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CAPPING AS AN ALTERNATIVE FOR REMEDIATING AND MIXED WASTE LANDFILLS

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CAPPING AS AN ALTERNATIVE FOR REMEDIATING RADIOACTIVE AND MIXED WASTE LANDFILLS

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1.0 INTRODUCTION AND PROBLEM STATEMENT

The primary purpose of DOE's Environmental Restoration Program is to manage the health and ecological risks associated with intentional and/or accidental releases of radioactive and hazardous contaminants to the environment. These releases are a consequence of past and ongoing DOE production and R&D activities and involve thousands of sites that are currently being evaluated for possible cleanup actions.

In selecting a cleanup action that adequately protects human health and the environment, the risk manager must synthesize and evaluate a large amount of technical, regulatory, and socio-economic information to arrive at an optimum, or best, decision for remediating the site (Figure 1). Depending on the level of risk from contaminants to both humans and ecosystems, the alternatives for remediating the site can range from a minimal (no further) action all the way to costly options, including removal of the source term via excavation and/or in-situ / ex-situ treatment processes. Most of the current R&D effort in DOE (Office of Technology Development) is to develop technologies that remove the contaminant source from the burial environment, either through physical removal of the source or conversion of it to a less toxic state. Relatively few of the contaminated DOE sites will require these relatively drastic cleanup actions to reduce what will be obvious (i.e. based on risk assessments) health and environmental concerns. The recent reorganization of DOE/OTD programs into technology areas, including one on Containment, reflects an emerging awareness of important technical needs in DOE's ER and WM programs.

This report describes some of the regulatory and technical issues concerning the use of capping as a containment strategy for radioactive and hazardous waste. Much of the information has been distilled from regulatory and guidance documents and a compilation of research activities on waste disposal, contaminant transport processes, and technology development for landfills that has been conducted over the last 21 years.

The primary message that I want to convey in this report is that capping technologies will be heavily used in remediating radioactive, hazardous, and municipal waste landfills and that there is no one cap that will work universally across all sites. The cap design selected for remediating a particular waste site should be designed to adequately control contaminant transport to ensure protection of human health and the environment. Developing that design not only must incorporate good engineering principals but must also include sound ecological principals to account for the interactions between the physical, biological, and chemical factors influencing waste site integrity and contaminant transport.

The exclusion of ecological principals is, in my opinion, the greatest failing of current practices in designing capping technology. This omission prevents the designer from using (or maximizing) beneficial (and very inexpensive) processes (i.e., evapotranspiration) and from foreseeing failure modes (that are usually very expensive to remedy) that would be obvious to an ecologist (e.g., plant root intrusion into a clay hydraulic barrier). In my view, the use of capping alternatives for closure of landfills, is not just an engineering problem, as is often stated, but rather involves complex physical,

biological, and chemical processes requiring a multidisciplinary approach to develop designs that will work over the long haul and are cost-effective.

2.0 TECHNICAL ISSUES

2.1 HISTORICAL PERSPECTIVE ON LANDFILL PRACTICES

The practice of using shallow earth excavations, or landfills, for disposal of liquid and solid waste has a very long history (*Langer 1968*). Land filling practices basically followed the design philosophy of "out of sight, out of mind" in that a pit or trench was excavated into the ground (Figure 2), waste was placed into the excavation, and, when full, the landfill was covered with soil. If thought was ever given to the matter, it was likely assumed that the soil surrounding the waste effectively prevented contaminant migration from the burial zone. In light of current knowledge, we know that conventional land filling practices can be inadequate in preventing contaminants from migrating from the burial zone to man and biota (*Hakonson et al. 1982; Suter et al. 1993*). Many examples exist, just within DOE, of the failures of conventional land filling practices in preventing contaminant migration to ground water and biota (*Duguid 1977; Jacobs et al. 1980; Hakonson et al. 1982*).

It was not until about 1970 when increasing concern about the health and environmental effects of radioactive and hazardous wastes (Figure 3) led to Federal and State regulations mandating improved methods for waste disposal in landfills. Today there are a plethora of Federal and State regulations controlling all aspects of landfill disposal of municipal, radioactive, and hazardous waste.

The problem, however, is that thousands of landfills in the US were operated and then decommissioned prior to current regulations. For example, in the 52 year history of DOE's (AEC, ERDA, etc.) nuclear weapons program, an estimated 3000+ landfills, covering thousands of acres of real estate, were used for radioactive, and hazardous waste disposal and then decommissioned. Most of those old landfills are currently being evaluated under DOE's Environmental Restoration Program to determine whether they pose unacceptable health and environmental risks and, if so, to remediate them to reduce risks to acceptable levels.

2.2 GENERAL CONSIDERATIONS

Capping is a part of the technology area referred to as Containment (Figure 4) and involves leaving the contaminant source in-place and controlling the processes that cause the waste to migrate. Containment is viewed as a viable cleanup solution for most DOE sites with levels of residual contaminants that pose low risks to humans and/or ecosystems. Control of contaminant migration can be achieved with natural or synthetic barriers that can be placed around the waste to control the movement of water and/or gases (Figure 4). Migration barriers can be permeable or impermeable depending on the type of contaminant and its mode of transport although I would note that side wall- and under- barrier technology is currently not well developed. The cap placed over the waste is a central feature of most containment strategies and can range from a very simple soil cover to a very complex engineered design that is intended to mitigate both the vertical and lateral flow of water and gases.

Even at this early stage in DOE's cleanup program, it is certain that capping technologies will be heavily used, either alone or in combination with other technologies, to remediate the 3000+ landfills on DOE property. Capping is a viable cleanup alternative because human and ecological risks are considered to be low at most of these sites (based on known levels of contaminants and preliminary baseline risk assessments) and the regulatory requirements for final closure of old landfills can be met using a well designed cap to isolate the buried waste.

Under ideal conditions, the primary functions of the cap (see Figure 4) are to isolate the buried waste from the surface environment and to control hydrologic processes, including erosion, that can cause contaminant migration from the site (*Hakonson et al. 1992*). Excessive erosional loss of cap soil can expose buried waste leading to the potential for off site transport of contaminants. Likewise, water that infiltrates into the cap soil can lead to enhanced percolation of water and solutes out of the burial environment.

Biological processes, including plant root and burrowing animal intrusion into the waste can also contribute to migration of contaminants from the burial environment (*Hakonson et al. 1992*, Figure 2). However, the relative importance of biological processes, in either positively or negatively affecting the migration of the waste, is strongly related to the hydrologic characteristics of the site (*Hakonson et al. 1992*).

Cost will always be an important criteria for selecting options for remediating contaminated sites. In general, the objective is to reduce costs to a minimum while satisfying technical, regulatory, and political/social constraints. The technical basis for defining the level of control needed to reduce contaminant migration should be derived from the health and environmental risk assessments. A comparison of estimated unit costs for construction (i.e., O&M costs not included) of several capping alternatives at Los Alamos is compared to the cost of excavating the waste in Table 1. Note that the most costly capping alternative (i.e., the RCRA cap at \$4.9M/ha) is still a factor of 15 less expensive than removal of the waste. Additionally, the cost of different capping alternatives can vary by at least a factor of 10 (i.e., from \$0.12M - \$4.9M), depending on the complexity of the design and, again, the need for reducing risks. Although capping costs are relatively inexpensive compared to other options, they still represent substantial outlays of capital when considering that thousands of hectares of landfill area exist in the U.S.

Table 1. Estimated 1992 Costs Of Remediation Alternatives For Landfills

<u>Alternative¹</u>	<u>Cost/Unit²</u>
Excavate	\$80M/Ha
RCRA Cap	\$4.9M/Ha
Soil/Capillary Barrier Cover	\$3.7M/Ha
Bio-Engineered Soil/Vegetative Cover	\$0.24M/Ha
Surface Management with Erosion Control	\$0.12M/Ha

¹Technical basis for selection of alternatives should be based on human and ecological risk assessment.

²Costs for excavation option from DOE's ER 5 year plan, RCRA cap from Maxey Flats Corrective Measures Study, and remaining options estimated by author based on field experience.

2.3 THE CONCEPT OF WATER BALANCE

The fate of meteoric water falling on the surface of a landfill is often referred to as the water balance of the site. A simplified representation of water balance describes surface runoff and one-dimensional movement of water in the soil profile to the plant rooting depth. For net rates and amounts, the water balance equation is:

$$dS/dt = (P - Q - ET - L)/dt \quad (\text{Equation 1})$$

where dS/dt is the time rate of change in soil moisture, P is the precipitation per unit area, Q is the runoff per unit area, ET is the evapotranspiration per unit area, L is the percolation below the root zone per unit area, and t is the unit of time used in solving the equation.

Application of the concept of water balance to design of landfill caps takes advantage of the fact that there are strong interactions between the various components of water balance. For example, a reduction or elimination of the runoff term (Q), increases infiltration of water into the soil, resulting in increased soil moisture storage followed by an increase in ET and/or percolation. Likewise, reducing percolation necessitates that more of the precipitation be partitioned between soil moisture storage, ET , and/or runoff. The coupled nature of the processes comprising the water balance can be used to advantage in designing landfill caps that minimize or eliminate processes in Equation 1 that contribute to contaminant migration (i.e., percolation) while enhancing other terms (i.e., ET) that do not.

The concept of water balance and, especially methods to manipulate its various components, has served as the basis for several studies to design, test, and evaluate a variety of capping alternatives for radioactive and hazardous waste landfills (Nyhan *et al.* 1990; Hakonson *et al.* 1992; Hakonson *et al.* 1993; Lane 1984; Lane and Nyhan 1984).

2.4 CAUSES OF COVER SYSTEM FAILURE

2.4.1 Physical Factors

If we examine the factors that affect cap performance, it is apparent that hydrologic and erosional processes account for most of the performance-related problems (Duguid 1977; Jacobs *et al.* 1980; Hakonson *et al.* 1982). For example, erosion associated with runoff can breach the cap and expose waste to the biosphere (Nyhan and Lane 1982; Nyhan *et al.* 1984). Consequently, erosion rates must be within tolerances to leave the cap intact over the mandated lifetime of the facility.

To assist the designer in predicting erosion potential of various design options, EPA recommends use of an empirical formula called the Universal Soil Loss Equation (USLE) which is used to calculate the average annual soil loss. The average annual soil loss is predicted based upon a number of factors including the geographical location, the length and steepness of slopes, the texture of the cover soil, and the vegetation cover. More recent developments by the USDA-Agricultural Research Service on erosion prediction methods are available, including the Revised Universal Soil Loss Equation (RUSLE) and Chemicals, Runoff, and Erosion in Agricultural Management Systems (CREAMS).

Cover design features that are used to prevent erosion include the establishment of vegetation, the use of mulching techniques, controlling slope and slope length, and the construction of terraces or benches. Current EPA guidance suggests that the average annual soil loss not exceed 2.0 tons/acre in order to minimize the potential for gully development and future maintenance.

Likewise, water that infiltrates into the cap can accumulate in the trench (bathtub effect) and/or percolate with solutes into groundwater. Percolation also can increase subsidence of the cap as a result of enhanced decomposition of bulky waste in the trench.

Subsidence of the waste is most likely to occur after closure of the land disposal unit and final placement of the cover. Although subsidence has the potential to seriously damage a land disposal unit cover, the analytical methods available to estimate the effects are still inexact and require additional experimentation and field observation.

Another potential threat to the continued soundness of the cover is displacement due to the slope instability. Because many cap designs contain barriers that generate lateral flow of soil water, saturated conditions can occur, especially near the downslope end of the barrier. Slope stability analyses should be performed to assess the potential for slope failure by various failure modes (e.g., rotational, sliding, wedge), as appropriate, based upon the slope configuration. To adequately perform the stability analyses, the strength properties of the cover system components, the waste, and the foundation soils must be known along with seepage conditions.

In climates that experience freezing temperatures or drought, the cover may be damaged by the freezing or drying of soil or man-made construction materials. Critical design components of the cover should be placed below the depth of freezing or severe drying. Freezing may also increase the amount of runoff during winter months, since percolation through frozen ground can be reduced.

2.4.2 Biological Factors

Although vegetation is important in controlling erosion and percolation (Nyhan *et al.* 1984), deep-rooted plants can access buried radionuclides and bring them to the surface of the site (Foxy *et al.* 1984). Radionuclides in plant tissue can be transported through the food web to humans by herbivorous or nectivorous organisms (Anonymous 1967). For example, at Los Alamos, one of the pathways of tritium transport away from a controlled low level waste site is via the soil moisture/plant nectar/honey bee/honey pathway (Hakonson and Bostick 1976). Likewise, tumbleweeds (*Salsola kali*) growing over the cribs at Hanford, accumulate Sr-90 and then transport the contaminant away from the site as the matured plants blow away from the site after the growing season is over (Klepper *et al.* 1979).

The importance of preventing buried waste from reaching the ground surface is that erosional processes dominate in the movement of contaminants on the ground surface to biological surfaces. For example, rain splashed and/or wind re-suspended soil particles (especially the fine silts and clays) are deposited on plants (Dreicer *et al.* 1984; Foster *et al.* 1985) and animals (Romney and Wallace 1977; Hakonson and Nyhan 1980). Field studies (Hakonson and Nyhan 1980; Watters *et al.* 1980) with plutonium show that physical deposition of contaminated soil particles on vegetation surfaces is 100-1000 times more important than root uptake in contaminating vegetation with this radionuclide.

The role of burrowing animals in mobilizing buried waste is generally unknown. A limited database (O'Farrell and Gilbert 1975; Winsor and Whicker 1980; and Arthur and Markham 1983) demonstrated that burrowing animals can transport radionuclides vertically in the soil profile and influence water balance and erosion of the cap by changing the physical and hydrologic characteristic of the soil (Aubertin 1971; Grant *et al.* 1980; Lysikov 1982).

3.0 REGULATORY ISSUES

3.1 GENERAL PERFORMANCE REQUIREMENTS

The regulatory requirements for closure of hazardous and mixed waste landfills are found in 40CFR Parts 264 and 265, Subpart N. Under these regulations, owners/operators of landfills are required to perform landfill closures. The primary closure requirements of 264.310 and 265.310 require the owner/operator to design and construct a low-permeability cover over the landfill to minimize migration of liquids into the waste and to provide 30 years of post-closure monitoring and maintenance in order to prevent waste migration into the environment.

EPA guidance to permit applicants (EPA-530-SW-84-004) recommends that an analysis of the final cover design be presented in the closure plan. The analysis of the final cover design should describe how the design meets the following performance standards:

1. minimizes liquid migration,
2. promotes drainage while controlling erosion,
3. minimizes maintenance,
4. has a permeability equal to or less than the permeability of natural subsoil,
5. accounts for freeze/thaw effects, and
6. accommodates settling and subsidence so that the covers integrity is maintained.

These cover requirements are performance standards that allow some flexibility in design. Several EPA guidance documents interpret regulatory requirements for final covers including:

- Technical Guidance Document: Final Covers on Hazardous Waste Landfills and Surface Impoundment's, EPA/530-SW-89-047, July 1989;
- Evaluating Cover Systems for Solid and Hazardous Waste, EPA#SW-867, GPO#055-000-00228-2, 1982;
- Design and Construction of Covers for Solid Waste Landfills, EPA-600/2-79-165, August 1979; and Covers for Uncontrolled Hazardous Waste Sites, EPA/540/2-85/002, September 1985.

In order to demonstrate that a proposed final cover design complies with the regulatory performance standard, DOE (DOE/EGD-RCRA-002/0690, June 1990) indicates that it will be necessary to model the hydrologic performance and erosion potential of the proposed cover. EPA suggests that the water balance model, HELP, be used for these demonstrations (User's Guide for the Hydrologic Evaluation of Landfill Performance (HELP) Model, EPA/530-SW-84-009. Version 2.05 of HELP (EPA/530-SW-84-009) contains some conceptual and coding errors and its use is not recommended by the author without extreme caution in interpreting the output. A detailed description of the HELP model appears in a later section of this report. An improved version of HELP is to be issued by EPA in mid- to late 1993 and its use is recommended for evaluating the hydrologic response of capping alternatives.

It is also recommended that data or model predictions demonstrate that the proposed design will not result in erosion in excess of 2 tons/acre/ year. EPA recommends the use of the USLE but better erosion prediction technologies, developed by the USDA-Agricultural Research Service, are available, including RUSLE and/or CREAMS. A detailed description of the CREAMS model appears in a later section of this report.

3.2 GUIDANCE ON COVER DESIGNS

EPA's technical guidance for final covers describes a recommended design, often called EPA's RCRA cap (see Figure 5), that will meet the final cover performance standard. It is important to note that EPA offers the RCRA cap design as guidance and does not require its use if another design can be shown to meet the technical performance standards.

Typical cover designs that are recommended (but not mandated) in the EPA (1989) technical guidance document "Final Covers on Hazardous Waste Landfills and Surface Impoundments" (see Table 2) are composed of three layers for liquids management (see RCRA design in Figure 5):

1. an uppermost vegetated layer to prevent erosion and promote evapotranspiration;
2. underlying drainage layer/s to convey percolation out of the cover, and
3. moisture barrier(s) to prevent infiltration.

For the vegetative cover (Table 2), EPA's guidance recommends a minimum thickness of 2 feet and final upper slopes of between 3 and 5 percent, after taking into account total settlement and subsidence of the waste. The middle drainage layer should have a minimum thickness of 1 foot and minimum hydraulic conductivity of $1.0\text{E-}03$ cm/sec. EPA's revised draft guidance upgrades that standard by an order of magnitude to $1.0\text{E-}02$ cm/sec to reduce capillary rise and hydraulic head above the composite liner system. For the composite liner system at the bottom of the cap, it is critical that both the flexible membrane liner (FML) and the compacted soil components be below the average depth of frost penetration. The FML should also have a minimum thickness of 20 mils, but 20 mils will not be a sufficient thickness for all FML materials. The soil component under the FML must have a minimum thickness of 2 feet and a maximum saturated hydraulic conductivity of $1.0\text{E-}07$ cm/sec. The final upper slope of the composite liner system must be no less than 2 percent after settlement.

The requirements for the cover are performance-based. Therefore, the elements incorporated into the design may vary depending on the type of materials available, the environment in which it is placed, and the type of wastes landfilled.

4.0 DESIGN CONSIDERATIONS

4.1 BASIC ELEMENTS OF THE RCRA COVER SYSTEM

The functional requirements of the topsoil layer are to promote runoff from major storms but restrict erosion rates to acceptable limits. While runoff can promote erosion and degradation of the cover system, vegetation or cobbles impede erosion and support the long-term integrity of the cover. An added benefit of a good vegetation and/or mulch on the surface in arid/semiarid climates is that it enhances soil moisture and stimulates vegetation growth and the rate of plant transpiration. Studies at Los Alamos show that mulched cap surfaces produce 3-4 times more vegetation biomass than unmulched surfaces with a commensurate increase in soil water removal via evapotranspiration (Nyhan *et al.* 1984; Hakonson *et al.* 1992). The topsoil must also be thick enough to provide storage for evapotranspiration, and protect the hydraulic barrier layer from freezing and desiccation. Typically, a thickness of 60 to 90 cm (2 to 3 ft) is sufficient, but the actual requirement is site and design specific and should be determined through analysis of the water balance.

Drainage layers are not necessary at all sites since some sites may not have sufficient rainfall and infiltration to produce standing head on the hydraulic barrier for long duration. If used, the drainage layer should be designed to reduce leakage through the hydraulic barrier layer by lowering the hydraulic head. Materials should be used that have high hydraulic conductivities to rapidly drain lateral flow and

prevent build-up of a hydraulic head. Careful planning for draining lateral barrier flows to a collection pipe or toe drain is essential to reduce the probability of saturated conditions contributing to slope failure.

Table 2. EPA Guidance On Landfill Caps

Vegetative Soil Layer

- A. Thickness ≥ 2 ft;
- B. Minimal erosion and maintenance (e.g., fertilization, irrigation);
- C. Vegetative root growth not to extend below 2 ft;
- D. Final top slope between 3 and 5% after settlement or subsidence. Slopes greater than 5% not to exceed 2.0 tons/acre erosion (USDA Universal Soil Loss Equation); and,
- E. Surface drainage system capable of conducting run-off across cap without rills and gullies.

Drainage Layer

- A. Thickness ≥ 1 ft;
- B. Saturated hydraulic conductivity $\geq 1.0E-03$ cm/sec;
- C. Bottom slope $\geq 2\%$ (after settlement/subsidence);
- D. Overlain by graded granular or synthetic filter to prevent clogging;
- E. Allow lateral flow and discharge of liquids.

Low Permeability Liner Design FML Component

- A. Thickness ≥ 20 mil;
- B. Final upper slope $\geq 2\%$ (after settlement); and,
- C. Located wholly below the average depth of frost; penetration in the area.

Barrier Soil Layer

- A. Thickness ≥ 2 ft;
- B. Saturated hydraulic conductivity $\leq 1.0E-07$ cm/sec;
- C. Installed in 6-in lifts.

Depending on the type and thickness of the materials used, the drainage layer can also reduce root and animal penetration of the hydraulic barrier layer and provides additional depth and a capillary break to lessen desiccation and frost penetration of the barrier. Studies at Los Alamos (*Hakonson 1982*) show that a cobble layer in the cap profile can reduce both plant and animal intrusion through the cap. Measures may also be needed to decrease migration of fines and prevent the fines from clogging the drain.

Since the regulations do not specify designs of materials for the final cover or cap, designers can use their own judgment in designing the final cover and selecting materials. For example, the amount of flexibility in selecting FML materials for the final cover varies from region to region, based on how strictly the statutory phrase "no more permeable than" is interpreted. In practice, many sites are applying the RCRA cap without the FML component (Figure 6) based on agreements with cogent regulatory authorities. Nevertheless, from a design perspective, the selection of FML materials in the final cover should emphasize the physical rather than the chemical properties of the liner material, since the main objective is to minimize percolation of precipitation into the waste.

The hydraulic barrier layer or liner should be designed to minimize the infiltration of water into the waste layer over the long term. In conventional cover designs, the barrier layer is considered by EPA to be the most important layer in controlling leakage through the cover system. The author strongly disagrees with this position as it requires complete, long-term, reliance on an engineered structure for which there are no long-term performance data. The author believes that the primary barrier in preventing percolation of water through the cap is the vegetated topsoil. Studies at Los Alamos (*Nyhan et al. 1987*) and at Hill Air Force Base in Utah, show that, in arid/semiarid climates, a well designed, vegetated topsoil can greatly reduce the need for an engineered subsurface hydraulic barrier, and, certainly, the need to rely on the engineered barrier as the primary component of a soil water management system.

As mentioned, the final cover component, the vegetated topsoil layer, functions as the primary barrier to percolating water and protects the deeper layers from the effects of wind and water erosion. The topsoil layer, as per EPA guidance, is generally two feet thick to accommodate the roots of the vegetation but the thickness should be governed by the need for storage capacity, climate, soil type, and vegetation species.

The major characteristics that should be considered during species selection, include compatibility with local environment, water use characteristics, ease of establishment, self maintenance, and resistance to fire, insects, and disease. Grasses and legumes are usually selected but the author maintains that the more complex the vegetation community (i.e., multiple species and growth forms), the greater will be its ability to remove soil moisture via evapotranspiration.

Planting or seeding is generally recommended before major seasonal occurrences of precipitation. It is important for the seedlings to establish a root system during a cool, moist period before enduring a winter freeze or summer drought. Mulching has been found to greatly increase reseeding success on landfill caps (*Hakonson et al. 1992; Nyhan et al. 1986*).

EPA's minimum technology guidance (Table 2) and regulations for new hazardous waste land disposal facilities emphasize the importance of proper design and construction in the performance of the facility. The current trend in the regulatory programs is to develop standards and recommend designs based on the current state-of-the-art technology. Innovations in technology are, therefore, welcomed by EPA and are taken into account when developing these regulations and guidance.

Many good resources (see Section 6.0) are available to assist the designer in the selection of the plant species, the seeding rates and seasons, and the fertilization applications required. Sites in arid regions of the country tend to use a mulch (e.g. gravel) over the topsoil layer. This is done because conditions are such that the vegetation is very difficult to establish and keep growing due to low rainfall. The mulch enhances infiltration of precipitation into the soil, moderates extremes in temperature, and very effectively protects the soil surface against erosion. Conditions under the mulch are ideal for successful germination and establishment of vegetation.

4.2 ALTERNATIVE COVER DESIGNS

The hazardous waste landfill cover designs developed and published by the US. Environmental Protection Agency (EPA) are generic in nature and intended to meet the regulatory criteria for covers on a national basis. This section briefly reviews alternative designs that the author believes would be acceptable to the regulatory community if they meet performance requirements and protect human health and the environment as shown through analysis of the risks.

The RCRA cap design for hazardous waste landfills incorporates natural soil (clay), geomembrane, drainage, and vegetation layers. This generic design, however, does not take into account site-specific concerns, such as siting in arid areas where rainfall is very low. Under these conditions, a barrier layer

composed of both a natural soil (clay) and a FML layer probably would not be effective. A recent analysis of failure modes for compacted soil barriers at landfills (*Suter et al.* 1993) strongly supports the latter statement. The clay soil barrier layer is designed to be placed "wet" to achieve the minimum hydraulic conductivity. When placed in a relatively dry environment, this layer will likely dry and crack, making it less effective. In selected cases, the newer bentonite blankets may be an acceptable alternative although very little relevant field data on performance are available. The author has conducted limited laboratory testing with CLAYMAX, one brand of geosynthetic, and found that plants rapidly desiccate the contained bentonite, causing it to shrink and crack.

In some cases, a vegetated soil layer alone may be demonstrated (via water balance modeling) to meet the performance criteria (Figure 7). For example, a thicker soil layer may be adequate to establish vegetation and to act as a storage reservoir for the reduced precipitation. As mentioned, a well designed vegetated soil cap can return 85-100% of the precipitation to the atmosphere, greatly reducing and/or eliminating percolation.

Capillary barriers have been investigated extensively as components of landfill cap designs since 1980 (*Hakanson et al.* 1992). Conceptually, they function similar to a clay hydraulic barrier in that they impede vertical percolation and divert flow laterally from the cap. They function in impeding flow because of the differences in saturated hydraulic conductivities of two layer materials such as a fine grained soil over a gravel (Figure 8).

Water moving downward through the soil encounters the gravel layer, where capillary forces in the soil prevent breakthrough of the water into the gravel when soil moisture conditions are less than saturation. When saturation occurs, breakthrough of water occurs and the capillary barrier fails. By placing an angle on the interface between the soil and gravel, lateral flow can occur, reducing the potential for saturation and barrier failure. Selection of materials for the capillary barrier system is critical in that rapid lateral flow is essential to prevent the buildup of water as it drains laterally downslope. Soil and gravel systems, such as depicted in Figure 8 are not optimal for the performance of the capillary barrier. Current research at Los Alamos is investigating sand-gravel capillary barriers to enhance lateral flows and reduce the potential for barrier failure.

The advantage of capillary barrier systems over clay hydraulic barriers is that they are not subject to desiccation and cracking, and they are less expensive to install. However, our experience with soil-gravel capillary barrier systems is that they will fail periodically although they perform much better than a conventional soil cap. The eventual role they play as candidate cap designs for closure of landfills will be dependent on the outcome of on-going research.

In summary, the design criteria were established for a national generic design. EPA states that they are interested in reviewing alternative designs that are innovative and utilize site-specific information. EPA also states that these alternative designs should be equivalent in performance to the generic RCRA design. Unfortunately, the performance of EPA's RCRA cap design has not been adequately field tested to establish equivalency criteria.

5.0 MODELS FOR DESIGNING AND EVALUATING LANDFILL COVERS

5.1 CREAMS (Chemicals, Runoff, Erosion, in Agricultural Management Systems) MODEL

In 1980, the USDA developed the CREAMS (Chemicals, Runoff, Erosion, in Agricultural Management Systems) Model. CREAMS includes hydrology and erosion/sediment transport components. The CREAMS model has received wide use and acceptance and has recently been proposed as a useful tool in waste management studies. The hydrology component includes two options. The first is a daily rainfall model based on the SCS runoff equation and the second, and infiltration model using time-intensity rainfall data. The soil profile, to the plant rooting depth, is represented by up to seven layers (which can represent multi-layered cover systems), each with a representative thickness and water storage capacity.

The evapotranspiration calculations include soil evaporation and plant transpiration estimates based on monthly air temperature, solar radiation, and a leaf area index. Flow through the root zone is computed using a soil water storage-routing routine and percolation is computed when soil moisture exceeds field capacity. Using the hydrologic inputs of rainfall amount, rainfall erosivity index (EI), runoff volume, and peak rate of runoff, the erosion/deposition component computes soil detachment, sediment transport, and deposition by routing sediment through overland flow and concentrated flow. Gross erosion and sediment yield are computed by sediment particle size classes, including soil aggregates. The two CREAMS components needed to perform a surface water balance at SLB sites are the hydrology and the sediment yield/erosion components.

Sediment load is assumed to be limited by either the amount of detached sediment or by transport capacity. Also, a quasi-steady state is assumed so that a rainfall and a runoff rate characteristic of each storm can be used in the computations. Sediment movement downslope obeys continuity of mass. Lateral sediment inflow is from inter-rill erosion or overland flow elements, or from overland flow (or a channel, or if two channel segments are in the sequence) for the channel elements. Rill flow on overland flow areas or channels transports the sediment load downstream. Lateral sediment inflow is assumed regardless of whether the flow is detaching or depositing.

For each segment, either the overland flow element or channel element, CREAMS Erosion computes an initial sediment load from the immediate upslope segment plus that added by lateral inflow within the segment. If this potential load is less than the transport capacity, as calculated by the Yalin equation, detachment occurs at the lesser of the detachment capacity rate or the rate determined by transport capacity. When detachment by flow occurs, it adds particles having the same particle-size distribution for detached sediment given as input. No sorting is allowed during detachment. If the initial potential sediment load is greater than the transport capacity, deposition is assumed to occur.

Four possible cases may exist for a segment: 1) Deposition may occur over the entire segment; 2) Detachment by flow in the upper end may (but not necessarily) occur when transport capacity decreases in a segment; 3) Deposition on the upper end and detachment by flow in the lower end may (but not necessarily) occur when transport capacity increases within the segment; and 4) Detachment by flow may occur all along the segment. Sediment eroded on field-sized areas is a mixture of primary particles and aggregates (conglomerates of primary particles). The distribution of these particles as they are detached is a function of soil properties, management and rainfall and runoff characteristics. If deposition occurs, usually the coarse and dense particles are deposited first, leaving a finer sediment mixture.

The input to the model is the distribution of the sediment as it is detached; the model calculates a new distribution if it calculates that deposition occurs. Detachment due to flow and raindrop impact is calculated using a modified USLE formula. Detachment and sediment transport in channels and waterways is represented by concentrated flow. The erosion component contains models for estimating deposition in impoundment's that drain following each storm. The amount of sediment trapped in an impoundment is a function of the time available for sediment to settle to the bottom of the impoundment. The erosion component also contains models for estimating erodible channel and ephemeral gully routines.

5.2 HELP 2.05 (Hydrologic Evaluation of Landfill Performance) MODEL

5.2.1 Overview

EPA has developed a computer program called the Hydrologic Evaluation of Landfill Performance (HELP) which 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 which accounts for the effects of surface storage, runoff, infiltration, percolation,

evapotranspiration, soil moisture storage, and lateral drainage. The program estimates runoff drainage and leachate expected to result from a wide variety of landfill conditions, including open, partially open, and closed landfill cells. Most importantly, in consideration of this topic, the model can be used to estimate the buildup of leachate above the bottom liner of the landfill. The HELP program can be used to estimate the depth of leachate above the bottom liner for a variety of landfill designs, time averages, and storm events. The results may be used to compare designs or to design leachate drainage and collection systems.

Landfills typically contain two liquids management systems. The cover is the principal liquids management system for controlling leachate generation. Leachate, as evaluated by the HELP model, is any rainfall or snowmelt that combines with liquids in the waste and moves by gravity forces to the bottom of a landfill. During its migration through the waste, the liquid takes on pollutants that are characteristic of the waste. As such, the leachate quantity and quality is site specific and waste specific. The HELP model generates estimates of leachate quantity given site-specific descriptions of climate, cover design, and initial moisture content of the waste and soil layers. The model does not predict leachate quality or any contribution to the leachate quantity by subsurface inflow of ground water. Good landfill design and site selection would minimize any contribution from ground water.

The second liquids management system now required for new landfills is the leachate collection/liner system. A typical single liner system consists of a drainage layer overlain by a filter, either soil or geosynthetic, and a hydraulic barrier layer composed of low hydraulic conductivity soil. The soil liner is frequently overlain by a geosynthetic geomembrane to greatly improve its performance.

The performance of these layers for liquids management is the same as described above for cover systems except that the layers are controlling leakage from the landfill instead of infiltration into the waste layer and leachate generation. A typical double liner system is used both for leachate collection and leakage detection. The top drainage layer and geomembrane is the primary leachate collection system. The bottom drainage layer and composite liner (low hydraulic conductivity soil overlain by a geomembrane) is the secondary leachate collection system and leakage detection system.

The HELP model was developed by the US Army Engineer Waterways Experiment Station for the US EPA Office of Solid Waste (OSW) to provide technical support for the Resource Conservation and Recovery Act (RCRA) and Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) programs. Development of the model began in 1982 and Version 1 was released for public comment in June 1984. The program was a mainframe computer model that ran on the National Computer Center's IBM system. In 1986, the program was modified to run on IBM-compatible personal computers. Additional capabilities and refinements were included in Version 2 of the model released in 1988. The most current version is Version 2.05, which was released in July 1989. Version 3 of the model is currently in preparation for release in 1993.

The HELP model is a quasi-two-dimensional, gradually varying, deterministic, computer-based water budget model. It is termed quasi-two-dimensional because it contains a one-dimensional vertical drainage model and a one-dimensional lateral drainage model coupled at the base of lateral drainage layers or the top of liners. The program computes free vertical drainage down to the top of a liner, at which point the liner restricts drainage and a zone of saturation develops. The models for lateral drainage and leakage or percolation through the liner then use the height of saturated material above the liner to compute simultaneously the rates of lateral drainage to collection systems and vertical leakage through the liner, respectively.

The model is termed gradually varying because the simulation progresses through time using analyses that are assumed steady for each time period. Version 2 of the model uses a time period of 6 hours. The model is deterministic and numerical as opposed to stochastic and qualitative.

Finally, the HELP model is a computer-based water budget model; that is, the model uses a computer to apportion the precipitation and initial moisture content into estimates of the following water budget components: surface runoff, evapotranspiration, changes in snow storage, changes in moisture content, lateral drainage collected in each drain system, and leakage or percolation through each liner system. Daily, monthly, annual, and long-term average water budgets can be generated. The HELP model is a tool developed specifically to aid permit evaluators and landfill designers in the evaluation and comparison of alternative landfill designs.

The model was built to evaluate whether alternative designs perform as well as the minimum technical guidance systems over a long period of time. Therefore, its primary utility is for tasks involving comparison of alternative designs and sensitivity of design parameters. A secondary goal of the model's development was the accurate prediction of water budget components. Nevertheless, additional testing, verification studies, and refinements are ongoing to improve its accuracy.

In general, the accuracy and precision of the model is limited by uncertainty and variability in the properties of material existing in landfills. As such, simulation results would be expected to be best used to rate relative merits of designs rather than to accurately predict the water budget components.

The HELP model is a valuable tool for design and permit evaluation; however, it requires the user to exercise good judgment. In particular, the user must have a good understanding of landfill design, vegetative systems, and the model to obtain reliable results and correct conclusions. The user must ensure the integrity of the design and the data because the model does not evaluate the data.

An example of a cover system lacking design and data integrity is a two-layer system with the following characteristics. The top layer is 5 cm (2 in.) of topsoil vegetated with a good stand of grass. The lower layer is 5 cm (2 in.) of compacted clay having a saturated hydraulic conductivity of $10E-08$ cm/sec. With this description, the HELP model would predict a very large quantity of runoff and a small quantity of evapotranspiration since the topsoil layer has very little storage capacity. In addition, very little leakage through the clay liner would be predicted because the saturated hydraulic conductivity of the liner is so low. The actual results would be expected to be quite different. Construction of 5-cm (2-in.) layers is not practicable, especially, construction of a thin lift of clay compacted uniformly to achieve an effective hydraulic conductivity of $10E-08$ cm/sec. Besides the difficulties in construction, the layers would lack integrity to maintain the described properties. Both layers would quickly form desiccation cracks, producing much larger hydraulic conductivity's. As such, the leakage and evapotranspiration would be much greater than predicted and the runoff would be much less.

The primary anticipated use of the HELP model is to perform quick comparisons of the long-term performance of alternative designs, often with very little data. As such, the following approach was taken to select simulation methods and data entry options. Process simulation methods had to be well-accepted techniques described in the literature that are computationally efficient, require minimum data that are readily available, and account for all major design and climate conditions. Conservative assumptions are made when necessary because of uncertainty. The term "conservative" implies that any resulting error would tend to result in an overestimation of vertical drainage or leakage through liners.

Options are provided to permit use of data from a default data base or from user entry. Guidance and recommendations are given for poorly understood parameters. In addition, the program is interactive and user friendly and runs on IBM-compatible personal computers to facilitate widespread use.

5.2.1.a Detailed Theory

The HELP model was adapted from the Hydrologic Simulation Model for Estimating Percolation at Solid Waste Disposal Sites (HSSWDS) of the US. EPA and the Chemical Runoff and Erosion from Agricultural Management Systems (CREAMS) and Simulator for Water Resources in Rural Basins (SWRRB) models of the US. Department of Agriculture (USDA) Agricultural Research Service (ARS).

The following sections describe all of the principal hydrologic and physical processes modeled by the HELP model, including a discussion of the assumptions and limitations of the models of the principal processes. Understanding of the processes, simulation methods, and their assumptions and limitations is critical for the proper application of the HELP model.

5.2.1.b Infiltration

Daily infiltration into the landfill is determined indirectly from a surface water balance. Infiltration equals the sum of rainfall and snowmelt, minus the sum of runoff and surface evaporation. Runoff and surface evaporation are in part a function of interception. Precipitation on days having a mean temperature below 0°C (32°F) is treated as snowfall and is added to the surface snow storage. Decreases in snow storage occur by snowmelt and surface evaporation.

Daily precipitation is an input parameter. Precipitation data may be synthetically generated, specified by the user or selected from the default data base of historical rainfall data. The synthetic weather generator will be described later in this section. Snowmelt is computed using a slightly modified version of the simple degree-day method with 0°C (32°F) as the base temperature. The inch/degree-day snowmelt constant was increased from 0.06 to 0.10, a value more typical of open areas. In addition, the modification permits a small quantity of snowmelt to occur at mean daily temperatures between -5- and 0°C (23- and 32°F) to account for the variation in temperature during a day and for the fact that landfills often have higher soil temperatures because of heat generated from biodegradation. Snowmelt contributes to runoff, evaporation, and infiltration.

Interception is modeled after the work of Horton. Interception approaches a maximum value exponentially as the rainfall increases to about 0.5 cm (0.2 in.). The maximum interception is a function of the quantity of aboveground biomass or leaf area index and is limited to a maximum of 0.13 cm (0.05 in.). The interception evaporates from the surface and decreases the evaporative demand placed on the plants and soil column.

The HELP model uses the Soil Conservation Service (SCS) curve number method for estimating surface runoff, as presented in the Hydrology Section of the National Engineering Handbook. The SCS curve number method is an empirical method developed for small watersheds (about 12.1 to 202.4 hectares [30 to 500 acres) with mild slopes (about 3 to 7 percent). The method correlates daily runoff with daily rainfall for watersheds with a variety of soils, types of vegetation, land management practices, and antecedent moisture conditions (levels of prior rainfall). As applied, the technique accounts for changes in runoff as a function of soil type, soil moisture, and vegetative conditions. Version 3 of the model will include a procedure to adjust the curve number as a function of surface slope since surface slopes greater than 20 percent can produce significantly greater runoff.

Many assumptions and limitations exist in the application of this method in the HELP model, including the following: 1) The SCS curve number method is applicable for landfills that are much smaller in area than watersheds. Verification studies have shown good agreement between the predicted and observed cumulative annual volume of runoff. 2) Cumulative volume of runoff is independent of rainfall duration and intensity since over a long simulation period a variety of precipitation events will occur, 3) No surface run-on from surrounding areas is permitted by the model, 4) Estimates of runoff greater than predicted by the SCS curve number method are produced when the surface soils are saturated or limit infiltration due to very low hydraulic conductivity.

5.2.1.c Evapotranspiration

Evapotranspiration consists of three components: evaporation of water from the surface, from the soil, and from the plants. Each component is computed separately. Evaporation of water from the surface is limited to the smaller of the potential evapotranspiration and the sum of the snow storage and interception.

The HELP model uses a modified Penman method to compute potential evapotranspiration. This method, developed by Ritchie, is also used in the CREAMS program. The potential evapotranspiration is a function of ground cover, daily temperature, and daily solar radiation. Evaporation of surface water decreases the evaporative demand placed on the plants and soil column. The HELP model uses Ritchie's method of evaporation from soil as applied in the CREAMS and SWRRB models. The method uses a two-stage, square root of time routine. In stage one, the soil evaporation equals the evaporative demand placed on the soil column. Demand is based on energy and is equal to the potential evapotranspiration discounted for surface evaporation and shading from ground cover.

A vegetative growth model is used to compute the total quantity of vegetation, both active and dormant, which provides shading. In stage two, evaporation from the soil column is limited by low soil moisture and low rates of water vapor transport to the surface by soil suction. Stage two soil evaporation is a function of the square root of the length of time that the soil has been in this dry condition.

The HELP model estimates plant transpiration in the manner of the CREAMS and SWRRB models whereby the potential plant transpiration is a linear function of the potential evapotranspiration and the active leaf area index. The leaf area index of actively transpiring plants is computed using a vegetative growth model that accounts for seasonal variation in active and dormant aboveground biomass and leaf area index. This model was extracted from the SWRRB model developed by the USDA ARS.

Many assumptions and limitations exist in the application of this three-component evapotranspiration method in the HELP model, including the following: 1) The potential evapotranspiration is a function solely of the energy available at the surface and, therefore, is not a function of energy produced in the landfill, soil temperature, wind, and humidity. As such, the program uses a vapor pressure gradient that is a function solely of mean daily ambient air temperature. 2) A constant value is used for the albedo (fraction of incident solar radiation that is reflected). The value is typical for brown soils and grasses and is modified only when the surface is covered with snow. 3) The program uses a constant evaporative zone depth. This depth is the maximum depth to which soil suction can draw water to the surface. The depth is a function of soil properties, design, vegetation, and climatic conditions. 4) Ritchie's two-stage soil evaporation method is applicable for all materials, not just soils. 5) Synthetically generated daily temperature and solar radiation values are sufficient for estimating potential evapotranspiration. 6) The vegetative growth model produces representative leaf area indices and biomass estimates that are sufficient to estimate interception, surface shading, and plant transpiration.

5.2.1.d Subsurface Water Routing

Subsurface water routing processes modeled by the HELP model include vertical unsaturated drainage, percolation through saturated soil liners, leakage through geomembranes, and lateral saturated drainage. In modeling these processes, the soil moisture of each layer of the landfill profile being modeled is computed by sequential analysis proceeding forward through time.

The soil moisture controls the rate of subsurface water movement by each of the subsurface processes, but the rates of water movement by these subsurface processes yield the resulting soil moisture. Consequently, the soil moisture and rates of subsurface water routing are computed simultaneously in the HELP model by an iterative process after accounting for extraction by soil evaporation and plant transpiration.

The HELP model simulates unsaturated vertical drainage using a unit hydraulic pressure gradient approach (saturated Darcy's law) where drainage occurs at a rate equal to the unsaturated hydraulic conductivity. Under this approach, vertical water routing is only downward except in the evaporative zone where water is removed upward by evapotranspiration. The unsaturated hydraulic conductivity is computed by the Campbell equation using Brooks-Corey soil parameters to define the shape of this

power function. This approach incorporates the moisture retention properties (capillarity) of the soil in the determination.

The model considers limited interactions between layers of materials. As such, the model does not allow drainage from one layer at a rate greater than the maximum infiltration rate of the layer below it, allowing placement of a lower hydraulic conductivity nonlinear layer below a layer of higher hydraulic conductivity.

Future versions may consider soil matrix interactions in the recommendation of values for the evaporative zone depth and in the selection of the moisture content where the drainage from one layer into another will cease. These additions will better model the physical situations where fine-grained materials overlie coarse-grained materials. In these situations, the coarse-grained material may restrict the depth of evapotranspiration and the fine-grained material may retain a higher water content before draining into the coarse-grained material despite very low water content in the coarse-grained material. Conversely, coarse-grained material overlying fine-grained material will restrict the transport of water vapor up from below for evaporation but will freely drain to very low moisture contents. These phenomena occur because the soil suction of fine-grained material is much greater than that of coarse-grained material.

Vertical drainage through saturated soil liners is termed percolation in the HELP model. The barrier soil liners are assumed to remain permanently saturated, but percolation occurs only when there is a zone of saturation directly above the liner. Percolation is computed by Darcy's law using the saturated hydraulic conductivity of the liner material. The head loss gradient is equal to the average head above the base of the liner divided by the thickness of the liner.

Leakage through geomembranes is modeled as a reduction of the cross-sectional area of flow through the subsoil below the geomembrane. The rate of flow through the leaking subsoil is computed as the percolation rate through a saturated barrier soil liner. This method provides good results for composite liners but is not very good for just a geomembrane. Therefore, Version 3 will include an improved leakage model for geomembranes based on the work of Brown and Giroud et al.

The HELP model simulates lateral drainage using a steady-state analytical approximation of the numerical solution of the Boussinesq equation (Darcy's law for saturated lateral flow through unconfined porous media coupled with the continuity equation). The analytical approximation was developed by converting the Boussinesq equation into a non-dimensional form and solving it for two analytical solutions at the extremes in non-dimensional average saturated depth. These two solutions were then fitted with the same value and slope in an approximation that covers the rest of the range of non-dimensional depths. The approximation matched the numerical steady-state solution of the Boussinesq equation within 1 percent of the predicted drainage rate. The solution is not linear; therefore, the HELP model uses a Newton-Raphson method to converge onto the solution of the nonlinear approximation. The model uses the average depth of saturation in the approximation since the HELP model is quasi-two-dimensional and, therefore, cannot determine the saturated depth profile. The lateral drainage, percolation, and leakage through the geomembrane are solved simultaneously with the average depth of saturation using an implicit solution technique.

5.2.2 Limitations of the HELP Model

Many assumptions and limitations exist in the application of the subsurface water routing methods, including the following: 1) All flow is considered to follow Darcy's law. As such, the only driving force for water routing is gravity, and all movement has a downward component. 2) All layers of materials are spatially homogeneous and uniform. All properties of the layers and materials not related to soil moisture are assumed to remain constant throughout the simulation. 3) No subsurface inflow occurs. The layers being modeled are above the surrounding water table or cut off from it. 4) Brooks-Corey

relationships and the Campbell equation are applicable for estimating the unsaturated hydraulic conductivity of all types of materials. 5) Percolation and leakage through liner systems occur only when a zone of saturation (head) lies on the top surface of the liner. The zone covers the entire area of the liner and, therefore, percolation and leakage are spatially uniform. 6) The liner and drainage layers cover the entire area of the landfill since the water routing in the vertical and lateral directions is performed separately by one-dimensional models. 7) The liner system is permanently saturated and the pressure head at the base of the liner is zero (liner is above the water table). 8) Synthetic liners (geomembranes) are impermeable except through specific failure points (holes, punctures, cracks, faulty seams, etc.) and function by reducing the area of flow through the subsoil beneath the liners. 9) The rate of leakage through geomembranes is mainly a function of the number of holes, depth of saturation above the liner, and the saturated hydraulic conductivity of the subsoil. 10) The saturated depth profile (water table) in the lateral drainage layer is typical of steady-state drainage and gradually varies between different steady-state profiles characteristic for different depths of saturation as the simulation progresses. 11) The lateral drainage rate can be reliably estimated from the average depth of saturation throughout the drain layer which is estimated from the average soil moisture content of the drain layer. 12) The depth of saturation at the edge of the drain layer or at the collector is zero. Therefore, lateral drainage is not retarded by standing water in the drain trench.

5.2.2.a Vegetative Growth

The HELP model accounts for seasonal variation in active and dormant aboveground biomass and leaf area index through a general vegetative growth model. This model was extracted from the SWRRB model developed by the USDA-ARS. The vegetative growth model computes daily values of biomass and leaf area index based on a maximum allowable value from input, daily temperature and solar radiation data, and the beginning and ending dates of the growing season.

The maximum value of leaf area index depends on type of vegetation, soil fertility, climate, and management factors. The program supplies typical values for selected covers; these range from 0 for bare ground to 5.0 for an excellent stand of grass. The HELP model maintains a data file containing mean monthly temperatures and beginning and ending dates of the growing season for 183 locations in the United States. Vegetative growth is a linear function of the available solar radiation during the first 75 percent of the growing season. Growth can be limited by temperatures below 10°C (50°F) and low soil moisture. Vegetative decay is modeled as exponential decay and is also a function of temperature and soil moisture. The decay process is modeled continuously, during both the active growing and dormant seasons.

5.2.2.b Accuracy

As stated previously, the primary purpose of the model is to simulate alternatives for comparison, showing relative value of alternatives and sensitivity of design parameters. The secondary purpose is to quantify the water budget components accurately. Generation of accurate predictions requires good understanding of the model, hydrologic processes, and landfill design and construction. In addition, accurate data describing the properties and variability of all materials and the climate are essential. Even with the best of data and knowledge of the model and landfill, significant errors should be expected in the estimates of the water budget components due to minimum data requirements and limitations in the modeling techniques.

The following error bounds are believed, by the developers of the HELP model, to be generally achievable when extensive and accurate data are available to a knowledgeable user (ideal circumstances). The cumulative annual total for a water budget component can typically be estimated within the larger of the following error bounds: 25 percent of the total or 2 percent of the precipitation for the surface runoff component, 10 percent of the total or 7 percent of the precipitation for the evapotranspiration component, and 10 percent of the total or 0.1 percent of the precipitation for the percolation or leakage through liners component.

The error bound for cumulative annual lateral drainage to collection systems is about 7 percent of the precipitation and is equal to the sum of the other errors. Its error is dependent on all other errors because those processes occur first and any excess or shortfall in the extraction by those processes controls the quantity of water available for lateral drainage. These error bounds would be several times larger when simulations are run with poor data and a poor understanding of the model and landfill design.

5.2.3 Input Requirements

5.2.3.a Climatological Data

Required climatological data include daily precipitation, daily mean temperature, daily solar radiation, maximum leaf area index, growing season, and evaporative zone depth. Daily precipitation data can be provided by three options. The user may enter each value into the precipitation data file. The second option is to select 5 years of daily precipitation data from a default data set that has data for 102 cities throughout the United States. The third option is to synthetically generate daily precipitation data using a synthetic weather generator available in the program. The program has statistical coefficients describing the daily precipitation at 139 cities throughout the United States. Improvement in the data generation can be obtained by specifying the normal mean monthly precipitation at the landfill site.

The synthetic weather generator was adapted from the WGEN model developed by the USDA Agricultural Research Service. Daily mean temperature and daily solar radiation data are synthetically generated by the program after the user selects a location with similar weather from a set of cities having available data. The program contains statistical coefficients describing temperature and solar radiation values at 183 cities throughout the United States.

The generation of daily temperature values can be improved by specifying the normal mean monthly temperatures for the landfill site. Similarly, the daily solar radiation values can be improved by specifying the latitude of the landfill site.

When executing the program, guidance is available from a permanent data file for the remaining three climate-related parameters--growing season, maximum leaf area index, and evaporative zone depth. Typically, the growing season is that portion of the year when the mean daily temperature is above about 11°C (53°F). The maximum leaf area index is dependent on climate, soil fertility, cover design, and management practices. Thick layers of fine-grained soils have better fertility and moisture retention than thin layers and coarse-grained soils and, therefore, support better stands of vegetation.

The evaporative zone depth is dependent on climate, vegetation, and soil properties. Representative evaporative zone depths for silty, loamy topsoil are given in the program as a function of location and quantity of vegetation. Typical values would be greater for thick clayey layers while the values for sandy layers would be smaller. In addition, thin layers of materials and the presence of synthetic material near the surface also may restrict the evaporative zone depth.

5.2.3.b Soil and Design Data

The second set of required data consists of a description of each layer of material and a description of the landfill design. Material descriptions can be selected from a default set of material properties or specified individually by the user. The material properties that must be specified by the user are porosity, field capacity, wilting point, and the saturated hydraulic conductivity.

Porosity is defined as the volume of voids in a layer of material (or volume of water in a saturated layer) divided by the total volume of the layer. Field capacity is defined as the volume of water remaining in a layer of material after it ceases to drain by gravity divided by the total volume of the layer. It

corresponds to the moisture content remaining when the material exerts a soil suction of 1/3 atmospheres.

Wilting point is defined as the volume of water remaining in a layer of material after a plant extracts as much water as possible and goes into a permanent wilt, divided by the total volume of the layer. It corresponds to the moisture content remaining when the material exhibits a soil suction of 15 atmospheres.

User-specified descriptions are recommended since material properties vary greatly within a given soil classification. The default set of material descriptions contains properties for 15 soil types ranging from coarse sand to high plasticity clay. These 15 types also include fine sands, loams, silts, and low plasticity clays.

These soils also may be specified as compacted, which causes the porosity, field capacity, and saturated hydraulic conductivity to be lower. Compaction is recommended only for the fine-grained materials. In addition to the 15 soils, there are also two descriptions of very low hydraulic conductivity soils suitable for liners and one description of municipal waste with daily cover. When using either option of describing materials, the user has two options for initializing the moisture content of the materials.

The user may specify an initial moisture content ranging from porosity to wilting point. This option is used when the effects of changing moisture storage are important in the water budget. Under the second option, the program initializes the moisture content of the layer to the approximate long-term, steady-state value. This option is used when changes in water storage are unimportant or when the long-term, pseudo-steady-state water budget is desired.

The landfill description consists of the SCS runoff curve number, surface area, runoff area, and a description of the layers including the number of layers, their order and function, and their thickness. Four types of layers, based on how they function, are used by the model vertical percolation layers, lateral drainage layers, barrier soil liners, and geomembranes with barrier soil. Vertical percolation layers are layers that serve no purpose other than water storage. The topsoil layer and waste layers are typical examples of this type. Lateral drainage layers are layers designed to promote lateral drainage to a collection system. They typically have very large saturated hydraulic conductivity's and are underlain by a sloped liner. Barrier soil liners are layers of low hydraulic conductivity porous material designed to restrict vertical percolation or leakage. A geomembrane with barrier soil is a synthetic membrane underlain by subsoil and is used to restrict vertical percolation and leakage. In addition, the slope and drain spacing are needed for lateral drainage layers and the liner leakage fraction is needed for geomembranes.

5.2.4 Output Description

The output from the HELP model is a listing of the input data followed by an account of the water budget components in a tabular format. Information on precipitation, surface runoff, evapotranspiration, lateral drainage from each liner/drain system, percolation or leakage through each liner and from the bottom of the profile, moisture storage, snow accumulation, and depth of saturation on the surface of liners is reported.

Simulation results are available at several levels of detail. The cumulative quantity of the water budget components and its variance are tabulated on an average monthly and annual basis for the entire simulation period and optionally on a daily, monthly, and annual basis. In addition, peak daily results during the entire simulation period and final moisture contents of the layers are reported.

6.0 DATA SOURCES

A reference manual which is readily available and highly recommended is the U. S. Bureau of Reclamation "Earth Manual" (U. S. Bureau of Reclamation), which gives abundant information of direct interest to the cover designer for obtaining background information and also as regards all phases of soils. Data collection activities are discussed in the following paragraphs for each type of data required.

6.1 TOPOGRAPHY

The topographic map is probably the most useful single document relative to a cover project. The map reveals the lay of the land at the project site and in its vicinity; shows the surface drainage network, a matter of fundamental importance; gives information as to presence and location of cultural (man-made) features; and makes it possible to define place locations specifically by any desired system: latitude and longitude, public-land system (township, range, section, and subsection), or state coordinate system.

The U. S. Geological Survey (USGS) is the source of most published topographic maps. The scales of published topographic maps are 1:24,000 (1 inch equals 2,000 ft) or 1:31,680 (1 inch equals 1/2 mile) for 7-1/2-minute quadrangles, 1:62,500 (1 inch equals approximately 1 mile) for 15-minute quadrangles, and 1:250,000 (1 inch equals about 4 miles).

It will always be necessary to have a site topographic map at a larger scale than that of the published maps. Nevertheless the published quadrangle map should be obtained as a basic reference. An index of each state showing the available coverage and topographic quadrangle maps may be obtained directly from the USGS. In many cases selected maps are also available locally in various cities from commercial dealers.

6.2 SOILS

The US. Department of Agriculture has published an extensive series of soil survey maps. These maps are discussed and described by the U. S. Bureau of Reclamation. Commonly these surveys are performed on a county basis, but many are on an area basis and include portions of one or more than one counties. These surveys are performed for agricultural purposes and they are biased toward agricultural requirements.

Mapped soil units are called soil series and are named for a county, city, river valley, etc., where they are typically developed. A soil series, however, reflects only the soils in the agricultural soil profile, which is usually less than 6 ft deep. Reports since 1975 contain engineering uses of soils mapped, parent materials, geologic origin, climate, physiographic setting, and soil profiles. The soil maps are presented on photomosaic background for each county at a scale of 1:15,840 or 1:20,000.

Recent reports include engineering test data for soils mapped, depth to water and bedrock, grain-size distributions, engineering interpretations, and special features. For many sites, information from nearby soil borings may be found in the files of the pertinent state highway department.

6.3 GEOLOGY

A variety of geological reports and maps are available for the cover designer. The scales of geologic maps include 1:24,000, 1:62,500, 1:100,000, 1:250,000, and smaller. There are two major types of geologic maps. One is the formation or "bedrock" geologic map, which, for a given area, indicates the

material underlying the overburden soils. This is the most common type of geologic map; state geologic maps fall in this category.

The other type is the surficial geologic map, which specifically indicates the material lying at the ground surface. Glacial-geology maps are probably the most common geologic maps in this category. Both types may be useful in locating sources of natural cover material.

The principal sources of geologic maps and reports are the USGS and the State Geological Surveys or Departments of Natural Resources. A new series of indexes of geologic maps for each state was started in 1976, and lists of geological maps and reports for each state are published periodically by the USGS. Each state geological survey has a list of maps and reports published covering its state.

6.4 HYDROLOGY AND GEOHYDROLOGY

Maps showing hydrologic and hydrogeological information provide a valuable source of data in surface drainage, well locations, ground-water quality, ground-water levels, seepage patterns and aquifer locations and characteristics. A good source is the USGS which has prepared Atlases with a principal map scale of 1:24,000. The atlases include water availability, flood areas, surface drainage, precipitation and climate, geology, availability of ground and surface water, water quality and use, and stream flow characteristics. Some maps show ground-water contours and location of wells. Some of the state field offices of the Water Resources Division of the USGS have water well logs which may be useful.

6.5 AERIAL PHOTOGRAPHS

High-quality, large-scale (1:20,000) stereoscopic aerial photographs are particularly useful for interpreting drainage patterns, topography, land forms, vegetation, land use, and cultural features. The most readily available aerial photographs are panchromatic (black and white). Other types that are available include color and color infrared, which are extremely useful but coverage is less extensive and more expensive than black-and-white air photos.

The principal sources of aerial photographs are the Department of Agriculture's Agricultural Stabilization and Conservation Service (ASCS) Aerial Photography Field Office, 2511 Parley's Way, Salt Lake City, Utah 84109, and the USGS. The USGS has four mapping centers where aerial photographs may be obtained, located in Denver, CO, Rolla, MO, Menlo Park, CA, and Reston, VA. Good discussions of the use of air photos and how to obtain them are given by the U. S. Bureau of Reclamation.

6.6 CULTURAL FEATURES

Cultural features that should be the concern of the cover designer include transportation, network utilities (pipelines, telephone and power lines), location of urban centers, and availability of manufactured construction materials. Some of the data listed above can be extracted from the maps previously discussed, and other data can be obtained from the local Chamber of Commerce, the city or county engineer, utility companies, and local construction contractors.

6.7 VEGETATION DATA

Information on existing vegetation in the site vicinity is important from a cover standpoint. Vegetative protection of the cover is an important factor. Volunteer plant species in the area are an indicator of highly stable species and of species likely to invade the cover spontaneously. Cultivated plants in the

area are also obviously stable locally, although requiring certain specific management practices. Sources of background information include:

- USDA - Agricultural County Agents
- ARS - Agricultural Research Centers
- SCS - Local Offices
- Technical Service Centers
- Plant Materials Centers
- Plant Materials Specialists
- US. Forest Service - Local or State Offices
- Forest and Range Experiment Stations
- US. Army Corps of Engineers - District Offices, Environmental¹
- Resources Section
- USAE Waterways Experiment Station,
- Environmental Laboratory
- County or Municipality - Land Use Planners
- Land Use Plans
- State Universities - Local Faculty - Plant Identification

6.8 CLIMATIC DATA

The climatic or meteorological data for a given site is an important factor as regards cover. The cover, more than any other component of the remedial system, is directly exposed to the weather. Climate directly affects vegetation; the climatic factor of precipitation forms the input to the infiltration-percolation process that the cover system is intended to control; other climatic factors and their distribution influence the process strongly.

Specific climatic data are required as input to the hydrologic modeling methods to predict a cover system's effectiveness. Weather conditions directly affect construction operations and may be important in planning the construction phase of cover installation. Climatic data must be obtained from background sources, since a historical picture, rather than merely a short-term sampling, is important.

The primary source of climatic data in the United States is the National Climatic Center (NCC), operated by the National Oceanic and Atmospheric Administration of the U. S. Department of Commerce. The NCC's address is: National Climatic Center, Federal Building, Asheville, NC 28801 (Telephone number: (704) 258-2850).

6.9 WASTE CHARACTERISTICS

From the point of view of the remedial action as a whole, it is important to know as specifically as possible the type and form, the quantity, and the location of buried wastes. Material representing a collapsible foundation, such as buried drums of liquid, presents a threat to cover stability. Wastes that evolve gases are of concern to the cover designer; he should know if possible what will be evolved and in what quantities.

In general, the cover is probably free from attack by aggressive liquids in the waste; in this respect the cover designer's problem is very much simpler than that of the designer of a liner or a slurry wall. In some topographic situations, a sloping cover might be attacked by laterally migrating liquids. In such cases the designer should be informed as to the compatibility of his cover materials with the wastes.

Source of available data on the waste site include the city or county sanitation department or the operator/owner of the site.

The state EPA or its equivalent may have data on the site. A high probability exists that available data pertaining to a Superfund site have been collected because these data were necessary to place a site on the list of Superfund sites.

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**FIGURE 1- RISK BASED DECISION PROCESS
FOR SELECTING REMEDIATION ALTERNATIVES**

FIGURE 2
CONVENTIONAL LANDFILLING PRACTICE

FIGURE 3
ENVIRONMENTAL LAWS
POWER CURVE

FIGURE 4
INTEGRATED MIGRATION BARRIER SYSTEM

BARRIER TYPES

IMPERMEABLE

CLAYS
CAPILLARY
MEMBRANES
GROUTS

PERMEABLE

GEOCHEMICAL
BIOLOGICAL

**TABLE 1 ESTIMATED 1992 COSTS OF REMEDIATION
ALTERNATIVES FOR LANDFILLS.**

<u>ALTERNATIVE</u>¹	<u>COST/UNIT</u>²
EXCAVATE	\$80M/ha
RCRA CAP	\$4.9M/ha
SOIL/CAPILLARY BARRIER COVER	\$3.7M/ha
BIO-ENGINEERED SOIL/VEG COVER	\$0.24M/ha
SURFACE MGMT W/ EROSION CONTROL	\$0.12M/ha

¹ Technical basis for selection of alternatives should be based on human and ecological risk assessment

² Costs for excavation option from DOE's ER 5 year plan, RCRA cap from Maxey Flats corrective measures study, and remaining options estimated by author based on field experience.

FIGURE 5- POSSIBLE COMPONENTS OF AN ENGINEERED LANDFILL COVER

FIGURE 6 MODIFIED RCRA COVER DESIGN

FIGURE 8 CAPILLARY BARRIER COVER DESIGN

Table 2-EPA GUIDANCE OF LANDFILL CAPS

Vegetative Soil Layer

- A. Thickness ≥ 2 ft;**
- B. Minimal erosion and maintenance (e.g., fertilization, irrigation);**
- C. Vegetative root growth not to extend below 2 ft;**
- D. Final top slope between 3 and 5% after settlement or subsidence. Slopes greater than 5% not to exceed 2.0 tons/acre erosion (USDA Universal Soil Loss Equation); and**
- E. Surface drainage system capable of conducting run-off across cap without rills and gullies.**

Drainage Layer

- A. Thickness ≥ 1 ft;**
- B. Saturated hydraulic conductivity $\geq 1.0\text{E-}03$ cm/sec;**
- C. Bottom slope $\geq 2\%$ (after settlement/subsidence);**
- D. Overlain by graded granular or synthetic filter to prevent clogging;**
- E. Allow lateral flow and discharge of liquids.**

Low Permeability Liner Design FML Component

- A. Thickness ≥ 20 mil;**
- B. Final upper slope $\geq 2\%$ (after settlement); and**
- C. Located wholly below the average depth of frost; penetration in the area.**

Barrier Soil Layer

- A. Thickness ≥ 2 ft;**
- B. Saturated hydraulic conductivity $\leq 1.0\text{E-}07$ cm/sec;**
- C. Installed in 6-in lifts.**

END

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