPA, 1989

Figure 4-10. Leachate Collection Pipe Sizing Chart



Source: U.S. EPA. 1989

Figure 4-11. Vertical Ring Deflection Versus Vertical Soil Pressure for 18-inch Corrugated Polyethylene in High Pressure Soil Cell



Source: U.S. EPA, 1989

Figure 4-12. Example of the Effect of Trench Geometry and Pipe Sizing on Ring Deflection

Engineers (GCA Corporation, 1983) has established design criteria using graded filters to prevent physical clogging of leachate drainage layers and piping by soil sediment deposits. When installing graded filters, caution should be taken to prevent segregation of the material (USEPA, 1991a).

Clogging of the pipes and drainage layers of the leachate collection system can occur through several other mechanisms, including chemical and biological fouling (USEPA, 1988). The LCS should be designed with a cleanout access capable of reaching all parts of the collection system with standard pipe cleaning equipment.

Chemical clogging can occur when dissolved species in the leachate precipitate in the piping. Clogging can be minimized by periodically flushing pipes or by providing a sufficiently steep slope in the system to allow for high flow velocities for self-cleansing. These velocities are dependent on the diameter of the precipitate particles and on their specific gravity. ASCE (1969) discusses these relationships. Generally, flow velocities should be in the range of one or two feet per second to allow for self-cleansing of the piping (U.S. EPA, 1988).

Biological clogging due to algae and bacterial growth can be a serious problem in MSWLF units. There are no universally effective methods of preventing such biological growth. Since organic materials will be present in the landfill unit, there will be a potential for biological clogging. The system design should include features that allow for pipe system cleanings. The components of the cleaning system should include (U.S. EPA, 1991b):

- A minimum of six-inch diameter pipes to facilitate cleaning;
- Access located at major pipe intersections or bends to allow for inspections and cleaning; and
- Valves, ports, or other appurtenances to introduce biocides and/or cleaning solutions.

In its discussion of drainage layer protection, the following section includes further information concerning protection of pipes using filter layers.

Protection of the High-Permeability Drainage Layer

The openings in drainage materials, whether holes in pipes, voids in gravel, or apertures in geonets, must be protected against clogging by accumulation of fine (silt-sized) materials. An intermediate material that has smaller openings than those of the drainage material can be used as a filter between the waste and drainage layer. Sand may be used as filter material, but has the disadvantage of taking up vertical space (USEPA, 1989). Geotextiles do not use up air space and can be used as filter materials.

Soil Filter Layers

There are three parts to an analysis of a sand filter that is placed above drainage material. The first determines whether or not the filter allows adequate flow of liquids. The second evaluates whether the void spaces are small enough to prevent solids from being lost from the upstream materials. The third estimates the long-term clogging behavior of the filter (U.S. EPA, 1989).

The particle-size distribution of the drainage system and the particle-size distribution of the invading (or upstream) soils are required

in the design of granular soil (sand filter) materials. The filter material should have its large and small size particles intermediate between the two extremes. Equations for adequate flow and retention are:

- Adequate Flow:
  $d_{85f} > (3 \text{ to } 5)d_{15d.s.}$

- Adequate Retention:
  $d_{15f} < (3 \text{ to } 5)d_{85w.f.}$

Where f = required filter soil;
d.s. = drainage stone; and
w.f. = water fines.

There are no quantitative methods to assess soil filter clogging, although empirical guidelines are found in geotechnical engineering references.

The specifications for granular filter layers that surround perforated pipes and that protect the drainage layer from clogging are based on a well-defined particle size distribution. The orientation and configuration of filter layers relative to other LCS components should be shown on all drawings and should be described, with ranges of particle sizes, in the materials section of the specifications (U.S. EPA, 1988a).

Thickness is an important placement criterion for granular filter material. Generally, the granular filter materials will be placed around perforated pipes by hand, forming an "envelope." The dimensions of the envelope should be clearly stated on the drawings or in the specifications. This envelope can be placed at the same time as the granular drainage layer, but it is important that the filter envelope protect all areas of the pipe where the clogging potential exists. The plans and specifications should indicate the extent of the envelope. The construction quality control program should document that the envelope was installed according to the plans and specifications (U.S. EPA, 1988).

A granular filter layer is generally placed using the same earthmoving equipment as the granular drainage layer. The final thickness should be checked by optical survey or by direct test pit measurement (U.S. EPA, 1988).

This filter layer is the uppermost layer in the leachate collection system. A landfill design option includes a buffer layer, 12 inches thick (30 cm) or more, to protect the filter layer and drainage layer from damage due to traffic. This final layer can be general fill, as long as it is no finer than the soil used in the filter layer (U.S. EPA, 1988). However, if the layer has a low permeability, it will affect leachate recirculation attempts.

Geotextile Filter Layers

Geotextile filter fabrics are often used. The open spaces in the fabric allow liquid flow while simultaneously preventing upstream fine particles from fouling the drain. Geotextiles save vertical space, are easy to install, and have the added advantage of remaining stationary under load. Geotextiles also can be used as cushioning materials above geomembranes (USEPA, 1989). Because geotextile filters are susceptible to biological clogging, their use in areas inundated by leachate (e.g., sumps, around leachate collection pipes, and trenches) should be avoided.

Geotextile filter design parallels sand filter design with some modifications (U.S. EPA, 1989). Adequate flow is assessed by

comparing the material (allowable) permittivity to the design imposed permittivity. Permittivity is measured by the ASTM D-4491 test method. The design permittivity utilizes an adapted form of Darcy's law. The resulting comparison yields a design ratio, or factor of safety, that is the focus of the design (U.S. EPA, 1989):

$DR = ø_{allow}/ø_{reqd}$

where:

$ø_{allow}$ = permittivity from ASTM D-4491

$ø_{reqd} = (q/a)\ (1/h_{max})$

q/a = inflow rate per unit area

h_{max} = 12 inches

The second part of the geotextile filter design is determining the opening size necessary for retaining the upstream soil or particulates in the leachate. It is well established that the 95 percent opening size is related to particles to be retained in the following type of relationship:

$O_{95} < \text{fct.}\ (d_{50}, CU, DR)$

where:

O_{95} = 95% opening size of geotextile;

d_{50} = 50% size of upstream particles;

CU = Uniformity of the upstream particle size; and

DR = Relative density of the upstream particles.

The O_{95} size of a geotextile in the equation is the opening size at which 5 percent of a given value should be less than the particle size characteristics of the invading materials. In the test for the O_{95} size of the geotextile, a sieve with a very coarse mesh in the bottom is used as a support. The geotextile is placed on top of the mesh and is bonded to the inside so that the glass beads used in the test cannot escape around the edges of the geotextile filter. The particle-size distribution of retained glass beads is compared to the allowable value using any of a number of existing formulas (U.S. EPA, 1989).

The third consideration in geotextile design is long-term clogging. A test method for this problem that may be adopted by ASTM is called the Gradient Ratio Test. In this test, the hydraulic gradient of 1 inch of soil plus the underlying geotextile is compared with the hydraulic gradient of 2 inches of soil. The higher the gradient ratio, the more likely that a clog will occur. The final ASTM gradient ratio test will include failure criteria. An alternative to this test method is a long-term flow test that also is performed in a laboratory. The test models a soil-to-fabric system at the anticipated hydraulic gradient. The flow rate through the system is monitored. A long-term flow rate will gradually decrease until it stops altogether (U.S. EPA, 1989).

The primary function of a geotextile is to prevent the migration of fines into the leachate pipes while allowing the passage of leachate. The most important specifications are those for hydraulic conductivity and retention. The hydraulic conductivity of the geotextile generally should be at least ten times the soil it is retaining. An evaluation of the retention ability for loose soils is based on the average particle size of the soil and the apparent opening size (AOS) of the geotextile. The maximum apparent opening size, sometimes called equivalent opening size, is determined by the size of the soil that will be retained; a geotextile is then selected to meet that specification. The material specifications should contain a range of AOS values for the geotextile, and

these AOS values should match those used in the design calculations (U.S. EPA, 1988).

One of the advantages of geotextiles is their light weight and ease of placement. The geotextiles are brought to the site, unrolled, and held down with sandbags until they are covered with a protective layer. They are usually overlapped, not seamed; however, on slopes or in other configurations, they may be sewn (U.S. EPA, 1988).

As with granular filter layers, it is important that the design drawings be clear in their designation of geotextile placement so that no potential route of pipe or drainage layer clogging is left unprotected. If geotextiles are used on a slope, they should be secured in an anchor trench similar to those for geomembranes or geonets (U.S. EPA, 1988).

Leachate Removal System

Sumps, located in a recess at the low point(s) within the leachate collection drainage layer, provide one method for leachate removal from the MSWLF unit. In the past, low volume sumps have been constructed successfully from reinforced concrete pipe on a concrete footing, and supported above the geomembrane on a steel plate to protect the geomembrane from puncture. Recently, however, prefabricated polyethylene structures have become available. These structures may be suitable for replacing the concrete components of the sump and have the advantage of being lighter in weight.

These sumps typically house a submersible pump, which is positioned close to the sump floor to pump the leachate and to maintain a 30 cm (12 in) maximum leachate depth. Low-volume sumps, however, can present operational problems. Because they may run dry frequently, there is an increased probability of the submersible pumps burning out. For this reason, some landfill operators prefer to have sumps placed at depths between 1.0 and 1.5 meters. While head levels of 30 cm or less are to be maintained on the liner, higher levels are acceptable in sumps. Alternatively, the sump may be designed with level controls and with a backup pump to control initiation and shut-off of the pumping sequence and to have the capability of alternating between the two pumps. The second pump also may be used in conjunction with the primary pump during periods of high flow (e.g., following storm events) and as a backup if the primary pump fails to function. A visible alarm warning light to indicate pump failure to the operator also may be installed.

Pumps used to remove leachate from the sumps should be sized to ensure removal of leachate at the maximum rate of generation. These pumps also should have a sufficient operating head to lift the leachate to the required height from the sump to the access port. Portable vacuum pumps can be used if the required lift height is within the limit of the pump. They can be moved in sequence from one leachate sump to another. The type of pump specified and the leachate sump access pipes should be compatible and should consider performance needs under operating and closure conditions (U.S. EPA, 1988).

Alternative methods of leachate removal include internal standpipes and pipe penetrations through the geomembrane, both of which allow leachate removal by gravity flow to either a leachate pond or exterior pump station. If a leachate removal standpipe is used, it should be extended through the entire landfill from liner to

cover and then through the cover itself. If a gravity drainage pipe that requires geomembrane penetration is used, a high degree of care should be exercised in both the design and construction of the penetration. The penetration should be designed and constructed in a manner that allows nondestructive quality control testing of 100 percent of the seal between the pipe and the geomembrane. If not properly constructed and fabricated, geomembrane penetrations can become a source of leakage through the geomembrane.

Other Design Considerations

The stability of the individual leachate collection system components placed on geomembrane-covered slopes should be considered. A method for calculating the factor of safety (FS) against sliding for soils placed on a sloped geomembrane surface is provided in Koerner (1990). This method considers the factors affecting the system, including the slope length, the slope angle, and the friction angle between the geomembrane and its cover soil. Generally, the slope angle is known and is specified on the design drawings. A minimum FS is then selected. From the slope angle and the FS, a minimum allowable friction angle is determined, and the various components of the liner system are selected based on this minimum friction angle. If the design evaluation results in an unacceptably low FS, then either the sidewall slope or the materials should be changed to produce an adequate design (U.S. EPA, 1988). For short slopes in a landfill unit, the FS can be as low as 1.1 to 1.2 if the slope will be unsupported (i.e., no waste will be filled against it) for only a short time, and if any failures that do occur can be repaired fairly easily. Longer slopes may require higher factors of safety due to the potential of sliding material to tear the geomembrane along the slope or near the toe of the slope.

Construction Quality Assurance and Quality Control

The following section is excerpted from U.S. EPA (1992). This section discusses quality assurance and quality control (QA/QC) objectives. For a more detailed discussion on QA/QC and specific considerations, refer to U.S. EPA (1992).

CQA/CQC Objectives

Construction quality assurance (CQA) consists of a planned series of observations and tests to ensure that the final product meets project specifications. CQA plans, specifications, observations, and tests are used to provide quantitative criteria with which to accept the final product.

On routine construction projects, CQA is normally the concern of the owner and is obtained using an independent third-party testing firm. The independence of the third-party inspection firm is important, particularly when the owner is a corporation or other legal entity that has under its corporate "umbrella" the capacity to perform the CQA activities. Although "in-house" CQA personnel may be registered professional engineers, a perception of misrepresentation may exist if CQA is not performed by an independent third party.

The CQA officer should fully disclose any activities or relationships with the owner that may impact his impartiality or objectivity. If such activities or relationships exist, the CQA officer should describe actions that have been or can be taken to avoid, mitigate, or neutralize the possibility they might affect the CQA

officer's objectivity. Regulatory representatives can then evaluate whether these mechanisms are sufficient to ensure an acceptable CQA product.

Construction quality control (CQC) is an on-going process of measuring and controlling the characteristics of the product in order to meet manufacturer's or project specifications. CQC is a production tool that is employed by the manufacturer of materials and by the contractor installing the materials at the site. CQA, by contrast, is a verification tool employed by the facility owner or regulatory agency to ensure that the materials and installations meet project specifications. CQC is performed independently of the CQA Plan. For example, while a geomembrane liner installer will perform CQC testing of field seams, the CQA program will require independent CQA testing of those same seams by a third-party inspector.

The CQA/CQC plans are implemented through inspection activities that include visual observations, field testing and measurements, laboratory testing, and evaluation of the test data. Inspection activities typically are concerned with four separate functions:

- Quality Control (QC) Inspection by the Manufacturer provides an in-process measure of the product quality and its conformance with the project plans and specifications. Typically, the manufacturer will QC test results to certify that the product conforms to project plans and specifications.

- Construction Quality Control (CQC) Inspection by the Contractor provides an in-process measure of construction quality and conformance with the project plans and specifications, thereby allowing the contractor to correct the construction process if the quality of the product is not meeting the specifications and plans.

- Construction Quality Assurance (CQA) Testing by the Owner (Acceptance Inspection) performed by the owner usually through the third-party testing firm, provides a measure of the final product quality and its conformance with project plans and specifications. Due to the size and costs of a typical MSWLF unit construction project, rejection of the project at completion would be costly to all parties. Acceptance Inspections as portions of the project become complete allow deficiencies to be found and corrected before they become too large and costly.

- Regulatory Inspection often is performed by a regulatory agency to ensure that the final product conforms with all applicable codes and regulations. In some cases, the regulatory agency will use CQA documentation and the as-built plans or "record drawings" to confirm compliance with the regulations.

Soil Liner Quality Assurance/Quality Control

Quality control testing performed on materials used in construction of the landfill unit includes source testing and construction testing. Source testing defines material properties that govern material placement. Source testing commonly includes moisture content, soil density, Atterberg limits, grain size, and laboratory hydraulic conductivity. Construction testing ensures that landfill

construction has been performed in accordance with the plans and technical specifications. Construction testing generally includes tests of soil moisture content, density, lift thickness, and hydraulic conductivity.

The method of determining compliance with the maximum hydraulic conductivity criterion should be specified in the QA/QC plan. Some methods have included the use of the criterion as a maximum value that never should be exceeded, while other methods have used statistical techniques to estimate the true mean. The sample collection program should be designed to work with the method of compliance determination. Selection of sample collection points should be made on a random basis.

Thin wall sampling tubes generally are used to collect compacted clay samples for laboratory hydraulic conductivity testing. It is important to minimize disturbance of the sample being collected. Tubes pushed into the soil by a backhoe may yield disturbed samples. A recommended procedure (when a backhoe is available during sample collection) is to use the backhoe bucket as a stationary support and push the tube into the clay with a jack positioned between the clay and the tube. The sample hole should be filled with bentonite or a bentonite clay mixture, and compacted using short lifts of material.

If geophysical methods are used for moisture and density measurements, it is recommended that alternative methods be used less frequently to verify the accuracy of the faster geophysical methods. Additional information on testing procedures can be found in U.S. EPA (1988b) and U.S. EPA (1990a).

Quality assurance testing for soil liners includes the same testing requirements as specified above for control testing. Generally, the tests are performed less frequently and are performed by an individual or an entity independent of the contractor. Activities of the construction quality assurance (CQA) officer are essential to document quality of construction. The CQA officer's responsibilities and those of the CQA officer's staff members may include:

- Communicating with the contractor;
- Interpreting and clarifying project drawings and specifications with the designer, owner, and contractor;
- Recommending acceptance or rejection by the owner/operator of work completed by the construction contractor;
- Submitting blind samples (e.g., duplicates and blanks) for analysis by the contractor's testing staff or one or more independent laboratories, as applicable;
- Notifying owner or operator of construction quality problems not resolved on-site in a timely manner;
- Observing the testing equipment, personnel, and procedures used by the construction contractor to check for detrimentally significant changes over time;
- Reviewing the construction contractor's quality control recording, maintenance, summary, and interpretations of test data for accuracy and appropriateness; and

- Reporting to the owner/operator on monitoring results.

Soil Liner Pilot Construction (Test Fill)

A pilot construction or test fill is a small-scale test pad that can be used to verify that the soil, equipment, and construction procedures can produce a liner that performs according to the construction drawings and specifications. An owner or operator may want to consider the option of constructing a test fill prior to the construction of the liner. A test pad is useful not only in teaching people how to build a soil liner, it also can function as a construction quality assurance tool. If the variables used to build a test pad that achieves a $1x10^{-7}$ cm/sec hydraulic conductivity are followed exactly, then the completed full-size liner should meet the regulatory requirements (U.S. EPA, 1989). A test fill may be a cost-effective method for the contractor to evaluate the construction methods and borrow source. Specific factors that can be examined/tested during construction of a test fill include (U.S. EPA, 1988b):

- Preparation and compaction of foundation material to the required bearing strength;
- Methods of controlling uniformity of the soil material;
- Compactive effort (e.g., type of equipment, number of passes) to achieve required soil density and hydraulic conductivity;
- Lift thickness and placement procedures to achieve uniformity of density throughout a lift and the absence of apparent boundary effects between lifts or between placements in the same lift;
- Procedures for protecting against desiccation cracking or other site- and season-specific failure mechanisms for the finished liner or intermediate lifts;
- Measuring the hydraulic conductivity on the test fill in the field and collecting samples of field-compacted soil for laboratory testing;
- Test procedures for controlling the quality of construction;
- Ability of different types of soil to meet hydraulic conductivity requirements in the field; and
- Skill and competence of the construction team, including equipment operators and quality control specialists.

Geomembrane Quality Assurance/ Quality Control Testing

As with the construction of soil liners, installation of geomembrane liners should be in conformance with a quality assurance/quality control plan. Tests performed to evaluate the integrity of geomembrane seams are generally considered to be either "destructive" or "non-destructive."

Destructive Testing

Quality control testing of geomembranes generally includes peel and shear testing of scrap test weld sections prior to commencing seaming activities and at periodic intervals throughout the day. Additionally, destructive peel and shear field

tests are performed on samples from the installed seams.

Quality assurance testing generally requires that an independent laboratory perform peel and shear tests of samples from installed seams. The samples may be collected randomly or in areas of suspect quality. HDPE seams are generally tested at intervals equivalent to one sample per every 300 to 400 feet of installed seam for extrusion welds, and every 500 feet for fusion-welded seams. Extrusion seams on HDPE require grinding prior to welding, which can greatly diminish parent material strengths if excessive grinding occurs. Detailed discussion of polyethylene welding protocol can be found in U.S. EPA (1991a). For dual hot wedge seams in HDPE, both the inner and outer seam may be subjected to destructive shear tests at the independent laboratory. Destructive samples of installed seam welds are generally cut into several pieces and distributed to:

- The installer to perform construction quality control field testing;
- The owner/operator to retain and appropriately catalog or archive; and
- An independent laboratory for peel and shear testing.

If the test results for a seam sample do not pass the acceptance/rejection criteria, then samples are cut from the same field seam on both sides of the rejected sample location. Samples are collected and tested until the areal limits of the low quality seam are defined. Corrective measures should be undertaken to repair the length of seam that has not passed the acceptance/rejection criteria. In many cases, this involves seaming a cap over the length of the rejected seam or reseaming the affected area (U.S. EPA, 1988). In situations where the seams continually fail testing, the seaming crews may have to be retrained.

Non-Destructive Testing

Non-destructive test methods are conducted in the field on an in-place geomembrane. These test methods determine the integrity of the geomembrane field seams. Non-destructive test methods include the probe test, air lance, vacuum box, ultrasonic methods (pulse echo, shadow and impedance plane), electrical spark test, pressurized dual seam, electrical resistivity, and hydrostatic tests. Detailed discussion of these test methods may be found in U.S. EPA (1991a). Seam sections that fail appropriate, non-destructive tests must be carefully delineated, patched or reseamed, and retested. Large patches or reseamed areas should be subjected to destructive test procedures for quality assurance purposes. The specifications should clearly describe the degree to which non-destructive and destructive test methods will be used in evaluating failed portions of non-destructive seam tests.

Geomembrane Construction Quality Assurance Activities

The responsibilities of the construction quality assurance (CQA) personnel for the installation of the geomembrane are generally the same as the responsibilities for the construction of a soil liner with the following additions:

- Observation of liner storage area and liners in storage, and handling of the liner as the panels are positioned in the cell;

- Observation of seam overlap, seam preparation prior to seaming, and material underlying the liner;
- Observation of destructive testing conducted on scrap test welds prior to seaming;
- Observation of destructive seam sampling, submission of the samples to an independent testing laboratory, and review of results for conformance to specifications;
- Observation of all seams and panels for defects due to manufacturing and/or handling and placement;
- Observation of all pipe penetration boots and welds in the liner;
- Preparation of reports indicating sampling conducted and sampling results, locations of destructive samples, locations of patches, locations of seams constructed, and any problems encountered; and,
- Preparation of record drawings of the liner installation, in some cases.

The last responsibility is frequently assigned to the contractor, the owner's representative, or the engineer.

Leachate Collection System Construction Quality Assurance

The purpose of leachate collection system CQA is to document that the system construction is in accordance with the design specifications. Prior to construction, all materials should be inspected to confirm that they meet the construction plans and specifications. These include (U.S. EPA, 1988):

- Geonets;
- Geotextiles;
- Pipe size, materials, and perforations;
- Granular material gradation and prefabricated structures (sumps, manholes, etc.);
- Mechanical, electrical, and monitoring equipment; and
- Concrete forms and reinforcement.

The leachate collection system foundation (geomembrane or low permeability soil liner) should be inspected and surveyed upon its completion to ensure that it has proper grading and is free of debris and liquids (U.S. EPA, 1988).

During construction, the following activities, as appropriate, should be observed and documented (U.S. EPA, 1988):

- Pipe bedding placement including quality, thickness, and areal coverage;
- Granular filter layer placement including material quality and thickness;
- Pipe installation including location, configuration, grades, joints, filter layer placement, and final flushing;
- Granular drainage layer placement including protection of underlying liners, thickness, overlap with filter

fabrics and geonets if applicable, and weather conditions;

- Geonet placement including layout, overlap, and protection from clogging by granular material carried by wind or run-off during construction;
- Geotextile/geofabric placement including coverage and overlap;
- Sumps and structure installation; and
- Mechanical and electrical equipment installation including testing.

In addition to field observations, actual field and laboratory testing may be performed to document that the materials meet the design specifications. These activities should be documented and should include the following (U.S. EPA, 1988):

- Geonet and geotextile sampling and testing;
- Granular drainage and filter layer sampling and testing for grain size distribution; and
- Testing of pipes for leaks, obstructions, and alignments.

Upon completion of construction, each component should be inspected to identify any damage that may have occurred during its installation, or during construction of another component (e.g., pipe crushing during placement of granular drainage layer). Any damage that does occur should be repaired, and these corrective measures should be documented in the CQA records (U.S. EPA, 1988).

4.4 RELEVANT POINT OF COMPLIANCE 40 CFR §258.40(d)

4.4.1 Statement of Regulation

(a) *(See Statement of Regulation in Section 4.2.1 of this guidance document for the regulatory language for performance-based design requirements.)*

(b) *(See Statement of Regulation in Section 4.3.1 of this guidance document for the regulatory language for requirements pertaining to composite liner and leachate collection systems.)*

(c) *(See Statement of Regulation in Section 4.2.1 of this guidance document for the regulatory language for performance-based design requirements.)*

(d) The relevant point of compliance specified by the Director of an approved State shall be no more than 150 meters from the waste management unit boundary and shall be located on land owned by the owner of the MSWLF unit.

In determining the relevant point of compliance, the State Director shall consider at least the following factors:

(1) The hydrogeologic characteristics of the facility and surrounding land;

(2) The volume and physical and chemical characteristics of the leachate;

(3) The quantity, quality, and direction of flow of ground water;

(4) The proximity and withdrawal rate of the ground-water users;

(5) The availability of alternative drinking water supplies;

(6) The existing quality of the ground water, including other sources of contamination and their cumulative impacts on the ground water and whether the ground water is currently used or reasonably expected to be used for drinking water;

(7) Public health, safety, and welfare effects; and

(8) Practicable capability of the owner or operator.

4.4.2 Applicability

In States with approved permit programs, owners/operators may have the opportunity to employ an alternative liner design, as per §258.40(a)(1). In these situations, some flexibility is allowed in terms of establishing a relevant point of compliance. The relevant point of compliance may be located a maximum of 150 meters from the waste management unit boundary; however, the location must be on property owned by the MSWLF unit owner or operator.

In unapproved States the relevant point of compliance is set at the waste management unit boundary. The waste management unit boundary is defined as the vertical surface located at the hydraulically downgradient limit of the unit. This vertical surface extends down into and through the entire thickness of the uppermost aquifer.

4.4.3 Technical Considerations

At least eight factors should be considered in establishing the relevant point of compliance for any design under §258.40. The factors provide information needed to determine if the alternative boundary is sufficiently protective of human health and the environment and if the relevant point of compliance is adequate to measure the performance of the disposal unit.

Site Hydrogeology

The first factor to be considered when determining the relevant point of compliance is site hydrogeology. Site hydrogeologic characteristics should be used to identify additional information required to set the relevant point of compliance. The site data should be sufficient to determine the lateral well-spacing required to detect contaminant releases to the uppermost aquifer. Hydrogeologic information required to fully characterize a site is presented in greater detail in Section 5.6.3.

Leachate Volume and Physical Characteristics

Data on leachate volume and quality are needed to make a determination of the "detectability" of leakage from the facility at the relevant point of compliance. The net concentration at any given point resulting from the transport of contaminants from the landfill is a function of contaminant type, initial contaminant concentration, and leakage rate. Assessment of leachate volume is discussed in Sections 4.2 and 4.3. The assessment of contaminant fate and transport was discussed in Section 4.3.

Quality, Quantity and Direction of Ground-Water Flow

The hydrogeologic data collected should provide information to assess the ground-water flow rate, ground-water flow

direction, and the volume of ground-water flow. Background ground-water quality data should be used to establish baseline concentrations of the monitoring constituents. This information will be required as input to determine if contaminants from the landfill unit have been released and have migrated to the relevant point of compliance.

Ground-Water Receptors

The goal of establishing the relevant point of compliance is to ensure early detection of contamination of the uppermost aquifer. The distance to the relevant point of compliance should allow sufficient time for corrective measures to be implemented prior to the migration of contaminants to private or public water supply wells.

Existing users of ground water immediately downgradient from the facility should be identified on a map. Users located at a downgradient point where contaminants might be expected to migrate during the active life and post-closure care period of the facility should be identified.

Alternative Drinking Water Supplies

Consideration should be given to the availability of alternate drinking water supplies in the event of a ground-water contamination problem. If the uppermost aquifer is the sole water supply source available, all reasonable efforts should be made to locate the relevant point of compliance as close as possible to the actual waste management unit boundary.

Existing Ground-Water Quality

The existing ground-water quality, both upgradient and downgradient of the MSWLF unit, should be determined prior to establishing the relevant point of compliance (see Section 5.6.3). The performance standard for landfill design requires that landfill units be designed so that the concentrations listed in Table 1 are not exceeded at a relevant point of compliance. Issues for approved States to consider are whether the ground water is currently used or is reasonably expected to be used as a drinking water source when setting a relevant point of compliance. If the ground water is not currently or reasonably expected to be used for drinking water, the State may allow the relevant point of compliance to be set near the 150-meter limit.

Public Health, Welfare, Safety

Consideration should be given to the potential overall effect on public health, welfare, and safety of the proposed relevant point of compliance. Issues that should be considered include:

- Distance to the nearest ground-water user or potentially affected surface water;

- The response time (based on the distance to the proposed relevant point of compliance) required to identify and remediate or otherwise contain ground water that may become impacted and potentially affect downgradient water supplies; and

- The risk that detection monitoring data may not be representative of a worst case release of contaminants to ground water.

Practicable Capability of the Owner or Operator

If the relevant point of compliance is placed farther from the waste management unit boundary, the volume of water requiring treatment, should the ground water become contaminated, will increase. One or more of the following conditions could affect the owner's or operator's practicable capability (technical and financial) to remediate contaminant releases:

- Area of impact, remedial costs, scope of remedial investigation, and site characterization;
- Increased response time due to higher costs and increased technical scope of selected remedial method;
- A reduction of the removal efficiency of treatment technologies; and
- Increased difficulty in ground-water extraction or containment if these technologies are chosen.

The Director may require some indication of financial capability of the owner or operator to maintain a longer and more costly remedial program due to the longer detection time frame associated with a relevant point of compliance located at a greater distance from the waste management unit boundary. Additional information on remedial actions for ground water is provided in this document in Chapter 5.

4.5 PETITION PROCESS 40 CFR §258.40(e)

4.5.1 Statement of Regulation

(a) - (d) *(See Statement of Regulation in Sections 4.2.1, 4.3.1, and 4.4.1 of this guidance document for regulatory language.)*

(e) If EPA does not promulgate a rule establishing the procedures and requirements for State compliance with RCRA Section 4005(c)(1)(B) by October 9, 1993, owners and operators in unapproved States may utilize a design meeting the performance standard in §258.40(a)(1) if the following conditions are met:

(1) The State determines the design meets the performance standard in §258.40(a)(1);

(2) The State petitions EPA to review its determination; and

(3) EPA approves the State determination or does not disapprove the determination within 30 days.

[Note to Subpart D: 40 CFR Part 239 is reserved to establish the procedures and requirements for State compliance with RCRA Section 4005(c)(1)(B).]

4.5.2 Applicability

If EPA does not promulgate procedures and requirements for state approval by October 9, 1993, owners and operators of MSWLF units located in unapproved States may be able to use an alternative design (in compliance with §258.40(a)(1)) under certain circumstances.

Owners or operators of MSWLF units should contact the municipal solid waste regulatory department in their State to determine if their State has been approved by the U.S. EPA.

4.6 FURTHER INFORMATION

4.6.1 REFERENCES

(Specific to Performance-Based Design Assessment and Solute Transport Modeling)

Abriola, L.M., and G.F. Pinder, (1985a). A Multiphase Approach to the Modeling of Porous Media Contamination by Organic Compounds 1. Equation Development. Water Resources Research 21(1):11-18.

Abriola, L.M., and G.F. Pinder, (1985b). A Multiphase Approach to the Modeling of Porous Media Contamination by Organic Compounds 2. Numerical Simulation. Water Resources Research 21(1):19-26.

Aller, L., T. Bennett, J.H. Lehr, R.J. Petty, and G. Hackett, (1987). DRASTIC: A Standardized System for Evaluation Ground Water Pollution Potential Using Hydrogeologic Settings. EPA-600/2-87-035, Kerr Environmental Research Lab, U.S. Environmental Protection Agency, Ada, Oklahoma. 455 pp.

Auerbach, S.I., C. Andrews, D. Eyman, D.D. Huff, P.A. Palmer, and W.R. Uhte, (1984). Report of the Panel on Land Disposal. In: Disposal of Industrial and Domestic Wastes: Land and Sea Alternatives. National Research Council. National Academy Press. Washington, DC. pp. 73-100.

Beljin, M.S., (1985). A Program Package of Analytical Models for Solute Transport in Groundwater "SOLUTE". BAS15, International Groundwater Modeling Center, Holcomb Research Institute, Butler University, Indianapolis, Indiana. 163 pp.

Bond, F., and S. Hwang, (1988). Selection Criteria for Mathematical Models Used in Exposure Assessments: Groundwater Models. EPA/600/8-88/075, U.S. Environmental Protection Agency, Washington, DC.

Boutwell, S.H., S.M. Brown, B.R. Roberts, and D.F. Atwood, (1986). Modeling Remedial Actions at Uncontrolled Hazardous Waste Sites. EPA/540/2-85/001, U.S. Environmental Protection Agency, Athens, Georgia.

Cederberg, G.A., R.L. Street, and J.O. Leckie, (1985). A Groundwater Mass Transport and Equilibrium Chemistry Model for Multicomponent Systems. Water Resources Research, 21(8):1095-1104.

Dean, J.D., P.S. Huyakorn, A.S. Donigian, Jr., K.S. Voos, R.W. Schanz, Y.J.Meeks, and R.F. Carsel, (1989). Risk of Unsaturated/Saturated Transport and Transformation of Chemical Concentrations (RUSTIC). EPA/600/3-89/048a, U.S. EPA, Athens, Georgia.

de Marsily, G., (1986). Quantitative Hydrogeology: Groundwater Hydrology for Engineers. Academic Press, San Diego, California. 440 pp.

Dillon, R.T., R.M. Cranwell, R.B. Lantz, S.B. Pahwa, and D.S. Ward, (1978). Risk Methodology for Geologic Disposal of Radioactive Waste: The Sandia Waste Isolation Flow and Transport (SWIFT) model. Sand 78-1267/NUREG-CR-0424, Sandia national Laboratories, Albuquerque, New Mexico.

Domenico, P.A., and V.V. Palciauskas, (1982). Alternative Boundaries in Solid Waste Management. Ground Water, 20(3):303-311.

Domenico, P.A., and G.A. Robbins, (1985). A New Method for Contaminant Plume Analysis. Ground Water, 23(4):476-485.

Donigian, A.S., and P.S.C. Rao, (1990). Selection, Application, and Validation of Environmental Models. In: Proceedings of the International Symposium on Water Quality Modeling of Agricultural Non-Point Sources, Part 2. D.G. DeCoursey (ed.). ARS-81, U.S. Department of Agriculture Agricultural Research Services. pp. 577-600.

Erdogen, H., and R.D. Heufeld, (1983). Modeling Leachates at Landfill Boundaries. Journal of Environmental Engineering, 109(5):1181-1194.

Faust, C.R., J.H. Guswa, and J.W. Mercer, (1989). Simulation of Three-Dimensional Flow of Immiscible Fluids Within and Below the Unsaturated Zone. Water Resources Research, 25(12):2449-2464.

Freeze, R.A., and J.A. Cherry, (1979). Ground Water. Prentice-Hall, Englewood Cliffs, New Jersey. 604 pp.

GeoTrans, Inc., (1985). SWANFLOW: Simultaneous Water, Air and Non-Aqueous Phase Flow, Version 1.0-Code Documentation. Herndon, Virginia. 97 pp.

Grove, D.B., and K.G. Stollenwerk, (1987). Chemical Reactions Simulated by Groundwater Quality Models. Water Resources Bulletin, 23(4):601-615.

Gupta, S.K., C.R. Cole, C.T. Kincaid, and F.E. Kaszeta, (1982). Description and Applications of the FE3DGW and CFEST Three-dimensional Finite Element Models, Battelle Pacific NW Laboratories, Richland, Washington.

Gupta, S.K., C.T. Kincaid, P. Meyer, C. Newbill, and C.R. Cole, (1982). CFEST: Multidimensional Finite Element Code for the Analysis of Coupled Fluid, Energy and Solute Transport. PNL-4260, Battelle Pacific NW Laboratories, Richland, Washington.

Gureghian, A.B., D.S. Ward, and R.W. Cleary, (1980). A Finite Element Model for the Migration of Leachate from a Sanitary Landfill in Long Island, New York - Part I: Theory. Water Resources Bulletin, 16(5):900-906.

Guvanasen, V., (1984). Development of A Finite Element Code and Its Application to Geoscience Research. Proceedings 17th Information Meeting of the Nuclear Fuel Waste Management Program, Atomic Energy of Canada, Ltd. Technical Record TR-199. pp. 554-566.

Haji-Djafari, S., (1983). User's Manual GEOFLOW Groundwater Flow and Mass Transport Computer Program. D'Appolonia, Pittsburgh, Pennsylvania.

Huyakorn, P.S. et al., (1984). Testing and Validation of Models for Simulating Solute Transport in Groundwater: Development, Evaluation and Comparison of Benchmark Techniques. GWMI 84-13, International Groundwater Modeling Center, Holcomb Research Institute, Indianapolis, Indiana.

Huyakorn, P.S., M.J. Ungs, L.A. Mulkey, and E.A. Sudicky, (1987). A Three-Dimensional Analytical Method for Predicting Leachate Migration. Ground Water, 25(5):588-598.

Huyakorn, P.S., H.O. White, Jr., V.M. Guvanasen, and B.H. Lester, (1986). TRAFRAP: A Two-dimensional Finite Element Code for Simulating Fluid Flow and Transport of Radionuclides in Fractured Porous Media. FOS-33, International Groundwater Modeling Center, Holcomb Research Institute, Butler University, Indianapolis, Indiana.

Javandel, I., C. Doughty, and C.F. Tsang, (1984). Groundwater Transport: Handbook of Mathematical Models. Water Resources Monogram 10, American Geophysical Union, Washington, DC 228 pp.

Keely, J.F., (1987). The Use of Models in Managing Ground-Water Protection Programs. U.S. Environmental Protection Agency. EPA/600/8-87/003, Ada, Oklahoma. 72 pp.

Keely, J.F., (1989). Performance Evaluations of Pump-and-Treat Remediations. EPA/540/4-89/005, U.S. Environmental Protection Agency, Ada, Oklahoma. 19 pp.

Kincaid, C.T., J.R. Morrey, and J.E. Rogers, (1984a). Geohydrochemical Models for Solute Migration- Volume 1: Process Description and Computer Code Selection. EA-3417, Electric Power Research Institute, Palo Alto, California.

Kincaid, C.T., J.R. Morrey, S.B. Yabusaki, A.R. Felmy, and J.E. Rogers, (1984b). Geohydrochemical Models for Solute Migration- Volume 2: Preliminary Evaluation of Selected Computer Codes. EA-3417, Electric Power Research Institute, Palo Alto, California.

Kipp, K.L., Jr., (1987). HST3D: A Computer Code for Simulation of Heat and Solute Transport in Three-Dimensional Groundwater Flow Systems. WRI 86-4095, U.S. Geological Survey, Lakewood, Colorado.

Konikow, L.F., and J.D. Bredehoeft, (1985). Method-of-Characteristics Model for Solute Transport (1985 revision). U.S. Geological Survey.

Lindstrom, F.T., and L. Boersma, (1989). Analytical Solutions for Convective-Dispersive Transport in Confined Aquifers with Different Initial and Boundary Conditions. Water Resources Research, 25(2):241-256.

Lu, J.C.S., B. Eichenberger, and R.J. Stearns, (1985). Leachate Migration from Municipal Landfills. Pollution Technology Review No. 19. Noyes Publications, Park Ridge, New Jersey. 453 pp.

Mercer, J.W., S.D. Thomas, and B. Ross, (1983). Parameters and Variables Appearing in Repository Siting Models. NUREG/CR-3066. Prepared for U.S. Nuclear Regulatory Commission, Washington, DC. 244 pp.

Mulkey, L.A., A.S. Donigian, Jr., T.L. Allison, and C.S. Raju, (1989). Evaluation of Source Term Initial Conditions for Modeling Leachate Migration from Landfills. U.S. EPA, Athens, Georgia.

Narasimhan, T.N., A.F. White, and T. Tokunaga. 1986. Groundwater Contamination From an Inactive Uranium Mill Tailings Pile 2. Application of a Dynamic Mixing Model. Water Resources Research, 22(13):1820-1834.

National Research Council, (1990). Ground Water Models: Scientific and Regulatory Applications. National Academy Press, Washington, DC. 320 pp.

Nelson, R.W., and J.A. Schur, (1980). PATHS Groundwater Hydrologic Model. PNL-3162, Battelle Pacific NW Laboratories, Richland, Washington.

Osborne, M., and J. Sykes, (1986). Numerical Modeling of Immiscible Organic Transport at the Hyde Park Landfill. Water Resources Research, 22(1):25-33.

Ostendorf, D.W., R.R. Noss, and D.O. Lederer, (1984). Landfill Leachate Migration through Shallow Unconfined Aquifers, Water Resources Research, 20(2):291-296.

Oster, P.A. Review of Ground-Water Flow and Transport Models in the Unsaturated Zone, (1982). NUREG/CR-2917, PNL-4427. Pacific Northwest Laboratory, Richland, Washington.

Prakash, A., (1984). Groundwater Contamination Due to Transient Sources of Pollution. J. of Hydraulic Engineering, 110(11):1642-1658.

Prickett, T.A., T.G. Naymik, and C.G. Lonnquist, (1981). A Random-Walk Solute Transport Model for Selected Groundwater Quality Evaluations. Bulletin 65, Illinois State Water Survey, Champaign, Illinois.

Runchal, A.K., (1985). PORFLOW: A General Purpose Model for Fluid Flow, Heat Transfer and Mass Transport in Anisotropic, Inhomogeneous, Equivalent Porous Media, Volume I: Theory, Volume II: User's Manual. ACRI/TN-O11. Analytic and Computational Research, Inc. West Los Angeles, California.

Runchal, A.K., (1985). Theory and Application of the PORFLOW Model for Analysis of Coupled Flow, Heat and Radionuclide Transport in Porous Media. Proceedings, international Symposium on Coupled Processes Affecting the Performance of a Nuclear Waste Repository, Berkeley, California.

Salhotra, A.M., P. Mineart, S. Sharp-Hansen, and T. Allison, (1990). Multimedia Exposure Assessment Model (MULTIMED) for Evaluating the Land Disposal of Wastes--Model Theory. Prepared for U.S. Environmental Protection Agency, Environmental Research Laboratory, Athens, Georgia.

Schroeder, A.C., A.C. Gibson, and M.D. Smolen, (1984). The Hydrologic Evaluation of Landfill Performance (HELP) Model, Volumes I and II. EPA/530/SW-009 and EPA/530/SW-010, U.S. Environmental Protection Agency, Cincinnati, Ohio.

Sharp-Hansen, S., C. Travers, P. Hummel, and T. Allison, (1990). A Subtitle D Landfill Application Manual for the Multimedia Exposure Assessment Model (MULTIMED). Prepared for the U.S. EPA, Environmental Research Laboratory, Athens, Georgia.

Summers, K.V., S.A. Gherini, M.M. Lang, M.J. Ungs, and K.J. Wilkinson, (1989). MYGRT Code Version 2.0: An IBM Code for Simulating Migration of Organic and Inorganic Chemicals in Groundwater. EN-6531. Electric Power Research Institute, Palo Alto, California.

Temple, Barker and Sloane, Inc., (1988). Draft Regulatory Impact Analysis of Proposed Revisions to Subtitle D Criteria for Municipal Solid Waste Landfills. Prepared for Office of Solid Waste, U.S. Environmental Protection Agency.

Theis, T.L., D.J. Kirkner and A.A. Jennings, (1982). Multi-Solute Subsurface Transport Modeling for Energy Solid Wastes. Technical Progress Report for the Period September 1, 1981-August 31, 1982, COO-10253-3, Prepared for Ecological Research Division, Office of Health and Environmental Research, U.S. Department of Energy.

Travers, C.L., and S. Sharp-Hansen, (1991). Leachate Generation and Migration at Subtitle D Facilities: A Summary and Review of Processes and Mathematical Models. Prepared for U.S. EPA, Environmental Research Laboratory, Athens, Georgia.

Travis, B., (1984). TRACR3D: A Model of Flow and Transport in Porous/Fractured Media. LA-9667-MS. Los Alamos National Laboratory, Los Alamos, New Mexico.

Unge, M.J., K.V. Summers, and S.A. Gherini, (1986). MYGRT: An IBM Personal Computer Code for Simulation Solute Migration in Groundwater, User's Manual. EA-4545-CCM. Electric Power Research Institute, Palo Alto, California.

U.S. EPA, (1988). Superfund Exposure Assessment Manual. EPA/540/1-88/001, Washington, DC. NTIS No. PB89-135859. 157 pp.

U.S. EPA, (1993). Compilation of Ground-Water Models; PB93-209401; U.S. EPA; Office of Solid Waste; Washington, D.C.

van der Heijde, P.K., Y. Bachmat, J. Bredehoeft, B. Andrews, D. Holtz, and S. Sebastian, (1985). Groundwater Management: The Use of Numerical Models. American Geophysical Union, Washington, D.C.

van der Heijde, P.K., and M.S. Beljin, (1988a). Model Assessment for Delineating Wellhead Protection Areas. EPA-440/6-88-002, U.S. EPA, Washington, DC.

van der Heijde, P.K., El-Kadi, A.I., and S.A. Williams, (1988b). Groundwater Modeling: An Overview and Status Report. EPA/600/2-89/028, U.S. EPA, Ada, Oklahoma.

van Genuchten, M.T., (1978). Simulation Models and Their Application to Landfill Disposal Siting; A Review of Current Technology. In Land Disposal of Hazardous Wastes. EPA-660/9-78-016, U.S. EPA, Cincinnati, Ohio.

van Genuchten, M.T., and W.J. Alves, (1982). Analytical Solutions of the One-Dimensional Convective-Dispersive Solute Transport Equation. USDA, Technique Bulletin No. 1661. U.S. Department of Agriculture, Washington, DC.

Versar, Inc., (1987). Current and Suggested Practices in the Validation of Exposure Assessment Models, Draft Report. Prepared for U.S. EPA Office of Health and Environmental Assessment, Exposure Assessment Group, Washington, DC. EPA Contract No. 69-02-4254, Work Assignment No. 55.

Voss, C.I., (1984). SUTRA: A Finite Element Simulation Model for Saturated-Unsaturated Fluid Density-Dependent Groundwater Flow with Energy Transport or Chemically Reactive Single Species Solute Transport. Water Resources Investigations 84-4369, U.S. Geological Survey.

Walton, W.C., (1984). 35 Basic Groundwater Model Programs for Desktop Microcomputers. GWMI 84-06/4, International Groundwater Modeling Center, Holcomb Research Institute, Butler University, Indianapolis, Indiana.

Weaver, J., C.G. Enfield, S. Yates, D. Kreamer, and D. White, (1989). Predicting Subsurface Contaminant Transport and Transformation: Considerations for Model Selection and Field Validation. U.S. EPA, Ada, Oklahoma.

Yeh, G.T., (1981). AT123D: Analytical, Transient, One-, Two-, Three-Dimensional Simulation of Waste Transport in the Aquifer System. Publication No. 1439. Oak Ridge National Laboratory, Oak Ridge, Tennessee.

Yeh, G.T., (1990). Users' Manual of a Three-Dimensional Hybrid Lagrangian-Eulerian Finite Element Model of WASTE Transport through Saturated-Unsaturated Media. Pennsylvania State University, University Park, PA.

Yeh, G.T., and D.S. Ward, (1981). FEMWASTE: A Finite-Element Model of Waste Transport through Saturated-Unsaturated Porous Media. ORNL-5601. Oak Ridge National Laboratory, Oak Ridge, Tennessee.

Yeh, G.T., and D.S. Ward, (1987). FEMWATER: A Finite-Element Model of Water Flow through Saturated-Unsaturated Porous Media. ORNL-5567/R1. Oak Ridge National Laboratory, Oak Ridge, Tennessee.

4.6.2 REFERENCES

(Specific to Design Criteria)

ASCE, (1969). "Design and Construction of Sanitary and Storm Sewers"; ASCE Manual on Engineering Practice; No. 37.

Bear, Jacob and Arnold Veruijt, (1987). "Modeling Groundwater Flow and Pollution"; D. Reidel Publishing Company; Dordracht, Holland.

Benson, Craig H. and David E. Daniel, (1990). "Influence of Clods on Hydraulic Conductivity of Compacted Clay"; Journal of Geotechnical Engineering; Volume 116, No. 8; August, 1990.

Bonaparte, R. and Gross, B.A., (1990). "Field Behavior of Double-Liner Systems. In Waste Containment Systems: Construction, Regulation, and Performance, Edited by R. Bonaparte. Geotechnical Pub 1.26, ASCE.

Carroll, Jr., R.G., (1987). "Hydraulic Properties of Geotextiles." Geotextile Testing and the Design Engineers, ASTEM 952, American Society for Testing and Materials, Philadelphia, PA, pp 7-20.

COE, (1970). "Laboratory Soils Testing"; EM1110-2-1906; Headquarters, Department of the Army; Office of the Chief of Engineers; Washington, DC 20314.

FHWA, (1985). "FHWA Geotextile Engineering Manual." Contract No.l DTF H61-83-C-00150.

FHWA, (1990). "Geotextile Design & Construction Guidelines. Contract No. FHWA DTFH61-86-C-00102.

GCA Corporation, (1983). "Draft Permit Writers' Guidance Manual for Hazardous Waste Treatment, Storage, and Disposal Facility"; 1983.

Giroud, J.P., (1982). "Filter Criteria for Geotextiles," Proceeding 2nd International Conference on Geotextiles, Las Vegas, Nevada.

Giroud, J.P. and R. Bonaparte, (1989). "Leakage Through Liners Constructed with Geomembranes - Part I: Geomembrane Liners"; Geotextiles and Geomembranes 8(2); 0266-1144/89; pp. 27-67; Elsevier Science Publishers Ltd., England, Great Britain.

Giroud, J.P. and R. Bonaparte, (1989). "Leakage Through Liners Constructed with Geomembranes - Part II: Composite Liners"; Geotextiles and Geomembranes 8(2); 0266-1144/89; pp. 71-111; Elsevier Science Publishers Ltd., England, Great Britain.

Giroud, J.P., A. Khatami and K. Badu-Tweneboah, (1989). "Technical Note - Evaluation of the Rate of Leakage Through Composite Liners"; Geotextiles and Geomembranes 8; 0266-1144/89; pp. 337-340; Elsevier Science Publishers Ltd., England, Great Britain.

Haxo, H.E., Jr., (1983). "Analysis and Fingerprinting of Unexposed and Exposed Polymeric Membrane Liners"; Proceedings of Ninth Annual Research Symposium: Land Disposal, Incineration, and Treatment of Hazardous Waste; EPA/600/9-83/018; U.S. EPA; Cincinnati, Ohio.

Haxo, H.E., Jr., J.A. Miedema and H.A. Nelson, (1984). "Permeability of Polymeric Membrane Lining Materials"; Matrecon, Inc.; Oakland, California; International Conference on Geomembranes; Denver, Colorado.

Industrial Fabrics Association International (1990). "1991 Specifiers Guide;" Geotechnical Fabrics Report, Volume 8, No. 7, 1990.

Javendale, I., C. Doughty and C.F. Tsang, (1984). "Groundwater Transport; Handbook of Mathematical Models"; American Geophysical Union; Washington, DC 20009.

Jayawickrama, P.W., K.W. Brown, J.C. Thomas and R.L. Lytton, (1988). "Leakage Rates Through Flaws in Membrane Liners"; Journal of Environmental Engineering; Vol. 114, No. 6; December, 1988.

Kastman, Kenneth A., (1984). "Hazardous Waste Landfill Geomembrane: Design, Installation and Monitoring"; Woodward-Clyde Consultants, Chicago, Illinois; International Conference on Geomembranes; Denver, Colorado.

Koerner, Robert M., (1990). "Designing with Geosynthetics"; 2nd Edition; Prentice Hall; Englewood-Cliffs, New Jersey 07632.

Radian Corporation, (1987). "Technical Data Summary: Hydraulic Performance of Minimum Technology Double Liner Systems"; Radian Corporation; Austin, Texas 78766 for U.S. EPA; Contract No. 68-01-7310; Task 7-4.

U.S. EPA, (1982). "Landfill and Surface Impoundment Performance Evaluation"; SW-869; Charles A. Moore; U.S. EPA. NTIS PB-81-166357.

U.S. EPA, (1983). "Lining of Waste Impoundment and Disposal Facilities"; SW-870; U.S. EPA; Office of Solid Waste and Emergency Response; Washington, DC 20460. NTIS PB-81-166365 Revised: PB-86-192796.

U.S. EPA, (1987a). "Background Document on Bottom Liner Performance in Double-Lined Landfills and Surface Impoundments"; EPA/530/SW-87/013; U.S. EPA; Washington, DC. NTIS PB-87-182291.

U.S. EPA, (1987b) " Characterization of MWC Ashes and Leachates from MSW Landfills, Monofills and Co-Disposal Sites: Volume VI of VII ; Characterization of Leachates from Municipal Solid Waste Disposal Sites and Co-Disposal Sites"; EPA/530/SW-87/028F, Washington, D.C. NTIS PB-88-127998.

U.S. EPA, (1988). "Guide to Technical Resources for the Design of Land Disposal Facilities"; EPA/625/6-88/018; U.S. EPA; Risk Reduction Engineering Laboratory; Center for Environmental Research Information; Cincinnati, Ohio 45268.

U.S. EPA, (1988a). Superfund Exposure Assessment Manual. EPA/540/1-88/001, Washington, D.C., NTIS No. PB89-135.859, 157 pp.

U.S. EPA, (1988b). "Design, Construction and Evaluation of Clay Liners for Waste Management Facilities; EPA/530/SW-86/007F; U.S. EPA; Office of Solid Waste and Emergency Response; Washington, DC 20460. NTIS PB-86-184496.

U.S. EPA, (1988c). "Groundwater Modeling: An Overview and Status Report"; EPA/600/2-89/028; U.S. EPA; Environmental Research Laboratory; Ada, Oklahoma 74820. NTIS PB-89-224497.

U.S. EPA, (1988d). "Multimedia Exposure Assessment Model for Evaluating the Land Disposal of Hazardous Wastes, Volume I."; Woodward-Clyde Consultants, Oakland, CA 94607-4014 for U.S. EPA; Environmental Research Laboratory; Office of Research and Development; Athens, Georgia 30613.

U.S. EPA, (1988e). "Lining of Waste Containment and Other Impoundment Facilities"; EPA/600/2-88/052; U.S. EPA; Risk Reduction Engineering Laboratories; Cincinnati, Ohio 45268. NTIS PB-89-129670.

U.S. EPA, (1989). "Seminar Publication - Requirements for Hazardous Waste Landfill Design, Construction and Closure"; EPA/625/4-89/022; U.S. EPA; Center for Environmental Research Information; Office of Research and Development; Cincinnati, Ohio 45268.

U.S. EPA, (1990a). "Seminars - Design and Construction of RCRA/CERCLA Final Covers", CERI 90-50; U.S. EPA; Office of Research and Development; Washington, DC 20460.

U.S. EPA, (1990b). "Draft - LDCRS Flow Data from Operating Units - Technical Support for Proposed Liner/Leak Detection System Rule"; Geoservices, Inc. Consulting Engineers; Norcross, Georgia 30093.

U.S. EPA, (1990c). "Relationship of Laboratory- and Field-Determined Hydraulic Conductivity in Compacted Clay Layer"; EPA/600/2-90/025; U.S. EPA; Risk Reduction Engineering Laboratory; Cincinnati, Ohio 45268. NTIS PB-90-257775.

U.S. EPA, (1991a). "Technical Guidance Document: Inspection Techniques for the Fabrication of Geomembrane Field Seams"; EPA 530/SW-91/051, May 1991, Cincinnati, Ohio.

U.S. EPA, (1991b). "Landfill Leachate Clogging of Geotextiles (and Soil) Filters"; EPA/600/2-91/025, August 1991; Risk Reduction Engineering Laboratory; Cincinnati, Ohio, 45268. NTIS PB-91-213660.

U.S. EPA, (1992). "Technical Guidance Document: Construction Quality Management for Remedial Action and Remedial Design Waste Containment Systems"; EPA/540/R-92/073, October 1992; Risk Reduction Engineering Laboratory, Cincinnati, Ohio 45268 and Technology Innovation Office, Washington, D.C. 20460.

4.6.3 Models

List of Contacts for Obtaining Leachate Generation and Leachate Migration Models

Center for Exposure Assessment Modeling (CEAM), U.S. EPA, Office of Research and Development, Environmental Research Laboratory, Athens, Georgia 30605-2720, Model Distribution Coordinator (706) 546-3549, Electronic Bulletin Board System (706) 546-3402: MULTIMED, PRZM, FEMWATER/FEMWASTE, LEWASTE/3DLEWASTE

Electric Power Research Institute, Palo Alto, California, (214) 655-8883: MYGRT, FASTCHEM

Geo-Trans Inc., 46050 Manekin Plaza, Suite 100, Sterling, VA 20166, (703) 444-7000: SWANFLOW, SWIFT, SWIFT II, SWIFT III, SWIFT/386.

Geraghty & Miller, Inc., Modeling Group, 10700 Parkridge Boulevard, Suite 600 Reston, VA 22091: MODFLOW[386], MODPATH[386], MOC[386], SUTRA[386], Quickflow,

International Groundwater Modeling Center, Colorado School of Mines, Golden, Colorado (303) 273-3103: SOLUTE, Walton35, SEFTRAN, TRAFRAP,

National Technical Information Services (NTIS), 5285 Port Royal Road, Springfield, VA 22161, (703) 487-4650: HELP

Dr. Zubair Saleem, U.S. EPA, 401 M Street SW, Washington, DC, 20460, (202) 260-4767: EPACML, VHS

Scientific Software Group, P.O. Box 23041, Washington, DC 20026-3041 (703) 620-9214: HST3D, MODFLOW, MOC, SUTRA, AQUA, SWIMEV.