Alternative Landfill Covers

July 2001

Prepared for the
Air Force Center for Environmental Excellence
Technology Transfer Division
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For Use by the
Interstate Technology & Regulatory Cooperation (ITRC)
at the Alternative Landfill Covers Summit, September 2001

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Mitretek Systems

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1 INTRODUCTION

The purpose of this paper is to present the benefits and opportunities—as well as the potential problems—associated with use of alternative, vegetative landfill covers. It provides a common point of departure for a one-day discussion of alternative landfill covers, including differing views of the technology and its application. It is not intended to be an exhaustive review of alternative landfill covers.

Several alternative technologies for landfill covers are described in recent literature. Most of them, however, are variations of the established barrier-type landfill cover technology; they are only briefly described. This paper principally deals with new and innovative uses of plants and soil to produce an effective, economical landfill cover without the use of barrier layers. It focuses specifically on the evapotranspiration (ET) landfill cover.

The ET landfill cover is designed to work with the forces of nature rather than attempting to control water flow with barrier layers. It uses two natural processes to control infiltration of water into the waste: (1) the soil stores infiltrating water and (2) ET removes the water from the soil water reservoir. Details regarding requirements for successful use of the ET landfill cover concept are contained in the following pages.

The ET landfill cover concept was defined in several papers, beginning in 1994, including Hauser and Shaw (1994a and 1994b), Hauser et al. (1994, 1995, and 1996), Hauser (1997), Weand and Hauser (1997), and Hauser and Weand (1998). In addition, the principles for applying ET landfill covers have been presented at several national conferences. Although the principles for the cover are widely available, the authors have found that the terminology has been appropriated over the past several years, and in some cases misapplied. Several vegetative landfill covers that do not meet the specific requirements for an ET landfill cover were constructed and referred to as "ET covers." For example, it is important that soil density in an ET cover be such that it will support robust root growth in all layers of the cover to allow rapid and complete removal of soil water by the vegetation growing on the cover. Some literature reports have described cover designs with soil that was compacted sufficiently to limit or prevent plant root growth at depth, yet the authors labeled these designs as ET covers.

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One important issue for the Alternative Landfill Covers Summit is to define essential requirements for an ET landfill cover design, thus differentiating it from more generic vegetative covers.

2 REQUIREMENTS

2.1 Requirements for Landfill Covers

Landfills typically contain large volumes of waste and cover large land areas. Because of the expense and risk associated with treating or removing these wastes, they are usually contained in place, which requires the construction of a suitable cover. Regulators and the public usually accept covers as presumptive remedies for final landfill remediation.

Landfill remediation must protect both public health and the environment. A modern philosophy has evolved requiring contaminants in the waste to be isolated from receptors and contained within the landfill. As a result of that philosophy, landfills have become warehouses in which wastes are stored for an indefinite time, possibly centuries.

To offer environmental benefits, landfill covers must meet three preeminent functional requirements:

- **Minimize infiltration**: Water that percolates through the waste may dissolve contaminants and form leachate, which can pollute both soil and groundwater as it travels from the site.
- **Isolate wastes**: A cover over the wastes prevents direct contact with potential receptors at the surface.
- **Control landfill gas**: Landfills may produce explosive or toxic gases that, if accumulated or released, can create a hazard in the vicinity.

These three principal requirements are common to all landfill cover designs, but the way in which they are technically implemented can be quite different.

2.2 Landfill Age and Characteristics

Landfill age and characteristics differ between sites and impact the requirements for remediation. The modern concept of landfills has been shaped by government rules and regulations for municipal and hazardous waste landfills. The current concept envisions landfills containing fresh waste placed over effective and expensive lining systems.

There are a large number of landfills needing remediation that have characteristics quite different from municipal landfills. For example, the Air Force has more than 550 landfills within the continental United States (Hauser et al., 1999a), and most of them have not yet been remediated. Approximately 86 percent of these landfills have been dormant for more than 20 years, virtually none have liners, and relatively few have caused significant groundwater contamination. About 12 percent of the closed Air Force landfills required no further action. The U.S. Environmental Protection Agency (EPA) indicates that landfills on military bases contain typical household refuse intermingled with industrial waste. Military-specific wastes (e.g., munitions) were found at only 10 percent of 51 landfills surveyed (USEPA, 1996).

Because of their age and decayed contents, Air Force landfills may pose less risk than typical municipal landfills. However, their remediation in place may require containment and an effective cover. Other government agencies also have many old, unremediated landfills.

2.3 Landfill Cover Selection Relative to Site Requirements

While the purposes of a landfill cover are clear, the particular implementation as translated into design elements is dependent on specific site characteristics. The site characteristics that have a dominant influence on the choice of an appropriate final cover include climate, soils, landfill waste characteristics, hydrogeology, gas production, seismic environment, and reuse of landfill areas. Before choosing remediation methods, the site should be evaluated and all parties should agree on site-specific requirements for the landfill cover. Then, any cover design that meets these site-specific requirements could be used as part of the remediation.

3 LANDFILL COVER TECHNOLOGY

This section provides a brief overview of landfill cover types to provide the setting for the alternative cover discussion. Additional detail is available in Weand et al. (1999), Hauser et al. (1999a), Boyer et al. (1999), Gill et al. (1999), and Koerner and Daniel (1997), as well as in U.S. EPA (1991, 1993, and 1996).

In the pages to follow, we will demonstrate that under many conditions, an alternative vegetative landfill cover may offer more environmental protection at lower cost than is offered by currently used barrier technology. Therefore, it is important to understand the advantages, limits of application, and proof of the vegetative landfill cover concept.

3.1 Current Landfill Cover Technology

The dominant feature of covers currently in use is one or more barrier layers that are intended to stop or reduce the natural downward movement of water through the profile of the cover. The Resource Conservation and Recovery Act (RCRA) Subtitle C cover (Figure 1) includes several layers, including grass for surface cover. These covers typically include one or more barrier layers made of compacted clay, geomembranes, or geosynthetic clay. Clay barriers are required to have a maximum saturated hydraulic conductivity (K) value not greater than 1×10^{-7} cm/sec; these barriers are by definition permeable. Barrier-type covers are more completely described in Koerner and Daniel (1997), U.S. EPA (1991, 1993, and 1996), and elsewhere.

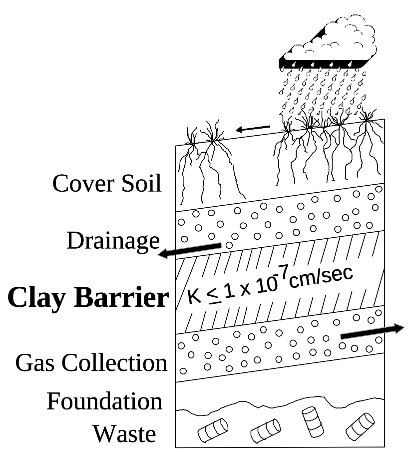

Figure 1. Conventional Cover

The Subtitle D cover is a modified barrier-type cover. It is less expensive than a RCRA cover and is used in dry climates (Ankeny, et al., 1997, and Warren et al., 1997).

3.2 Cost of Landfill Covers

Cost data contained in the AFCEE landfill survey reveal that construction costs for conventional covers constructed on eight landfills at Chanute, Keesler, Lackland, and Pease Air Force Bases (AFBs) range from $319,000 to $571,000 per acre of landfill. U.S. Air Force cost estimates for a landfill at F. E. Warren AFB, WY, indicate that using an ET cover rather than a conventional barrier-type cover resulted in potential construction cost savings exceeding $200,000 per acre of cover (Hauser et al., 1999a).

Other estimates show potential construction cost savings from using an alternative vegetative cover of $150,000 per acre of cover (Hauser and Weand, 1998). This appears to be a conservative figure that is appropriate for general use. Hauser et al. (1999a) estimated that if the Air Force used the ET cover where appropriate, the total savings in construction costs would exceed $500 million within the continental United States.

There is obviously a large potential construction cost savings when using vegetative landfill covers. In addition, there is the potential for reduced long-term maintenance cost if alternative vegetative covers are correctly applied.

Many of the required long-term care (operation and maintenance [O&M]) activities are similar for conventional and ET landfill covers. However, the ET cover offers substantial cost savings for the structural repairs of cover cracks or settlement that are typically encountered. We estimated the cost to repair a 100- and a 400-foot-long crack in both an ET cover and a conventional barrier-type cover to illustrate typical structural repair costs. Each cost estimate was based on published cost figures (Rast, 2001). These estimates indicated that repairing an ET landfill cover would cost 60 to 65 percent less than for a conventional barrier-type cover.

3.3 Alternative Barrier-Type Landfill Covers

Alternative barrier-type covers include the capillary barrier, the dry barrier, and the asphalt barrier. These are experimental systems with limited field use.

- **Capillary Barrier.** The capillary barrier (Figure 2) is formed by two layers—a layer of fine soil over a layer of coarser material (e.g., sand or gravel). The barrier is created in this type of cover by the large change in pore sizes between the layers of fine and coarse material (Stormont, 1997; Gee and Ward, 1997; and Ankeny et al., 1997). Capillary force causes the layer of fine soil overlying the coarser material to hold more water than if there were no change in particle size between the layers. This barrier can fail if too much water accumulates in the fine-particle layer or if the desired large change in pore size is missing in spots.

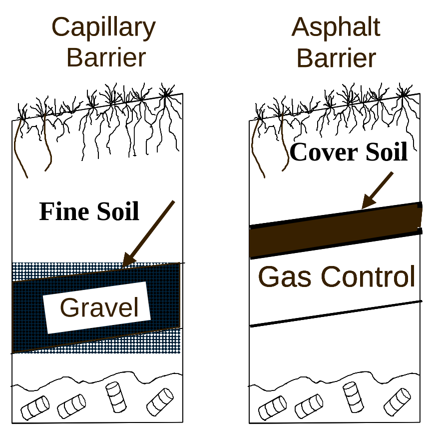

Figure 2. Alternative Barriers

- **Dry Barrier.** The dry barrier is sometimes called the convective air-dried barrier. It is similar to the capillary barrier cover except that wind-driven airflow through the layer of coarse material helps to remove water that may infiltrate this layer (Ankeny et al., 1997).

- **Asphalt Barrier.** The asphalt barrier (Figure 2) may replace the compacted clay layer in covers built in arid climates where a clay barrier may fail because of desiccation (Gee and Ward, 1997).

3.4 Alternative Landfill Covers With No Barrier

Because of the water-holding properties of soils and the fact that most precipitation returns to the atmosphere via ET, it is possible to devise landfill covers that meet the requirements for remediation and yet contain no barrier layer (Figure 3). These covers usually employ a layer of soil on top of the landfill where grass, shrubs, or trees grow for the purpose of controlling erosion and removing water from the soil.

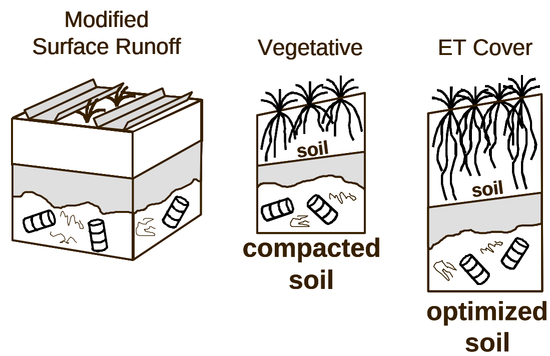

Figure 3. Alternative Covers with No Barrier

Schulz et al. (1997) describe a cover that we label the "Modified Surface Runoff" (MSR) cover (Figure 3). In their experiment, the amount of surface runoff was controlled by placing panels on the surface of the landfill cover to divert a portion of the precipitation. Between the panels, they planted Pfitzer junipers. This cover met the requirement for keeping the underlying waste dry at a Maryland site.

Karr et al. (1999) reported the results of a 21-month evaluation of the MSR cover (Figure 3) in Hawaii. All of their treatments—including a standard RCRA cover—allowed deep percolation below the cover. Since the climate allows year-round plant growth at that location, this result is surprising because up to 40 percent of rainfall was diverted to surface runoff by one of their MSR surface covers. The causes for this failure should be investigated.

Anderson (1997) summarized several recent experiments with vegetative covers (Figure 3). He stated that "…failures of earthen barriers as final caps on landfills in arid or semiarid regions likely result from insufficient depths of soil to store precipitation and support healthy stands of perennial plants." Requirements for success and the probable cause for failure of some experimental covers are discussed below.

The ET cover depicted in Figure 3 is an optimized vegetative cover and is discussed in detail later in this document. A major difference between the ET cover and the vegetative covers currently in use stems from the control of soil properties during construction and seeding operations.

4 REGULATORY LIMITATIONS TO VEGETATIVE LANDFILL COVERS

Federal and state regulations have long dictated not only the application of a landfill cover as a remedial alternative, but also its actual technical design. Given the prescriptive nature of RCRA and many state regulations, the intimate association among the Comprehensive Environmental Restoration, Compensation, and Liability Act (CERCLA), RCRA, and state regulations has historically been an impediment to the selection and installation of alternative landfill covers.

At the time when RCRA was implemented, barrier-type covers using multiple low permeability layers were considered the most permanent and protective landfill cover options. While allowing for some design flexibility, the regulations for both municipal and hazardous waste covers have specific permeability requirements reflecting this prejudice. For covers of hazardous waste landfills, Subtitle C states a general performance requirement to minimize migration of liquids through the closed landfill, while §[7]264.310(a)(5) imposes a permeability requirement: the final cover must have a permeability less than or equal to the bottom liner or natural subsoils.

For municipal waste landfills with Subtitle D covers, this same duality exists in the general goal of minimizing infiltration (§258.60[a]) and the specific requirement that the permeability of the final cover be less than or equal to the permeability of any bottom liner system or the natural subsoils. In any case, Subtitle D covers were required to contain a barrier layer with permeability no greater than $1x10^{-5}$ cm/sec (§258.60[a][1]).

Recently, EPA issued directives that appear to allow consideration of vegetative covers, and several states are revising their regulations (Weand et al., 1999).

5 INNOVATIVE VEGETATIVE LANDFILL COVERS—BASIC TECHNOLOGY

Controlling water is the key requirement for all landfill covers. Under current regulations, the goal for landfill cover design is to prevent water movement into, through, and out the bottom of the landfill waste contents. If water is successfully controlled, then the most important pathway for movement of contaminants from the waste to the environment is cut off.

The hydrologic cycle is well understood, and it is well known that the majority of precipitation falling on the land surface is returned to the atmosphere by evaporation from plants and soil (ET). The second largest pathway for water movement is surface runoff. Plants and soils play a dominant role in all aspects of the hydrologic cycle. It is necessary to understand both the requirements for plant growth and the properties of the soil used in a landfill cover in order to successfully design and construct the cover.

Robust plant growth is required to satisfy the requirements for a landfill cover, but many factors may limit plant growth and limit their effectiveness in landfill covers. Limitations to plant growth are easily and economically removed, controlled, or managed in constructed soils such as in a landfill cover. However, removal of limitations requires knowledge of the principles of plant growth, soil properties, and the multiple interactions with other factors.

5.1 What Do We Know?

There is a great body of knowledge about soils and plant production from agronomy, soils, agricultural engineering, and hydrology disciplines. However, the available knowledge requires interpretation to enable the effective use of plants and soils in landfill covers for the following reasons:

- Some requirements for plant performance in landfill covers are unique.
- Current landfill cover technology has a legacy of barrier-type cover concepts.

[7] Title 40, Part 264, of the Code of Federal Regulations

5.1.1 Hydrologic Cycle and Water Balance

The global hydrologic cycle is assumed to be a closed system that neither gains nor loses water—the system is in balance. The hydrologic cycle encompasses water movement from the oceans to clouds, then to precipitation, followed by movement back to the ocean by various routes.

The hydrologic cycle for a landfill site is most appropriately examined as a water balance—inputs should equal outputs at the site. The water balance is used to understand the pathways of water movement at a site as illustrated in Figure 4.

Based on the principle of mass conservation, the water balance for a site is as follows:

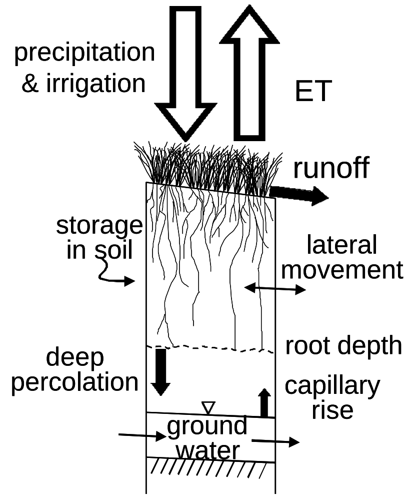

Figure 4. Site Water Balance

Precipitation + Irrigation = ET + Runoff + Change in Stored Soil Water + Lateral Movement + Deep Percolation + Capillary Rise + Change in Groundwater Storage

The sources for infiltration are precipitation and, where applied, irrigation. ET is the "combined loss of water from a given area, during a specified period of time, by evaporation from the soil surface and by transpiration from plants" (SSSA, 1997). ET moves the majority of the incoming water back to the atmosphere. Plants greatly affect the amount of evaporation from the soil surface, as well as the amount of transpiration. Therefore, growing plants impose the primary control of ET at a specific site. Plant residue may also affect total ET from a site by covering and insulating the soil.

At most sites, the second largest loss of water is by surface runoff. Changes in stored soil water, lateral movement, deep percolation, capillary rise, and change in groundwater storage must be entered into the equation with the appropriate algebraic sign. Site conditions frequently allow the assumption that lateral movement in the vadose zone is zero.

By analyzing each process, it is possible to develop a water balance that may be used to evaluate and design a landfill cover. The principles of water balance analysis are described in recent texts (Stewart and Nielsen, 1990; Camp et al., 1996; American Society of Civil Engineers, 1996; Koerner and Daniel, 1997; McAneny et al., 1985; and McBean et al., 1995).

The purpose of the landfill cover is to change the hydrologic cycle or water balance at a landfill site so that little or no water moves into or through the stored waste.

5.1.2 Robustness of Plant Cover

Plants best approach the performance goals of the cover design when the only limitation on growth is soil water content. However, plant growth may be limited by other factors, including soil and air temperature, precipitation, solar radiation, wind, humidity, disease, and insect attack, as well as the soil parameters discussed below. More than one limitation may be in effect at any given time, and there may be substantial interactions among limiting factors. It is also important to understand which limitations reduce the ability of plants to extract water from the soil, thereby reducing their effectiveness in landfill covers. Aboveground biomass on the ET cover may be a good indicator of the effective use of water from the soil cover because biomass production and soil water use are closely and linearly related.

ET landfill covers should include a diverse mixture of grass species that are native to the site. Such native mixtures evolved under the conditions of the site and therefore will be predisposed to survive there and successfully perform as desired. During any particular year, one or more species may encounter less than optimum conditions for growth. However, since natural systems "abhor a vacuum," other species in a native grass mixture thrive and dry the soil profile. Native grass mixtures are particularly well adapted to rapid regrowth after fire or drought.

The sections that follow provide additional detail regarding plant-growth requirements.

5.1.3 Soils

Soil tilth is "[t]he physical condition of soil as related to its ease of tillage, fitness as a seedbed, and its impedance to seedling emergence and root penetration." (SSSA, 1997). Tilth is affected by particle-size distribution, water content, aggregation of soil particles, and soil bulk density. Good soil tilth in a vegetative landfill cover will significantly improve the performance of the cover. Other soil properties that govern root and plant growth include soil fertility, oxygen content of the soil air, soil salinity, toxic substances (e.g., ammonia from decaying organic matter), and soil acidity.

The U.S. Department of Agriculture (USDA) soil textural classification system is shown in Figure 5. Soils that contain sufficient cation exchange capacity to (1) hold adequate plant nutrients, (2) hold an adequate amount of water, and (3) provide a good root-growth environment include loam, silt loam, clay loam, silty clay loam, clay and silty clay. Sandy clay and sandy clay loam soils may have high soil strength and may inhibit root growth. Sandy soils containing less than 20 percent clay and more than 50 percent sand usually have low water-holding capacity.

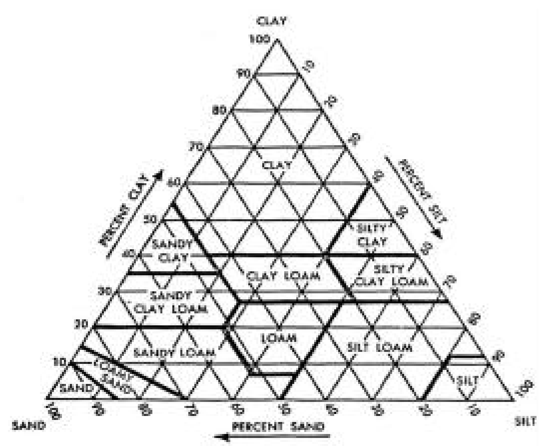

Figure 5. USDA Textural Classification of Soils

Humus, an important component of soils, is composed of organic compounds in soil exclusive of undecayed organic matter. Manure, compost, and grass clippings are organic matter, but they are not humus. Humus is relatively resistant to decay, provides significant additional cation exchange capacity, and improves soil structure. However, plants can grow well in fertile soils that contain little humus (such as volcanic soils in Hawaii and soils of the western Great Plains and the 11 western states). The dark soils in cold moist regions (such as the corn belt, the northeastern states, and Canada) typically contain large amounts of humus. Soil layers containing natural humus should be preserved and used carefully. The addition of organic material to soil to improve its properties may not be worth the expense because most of the added material oxidizes and disappears in a relatively short time.

Soil pore space contains both water and air. Rapid growth of plants requires adequate water as well as adequate oxygen content in the soil air. Soils with good tilth and low soil density normally contain adequate oxygen and are favorable for storage of soil water.

All plants require an adequate amount of nutrients. The nutrient used in largest amount in plant growth is nitrogen, followed by phosphorus and potassium. Some western U.S. soils contain large amounts of phosphorus, but it is sometimes held in an unavailable form because of the excess calcium found in some of these soils. Potassium may be deficient in soils that have been leached, particularly those that are acid. There are a number of other essential plant nutrients that are required in small quantities that are normally found in most soils. Nutrient amendments to landfill cover soils are usually practicable, if necessary.

Landfill cover soils should be free of harmful constituents, such as manmade chemicals, oil, and natural salts. The salts of calcium, magnesium, and sodium may occur naturally, but they can create high salinity in the soil solution. Soil salts may raise the osmotic potential of the soil solution high enough to prevent plants from using all of the soil water. In addition to its contribution to soil salinity, sodium can cause deflocculation of clay particles, thereby causing serious soil crusts, and poor soil tilth, structure, and aeration.

5.1.4 Plants

The successful use of plants in landfill covers requires the optimization of all, or nearly all, factors controlling plant growth, except for soil water supply. The goal is to make soil water content a limiting factor to plant growth for at least part of each growing season. Several features common to plant growth must be considered to achieve that goal.

The distribution of living plant roots in soil controls the drying of each soil layer. Figure 6 illustrates general root distribution patterns. When all layers are adequately wetted, roots often develop as shown for condition 1; the majority of the roots are near the surface, (top 6 to 12 inches). However, as the soil dries, the natural rooting pattern dries the top layers first; after surface soils dry, the root distribution may shift to a pattern similar to condition 2. After extreme drought, most of the active roots will be found deep in the soil profile.

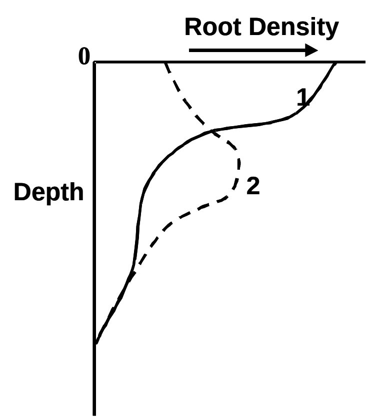

Figure 6. Root Distribution

The density of living and active roots in each layer may increase and then decrease more than once during the growing season as a result of changing conditions. Many plant roots under native grass die but later regenerate in a given soil layer in response to changes in resources and conditions in each soil layer (Camp et al., 1996; Stewart and Nielsen, 1990; and Merva, 1995). It is therefore vital that the soil conditions allow rapid growth of new roots in order for the grass to remove the soil water quickly after a storm. Under favorable conditions, grass root axes may grow 2 cm/day and root laterals may grow 0.5 cm/day; however, some investigators report growth rates up to 6 cm/day (Russell, 1977).

Almost all plants experience a dormant season when they use little water. Cool- and warm-season native grasses may be successfully grown together at most sites. The combination of cool- and warm-season grasses substantially increases the length of the growing season and the soil drying action of the grass cover. The inclusion of both cool- and warm-season plants in the cover more completely ensures that the goals for the cover will be achieved.

Most native grasses or associated species have the potential to root to depths greater than 8 feet. At many natural sites, soil characteristics—rather than the plant potential—limit the rooting depth. The soil conditions for root growth should be optimized throughout the full depth of the cover at all vegetative landfill cover sites for two primary reasons:

- Good root growth is needed throughout the whole soil profile.
- It is relatively inexpensive to optimize the physical properties during construction.

5.1.5 Plant Roots

Vegetative landfill covers are highly dependent on the action of plant roots, so it is necessary to understand the role of roots in the system and their requirements. Rendig and Taylor (1989) state that plant roots serve many complex functions:

- Roots provide the plant with water and nutrients absorbed simultaneously from deep and shallow soil layers, from moist and partially dry soil, and from soil zones of different biological, chemical, and physical properties.
- Roots provide anchorage for the plant.
- Fleshy roots store nutrients.
- Some plants develop adventitious shoots when the main root is damaged.

Roots and shoots (aboveground plant parts) are interdependent. Shoots are the source for organic metabolites used in growth and maintenance, and roots are the source for inorganic nutrients and water. If the top of a plant is pruned to reduce biomass, there is usually a reduction of root mass.

Parts of the root system, particularly small feeder roots, die in response to soil drying or other stresses in a particular layer, while, at the same time, new roots may be growing rapidly in another soil layer. Thus, the distribution of actively growing and functioning roots may change from upper to lower and back to upper soil layers during one growing season.

Under optimum conditions, some plant roots may grow 2 cm (0.8 inches) per day; however, most of the time, limiting factors reduce the rate of root growth below the optimum for the plant in question. Limitations on root growth result in limitations on the ability of the plant to extract water and plant nutrients from the soil. Rendig and Taylor (1989) discuss factors that may limit root growth, including the following:

- Unsatisfactory soil pH
- Soil strength and physical factors
- Soil temperature
- Salinity of the soil solution (caused by excess Ca, Mg, Na, and other salts)
- Soil water content
- Soil oxygen

- Air-filled porosity in the soil
- Chemical toxicity (e.g., pH, Al, Be, Cd, Pb, Cu, Cr, Fe, Hg, Zn, NH_3, B, and Se)
- Allelopathic toxicants

Unsatisfactory soil pH may be corrected or avoided in most instances. Application of lime to the soil can correct low soil pH at reasonable cost. High soil pH may be reduced by soil treatment and leaching, although it may be expensive. A better and normally available alternative for high soil pH is selection of a different soil. Potential problems arising from pH may sometimes be avoided by selecting native plants.

Soil strength and physical factors may limit root growth. Soil water lubricates friction planes if an adequate amount is present, thus reducing strength. The physical condition of the soil, particularly the size and distribution of soil particles and pore spaces, affects soil strength and the movement and availability of water in the soil. Soil oxygen is required in the root respiration process, and its movement and availability to roots is strongly affected by the soil's physical properties. Soil strength and bulk density are important physical factors in soils supporting plant growth (Rendig and Taylor, 1989). Issues that are important to soil physical properties include the following:

- **Soil strength** may exercise more control of root growth than any other parameter. Excessive soil strength can arise as a result of high soil bulk density, increased friction between soil particles, increased cohesion between particles or low soil water content. Soil bulk density and water content may be controlled or changed to improve rooting. The provision of optimum soil density values in fertile soil usually ensures adequate root growth.

- **Soil bulk density** is the mass of dry soil per unit bulk volume. Its value is expressed as Mg/m^3 or gm/cm^3. Soil bulk density is a physical parameter that strongly affects root growth—it can be measured and controlled in landfill covers. In most soils, plant root growth is reduced when soil bulk density exceeds 1.5 Mg/m^3, and values above 1.7 Mg/m^3 may effectively prevent root growth (Eavis, 1972; Monteith and Banath, 1965; Taylor et al., 1966; Jones, 1983; Timlin et al., 1998; and Gameda et al., 1985). Particle size distribution in the soil combines with soil density to control root growth. Roots usually grow well in sandy soils, but their low water-holding capacity discourages their use in ET landfill covers. Jones (1983) demonstrated that plant root growth is reduced at soil bulk density greater than 1.5 Mg/m^3 for most soils, and reduced to less than 0.2 optimum root growth for all soils containing more than 30 percent silt plus clay and having bulk density greater than 1.6 Mg/m^3. Grossman et al. (1992) summarized 18 laboratory studies and found that root growth was only 0.2 of optimum for soil bulk density greater then 1.45 Mg/m^3 except for three soils in which root growth was restricted at soil bulk density of 1.3 Mg/m^3. In addition to inhibiting root growth, high values of soil bulk density result in low soil water-holding capacity because pore space is limited in dense soils. Compacted soils have few large pore spaces, thus limiting soil air movement and oxygen diffusion to roots.

- **Soil modification by freezing and thawing** affects some soil properties. However, Sharatt et al. (1998) present evidence that adverse effects of soil compaction by steel

> wheels was not remediated by a century of freezing and thawing under native grass cover in Minnesota. They also cite other short- and long-term research that demonstrated the long-lasting adverse effects of excessive soil compaction on plant growth.

Soil temperature exerts strong control over the rate of root growth. The site design should ensure that the plants selected are adapted to the expected soil temperatures of the root zone. Each plant has an optimum temperature for root growth; soil temperatures either above or below that temperature result in reduced rate of growth. Beyond the high- or low-temperature limits for each plant, root growth stops.

Salinity of the soil solution may be an important issue. Many salts may contribute to the salinity level of the soil solution. As plants dry the soil, the volume of soil solution decreases and the salinity level increases rapidly. Saline soil solution produces an osmotic effect that reduces or stops water movement into plant roots. The plants remove pure water and only a small amount of salts. As a result, the osmotic strength of the soil solution will increase during soil drying. The resulting concentration of salts in the vadose zone may become a problem; therefore, soil salinity should be characterized for an ET cover soil.

Soil water must be available to the plant in sufficient quantity to maintain hydrostatic pressure within the root cells and thus allow them to divide. Water is required for cell walls and for the growth of hormones needed to loosen the bonds within the cell walls.

Soil oxygen is required in the root respiration process that converts carbohydrates to carbon dioxide and water, thus releasing energy needed by the plant for all of its processes. Oxygen moves through the soil by diffusion through air-filled pores and, to a lesser degree, by mass flow through air-filled pores in response to wind forces on the surface. In order to sustain plant life, an adequate supply of oxygen must be available at the roots. Most plants are stressed if the air-filled pore space in the soil is less than 10 percent although the rate of oxygen movement through the soil is also very important. If the air-filled pores are too small or not connected, little or no oxygen can move to the roots.

Air-filled porosity in the soil is important because each root requires oxygen and because during rain or irrigation these pores become channels for water and air to move rapidly through the soil. Soil pore space includes both large and very small pores. Small pores contribute little to the movement of air, but much of the water is stored in small pores. In an optimal soil structure, large and small pores are connected so that water and air may move freely and there is a desirable distribution of pore size. Total pore space and soil bulk density are inversely related; as a result, dense soils have little pore space and less dense soils have more pore space. One adverse impact of soil compaction is the reduction of large pore spaces. Sandy soils tend to have large pore spaces and be well aerated. Clay soils often contain more total pore space than sandy soils, but most of the pores may be small.

Chemical toxicity as a potential limitation to plant growth should be evaluated for each site. A few soils contain enough toxic material to reduce plant growth.

Allelopathic toxicants are chemicals produced by other plants that kill or limit growth of roots for the plant in question. Allelopathy is an unlikely source of problems because the site manager can control the type of plants grown at the site and the soil source. However, these toxicants may remain in the soil from previous vegetation and may create a problem. If, for example, the soil used in the ET cover was covered by salt cedar or juniper in the past, some grasses or trees may grow poorly in that soil for one or more seasons.

5.1.6 Soil Modification

During construction of an ET cover, the soil is modified, which offers an opportunity to beneficially amend cover soil physical properties at low cost. The amended soil can be designed to dramatically improve its properties for use in a vegetative landfill cover. Landfill cover soils are changed during placement in much the same way as soils that are deep plowed. Soils modified by deep plowing often produce more plant biomass, store more water than the native soil, and allow greatly increased rooting depth and root density (Taylor, 1967; and Unger, 1979). Soils modified by deep plowing, therefore, promote more rapid and complete drying of the entire soil profile. Soil modification remains effective for decades (Unger, 1993; Musick et al., 1981; and Allen et al., 1995).

The modification of soil physical properties during construction of a landfill cover is more complete and, thus, potentially more effective than deep plowing. Four minespoil covers that were built with subsoil or minespoil produced equivalent or better forage production than undisturbed soil because they were properly modified and amended during placement (Chichester and Hauser, 1991; and Hauser and Chichester, 1989). The soil modification during the construction process for the minespoil experimental plots was similar to the action of placing soil for a landfill cover. In spite of unfavorable chemical conditions in the minesoil, it produced biomass yields equal to those for undisturbed surface soil at the site. The improvement in physical properties of the minespoil was important to the success of the experiment.

5.1.7 The Physics of Soil Water Movement

The physics of water movement within the soil is important to an understanding of the principles that govern the performance of a vegetative landfill cover. The modern understanding of water movement in unsaturated soils has been under development for about 150 years, and the development of new concepts continues at a brisk pace in the modern era. Henri Darcy (1856) provided the earliest known quantitative description of water flow in porous mediums. He developed an equation for water flow in saturated sand, and modern equations for both saturated and unsaturated flow are based on his early work.

The currently used equations for water flow in unsaturated soil are based on the assumption that soils are similar to a bundle of capillary tubes and that water flow can be approximated by the Hagen-Poiseuille equation (Marshall et al., 1996). While it is obvious that the pore space in soil is not the same as a bundle of capillary tubes, the concept has proven highly useful and is currently used in mathematical descriptions of water flow in soil.

The Richards equation forms the basis for modern mathematical descriptions of water flow in unsaturated soil (Hillel, 1980). The Richards equation has been mathematically arranged in many forms and each of them requires assumptions. It is a highly non-linear, partial differential equation that must be solved by numerical methods.

Numerical solution of the Richards equation requires estimates of the relationship between hydraulic conductivity and both soil water content and soil water potential. The hydraulic conductivity relationships differ greatly between soils, being dependent on soil structure and on other factors. Figure 7 presents examples of measured hydraulic conductivity. In the unsaturated soils of an ET landfill cover, hydraulic conductivity may vary over four or five orders of magnitude. Furthermore, the relationship is different for soils that are increasing in water content, as compared to that in soils that are drying. The measurement of hydraulic conductivity for soils is difficult, and subject to error.

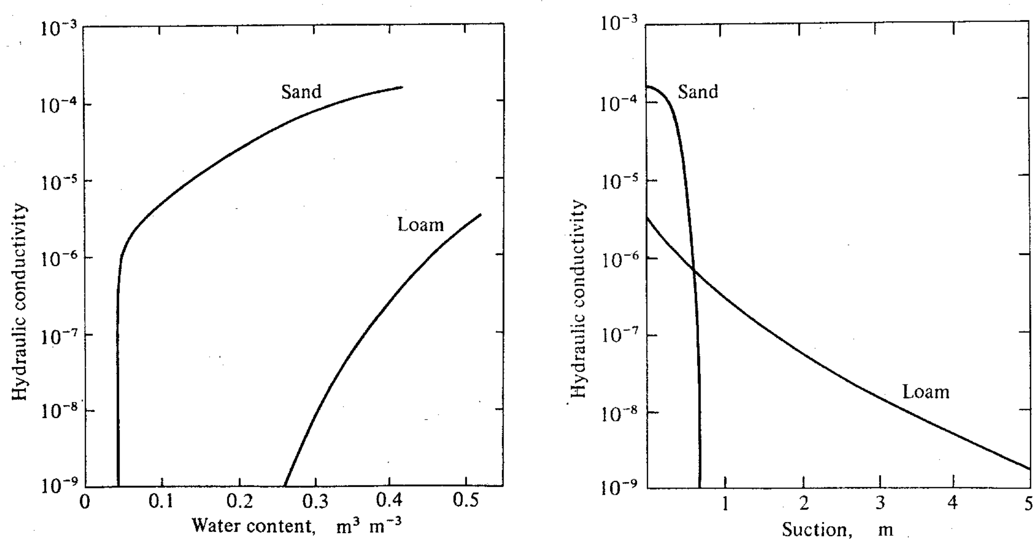

Figure 7. Hydraulic conductivity of sand measured by Day and Luthin (1956), and loam soil measured by Elrick and Bowman (1964) as a function of soil water content (left) and of soil water potential (suction) on the right.

During landfill cover design and construction, cost constraints may make it necessary to estimate the hydraulic conductivity relationship rather than measure it. There is uncertainty about whether laboratory measurements represent the finished soil. Numerous authors have developed methods for estimating the hydraulic conductivity functions from simpler and more easily measured soil parameters. For example, Savabi (2001) employed methods described by 12 different authors to estimate hydraulic conductivity in his model evaluation of the hydrology of a region in Florida. Van Genuchten et al. (1991) developed computer code to estimate hydraulic functions for unsaturated soils. Other models available for estimating soil hydraulic properties include those by Zang and van Genuchten (1994) and by Othmer et al. (1991).

Estimates of water flow in unsaturated soils are often based on the Richards equation, which produces useful estimates when applied in a research setting. However, in the realm of engineering design and field application, the answers from these mathematical models employing the Richards equation may be less accurate than the research data imply. Computer models that employ the Richards equation to estimate water movement in the soil include UNSAT-H (Fayer, 2000) and HYDRUS (Simunek et al., 1997) and Vogel et al. (1996).

5.1.8 Preferential Flow

Preferential flow is defined by the Soil Science Society of America (SSSA, 1996) as “[t]he process whereby free water and its constituents move by preferred pathways through a porous medium.” However, a group of Swiss research workers (Fluhler et al., 2001) state “[i]t is fascinating how the expression ‘preferential flow’ has been adopted by various scientific communities without having been properly defined.” Two national symposiums on preferential flow examine numerous issues surrounding the topic (ASAE, 1991 and 2001) in 95 papers. At this time, there is little consensus on issues related to preferential flow and no adequately tested models with which to predict its effect on water movement during engineering design.

Preferential flow can occur through soil cracks, worm holes, macro pores in the soil, root networks, burrows, and other large openings **if the water in the large pores exists at atmospheric or greater pressure.** In most instances, this requires that a large opening in the soil extend to the soil surface—for example a crack in a clay soil—and that water be ponded over the opening on the surface. Fluhler et al. (2001) explain that preferential flow depends on the saturation of the soil.

Preferential flow, while a possibility, is unlikely to contribute significantly to water flow in a vegetative landfill cover for the following reasons:

- The soil placement and cover construction process disrupt continuous pathways through the soil, e.g., root networks and worm holes.
- By definition of modern landfill cover design, the surface should have a continuous slope of 3 percent or greater and allow no ponds or drainage channels; thus, there is minimal opportunity for water to pond or stand on the surface.
- Burrowing animals protect their burrow from surface runoff by a diversion dam or mound. In addition, their presence is discouraged on landfill covers.
- Historical evidence presented in this paper demonstrates that in spite of known pathways for preferential flow, water did not penetrate below the root zone of native grasses.

5.2 What Do We NOT Know?

5.2.1 Soil Water Movement

The modern theory of soil water movement in unsaturated soils works well in support of irrigation and drainage design and evaluation, and in estimates of groundwater flow. It has successfully explained many water balance issues for rain-fed agriculture and forestry. However, one should remember that (1) these theories contain assumptions, (2) the equations have not been solved mathematically, and (3) while they are the best available, they are not proven natural laws. It is reasonable to assume that modern principles of soil water movement and soil physics, while quite good, are not perfect descriptions of the real world. Therefore, serious consideration should be given to concepts that may not follow modern theory exactly if they are based on field measurements, and especially so when the measurements are from full-scale systems.

5.2.2 Engineering Design

Currently, there are no accepted standardized models available for the design of vegetative covers. The HELP model has been widely used for landfill cover design, however, Benson and Pliska (1996) demonstrated that it produced poor estimates of the water balance. Water balance is one of the most important parts of design and evaluation of ET landfill covers. For design purposes, the part of the water balance of greatest importance is deep percolation—the water movement below the soil of the cover and into the waste. Deep percolation is effectively a remainder term and, as such, contains errors made in each of the larger parts of the water balance estimate.

Surface runoff is one of the critical estimates made during design because it is usually large compared to the potential leakage through the bottom of the cover. An error in estimating surface runoff may result in a large error in the estimate of water movement below the root zone of the vegetative cover. Available surface runoff models usually include significant error in the daily runoff volume estimate.

Actual ET (AET) is another important estimate needed in the design of a vegetative cover. It is the largest term on the outgoing side of the hydrologic balance. Any error in AET will introduce error in the estimate of deep percolation below the plant root zone. AET is normally derived from estimates of potential ET (PET). Even the best estimates of PET contain error, as shown by the comparison of 20 PET estimating systems with measured field data from around the world (Jensen et al., 1990). In addition, approximation of the AET fraction of PET is difficult and may result in significant error.

While contributing small but significant volumes of water movement in some natural settings, preferential flow has not been proven to be a significant factor in vegetative landfill covers.

6 VEGETATIVE COVER FAILURES

Some constructed vegetative covers have not met the requirements for an effective landfill cover. Therefore, it is worthwhile to examine the cause of poor performance.

Anderson (1997) summarized several recent experiments: *"Past failures of earthen barriers as final caps on landfills in arid or semiarid regions likely result from insufficient depths of soil to store precipitation and support healthy stands of perennial plants."*

Warren et al. (1996) reported the results of a four-year experiment with four landfill covers at Hill AFB in northern Utah. Their experiment included a RCRA cover, a control plot with a vegetative cover, and two capillary barriers with vegetative covers. They measured leachate (potential infiltration into the waste) for 46 months and collected the data shown in Table 1. Because the site is in a semi-arid climate, all of the vegetative covers should have minimized leachate, but none of the covers performed adequately.

Warren et al. (1996) stated that most of the leachate was the result of snowmelt and early spring rains and that leachate amount was unrelated to groundcover or plant biomass. Their data suggest that the vegetative cover might have controlled leachate had the soil thickness been increased and/or if the whole soil profile had dried adequately in the fall before the accumulation of snow. These results emphasize the need to evaluate the most critical event during design—in this case, snowmelt and early spring rain.

Table 1. Leachate Production during 46 Months under Four Landfill Covers (Warren et al., 1996). Total Precipitation during the Period = 79.5 inches.

Soil Depth (feet)	Treatment	Leachate (inches)
3.9	RCRA cover	<0.05
2.9	Control cover, grass	16.1
4.9	Capillary barrier, grass	9.4
4.9	Capillary barrier, grass & shrubs	11.8

Although not discussed by the authors, high soil density may have reduced root growth in these experimental plots and thereby reduced the amount of soil drying produced by the plant cover. Warren et al. (1996) compacted the soil in all treatments, including the vegetative cover, to a bulk density of 1.86 Mg m^{-3}. As explained in Section 5.1.5, root growth is reduced by soil bulk density above 1.5 Mg m^{-3}, and bulk densities above 1.7 Mg m^{-3} may effectively prevent root growth in most soils. In addition to inhibiting root growth, soil compaction reduces soil water-holding capacity, thus further limiting the potential for success.

It has often been suggested that soil freezing and thawing will amend poor physical properties important to plant growth in compacted soils. However, the evidence discussed in Section 5.1.5 indicates that this is not true.

Any of the following factors could cause poor performance of vegetative covers:

- Inadequate soil depth
- Reduction of water-holding capacity by soil compaction
- Poor root growth resulting from soil compaction.

Knowledge of limiting factors and application of good design and construction practice is critical to success of vegetative landfill covers.

7 EVAPOTRANSPIRATION (ET) LANDFILL COVER

The ET landfill cover is designed to work with the forces of nature rather than attempting to control them. It utilizes a layer of soil covered by native grasses, and it contains no barrier layers (Figure 8). The ET cover uses two natural processes to control infiltration into the waste, (1) the soil provides a water reservoir, and (2) natural evaporation from the soil plus plant transpiration (ET) empties the soil water reservoir. It is an inexpensive, practical, and easily maintained biological system that will remain effective over extended periods of time, perhaps centuries, at low cost.

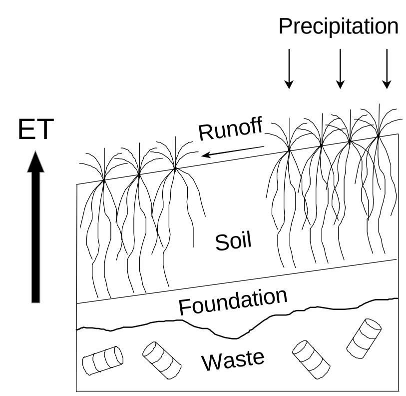

Figure 8. Cross-section of an ET Landfill Cover

The ET cover differs from those that are commonly called vegetative covers. It has the following minimum criteria:

- The soil must support rapid and prolific root growth in all parts of the soil cover

- The soil must hold enough water to minimize water movement below the cover during extreme or critical design periods.

Because of these minimum criteria, design and construction methods for ET covers differ from those of conventional vegetative and barrier covers.

In keeping with the requirements for all landfill covers, the ET cover must minimize infiltration, isolate wastes, control landfill gas, control erosion, and remain effective over long time periods. At many sites, ET landfill covers can meet these requirements. The concept and principles were previously verified and demonstrated as discussed below.

7.1 Verification of the ET Landfill Cover Concept

The technology that forms the basis for the ET landfill cover concept was developed, tested, and understood years ago, and field data are available from water balance measurements in soil layers similar to those required for ET covers. The concept was confirmed in the field by both short- and long-term measurements that were collected during the past century (Figure 9). The long-term measurements established the water balance under grass over time periods from three decades to several centuries and included unusually wet periods, fires, and other natural disasters. These data demonstrate that the ET cover can minimize movement of precipitation into stored wastes by using natural forces and the soil's water-holding capacity.

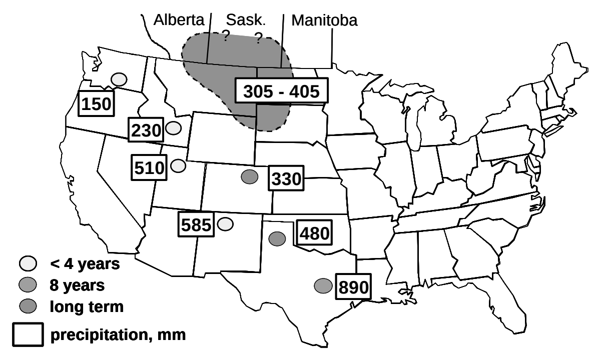

Figure 9. Field Verification Sites

7.1.1 Experimental Verification

Recent short-term field experiments (less than 4 or 8 years, Figure 9) demonstrated that vegetative covers could fulfill the requirement that landfill covers minimize infiltration of precipitation into the waste. Anderson et al. (1992), Anderson (1997), Hauser and Chichester (1989), Nyhan et al. (1990), and Waugh et al. (1994) evaluated water movement through soil covers for 3 to 8 years. These experiments—which sampled a variety of climates from the Pacific Northwest to Texas, with annual precipitation amounts from 160 to 900 mm per year—demonstrated that vegetative covers could indeed minimize the amount of precipitation that penetrates to the waste.

7.1.2 Long-Term Verification—Great Plains Water Balance

Cole and Mathews' (1939) classic paper contained the results of water balance experiments from five locations in the Great Plains extending from 1907 to 1936 (site locations not shown on Figure 9). Two locations provided continuous water balance measurements from native sod, and the others had partial records for native sod. In addition, each location included data from wheat grown every year (continuous wheat).

Soil water records were complete for native sod grown on a silty-clay loam soil for 21 years at Mandan, ND, as well as on a very fine sandy loam soil during 25 years at North

Platte, NE. Cole and Mathews (1939) stated that at neither site did water penetrate to depths beyond the roots of the native sod. Their database also indicated that water did not move below the root zone of continuous wheat at Havre, MT; Hays, KS; and Colby, KS, where record lengths were 21 to 28 years.

Cole and Mathews' (1939) review of 30 years of data demonstrated no evidence that water moved below the root zone of native grass or continuous wheat at these five locations. Either cool- or warm-season native plants grew throughout the year on native sod; thus, they quickly removed water from the soil. In spite of the three- to seven-month-long fallow period when water accumulated in the soil, they demonstrated no water movement below the root zone of continuous wheat.

7.1.3 Long-Term Verification—Pawnee National Grasslands

Sala et al. (1992) reported measurements of the soil water balance under native grassland in the Central Great Plains of Northeastern Colorado (Figure 9). During the 33-year study period, the mean annual precipitation at the site was 330 mm. The soil at the site is sandy loam in texture; thus it has, at best, moderate water-holding capacity. Based on field and lysimeter measurements, the authors concluded that it is unlikely that the soil profile within the potential rooting depth of native range grasses would ever be completely filled with water. Sala et al. (1992) stated that "[n]o deep percolation beyond 135 cm was recorded during the 33-year period."

7.1.4 Long-Term Verification—Saline Seep Region

Research on saline seeps in Montana and North and South Dakota, as well as the Canadian Provinces of Alberta and Saskatchewan, provides further confirmation of the ET cover concept (Figure 9). The hydrology of the region is described by Ferguson and Bateridge (1982), Halvorson and Black (1974), Doering and Sandoval (1976), Luken (1962), and Worcester et al. (1975).

Ferguson and Bateridge (1982) provide a description of the soils, plants, and hydrology associated with saline seeps. They state that the glacial till soils of the Northern Plains were formed on marine shales and debris about 12,000 to 14,000 years ago. The natural soils under native grass contain large amounts of soil salts beginning at depths of 0.5 to 1 m. Saline seeps first appeared about 30 years after cultivation of dryland crops began in the region. Summer fallow was widely practiced; that practice prevented all plant growth for a year, thus allowing water to move below the root zone of the crop during some years. Field investigations in Montana (Ferguson and Bateridge, 1982) show that about 90 Mg ha^{-1} of salt was moved downward by water percolating below the root zone of dryland crops. Figure 10 shows measurements by Ferguson and Bateridge

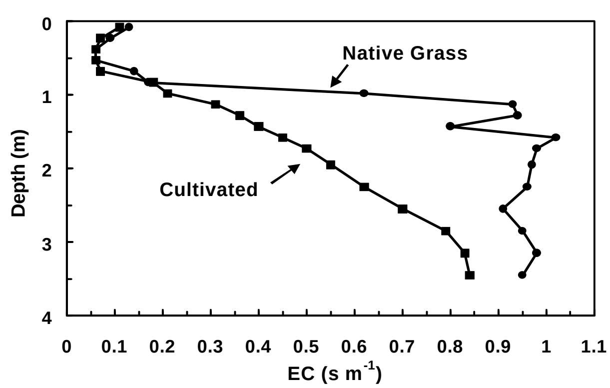

Figure 10. Electrical Conductivity (EC) in Siemen/m of Dryland Soils in Montana

(1982) of the typical soil salt content estimated by electrical conductivity of the soil under both native grass and cultivated dryland. These data show that percolating water removed significant quantities of salt from the subsoil under cultivated land but not from soils under native grass during the same time period.

Doering and Sandoval (1976) observed that the excess soil water accumulated on cultivated land moved downward to natural layers of low permeability, then proceeded laterally to produce saline seeps at the base of slopes or other outcrops. In contrast, excess soil water did not accumulate in soils covered continuously by native grass. Halvorson and Black (1974) stated "native grasslands generally support some actively growing vegetation throughout most of the growing season, reducing the chance of precipitation percolating beyond the root zone. As a result, saline seeps are generally absent on rangeland."

The soils formed over shale after the retreat of the glaciers in the northern Great Plains of the United States and southern Canada provide a natural "lysimeter" covering millions of hectares. This system demonstrated that native grasses prevented significant water movement through the soil profile during 12,000 years.

7.1.5 Long-Term Verification—Texas High Plains

Aronovici (1971) measured water content, chloride, and salt movement in soil profiles under native grasslands, cultivated dryland wheat and sorghum, and irrigated wheat and sorghum. His measurements extended from the surface to the 15 m depth at a site near Amarillo, Texas (Figure 9). Mean annual precipitation is about 480 mm at that Southern Plains location. The Pullman clay loam soil at the site cracks extensively when dry and was historically populated by prairie dogs and other small burrowing animals. The soil throughout the 15-m depth contained many root and wormhole casts ranging in size from less than 1 to 5 mm (Aronovici, 1971). The soil offered numerous preferential flow paths from the surface to the 15-m depth. He found that the soil water content was at or below the plant wilting point from 1 to 15 m below the surface under native grass.

Chloride and electrical conductivity data show large accumulations of the chloride ion and salts from 0.9 to 1.8 m under native grass. However the chloride and salt front was displaced downward by percolating water to about 2.4 m under both dryland cropping and minimum irrigation regimes and well below the 9 m depth under heavy irrigation, as Figure 11 illustrates (Aronovici, 1971). Because soil chloride moves easily with percolating water, it is a good indicator of depth of soil wetting. These data, along with the soil water content data, demonstrate that water did not penetrate beyond the maximum rooting depth of native grass for hundreds of years.

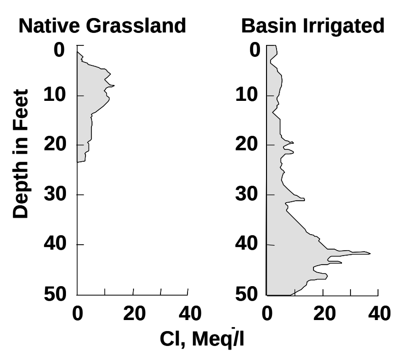

Figure 11. Soil Chloride near Amarillo, Texas

Aronovici (1971) concluded "[t]here has been little or no deep percolation on native or revegetated grassland within historic time where natural surface drainage occurs."

7.2 Proof of the ET Landfill Cover Concept

Some individuals propose that proof requires tests with lysimeters. Funding limitations often limit the length of these investigations because lysimeters are expensive to operate and their surface area is small. It is most desirable to base the proof of the concept on assessment resulting from decades or centuries of experience and the largest possible land mass.

7.2.1 Historical, Documented Assessment

The long-term concept verification presented here is based on agricultural research; much of it was classic soil or hydrologic research. The work by Sala et al. (1992) includes lysimeter measurements. The evidence presented in this paper proves the concept by use of lysimeter, tracer chemical, and soil-water measurement methods. The measurements presented were derived from both small and large land areas during both short- and long-time periods.

7.2.2 Alternative Cover Assessment Program (ACAP)

The ACAP program is part of the Remediation Technologies Development Forum (RTDF) organized by the EPA. In the ACAP program, the EPA and other governmental and industrial entities participate in cooperative field research. The ACAP program is evaluating vegetative covers at several sites in the United States.

7.2.3 Alternative Landfill Cover Demonstration (ALCD)

The U.S. Department of Energy sponsors the ALCD tests of several landfill cover types that are under way near Albuquerque, NM (Dwyer, S. F., 2001). The ALCD includes a vegetative cover that performed better than conventional Subtitle D or geosynthetic clay layer covers during a four-year period. However, the vegetative cover leaked an average of 0.19 mm per year in an arid climate where leakage should have been zero. The likely cause of leakage from the vegetative cover is excessive compaction of the soil that may have reduced or prevented root growth.

7.3 Advantages and Disadvantages for ET Landfill Covers

The ET cover is less costly to build than conventional covers because it requires no barrier layers and no drainage layers. Typically, the ET cover should cost less than half as much to build as a conventional cover. Since it is self-renewing, maintenance costs are minimized. If a depression, crack, or hole develops on an ET cover, it can be simply repaired by filling with soil to reestablish grade and replanting the grass cover. ET covers are inexpensive, practical, and easily maintained biological systems that will remain effective over extended periods of time, perhaps centuries, at low cost.

The ET cover should employ gas control if needed. The properties of the waste will determine whether gas control is needed; however, the ET cover is unlikely to trap and accumulate small quantities of gas produced by a landfill.

Short growing seasons and unsuitable soils are major disadvantages for the ET cover at some locations. While conventional covers can be built in almost any location, the ET cover requires adequate soil near the site. Depending on the amount and distribution of precipitation, short growing seasons may prevent use of the ET cover. The site should be evaluated by a suitable model before choosing the ET cover as the design remedy for a landfill.

8 ET COVER DESIGN AND CONSTRUCTION

The adequacy of an ET cover design for a site should be evaluated on a daily basis but with estimates of long-term performance. Daily precipitation and air temperature records are available for 100 years at many sites and for longer periods at other sites. Currently available hydrologic data and good design practice suggest use of a suitable model to simulate performance over a 100-year period. It is also necessary to consider the critical hydrologic event that will produce the maximum requirement for soil water storage.

The design of any landfill cover is dependent on factors that are specific to the site, including climate, hydrogeology, gas production, seismic environment, intended reuse of the area, and performance requirements for remediation. Landfill characteristics that affect cover design include the type of waste deposited, whether or not the landfill has a liner, the age of the landfill, and whether or not contaminated leachate may reach receptors. In addition to these factors, ET cover design is dependent on local soil resources, PET, locally adapted native plants, and the interaction between climate, soil, plants, and water balance.

8.1 Requirements for Design

The design of an ET cover requires the integration of several scientific disciplines, including soil physics, soil fertility, plant science, hydrology, and meteorology. The engineering disciplines required include agricultural engineering and environmental engineering. The design must consider numerous interactions between plants, soils, climate, plant disease, insect attack, and other issues.

One factor that has been overlooked in the design of previous vegetative covers is the issue of soil strength vs. plant root growth. Soil density—one of the parameters that affects soil strength—is easily controlled, and when controlled, it can ensure adequate to optimum conditions for root growth.

8.2 A Model for ET Cover Design

Because the ET cover cannot be tested at every landfill site, it is necessary to extrapolate the results from sites of known performance to specific landfill sites. It is also necessary to evaluate the potential for an ET landfill cover at a particular site. The model should effectively incorporate soil, plant, and climate variables and should include their interactions and the resultant effect on hydrology and water balance. Because the cover is expected to last decades, possibly centuries, the model should be capable of estimating long-term performance and the effect of extreme events. In addition to a complete water balance, the model's long-term performance estimates should include plant biomass production, need for fertilizer, wind and water erosion, deep percolation, and possible loss of primary plant nutrients from the ecosystem.

The Environmental Policy Integrated Climate (EPIC) model (personal communication from Williams, J. R.) and its earlier versions (Sharpley and Williams, 1990a; and Williams et al., 1990) meet the requirements for ET cover design stated above. The EPIC model is a comprehensive model that has been extensively tested for water balance estimates, including sites with significant accumulation of snow in winter (Nicks et al., 1990; Cole and Lyles, 1990; Sharpley et al., 1990; Smith et al., 1990a and 1990b; Favis-Mortlock and Smith, 1990; Steiner et al., 1990; Cooley et al., 1990; Kiniry et al., 1990; and Sharpley and Williams, 1990b).

Estimates of water movement through the cover (deep percolation) are of particular concern for ET cover design and evaluation. Meisinger et al. (1991) demonstrated that EPIC estimated deep percolation with good accuracy when compared with measurements from high-quality lysimeters. The average monthly percolation over a 3-year period that was measured by lysimeters and estimated by EPIC are compared in Figure 12. Regarding the accuracy of EPIC, Meisinger et al. (1991) state that "[t]he regression comparison of observed monthly percolation with predicted percolation for the three-year period (36 data points) had an R^2 of 0.86, a slope of 0.86 (not statistically different from 1.0), and an intercept of 0.1 inches (not statistically different from zero)." Chung et al. (1999) evaluated the performance of the EPIC model for two watersheds in southwestern Iowa and found that it estimated seepage flow well. Chung et al. (2001) evaluated EPIC against field measured drainage tile outflow in Minnesota and found that the model predicted annual drainage losses of similar magnitude to those measured and replicated the effects of cropping systems on nitrogen fate in the environment.

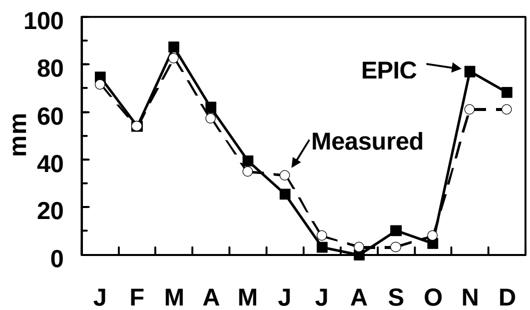

Figure 12. Average Monthly Percolation

8.3 The Critical Event

The ET cover should control the largest and most critical climatic event expected during the life of the cover. Therefore, a major concern for ET cover performance is the determination of the greatest amount of water that the ET cover soil must store. The critical event causing maximum soil water storage may result from a single-day storm or from a multiple-day storm (Figure 13). For example, we produced estimates with the EPIC model of soil water in storage for each day of a 100-year simulation period. The landfill was located on the western edge of the Central Great Plains; the cover soil was 0.6 m thick and composed of loam soil. Figure 13 presents the estimates of daily rainfall and daily soil-water content during the wettest year of a 100-year estimate, and it includes the greatest daily storage of soil water during the 100-year period. In this example, the critical event was the result of several days with rainfall followed by a large, single-day rainfall event.

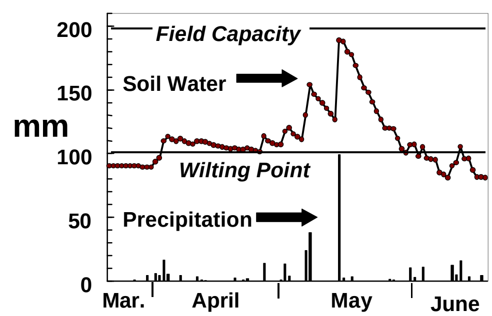

Figure. 13. The Critical Event

8.4 Safety Factor

As with conventional barrier covers, the ET cover should be designed with safety factors because both design and construction introduce some uncertainty regarding performance. Some safety-factor concerns are similar between ET covers and conventional covers. However, control of water flow into the waste requires new safety-factor considerations for the ET cover, including the following:

- The size of the soil water reservoir in the cover soil must be adequate to contain extreme or design storm events.
- The time required to empty the soil-water reservoir is critical to success.

8.4.1 Soil Thickness Basis

One basis for providing a safety factor is to increase the soil thickness (e.g., build the soil 50 percent thicker than indicated as adequate by design). However, this intuitive approach may not produce the desired result. Although the soil's total water-holding capacity is similar for all layers of a uniform soil, the distribution of roots and the rate and amount of water extraction are not (Figure 6 and Section 5.1.4). An increase in soil thickness from the design thickness (A) by 50 percent to B may result in only a small increase in plant-available water-holding capacity, as shown in Figure 14. Plants remove less water and extract it more slowly from deep soil layers than from near-surface soil layers.

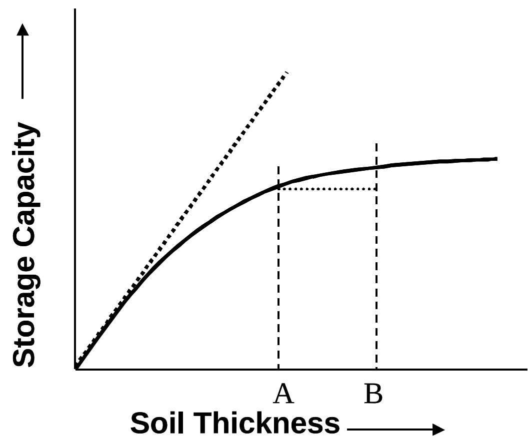

Figure 14. Plant-Available Soil Water

8.4.2 Hydrologic Basis

A better way to provide a safety factor for the size of the soil water reservoir and the time required to empty the reservoir is to utilize hydrologic factors that are known to affect soil water use and storage:

- Base the design on increased daily precipitation (e.g., 110 percent of annual precipitation)
- Increase surface runoff by replacing the top 6 inches of soil with a layer of clay soil.
- Design for either warm- or cool-season plants, but establish both warm- and cool-season plants to provide increased rates and totals of water use.
- Establish several species of native grasses to ensure adequate water use during all years.

9 AREA OF APPLICATION FOR ET COVERS

9.1 Effectiveness

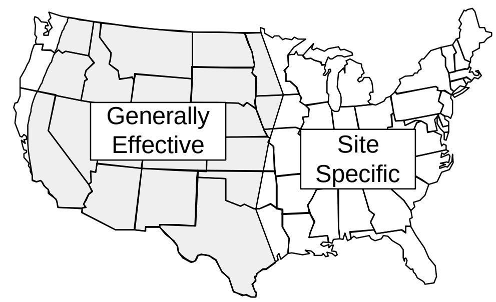

Figure 15. Effectiveness of the ET Cover

Climate is a primary determinant of ET cover performance at a given site and the evaporation-to-precipitation ratio is naturally most favorable in arid and semi-arid areas. Based on EPIC modeling evaluations, Hauser et al. (1994, 1995) concluded that properly designed ET covers could control infiltration into landfill wastes at most sites west of the Mississippi River and are applicable on a site-specific basis in the rest of the United States (Figure 15). They appear to be inappropriate for use in the coastal areas of Washington, Oregon, and Northern California because the climate is too cold and too wet.

In areas where they were judged generally effective, model estimates for ET covers with soil thickness from less than 0.2 m to 2 m showed that essentially no water moved below the cover. The required soil thickness and properties varied with the climate and the plants native to the area.

In the area shown as “site specific” on Figure 15, some water may percolate below a cover built with a uniform layer of soil. At these sites, an ET cover containing a top layer of clay soil may produce large amounts of surface runoff and result in acceptable performance. The effectiveness of the ET cover depends upon site requirements, cover design, and climate.

9.2 Potential ET (PET) in Continental USA

PET is the amount of water that would return to the atmosphere if abundant, freely transpiring plant leaves are available and the water supply to the plants is abundant and unrestricted. PET represents the maximum amount of water that a plant system can transfer back to the atmosphere. The performance of ET landfill covers is governed and limited by PET. While plant performance may be limited by several factors, the climatic factors that control PET present the largest single potential limitation to the use of plants in landfill covers. These climatic factors should be carefully considered during the first step of evaluating the possibility of using ET landfill covers.

We estimated the PET ratio (annual PET/annual precipitation), Figure 16, and classified 60 Air Force bases as affording *good, fair, or marginal* opportunities for using plants as part of the environmental remediation approach (Hauser and Gimon, 2001). The results for 60 Air Force bases are provided in Table 2.

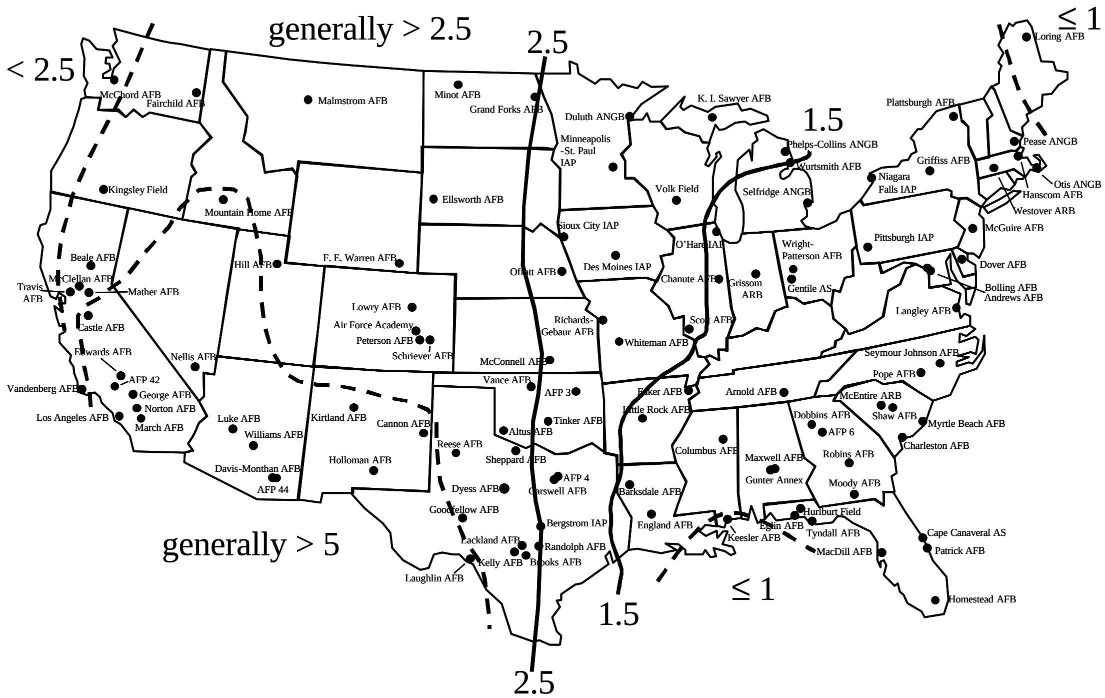

Figure 16. Ratio of Annual PET/Precipitation

Table 2. PET Ratios and Opportunity Classification for 60 Air Force Bases

Opportunity	PET Ratio	Number of Bases
Good	PET Ratio 1.5	42
Fair	1.2 PET Ratio < 1.5	14
Marginal	PET Ratio < 1.2	4

Where the PET ratio (see Figure 16) is greater than 1, the climate may be favorable for the ET cover. PET ratios greater than 1.2 suggest that the ET cover is likely to perform satisfactorily. The PET ratio is less than 1 in a small area on the gulf coast and in cold climates. The PET evaluation did not adequately assess the coastal fringe from San Francisco, CA northward to Canada, so no evaluation of that narrow strip with a wet cool climate is possible from these data. Climatic factors are generally favorable for the effective use of ET landfill covers at most locations in the continental United States. Of course, only a site-specific evaluation can identify the likelihood for success of the ET cover.

10 PERFORMANCE MEASUREMENT FOR COMPLETED ET COVERS

A primary reason for building any landfill cover is to limit and control the amount of precipitation that enters the waste, potentially causing groundwater contamination. In the past, there has been no attempt to monitor the performance of landfill covers, possibly because of the difficulty, uncertainty, and expense of such activity. However, in keeping with the goal for covers, groundwater at and near landfills has been routinely monitored to determine whether landfill wastes have entered the groundwater.

10.1 Methods to Measure Remediation Effectiveness

The effectiveness of a landfill cover may be evaluated in three ways:

- Install a “lysimeter” on or near the cover with presumed similar properties to those of the cover.
- Attempt to measure water flow through the soil cover by measuring soil water content and potential and then estimating the soil hydraulic conductivity relationship with soil water content.
- Monitor groundwater quality

10.2 Limitation of the Methods

Although lysimeters precisely measure the water exiting the lysimeter, they have the following problems:

- In order for water to flow out of the soil at the interface between the soil and the lysimeter collection gallery, the water pressure must be slightly greater than zero at the interface (by definition, a water table). The presence of a water table at the bottom of the profile ensures that the hydrologic water balance measured by the lysimeter is different from the ET landfill cover. An expensive alternative is to maintain a vacuum at the bottom of the profile at all times.
- The lysimeter may or may not represent the performance of the cover because lysimeters are small, thus quality control is much easier than on the landfill cover.
- Lysimeters without sidewalls can collect water that did not originate above the lysimeter.

Attempts to measure water flow through soil layers—like ET landfill cover soils—are fraught with controversy and often the results are not accepted by all parties. It is practically impossible to measure the relationship between hydraulic conductivity of the soil and its relation to soil-water pressure for the entire landfill cover soil mass. One can, of course, make this measurement in the laboratory, but that is not the same as the situation found in the field. There is controversy regarding acceptable ways to measure soil-water potential in a large soil mass such as an ET landfill cover.

Therefore, it appears that the best course for assessing effectiveness of remediation is the current practice of monitoring groundwater quality.

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