Summary of the Current State-of-Practice in the Design and Evaluation of Landfill Covers in Arid and Semi-arid Environments

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1.0 INTRODUCTION

The waste containment industry, of which landfill closure is a part, is a relatively new field of engineering. The origin and growth of the industry can be attributed primarily to regulations which have been enacted regarding the disposal of waste. A study has been conducted by the University of Nevada, Reno through funding by the State of Nevada's Division of Environmental Protection, Solid Waste Branch to assess the current state of practice in the design and evaluation of municipal solid waste (MSW) landfill alternative closure designs and technology in arid and semi-arid environments. The study consists of three parts; (1) a survey of practitioners and regulators in Western states; (2) a review of applicable literature and field studies and development of evaluation procedures, and; (3) application of an infiltration model appropriate to arid and semi-arid environments. This report presents the results of the literature search and the recommended evaluation procedures. The results of the survey are presented within Appendix B of this report. A report titled "Application of the Hydrus-2D Model to Landfill Cover Design in the State of Nevada" prepared by the Desert Research Institute presented under separate cover provides the application of an appropriate infiltration model.

This report is a compilation of numerous reports that have been issued primarily by researchers working with low level radioactive waste. There was not an extensive amount of information in the literature regarding alternative MSW landfill cover design and evaluation particularly with respect to field studies. I assume that the reasons for this may include; (1) a great majority of the MSW landfill cover designs to date have been "designed by prescriptive standard" and therefor do not lend themselves to alternative cover applications, (2) alternative covers for MSW have only recently began to receive regulatory acceptance and therefor do not have much of a history upon which to draw; and, (3) most MSW work is performed by consulting firms and the reports are typically either somewhat proprietary and/or confidential. The work performed in the low level radioactive disposal industry are generally public information and do not typically follow a prescriptive standard. These designs are regulated more by performance standards. Designing with performance standards for these types of facilities requires more engineering and science due at least in part to the long design lives and severe hydrological requirements of the regulations.

Section two of this report provides some general comments with respect to waste disposal and design. The third section of this report summarizes two approaches to landfill cover evaluation. The fourth section presents summaries of applicable field studies that were identified in the literature. Section five presents the summary and conclusions and section six presents the recommended evaluation procedure.

2.0 GENERAL COMMENTS WITH RESPECT TO WASTE CONTAINMENT DESIGN AND EVALUATION

While the scope-of-work for this report is to provide a summary of the current state of practice in MSW landfill closure in arid and semi-arid environments, the report will not be complete without some discussion of concepts and philosophy of design. The context of this section draws almost exclusively from "Deserts as Dumps; The Disposal of Hazardous Materials in Arid Ecosystems", Charles C. Reith & Bruce M. Thomson, Editors (Reith and Thomson, 1992) and "Principals and Practice of Waste Encapsulation", Jack A. Caldwell and Charles C. Reith (Caldwell and Reith, 1993). There are numerous other reference books that deal with the design of landfills, however, they have a tendency to be very quantitative and do not specifically address the unique aspects of waste disposal in arid and semi-arid environments and the associated alternative landfill cover strategies. The two references mentioned above address arid and semi-arid environments, alternative landfill design strategies and concepts as well as many of the qualitative aspects of waste containment. It should be cautioned that many of the concepts presented in these two publications, as well as many of the other references that will be cited in this report, were derived from work performed based upon the requirements for the disposal of low level radioactive waste. It is my opinion that the concepts and systematic approaches are valid for application in Nevada, but that the criteria upon which adequate performance is judged may be more stringent than what is needed for the disposal of MSW particularly for small landfills in rural Nevada. It is prudent to mention at the outset that acceptable performance standards need to be clearly defined in order for a proposed landfill alternative cover to be evaluated. The application of a risk based approach should be considered. The United States Environmental Protection Agency (EPA) has approved a risk based approach for petroleum releases from underground storage tanks. Due to the success of this program, many other waste program groups within the states and the EPA are attempting to expand this concept to other areas including RCRA (ASTM, 1995).

In Reith and Thomson, 1992, Mr. Jack Caldwell sums up what I believe to be a very truthful, practical and far reaching comment with respect to waste containment design;

> "... from an engineering perspective the design and construction of waste disposal facilities demands a philosophical mind set that is different from anything else in engineering. We design with nature, to avoid the effects of nature, for as long into the future as possible."

The overall concept of a landfill cover is to resist the destructive forces of nature (erosion, plants and animals) in order to keep the entombed waste isolated from the environment and to minimize infiltration of water into the waste and the concomitant leachate generation. The designer is often faced with contradictory elements within a design, that is, an element that will assist in minimizing erosion may in fact work to increase infiltration. In Caldwell and Reith, 1993, Mr. Caldwell goes on to say;

> "It has been said that the various components [of a landfill cover], properly selected, form a functional synergistic entity ... The designer should always look for opportunities to enhance the interactive or synergistic effect of the various components in a cover."

The designer must rely on the experience of other facilities in similar environments (provided that performance data is available), the results of research that has been performed with similar materials and engineering judgement. The regulator, in performing an evaluation of a proposed design is faced with literally the same challenges and the additional challenge of ultimately deciding what will be considered "adequate performance". Caldwell and Reith, 1993 state that judgement, as it applies to waste containment, is based on:

1. Observation of natural phenomena
2. Familiarity with the truths of science
3. Thorough analysis of available information, including collecting and examining all the data, doing all the calculations, and evaluating all reasonable options
4. Comprehensiveness, breadth of knowledge, and distinguishing and extracting important information from a plethora of irrelevance
5. Balanced consideration of multiple concerns and thoughtful reconciliation thereof
6. Examination of past mistakes
7. A "gut feeling" brought about by age, panic, a schedule deadline, or a drink.

It is the intent of this report to provide the reader with information, and sources of information, so that the elements of judgement that must be relied upon in the evaluation of a design can be further developed.

2.1 GENERAL LANDFILL COVER CONCEPTS FOR ARID AND SEMI-ARID ENVIRONMENTS

In general, a landfill cover serves to isolate the waste from the environment and to minimize the amount of water that infiltrates into the waste. With respect to waste isolation, a primary concern is erosion of cover soils resulting in a cover that is not thick enough to perform as intended or possibly even expose the waste. Historically, infiltration is typically minimized through the use of a low permeability compacted soil barrier layer, a geomembrane or a composite of the two (typically referred to as a resistive type of barrier). Alternative landfill covers are being proposed that do not incorporate a low permeability barrier layer but utilize the soils' unsaturated characteristics (storage, hydraulic conductivity) to minimize percolation of water into the waste. Typical alternative covers can be composed of; a thicker section of a single material (monofill), different layers of soils designed to form capillary breaks when unsaturated and lateral drainage layers when/if they become saturated, etc. Arid and semi-arid environments are especially well suited to alternative landfill cover technologies due to their inherent low annual precipitation and potentially high evapotranspiration. The U.S. Department of Energy provides a check list of alternative cover performance objectives in their Uranium Mill Tailings Remedial Action (UMTRA) Project technical approach document (DOE, 1989). These objectives are:

- Control erosion
- Limit infiltration
- Provide freeze/thaw protection
- Inhibit radon emanation
- Drain or shed precipitation
- Control biointrusion
- Be self-renewing and adaptable to climatic change if vegetation is used

Obviously, radon gas migration is not a concern in MSW landfills. The adaptability of vegetation may not be as much of a concern for MSW as the UMTRA Project guidelines are based upon a design life of 200 to 1,000 years.

2.2 GENERAL COVER DESIGN STRATEGIES

EROSION

Erosion is a major concern with the long term performance of landfill covers. One method to mitigate erosion of cover soil is to place a layer of engineered rock at the surface of the cover.

The size of the rock is designed based upon anticipated run-off flow velocities from the specified (regulated) design storm. This design requires an economical source of durable rock. It has been argued that rock-surfaced covers are most appropriate for arid and semi-arid environments due to the fact that vegetation is naturally sparse, there are few plants that can cause biointrusion problems and that the lack of plants on a soil-surfaced cover will leave it highly vulnerable to erosion from the low frequency, high intensity storm that is typical in arid and semi-arid environments (Caldwell and Reith, 1993). A problem with this approach is that the rock covers tend to act as one-way valves. Even in very dry climates, water will permeate through the rock and into the underlying soils. The overlying rock will limit evaporation and the lack of vegetation eliminates transpiration as a mechanism of removing water from the soil. Therefore, significant moisture accumulation (storage), deep infiltration and eventual percolation of water through the cover will most likely result. Eventually, plants will seek this abnormally moist soil, become established and gradually degrade the cover if it was not designed to account for vegetation. Typically, with rock covers, the vegetation that becomes established is the deep rooted plants and not the more desirable shallow rooted plants.

As evident by the results of the questionnaires, assuming the responses are representative, most practitioners and regulators consider vegetation as one of the primary methods to minimize erosion of cover soils. The establishment of vegetation on the cover has the added benefit of increasing evapotranspiration potential. In fact, the results of the field studies that are summarized later in this report indicate that evapotranspiration is the most important component of the water balance second only to precipitation. Vegetation protects the soil from erosion by (Caldwell and Reith, 1993):

Interception: foliage and plant residues intercept rainfall energy and prevent soil compaction from raindrops

Restraint: root system physically binds or restrains the soil particles while aboveground residues filter sediments out of run-off

Retardation: aboveground residues increase surface roughness and slow velocity of run-off

Infiltration: roots and plant residues help maintain soil porosity and permeability

Transpiration: depletion of soil moisture by plants delays the onset of saturation and run-off

Some disadvantages of establishing a substantial growth of vegetation is that the roots may intrude into a barrier layer, if present, compromising it's integrity; plant roots and biological processes associated with plants tend to increase the hydraulic conductivity of the surface soils; large rooted plants may establish themselves upon the cover which may in turn die and topple leaving large holes in the soil that water can pond and infiltrate, and; large diameter roots that can decay leaving avenues for moisture intrusion into underlying layers. In areas that receive snowfall, the plants are typically dormant during the winter and are unavailable for transpiration during the time that the snow melts. The accumulation of moisture in the soil during the time that the plants are not transpirationally active usually determines the minimum acceptable storage capacity for a soil layer over a landfill (Caldwell and Reith, 1993).

Some design philosophies rely on a purely resistive barrier and attempt to eliminate vegetation from the surface of the cover entirely. Various methods have been proposed to try and prevent vegetation from becoming established on the cover. One method is to construct the cover with a surface layer that is inhospitable to plants. Traditionally this has been a rock layer. Experience has shown that rock layers are not that effective in preventing vegetation from becoming established in the long term. The details of what combinations of rock size, rock layer thickness, and environmental characteristics that are needed to assure even a temporary resistance to plant invasion are still generally unknown (Caldwell and Reith, 1993).

There is concern that vegetative covers are also prone to erosion during "major storms". It should be emphasized that this concern has been advanced primarily by designers working in the nuclear containment field who are often working with design lives of 200 to 1,000 years and probable-maximum-precipitation (PMP) design storms. It is quite possible that the design criteria for small landfills in rural Nevada may indicate that erosion of vegetated covers is not as much of a concern and that the potential benefits of a vegetated cover in terms of evapotranspiration will far outweigh the potential disadvantages. A vegetative cover can contribute to a landfill cover's longevity and performance by (Caldwell and Reith, 1993):

- Resisting the invasion of unwanted deep-rooted plants
- Resisting erosion by wind and water, although not as well as a layer of rock
- Transpiring water back into the atmosphere, which is usually the most desirable (least damaging) fate of water that falls on the landfill cover

Based upon their experience, Caldwell and Reith recommend to assume that vegetation will become established on the cover and to therefore try and encourage the growth of shallow rooted, grassland community vegetation that will discourage deep rooted trees and shrubs. The basic concept is to "... initiate a vigorous and self sustaining biological cycle, but to confine the cycle to the upper layers of the cover; this confinement is achieved not by force, but by creating a such favorable biological environment in the upper layers that the physiological stress which might otherwise encourage deep root penetration (or deep animal burrowing) is removed." It can be difficult to establish such desirable vegetation on the landfill cover. The effective use of desert pavement and gravel mulches is suggested as a means of establishing such a plant community. Desert pavement decreases evaporation from that of bare soil and thereby increases the water supply for plants, the key being maintaining the water near the surface of the cover and not allowing deep infiltration as a pure rock-surfaced or bare soil cover will.

In determining which plant community to establish on the landfill cover Caldwell and Reith recommend that a multi disciplinary team survey nearby areas with similar climatic and topographic conditions. Native climax plant communities in these similar areas should be observed with the thought of identifying a model plant community to establish on the landfill cover. Ideally the model community will be shallow rooted grasses that will be naturally self perpetuating and discourage the growth of deep rooted trees and shrubs through competition. Soil properties such as texture, bulk density, grain-size-distribution, organic content, nutrient concentrations etc should be determined so that the vegetative layer constructed on the landfill cover will simulate as closely as possible the naturally occurring soils that the desired plant community inhabits. In addition, it is desirable to assess the density, and rooting patterns for inclusion into infiltration modeling. If possible, test plots should be constructed. For smaller landfills in rural areas test plots are most likely not practical, however, significant information may be obtained from test plots being performed (or planned) in mining reclamation and observing revegetation efforts that have been performed after wild land fires in Nevada. Additionally, erosion potential and patterns may also be at least qualitatively assessed from mining industry work and areas that have experienced a fire that has extensively damaged the natural vegetation. This information may have already been compiled and may be readily available. To this end it makes sense to consult with local experts in agronomy, range management, agriculture and other disciplines that have experience in revegetation.

It should be noted that Caldwell and Reith also state that establishment of vegetation is rarely successful on the first try. Monitoring and maintenance of the revegetated cover should be expected for at least some period of time to identify bare areas, identify the reason that vegetation is not taking and to implement repairs before erosion starts. It is therefore tempting to apply fertilizer and generous amounts of water to get the vegetation established. However, this will create plant dependency and a resulting dieback when the excess is used up or no longer applied. It is better to apply fertilizer and irrigation in quantities that are not more than would naturally occur during favorable conditions.

In summary, vegetation of one form or another will most likely establish itself on a landfill cover. A properly selected and established vegetative community can contribute, and in fact is essential, to the performance of an alternative landfill cover that does not incorporate a purely resistive barrier to inhibit deep infiltration. However, the unreliability of vegetation; it's dormancy during winter months, the potential for it to be absent during an intense rainstorm, must also be considered in design.

3.0 EVALUATION METHODOLOGIES

There are close correlations between designing a cover and evaluating a proposed cover design. Therefore, both design "checklists" and evaluation procedures that were identified are presented. The documents that were reviewed are a Department of Energy Technical Approach Document for the remediation of uranium mill tailings sites and a U.S. Environmental Protection Agency (EPA) document for evaluating covers for solid and hazardous wastes. At the conclusion of this report a summary presenting our recommended evaluation procedure is provided.

3.1 UMTRA PROJECT TECHNICAL APPROACH DOCUMENT

The Technical Approach Document (TAD) (DOE, 1989) provides a checklist approach to determining what types of layers to incorporate in a cover design. The procedure includes:

- Obtain site-specific data.
- Examine relevant characteristics of the natural landscape (gullies, vegetation and the like [geomorphology]).
- Examine the Checklist Cover and eliminate components on the basis of the component elimination criteria list in Table 3.1.
- Compile the final cover as a composite of the remaining components.

Site specific data and the relevent characteristics of the natural landscape can be required in the design report. The Checklist Cover and referenced Table 3.1 contains the following elements:

1. Erosion-barrier vegetation (<u>topslopes only</u>)
2. Erosion-barrier small diameter rock layer on topsoil on pea gravel/soil mulch (<u>topslopes only</u>)
3. Rooting medium (topslopes only)
4. Frost protection (random fill) (<u>top and sideslopes</u>)
5. Chocked rock filter (layer of pea gravel overlying layer of coarse aggregate) (<u>top and sideslopes</u>)
6. Erosion/biointrusion 2-3 feet of cobbles with a low coefficient of uniformity to prevent biointrusion (<u>top and sideslopes</u>)
7. High permeability drain (6" - 12" layer of pea gravel overlying clean sand)
8. Infiltration barrier - Claymax® liner system (<u>topslopes only</u>)
9. Radon barrier (clay/silt)(<u>top and sideslopes</u>)

Included in the table are columns describing the purpose and function of each cover component and the rationale for elimination based upon site specific conditions. While the details of the table are specific to the UMTRA project, a simpler concept may be able to be applied to MSW landfills in Nevada.

The TAD provides cover design methods for two different types of covers; rock covers and vegetated cover designs. The main design issues that are addressed in the TAD are:

- Surface Water Hydrology
- Rock Cover Design
  - Erosion Protection
  - Infiltration Protection
  - Biointrusion Protection
- Vegetated Cover Design
  - Plant Community
  - Rooting Medium
  - Biointrusion Protection
  - Water Balance Assessment

3.1.1 SURFACE WATER HYDROLOGY

Design considerations that the TAD addresses that may be applicable to MSW cover design include:

- Runoff from the top and side of the [cover] from local precipitation events
- Runoff from small upland watersheds [runon]
- Flooding from nearby large streams or rivers

The TAD then provides an extensive list of steps that are considered as being "...essential for an adequate evaluation of hydrologic impacts...". The main topics of the list that are appropriate for MSW include:

- Collection and Review of Available Data
- Field Investigation
- Hydrologic Description of the Site
- Flooding Determinations
- Geomorphic Considerations
- Erosion Protection Design

Details are provided to determine the probable maximum precipitation (PMP).

3.1.2 ROCK COVER DESIGN

During the previous discussions it was mentioned that, in general, rock cover designs will most likely not be the cover design of choice for most applications in Nevada. The TAD guidance for rock cover designs is presented here for the sake of completeness and also due to the potential that in certain situations, a portion of a cover may be best suited for a rock cover.

The rock cover design section of the TAD provides guidance for:

- Designing the "...required mean rock size needed to provide a stable rock slope..." with respect to erosion protection
- Toe protection
- Rock durability and material selection, testing and placement, included in this section is a table providing "Rock Quality Scoring Criteria"
- Filter design

INFILTRATION PROTECTION FOR ROCK COVER DESIGNS

At the time that the TAD was written (1989 or earlier) they stated that based upon the hydrogeologic conditions, cover characteristics, and climate at a site, a rock cover may be the appropriate design to meet the groundwater quality standards (NRC requirements). The means that were used to demonstrate minimal infiltration or to reduce infiltration were: unsaturated conditions in the radon barrier (note that with respect to uranium mill tailings, the radon barrier may or may not be the same layer as the infiltration barrier); highly permeable bedding layer (lateral drainage layer); or infiltration barriers.

At the time the TAD was written, the infiltration concepts were based upon a study performed at Shiprock, New Mexico. They reason that the results of this study can be qualitatively applied to other sites with similar climates. The other sites that they mentioned are Clive, Green River and Mexican Hat, Utah; Ambrosia Lake, New Mexico; Lakeview, Oregon; and Tuba City, Arizona. It would be of interest to try and obtain any available performance information on these sites if they have been constructed.

Rapid drainage of water off of the cover will leave less water available for infiltration. More rapid drainage can be accomplished by increasing slope angles, decreasing drainage lengths or increasing the hydraulic conductivity of the bedding (lateral draiange) layer. Due to stability, constructibility, and cost factors, the TAD states that increasing the hydraulic conductivity of the lateral draiange layer is the best alternative. This may not necessarily be the case for MSW landfills in Nevada.

An infiltration barrier may be required to minimize the amount of water that reaches the radon barrier. The infiltration barrier may consist of one or more of the following: a low permeable soil that also functions as the radon barrier; a bentonite amended soil that also functions as a radon barrier; or a geosynthetic clay liner (GCL).

BIOINTRUSION FOR ROCK COVER

As mentioned in Section 2, rock covers are prone to invasion of undesirable deep-rooted plants. At the time the TAD was written, they acknowledged that a rock cover had some potential for establishment of plants. The degree of biointrusion was stated to be related to local environmental conditions and cover characteristics. Environmental factors that indicate a higher potential for biointrusion are; nearby deep rooted plants; nearby burrowing animals; humid to subhumid climate; and deep or rich top soil.

A table is provided in the TAD (Table 4.6, pg. 89) that allows the risk for plant invasion for rock covers to be estimated and also provides some recommendations to reduce the risk of plant invasion. The table may require updating based upon new data. For example, lower risk may be achieved by incorporating a thicker layer of rock, using smaller rock, or placing a soil beneath the rock that is inhospitable to plants. Considerations for the soil underlying the rock include; a soil with a high hydraulic conductivity so that moisture for germination and growth will be minimized; constructing with soils of undesireable chemical properties; for example saline groundwater was used as a moisture conditioner at the Clive, Utah site for both the lateral drainage layer and the radon barrier.

3.1.3 VEGETATIVE COVER DESIGN (ENGINEERED VEGETATED COVER)

The TAD provides specific design guidance for vegetated covers. The TAD states that it is important to note the difference between their concept of a vegetated cover and a soil-surfaced cover upon which vegetation naturally becomes established or a soil-surfaced cover upon which a "...casually selected..." seed mixture is applied. The UMTRA TAD's concept of a vegetated cover is a cover in which the soil and plants have been carefully selected and the construction performed in such a manner as to establish the selected plant community as rapidly as possible. To avoid confusion and to emphasize the difference the term "engineered vegetated cover" will be used when referring to the UMTRA concept of a vegetated cover design.

The soils and plants selected have specific performance objectives that have been accounted for in the design of the cover and this performance must be met if the cover is to perform as designed. Performance parameters include controlling water balance, erosion resistance, and "...otherwise contributing to the long-term integrity..." of the cover.

Three principal attributes of an engineered vegetated cover as presented in the TAD are:

- Control of water balance through the effective use of evapotranspiration.
- Relative freedom from surveillance and maintenance. This refers specifically to biointrusion from animals and plants. It should be noted that what the UMTRA personnel consider "relative freedom from maintenance" most likely includes at least some maintenance and monitoring that may not necessarily be considered minimal by all landfill operators.
- Compliance with longevity requirements. This is based upon the assumption that a climax plant community will be established that will remain indefinitely, "...resisting minor disturbances and repairing itself after major disturbances." It should be noted that the UMTRA design life is 200 to 1,000 years.

Engineered vegetated covers may be less effective in humid climates due to evapotranspiration not being able to keep up with infiltration.

The critical aspects of an engineered vegetated cover are the proper selection of a plant community and soil to ensure that some plants survive the dry periods. They state that a rock mulch may be required at exceptionally arid sites to resist evaporation and provide more moisture for plants that will in turn provide additional erosion resistance. The results of numerous field studies performed with rock mulched covers are presented in Section 4, FIELD STUDIES, of this report.

The TAD provides specific guidance to selecting a plant community, selecting a rooting medium, erosion protection, biointrusion protection, and water balance. A brief summary of these sections is provided below.

TARGET PLANT COMMUNITY FOR ENGINEERIED VEGETATIVE COVERS

The goal is to establish a plant community with the highest evapotranspiration potential that the local climate and soils will support. Ideally a combination of cool season and warm season grasses and plants will be used to provide transpiration during the longest time period during the year. In addition, the plant community should provide a rapid accumulation of organic matter to provide erosion resistance. To identify the desired plant community, various plant communities within a few miles of the site should be surveyed for those that have the desired characteristics (this could be performed in conjunction with the geomorphological study). Consideration of the soils that the plant communities are growing in needs to be made. If the ideal top soil for the desired plant community is not readily available at the site then importation of desirable soil may be required to establish the vegetation. Importing the top soil (vegetative layer) may be cost prohibitive or impractical for some landfills in rural Nevada, requiring that other options be explored. Ideally on-site soils would be used and that is part of the rational behind selecting the target plant community by observation of communities in surrounding areas.

ROOTING MEDIUM FOR ENGINEERED VEGETATIVE COVERS

The TAD states that the most important component of an engineerd vegetative cover is the rooting medium. The rooting medium provides mechanical support for the roots and stores water and nutrients. Ideally, this layer will store all water that infiltrates into the cover for eventual transpiration back to the atmosphere by the plant community. The rooting layer can also provide frost protection for underlying layers. They recommend a soil with an even mixture of sand, silt and clay particles and one that will retain 30% or more of it's own weight in water at field capacity and will release all but 10% to plants at it's wilting point. The chemical properties of the soil should also be considered.

Care should be exercised in handling and stockpiling rooting medium soil. Stockpiled soil should be well drained to prevent anaerobic chemical processes that can introduce sulfides and other detrimental agents.

EROSION PROTECTION FOR ENGINEERED VEGETATIVE COVERS

The TAD identifies two types of erosion that should be addressed during design; sheetwash erosion or deflation and concentrated erosion by rills and gullies. The analysis for each type of erosion is treated separately. A vigorous stand of vegetation will greatly enhance the soil's ability to resist erosion. In arid areas where a vegetative community may be sparse, a properly designed rock mulch will improve the soil's erosion resistance.

With respect to sheetwash erosion and deflation the TAD mentions the use of the Universal Soil Loss Equation (USLE) and the Modified Soil Loss Equation (MUSLE). (It should be noted that in the response to the questionnaire, UMTRA stated that they use the Revised Soil Loss Equation (RUSLE) which has apparently come into use subsequent to the publication of this TAD). Some advantages of MUSLE over USLE are presented. MUSLE can be used to evaluate average soil losses for certain types of slopes as a function of time, it has factors for certain topographic and erosion control for construction conditions and it allows a site to be divided into multiple components.

Both methods have the limitations of not being able to account for rill and gully development, gully erosion, sediment yield or snow melt erosion. With respect to rill and gully erosion assessment the TAD presents a geomorphological approach as well as an analytical/empirical (tractive shear stress) approach.

A sixteen step procedure based upon the tractive shear stress method is provided to qualitatively determine the erosion potential of a vegetated top slope.

BIOINTRUSION PROTECTION FOR ENGINEERED VEGETATIVE COVERS

The TAD provides a table that can be used to evaluate the likelihood of biointrusion into a vegetated cover at a site. The table presents high risk and lower risk conditions based upon the local biota and the proposed cover design. It should be noted that the main concern with respect for biointrusion for the UMTRA Project is it's effect on a the infiltration and/or radon barrier. For a monofill cover design, biointrusion from plants is not a concern provided that the roots do not penetrate into the waste, however, intrusion by burrowing animals may radically alter infiltration patterns into the soil.

The TAD states that a loose cobble layer has proven effective in mitigating intrusion of roots and animals. They recommend that a filter layer be placed on top of the biointrusion layer and that a drain layer be placed below the biointrusion layer. Their position is that thicknesses of over 1 foot are impractical; make them more efficient not thicker. They recommend a minimum rock diameter of 1-inch and a maximum dimension less than one-half of the layer thickness.

The TAD also mentions providing a thick and favorable upper soil layer so that the plants do not become stressed and extend the roots deeper in search of more favorable conditions. They also mention using compaction water of lower layers that contains constituents unfavorable to plant growth.

WATER BALANCE FOR ENGINEERED VEGETATIVE COVERS

The TAD recommends using the HELP or CREAMS models. Our recommendations for estimating water balance are provided in a separate report.

3.2 UNITED STATES ENVIRONMENTAL PROTECTION AGENCY COVER EVALUATION PROCEDURE

The United States Environmental Protection Agency (EPA) has prepared a manual outlining procedures for evaluating covers for solid and hazardous waste facilities (EPA, 1980). The manual was prepared to assist Regional and State EPA offices in evaluating applications from owners/operators of solid and hazardous waste facilities. The manual draws from a previous EPA manual (EPA, 1979) which provides details of the design and construction of covers. It should be noted that there may be a more recent manual than the one reviewed for this report but I was unable to verify or obtain a copy. The general concepts should be appropriate for our purposes.

The manual presents a sequence of procedures which are outlined as follows:

1. Examine Soil Test Data
2. Examine Topography
3. Examine Climate Data
4. Evaluate Composition
5. Evaluate Thickness
6. Evaluate Placement
7. Evaluate Configuration
8. Evaluate Drainage
9. Evaluate Vegetation
10. Evaluate Post-closure Maintenance
11. Evaluate Contingencies Plan

The first three procedures are directed at the review of materials and conditions at the site. Procedures 4 through 9 are related to the characteristics of the proposed cover system within the constraints determined during the review of items 1 through 3. Procedures 10 and 11 evaluate the adequacy of the post-closure plan.

The manual states that there is the opportunity in the procedure to evaluate alternative designs from more conventional designs (it should be noted that this manual is dated 1980). To evaluate the alternative designs the manual states that the additional technical guidance provided in EPA, 1979 will be useful.

Within the manual a 36 step evaluation procedure that address the 11 procedures listed above is presented. The details of performing some of the steps in the evaluation are somewhat out of date with current understanding of landfill cover performance. The general concept presented in this evaluation procedure, however, can provide a good framework upon which an evaluation procedure specific to Nevada can be developed.

The evaluation steps along with brief descriptions of applicable evaluation criteria presented in the manual are provided below. It should be noted that within all steps in the evaluation procedure, a check for conformance with applicable regulations should be made.

TEST DATA REVIEW (Steps 1-3)

Step 1 Review Field Sampling of Soils

The objective of this task is to establish that the applicant has satisfactorily documented the physical characteristics, volume and spatial distribution of the soil types that are proposed for use in the cover.

<u>Step 2</u> Check Adequacy of Soil Testing Program

A table is provided that presents laboratory test methods for soils that are broken down into the following categories:

Index and Classification Tests
Moisture-Density Relations
Consolidation and Permeability
Shear Strength and Deformability

<u>Step 3</u> Check Soil Volumes Available

There should be enough information obtained from the site investigation and presented in the design report to allow verification that sufficient quantities of borrow materials are available to construct the proposed design.

TOPOGRAPHICAL REVIEW (Step 4)

<u>Step 4</u> Examine Configuration and Topography

Examine the configuration of the surface of the cover to ensure that an evaluation of slope stability and erosion can be performed. Cross sections of the cover should be provided in the application.

CLIMATOLOGICAL REVIEW (Steps 5-7)

<u>Step 5</u> Examine Precipitation Records

The design report should contain data on the precipitation that is being used for design of the cover. The source of the precipitation information should also be given.

<u>Step 6</u> Examine Evapotranspiration Estimates

The EPA states that "...it [evapotranspiration] must be regarded as a major factor in cover design." The results of the field studies that are summarized in this report indicate that evapotranspiration plays a major, if not the major, role in the water balance for a landfill cover.

<u>Step 7</u> Examine Design Storms

The cover design should consider not only average precipitation but also higher intensity, shorter duration events.

One researcher has shown that in order to have a model accurately predict the measured field response of runoff, hourly precipitation data was required as input to the model (Meyer, 1993). It is agreed that requiring an applicant to input hourly precipitation data is impractical, it does emphasize the importance of looking at higher frequency events. It should also be noted that in the above referenced research, when daily precipitation values were used, runoff was underpredicted which provided a more conservative result for design.

COVER MATERIALS COMPOSITION (Step 8)

Step 8 Evaluate Composition

The manual presents a table that provides a ranking of Unified Soil Classification System (UCS) soil types to performance of cover functions. The functions considered in the table include:

Trafficability; go/no-go, stickiness, slipperiness
Water Percolation; impede, assist
Gas Migration; impede, assist
Fire Resistance
Erosion Control; water and wind
Dust Control
Reduce Freeze Action; fast freeze, saturation
Crack Resistance
Side Slope; stability, seepage, drainage
Discourage Burrowing
Impede Vector Emergence
Discourage Birds
Support Vegetation
Future Use; natural, vegetation

The procedure checks a soil's suitability by establishing it's strengths and weaknesses for it's intended function be means of a rating system. Less favorable rankings generally indicate that special features need to be incorporated into the design to mitigate material shortcomings. The manual states that the reviewer needs to exercise good judgement in applying this method.

THICKNESS EVALUATION (Steps 9-13)

The EPA states that cover thicknesses greater than the regulatory minimums may be required based upon the results of an evaluation of one or more of the following factors:

Coverage
Infiltration
Gas Migration
Trafficability and Support Requirements
Freeze/Thaw or Dry/Wet Cycles
Cracking
Differential Settlement and Off-set
Membrane Protection
Vegetative Requirements

Step 9 Evaluate Coverage

Within this step the EPA provides what they term "...a reasonable criterion of adequacy for coverage over irregular waste...". Their criteria is:

$$T>2R$$

where T is the cover thickness and R is the relief. Relief is determined by measuring the difference in elevation between the high point and low point of irregularities over an area which is approximately equal to the size of the equipment that will be used to place the material.

Step 10 Evaluate Thickness for Infiltration

Based upon the use of a water balance technique. This type of approach is not necessarily applicable to Nevada and will be addressed in a subsequent report.

Step 11 Evaluate for Gas Migration

Step 12 Evaluate Structure Support Requirements

This step is primarily concerned with structures that will be built upon the landfill and is not applicable to this scope-of-work.

Step 13 Consider Freeze/Thaw and Dry/Soak

This step is primarily concerned with freezing and desiccation.

PLACEMENT EVALUATION PROCEDURE (Steps 14-17)

After selection of materials and thicknesses of layers, proposed construction procedures are evaluated.

Step 14 Evaluate Cover Compaction

The details provided by the EPA for this step are out of date and inappropriate for Nevada's application.

It is our opinion that compaction of alternative cover soils does need to be addressed. There should be some correlation between the soil parameters used in the model and the anticipated soil densities in the field.

Step 15   Evaluate Internal Layering

The specifics provided in this step are generally related to a prescriptive standard type of design.

Layering of soil types may be an option for some alternative cover designs, e.g. designs incorporating capillary barriers.

Step 16   Evaluate Top Soil

The proposed surface vegetative layer should be assessed for it's ability to support vegetation. The EPA states, "Untreated subsoils are seldom suitable directly, so it has been necessary frequently to supplement subsoil with fertilizers, conditioners, etc., as explained elsewhere (Steps 24-26)."

Due to the fact that vegetation is so critical to the performance of alternative landfill covers, it is our recommendation that individuals who specialize in this area be consulted.

Step 17   Review Proposed Construction Techniques

The EPA states, "The application should be carefully reviewed for the following general recommendations for layering (from the bottom up)..." The majority of the recommendations have to do with the prescriptive standard and compacted soil liner as a barrier layer and are not applicable to alternative cover designs.

CONFIGURATION EVALUATION PROCEDURE (Steps 18 and 19)

These evaluation procedures are concerned primarily with erosion and infiltration

Step 18   Evaluate Erosion Potential

The EPA presents the USLE approach. It appears that there are more appropriate methods available.

Step 19   Evaluate Surface Slope Inclination

The EPA generally discusses the relationship of increased slope and reduced infiltration vs erosion. They provide some rules of thumb for slope inclination that may or may not be applicable to Nevada:

- Slopes of 4(Horizontal):1(Vertical) are generally stable

- 2:1 slopes are the steepest upon which vegetation can be established and maintained with favorable soil conditions (low erodibility, adequate moisture holding capacity, [nutrients])
- 3:1 slopes are the steepest upon which a stable vegetative community can be maintained in less than ideal soil conditions
- 4:1 slopes or flatter slopes are optimum for vegetation stability

Wind erosion is addressed very briefly in the EPA report.

DRAINAGE EVALUATION PROCEDURE (Steps 20 - 22)

Step 20 Check Overall Drainage System

The EPA recommends that the documentation is reviewed to establish that surface runoff and adjacent surface water issues have been thoroughly addressed. They suggest that a review for obstacles that may cause ponding or excessive erosion be made. They also recommend that particular attention be paid to the toes of slopes where slopes may need to be excessively steep.

Step 21 Evaluate Ditch Design

Review for adequate hydraulic capacity and erosion protection where needed.

Step 22 Evaluate Culvert Design

Standard procedures are used to assess adequacy of culverts where needed.

VEGETATION EVALUATION PROCEDURE (Steps 23 - 29)

As previously mentioned, vegetation is a critical aspect of the performance of an alternative landfill cover design. The EPA states that rapid establishment of vegetation requires careful attention to soil type, nutrient and pH levels, climate, species selection, mulching and seeding time.

Brief descriptions of the EPA recommended considerations for each step are provided below, however, it is highly recommended that individuals experienced in the geographical area of the landfill be consulted.

Step 23 Evaluate Soil Suitability for Vegetation

Loam is recommended as the best soil for support of vegetation.

Step 24 Evaluate pH Level

They recommend a pH of approximately 6.5. They mention that the application of lime may be required.

Step 25 Evaluate Nitrogen and Organic Matter

The EPA recommends the application of fertilizer if nitrogen and organic matter levels are low. These recommendations may be somewhat contradictory to the approach that should be taken for Nevada landfills.

Step 26 Evaluate other Nutrients

The EPA mentions phosphorous and potassium requirements and fertilizing if necessary.

Step 27 Evaluate Species Selection

The EPA document generally discusses selection of plants based upon being low growing and spreading from rhizomes or stolons, rapid germination and development and resistance to fire, insects and disease. They provide a table of plant characteristics that are important to species selection and examples of grasses and legumes associated with these parameters. The characteristics used in the table include:

Texture; fine, coarse
Growth Height; short, medium, tall
Growth Habit; bunch, sod former
Reproduction; seed, vegetative, seed and vegetative
Annual; summer, winter
Perennials; short-lived, long-lived
Maintenance; difficult, moderate, easy
Shallow Rooted; weak, strong
Deep Rooted; weak, strong
Moisture; dry, moderate, wet
Temperature; hot, moderate, cold

The EPA also provides a table of grasses and legumes that are commonly used for vegetation. While these tables are not applicable to Nevada, a similar approach may be taken that is specific to Nevada.

It should also be noted that the EPA does not mention assessing native plant species as a part of the selection process.

Step 28 Evaluate Time of Seeding

According to the EPA, the time seeding is probably the most important aspect of the establishment of vegetation. The optimum time depends upon the species selected and the local climate.

Step 29 Evaluate Seed and Surface Protection

The EPA recommends the use of a mulch for temporary protection against large temperature and moisture fluctuations and rapid degeneration from wind and water erosion. Materials that they state can be used as mulch include; straw and other crop residues, sawdust, wood chips, wood fiber, bark, manure, brush, jute or burlap, gravel, stones, peat, paper, leaves, plastic film, and various organic and inorganic liquid. They also suggest mixing in some plant varieties that may act as a living mulch, particularly if construction is completed at a time that is not optimal for seeding of the target plant community.

MAINTENANCE EVALUATION PROCEDURE (Steps 30 - 32)

The amount of conservatism in the design with respect to erosion will affect the level of maintenance that may be required.

Step 30 Evaluate the Design/Maintenance Balance

The EPA recommends that a check be made to see that there is a balance between the design and the proposed monitoring, maintenance and repair. Many factors such as climate, waste type, soil, vegetation etc., are involved in evaluating this balance. Little specific guidance is offered by the EPA. It will most likely be based upon the past performance of covers in similar climates.

Step 31 Evaluate Maintenance of Vegetation

The EPA states, "After vegetation is established...maintenance is required to keep less desirable, native species from taking over...". They also mention mowing the cover up to twice a year and fertilizing once a year.

Step 32 Evaluate Provisions for Condition Surveys

The requirements should be site specific and will depend upon the agency involved. Provisions should be made for documentation during the site visits and record keeping.

CONTINGENCY PLAN EVALUATION PROCEDURE (Steps 33 - 36)

Step 33 Evaluate the Plan for Erosion Damage Repair

The EPA states that long term maintenance helps to avoid erosion problems. However, unusual climate conditions and shortcomings in the design may cause excessive damage to the cover at times due to such events as excessive winds or water even in well maintained covers. One important factor that needs to be considered is the future source of soil to implement repairs if and when they are needed. Additionally, provision should be made for redesign of the cover [or certain areas of the cover] should the original design result in inadequate performance.

Step 34 Evaluate Plan for Vegetation Repair

The EPA recommends that provisions be made to repair damaged areas.

It should be noted that the EPA's concept of a vegetated cover is different from the concept of a vegetated cover recommended in this report for arid and semi-arid climates. It is the intent that the vegetation be as sulfsustaining as possible and to minimize the amount of maintenance and repair.

Step 35 Evaluate the Plan for Drainage Renovation

Except for repairing damage caused by unexpected erosion, the EPA recommends maintenance that includes cleaning ditches and cutting brush.

Step 36 Evaluate Provisions for Other Cover Deterioration

The EPA recommends that plans for repair due to other types of cover deterioration be provided. Other types of damage to the cover may occur due to excessive root penetration, cracking, freezing, seepage and slope instability.

4.0 FIELD STUDIES

The following section summarizes applicable field studies that were identified in the literature. Tables are provided in Appendix A of this report which present summaries of the field studies that are outlined below.

4.1 EASTERN WASHINGTON, Fayer et al., 1992

Fayer et al. (1992) monitored eight field lysimeters at the Field Lysimeter Test Facility at Hanford, Washington. All of the lysimeters were non-vegetated and had no runoff. Six of the lysimeters were cylindrical approximately 1.93 m in diameter and 2.93 m high and were sealed at the bottom except for a drain to measure percolation. The other two lysimeters were rectangular parallelepipeds approximately 150 cm on the sides and 170 cm high. The bottoms of the rectangular lysimeters were also sealed except for a drain. The rectangular lysimeters were placed on scales so that the weight of the system could be monitored. The accuracy of soil moisture storage was able to be measured to within ± 0.03 cm.

Approximately 52% of the annual precipitation at this site occurs between the months of November and February and of this, 40% occurs as snow.

The cover design tested was the same in all of the lysimeters and consisted of, from the top down:

1.5 m of silty loam
5 cm of 20/30 sand (>90% between 0.25 mm and 1 mm)
5 cm of No. 8 sand (>90% between 1 mm and 2 mm)
5 cm of 1 cm gravel
10 cm of 2 cm gravel
15 cm of 4 cm to 5 cm railroad ballast
~ 1 m of basalt rip rap

No provision was made for lateral drainage at the interface between the fine soil and coarse grained layer (capillary break).

Two of the cylindrical lysimeters received ambient precipitation, two received twice the recorded ambient precipitation and two had water added until breakthrough occurred. One of the rectangular lysimeters received ambient precipitation and the other received twice the recorded ambient precipitation. Precipitation in excess of the ambient precipitation was applied with a sprinkler irrigation device. The writer's interpretation of a figure presenting cumulative precipitation indicate that ambient precipitation was approximately 12.8 cm and 26.0 cm for the first year and the entire study respectively and that twice average precipitation was approximately 22.5 cm and 49.0 cm for the first year and the entire study respectively.

Monitoring consisted of weather data and moisture content of the soil loam layer. Moisture contents of the sands and gravels was not performed. Moisture was monitored using a neutron probe. There is indication that soil suction was monitored but was not reported on in detail in this report.

The lysimeters data provided in this report was from November, 1987 through the end of April, 1989 for the ambient and twice ambient precipitation tests and through June, 1988 for the breakthrough test.

Generally, the soil moisture showed a cyclic seasonal trend; soil moisture storage increased during the winter months and decreased during the summer months. The driest soil moisture contents were recorded during November of 1988 and the wettest were recorded during March of 1989 associated with the beginning and end of the wet season.

No measurable percolation was obtained from either the ambient or twice ambient precipitation tests. This indicates that the relationship between the thickness and hydraulic properties of the silty loam were such that it was able to store the water during the winter months with out saturating the bottom of the layer and then release the stored moisture to evaporation during the summer months. A review of additional data from this study may reveal more information of the details of this test.

4.2 IDAHO NATIONAL ENGINEERING LABORATORY, COLD DESERT RANGELAND, SOUTHEASTERN IDAHO, Anderson et al., 1987 and Anderson et al., 1993

Anderson et al. (1993) provide details of field test plots performed in a cold desert rangeland in the Snake River Plain in Southeastern Idaho. The elevation of the test plots were approximately 1500 m. The mean annual precipitation is approximately 221 mm with approximately 36% of the precipitation falling between April and June.

This field study was "...designed to assess the potential for using vegetation to deplete soil moisture and prevent water from reaching buried waste at the Idaho National Engineering Laboratory (INEL)." (Anderson et al. 1993). An estimation of the thickness of soil cover required to store the maximum expected precipitation during the winter months (while the plants are dormant) was made. The efficiency of how well different plant types extract soil moisture was also assessed during this study.

Ten test trenches were established in the fall of 1983. The test plots were constructed as trenches excavated into the native soils and backfilled with soils that had been used as capping material at the site. The configuration of the test plots were (Anderson et al., 1993):

Constructed on level sites
3 m x 10.7 m in plan
Trenches were excavated approximately 2.4 m deep and backfilled

3 m wide vegetated buffer strips were maintained between the trenches to minimize lateral migration of moisture into the trenches

Soil Type and placement:

The soil used to backfill the trenches was composed of 26% sand, 54% silt and 20% clay.

The soil was placed in the trenches in layers and compacted with a front end loader. The resulting bulk density (dry?) was 1.4 g/cc.

Vegetation

Two test plots each were vegetated with a single species of either crested wheatgrass [*Agropyron desertorum* (Fisch. Ex Link) Schult.], great basin wildrye [*Leymus cinereus* (Scribn. & Merr.) A. Love], streambank wheatgrass [*Elymus lanceolatus* (Scribn. And Smith) Gould], or Wyoming big sagebrush [*Artemisia tridentata* Nutt. Subsp. Wyomingensis]. Two of the test plots were maintained as bare soil for comparison.

Precipitation and Irrigation:

From 1984 to 1986 all of the test plots were subject to only natural precipitation. During 1987 and 1988, one plot of each species was irrigated to simulate wetter than ambient conditions. The crested wheatgrass and wildrye plots were irrigated for a total of approximately 600 mm in 1987 and 460 mm to 500 mm in 1988. One streambank wheatgrass plot was irrigated for a total of 366 mm of precipitation in 1987 and one sagebrush plot was irrigated for a total of 366 mm during 1987 and 1988. The supplemental irrigation was distributed throughout the year in proportion to the mean monthly precipitation. Due to the fact that irrigation could not be performed during the winter, the first application of additional water, during March or early April, was larger (Anderson et al., 1993) .

Monitoring included:

soil moisture: (neutron probe)
soil water potential: (single junction, screen-caged thermocouple psychrometer) at one location approximately 0.75 m from one end of each plot.

Results

Evapotranspiration was estimated from the water balance equation. Runoff was assumed to be negligible. The authors state that there was no evidence for deep percolation for the vegetated plots and was therefore assumed to be zero in the water balance equation for calculation of evapotranspiration. There was evidence of deep percolation from the bare soil plots. Changes in soil moisture storage were calculated based upon changes in the volumetric soil moisture content measured with the neutron probe.

"Virtually all recharge of soil moisture at the INEL occurs in late winter and early spring as a result of the combined inputs of melting snow and early spring precipitation." (Anderson et al. 1993). The water available to plants was rapidly depleted during the months of May, June and July. After August the soil moisture content remained relatively constant until the following spring because "...virtually all of the plant-extractable water has been used." (Anderson et al., 1993). The test results indicated that all four species of plants were able to remove water from the cap to a depth of approximately 2.2 m and that all stored water could be removed (Anderson et al., 1993). The soil moisture storage was not closely correlated at the INEL site to precipitation events. Anderson et al. (1993) gave two reasons for this "...(I) precipitation falling in late fall or winter may not infiltrate if it falls as snow and/or the soil is frozen, and (ii) precipitation that falls in late spring, summer or early fall is returned to the atmosphere by evapotranspiration and does not enter storage."

Evapotranspiration from all of the irrigated plots, except for the streambank wheatgrass plots, exceeded 366 mm, which is the estimated maximum annual precipitation. The streambank wheatgrass plots experienced some mortality due to regrading of the plot surface to correct some settlement problems which may be an explanation for it's lower evapotranspiration values calculated during the study.

Crested wheatgrass

During the first growing season after transplanting, soil moisture was extracted down to approximately 1.6 m. An average of 243 mm of water was removed which was approximately 80% of the available water. By the end of the first year the volumetric moisture content of the entire profile was approximately 10% - 12% (Anderson et al., 1987).

In subsequent natural precipitation years the wetting front reached to approximately 0.6 m to 0.8 m. During this time the soil moisture content remained relatively constant below a depth of approximately 1 m with the moisture content above approximately 1 m cycling with the season (Anderson et al., 1987).

Wildrye

Water use during the first year was approximately 185 mm, less than crested wheatgrass, and was approximately 50% of the available water. By the end of the second season the volumetric moisture content was relatively consistent throughout the profile at approximately 10%. By the third season, 1986, the moisture content below approximately 1 m was relatively constant at approximately 10% (volumetric) with the moisture content above approximately 1 m cycling with the season (Anderson et al., 1987).

The moisture contents recorded at one end of this test plot during April, 1986, were at or very near the soil's field capacity for the entire profile (28% - 31%, volumetric). By the end of that growing season, the volumetric soil moisture content had been reduced to approximately 10% - 11% over the entire profile. Approximately 50% of the moisture extracted was from below 1 m. Total evapotranspiration for this section was 537 mm which was approximately 2.4 times the mean annual precipitation for this area (Anderson et al., 1987).

Streambank wheatgrass

This was the only plant species that was established from seed. The other plant species were transplanted. Water was removed to about 1.2 m during the first growing season. Approximately 186 mm of water was removed which was only slightly less than the precipitation of 224 mm. By the end of the second season water was extracted from all portions of the profile down to volumetric moisture contents of approximately 10% to 11%. By the third season, there were only minor fluctuations of moisture below approximately 0.8 m (Anderson et al., 1987).

Sagebrush

The sagebrush test plot extracted only about 45% of the available water during the first season. During the second season the sagebrush plot removed approximately 132 mm of moisture from the soil (Anderson et al., 1987). Observation of the moisture content vs. depth plots indicate that the sagebrush allowed deeper percolation than the other plant species and then extracted the moisture during the growing season. Data presented in Anderson et al., 1993, indicated that the volumetric moisture content got consistent at approximately 11% to 12% during 1987 and 1988, similar to the grasses, however, this may have been due in part to a drought during these two years.

Bare Soil

By the fall of 1984, approximately one year after the plot was established, the volumetric soil moisture content was nearly uniform throughout the profile at approximately 17%. By the fall of 1985 they had a large increase in soil moisture storage throughout the entire profile and in one of the bare soil test plots the moisture content was above the soil's field capacity. In subsequent years the moisture content of the bottom approximately one meter of soil was at or above field capacity and it is likely that there was considerable drainage from the bottom of the profile (Anderson et al., 1993). Observation of the moisture content vs. depth plots also indicated that there was a general trend of increasing soil moisture content with depth for the bare soil plots distinctly different from the vegetated plots which showed seasonally cyclic soil moisture in the upper approximately 1 m and relatively constant moisture contents below.

Field Capacity Determination

The field capacity (drained upper limit) of the soil was determined in the field on two of the test plots. Anderson et al. (1993) describes how the drained upper limit was estimated. The vegetation was removed and the top 150 mm of the soil surface roto-tilled. Water was then applied to the surface of the test plot until the upper 1 m of the test plot soils were "...thoroughly wet...At that time, infiltration was very slow and water stood on the surface of both plots." The plots were then covered with plastic and the moisture content monitored with the neutron probes. The average moisture content of the upper 1 m of soil when the average drainage rate across all neutron tubes was negligible was considered the field capacity (drained upper limit). The volumetric moisture content at field capacity was determined to be

28% for this study (Anderson et al., 1993).

Minimum Soil Cover Thickness

The estimation of the minimum soil cover thickness was based upon the difference between the anticipated volumetric soil moisture content at the beginning of the wet season, the volumetric moisture content of the soil at it's field capacity and the amount of water the soil will be required to store. The soil's volumetric moisture content at the beginning of the wet season was estimated at 11% based upon the results of the field study (Anderson et al., 1993). The soil's volumetric moisture content at field capacity was estimated as 28% from the test described above. With respect to the amount of water to store, Anderson et al. 1987 based there estimation on the maximum annual precipitation that can be expected but argue that some of the precipitation occurs during the growing season when it can be readily evapotranspirated and therefore not require storage. They based their water storage requirements on the maximum precipitation that was recorded in the 40 years of record available during the months of October through May.

An anticipated volumetric soil moisture content of 11% at the beginning of the wet season (from the results of the field study) and an estimated field capacity of 28% (determined as described above) resulted in volumetric difference of 17% available for soil moisture storage. This resulted in a minimum soil cover thickness of 1.6 m. However, the wetting front will typically extend a distance below that portion of the soil that is at field capacity. Their field data indicated that the wetting front might be expected to reach 1.8 m. To account for the potential effects of subsidence and resulting ponding or deep snow accumulations in small areas, they increased the recommended cover thickness to 2 m. This recommendation was also supported with computer modeling.

Conclusion

"It is evident that vegetation is essential to remove water from the entire soil cap and thereby empty the storage reservoir each year." (Anderson et al., 1993).

With respect to the vegetation, Anderson et al. (1993) recommended the crested wheatgrass for long-term stability and minimal maintenance. "It establishes well on severely disturbed sites and once established are very resistant to invasion by other species ... will tolerate mowing and is very tolerant of drought." Research referenced by Anderson et al. (1993) demonstrated that "... crested wheatgrass was as effective as the rhizomatous streambank wheatgrass for controlling erosion due to extreme rainfall events." In general, however, the choice of a plant species will depend upon the local climate and "In many cases, native species from the local area should perform optimally." (Anderson et al., 1993).

Another interesting comment with respect to the results of this study has to do with the fairly consistent minimum soil moisture content for all plant species. There may be some variation in the maximum suction that the different plant species can withstand and still draw moisture for the soil. Green house studies indicate that lower limit for wildrye is lower than for crested wheatgrass (Anderson et al., 1987). However, both species achieved essentially the same minimum soil moisture contents and therefore soil suction. Anderson et al., 1987, went on to state, "Such differences [in the lower limit for water extraction] are small, and they often are considered to be trivial because the additional volume of water extracted would support transpiration ...for only a few days." The differences could be important, however, because "...they may allow the plant to maintain growth of roots and explore greater volumes of soil ... [and] effective depletion of soil moisture may be more important for excluding competitors...".

Anderson et al., 1993 also state that the specific recommendations and values are applicable only to the INEL site, however, most of the concepts are applicable to other arid regions.

With respect to estimating the thickness of soil cover required to store water for eventual evapotranspiration, it will depend on, among other things, the timing of precipitation in relation to plant growth.

4.3 SOUTHERN NEVADA, Andraski, 1990

Two test trenches were constructed at the low level radioactive waste (LLRW) site near Beatty, Nevada. Both of the trenches were backfilled with soil filled drums to simulate the waste in a LLRW landfill. In one of the trenches the drums were randomly placed and in the other trench the drums were orderly placed. The surface of the trenches were kept free from vegetation.

Monitoring included soil moisture by the neutron probe method, soil-water potential (soil suction), precipitation, surface erosion, precipitation and subsidence.

By the first year, there had been 160 mm of precipitation and infiltration had advanced to 0.75 m. "As much as 84 percent of the total precipitation that infiltrated the trench covers was depleted by evapotranspiration. There were differences noted in evaporation between the two test plots. It was postulated that the difference "... may be due, in part, to the amount of coarse fragments occurring at the surface [45 percent >2 mm vs. 23 percent >2 mm]."

4.4 SOUTHERN NEVADA, Andraski and Prudic, 1995

"Investigations at the Mojave Desert site show that even under extremely arid conditions, the interactive effects of climate, soils, and plants must be considered in the design of surface barriers for long term waste isolation." They also stated, "Greater rock-fragment concentration in the near surface of the trench covers resulted in greater accumulation of infiltrated water and decreased erosion. Incorporation of this factor into barrier design may enhance vegetation establishment and control erosion."

4.5 HILL AIR FORCE BASE, NORTHERN UTAH, Warren et al., 1996

Warren et al. (1996) performed a large, field lysimeter study at the Hill Air Force Base in Utah. The lysimeters were monitored from January 1, 1990 to September 20, 1993. "The objective of the study was to measure water balance and erosion from each of four cover designs and to determine the effectiveness of each in preventing water from penetrating through the covers in an area where a high percentage of the precipitation falls as snow." (Warren et al., 1996).

The study site was located approximately 2 Km south of Ogden, Utah at an elevation of 1460 m. The site receives an annual precipitation of 51 cm and an average annual snowfall of 182 cm. Approximately 40% of the precipitation falls as snow (Warren et al., 1996). During the course of the experiment most of the precipitation fell during late winter and early spring and snow cover was "...fairly persistent from November through February..." (Warren et al., 1993). The percentage of precipitation that fell as snow during 1990 and 1992 was 4% and 14% lower, respectively, than the long-term annual average of 40%. During 1991, 42% of the total annual precipitation fell as snow.

Four different lysimeters were constructed and monitored. The lysimeters consisted of fiberglass swimming pools with the following configuration:

> Approximately 5 m x 10 m in plan,
>
> The top surface of all cover designs were sloped at 4% and all of the layers within the cover designs were sloped at 4%,
>
> The depth of the soils within the lysimeters varied with the cover design being tested.

Four different cover designs were tested. These cover designs were:

Typical Soil Cover (Control)

Consisted of 90 cm of local topsoil. The following properties were reported for the topsoil:

Sandy Loam
$K_{sat} = 5.3 \times 10^{-5}$ cm/sec
Volumetric Moisture Content at Saturation = 30%

Modified EPA RCRA Cover

Consisted of, from the top down,

120 cm of local topsoil
Geotextile
30 cm sand drainage layer
60 cm bentonite amended compacted barrier layer with the following reported properties:

Clay loam
$K_{sat} = 3.4 \times 10^{-6}$ cm/sec
Volumetric Moisture Content at Saturation = 50%

LA-1

A capillary barrier design incorporating a gravel which consisted of, from the top down:

Approximately 1 cm gravel mulch covering 70% to 80% of the surface

150 cm of local topsoil

Geotextile

30 cm of approximately 1 cm diameter washed gravel (capillary break)

LA-2

A capillary barrier design which was the same as LA-1 except that it had different vegetation as described below.

Vegetation

All of the covers were seeded with a mixture of native perennial grasses. The grasses included:

Western wheatgrass (*Agropyron smithii*)
Great basin wildrye (*Elymus cinereus*)
Streambank wheatgrass (*Agropyron riparium*), and

Viva galleta grass (*Hilaria jamesii*)
Sand drop seed (*Sporobolus cryptandrus*)
Sheep fescue (*Festuca ovina*).

In addition to the native grasses, cover LA-2 was also transplanted with:

Rabbitbrush (*Chrysothamnus nauseosus*), and
Four-winged saltbrush (*Atriplex canescens*).

Monitoring

The following parameters were measured during the study:

- Runoff
- Erosion
- Soil Temperature at four depths
- Air temperature
- Relative humidity
- Wind speed and direction
- Soil Moisture: (neutron probe)
- Capillary or Hydraulic Barrier Interflow (lateral flow)
- Leachate Production: as a function of distance of lateral flow, this was accomplished utilizing four collection pans placed along the bottom of the lysimeter.

Precipitation

All four lysimeters were exposed to natural climate and precipitation for the duration of the experiment.

RESULTS

Water Balance

The largest component of the water balance was evapotranspiration comprising between 70% and 86% of the total precipitation falling on the plots over the four years of the study. Individually, the LA covers had 85% to 86% of total precipitation lost to evapotranspiration while the RCRA and control covers had 71% and 82% respectively of the total precipitation lost to evapotranspiration. Evapotranspiration was calculated from the water balance equation.

The second largest component of the water balance was either leachate (percolation) or interlayer (lateral) flow depending upon the design. For both of the LA plots leachate production was higher than interflow with leachate production being 12% and 15% of total precipitation for the LA-1 and LA-2 designs respectively.

For the RCRA plot lateral diversion was greater than leachate production with lateral diversion measured at 21% of total precipitation. Leachate production was less than 1% of total precipitation for the RCRA cover. There was no layering for the control cover so lateral diversion did not occur. Leachate production for the control cover was 20% of total precipitation.

With respect to the RCRA design, the authors stated "...it is clear from the soil moisture data that the conditions were dynamic and the nearly four years of study were not enough to fully evaluate this cover design."

Runoff from the LA-1 and LA-2 test plots was 0.7% and 1% of total precipitation respectively. Runoff from the RCRA and control test plots were approximately 3% of total precipitation.

The change in soil moisture, and therefore change in soil moisture storage, was very sensitive to the time that the readings were taken. The authors state that in their opinion the changes would have been very near zero in the long-term.

Vegetation

The gravel mulch enhanced the growth of vegetation. Vegetation cover measurements were made in June of 1992 and September of 1993. During June of 1992 the LA-1 and LA-2 covers had 13% to 23% more canopy cover than both the control and the RCRA covers. During September of 1993 the LA-1 and LA-2 covers had 5% to 11% more canopy cover than the control and RCRA covers.

Of particular interest are the author's comments with respect to invasion of plants onto the covers. They stated that, "Natural invasion of vegetation onto all covers occurred rapidly. For example, forbs and shrubs, such as big sagebrush (*Artemisia tridentata*), which is a seral climax species for the project site, greatly increased on the covers. ... it is clear that if certain plant covers were preferred on a landfill cover in this area (e.g., a pure grass cover), active maintenance or other management practices would be required." (Warren et al., 1996).

Runoff

Less runoff was produced from the gravel mulch covers indicating more infiltration. During the course of the study runoff "...was observed eight times on both of the LA covers and 22 and 23 times on the control and RCRA covers, respectively." The total runoff measured for the covers was 1.4 cm for the LA-1 cover, 2.2 cm for the LA-2 cover, 5.5 cm for the RCRA cover and 5.8 cm for the control cover. The majority of the total runoff measured (60% to 99%) occurred during the first year before vegetation had become established.

Erosion

The gravel mulch covers, LA-1 and LA-2, lost 15 to 25 times less sediment than the RCRA and control covers. It is not certain if this difference was due to the presence of the gravel or to the resulting increased vegetative cover. However, it should be noted that the RCRA and control covers were both "...still well below the EPA guidance limits of 4.4 metric tons...per ha per year." (Warren et al., 1996).

Soil Moisture

The soil moisture showed seasonal cyclic trends; generally increasing during the winter and early spring months, primarily due to snowmelt, and then decreasing during the early summer due to a decrease in precipitation and increased evapotranspiration. The total soil moisture in storage in the RCRA cover cycled with the seasons and showed a net increase. The increase in total soil moisture in the RCRA cover was due to the continual absorption of moisture by the clayey barrier layer. By the end of the study the clayey barrier layer was at or near saturation. The moisture within the topsoil of the RCRA cover cycled with the seasons. The total soil moisture in storage in the LA covers and the control cover cycled with the seasons and appeared to have a slight decrease during the course of the study.

Interflow (Lateral flow)

Infiltrated water that was diverted laterally either in top of the clayey barrier layer in the RCRA design or on top of the capillary barrier layer in the two LA designs was considered as interflow. The LA-1 cover and LA-2 cover diverted approximately 10% to 6% of the total precipitation laterally while the RCRA cover diverted approximately 21% of the total precipitation laterally.

After the clay layer had absorbed water for about a year, it began to produce lateral drainage at a rate 2 to 5 times higher than the LA covers. "Between 92 and 95 percent of interflow from all covers occurred during the months of February through May, primarily as a result of snowmelt and early spring rains when evapotranspiration was low..."

Leachate (Percolation)

Water that infiltrated vertically through the cover was considered leachate or percolation as it is some times referred. Water did not break through the RCRA cover until two years after it broke through the other cover designs. "Over 90 percent of all leachate [production] occurred during the months of February through May." and seemed to be associated with late snowmelt and rain during late winter and early spring. Evidence indicates that the topsoil overlying the capillary barrier in the LA covers became saturated and allowed water to breakthrough. It should be noted that there was not necessarily a uniform flux of water from the topsoil into the capillary barrier across it's entire surface. Rather, leachate collection measurements "..indicated that leachate production was higher at mid-slope locations for the two LA designs rather than at the lower end of the covers as was observed in the control and RCRA covers." (Warren et al., 1996).

Evapotranspiration

Evapotranspiration was backcalculated using the water balance method.

Both of the LA covers and the control cover had higher evapotranspiration totals than the RCRA cover. Evapotranspiration rates followed the expected trends with the rates being generally higher in the spring and summer months and lower in the winter months. A total of 174 cm and 172 cm of water was lost from the LA-1 and LA-2 covers respectively to evapotranspiration. The RCRA and control covers lost 143 cm and 166 cm of water respectively to evapotranspiration.

There was some indication that the moisture content of the clayey barrier layer was being influenced by evapotranspiration during the summer months during the last three summers of the study as evidenced by decreases in soil moisture during the late summer months. The authors state that since the clayey barrier layer "... was 150 cm below the top of the ground surface , evaporation was not believed to be a factor.", leaving removal of water by plant roots as the most likely cause of the reduction on moisture content. This left them with a concern that the long term performance of the clayey barrier layer at that depth may be compromised by intrusion of plant roots in the long-term.

Conclusions

The conclusions drawn by the authors were, "The ability of the capillary barriers to divert water laterally was limited and a function of the hydraulic conductivity of the soil overlying the capillary break." (Warren et al. 1996). The physical properties and higher compaction of the overlying soil resulted in a low hydraulic conductivity and decreased it's ability to allow lateral drainage. "In more arid locations, it may be adequate for water to be held from percolating downward, allowing evapotranspiration processes to remove it." (Warren et al. 1996).

4.6 LOS ALAMOS, NEW MEXICO, Nyhan et al., 1990

Nyhan et al., 1990 describe the results of field test plots that were constructed and monitored at Los Alamos, New Mexico. The purpose of the experiment was to "... monitor and compare water balance on the conventional landfill cover design...with that on an improved design."

Two replicates of two different designs, a control design and an improved design, were constructed and monitored from the fall of 1984 to the fall of 1987. The designs were:

Control Design;

3.0 m x 10.7 m in plan
0.5% slope of the surface

The soils consisted of, from the top down:

20 cm of topsoil
108 cm of crushed tuff

Improved Design (capillary barrier):

3.7 m x 10.7 m in plan
0.5% slope of the surface
5% lateral slope at the interface of the topsoil and the capillary barrier

The soils consisted of, from the top down:

71 cm of topsoil
geotextile
46 cm gravel (5 mm - 10 mm diameter) to act as a capillary barrier
91 cm cobble (10 cm - 30 cm) biointrusion layer
38 cm crushed tuff

All test plots received a 60% to 70% cover of gravel (<2 cm in diameter), gravel mulch, at the surface.

Vegetation

All test plots received plant cover of blue grama (*Bouteloua gracilis*) and western wheatgrass (*Agropyron smithii*). Within two years all plots had 100% vegetative cover.

Monitoring

The test plots were monitored for:

- runoff
- soil water storage (neutron probe)
- lateral flow from on top of the capillary barrier
- percolation
- precipitation

Precipitation

Other than small amounts of irrigation that were applied to establish the vegetation in May, June, July and August of 1984 the test plots were subjected to only natural precipitation during the study.

From May of 1984 through mid 1987, the study site generally received more precipitation than the historical record (1911-1986). The total precipitation for the fall of 1984 was 12.54 cm. The winter of 1984-1985 received 13.73 cm of precipitation with above average snowfalls recorded in February and March, 1985. Precipitation for the fall of 1985 was approximately the average for the area of 8.38 cm. The spring of 1986 received 24.69 cm of precipitation which was a record for the area. The summer of 1986 had below average precipitation. The winter of 1986-1987 received record snowfalls in January (165 cm of snow) and February. The spring of 1987 had below average precipitation receiving 6.4 cm.

The total precipitation during the course of this study, August 13, 1984 through September 4, 1987 totaled 173.72 cm.

Results

Soil Moisture

Both test plots showed a pronounced increase in soil moisture during the first winter of the field experiment (1984-1985). By the spring of 1985 the vegetation became fully established on all of the plots and substantial decreases of soil moisture were experienced by the test plots as a result of evapotranspiration. In the control plot the plants extracted water from below 100 cm of the ground surface. In the improved plot, the moisture content of the bottom tuff layer increased but did not show the seasonal decrease typical of evapotranspirational losses as did the control plot (Nyhan et al. 1990). The fact that the bottom tuff layer in the improved plot did increase in moisture during the winter/spring seasons of 1984-1985 and 1986-1987 indicates that the storage capacity of the soil above the capillary barrier was such that water was allowed to break through. This is further substantiated by observation of the soil water storage vs. time plot. Times when the soil moisture increased in the underlying tuff layer were preceded by times when the soil water storage of the upper topsoil layer was within a few inches of its maximum (approximately saturated) value. The moisture content of the bottom tuff layer in the improved plot remained relatively constant from the summer of 1985 through the summer of 1986.

Vegetation

"Biomass and species composition were determined in August 1986 for all four field plots..." (Nyhan et al., 1990). All four of the test plots had "...practically 100% plant cover..." as compared to an approximately 20% coverage on adjacent, undisturbed areas (Nyhan et al., 1990). The authors state that the higher percentage of vegetative cover on the test plots was due to the gravel mulch at the surface. Although all of the test plots had approximately the same vegetative surface coverage, the two improved test plots had more than twice the biomass than the control plots. The authors postulated that the capillary barrier inhibited the downward migration of water leaving more water available for plant growth for a longer period of time.

Lateral Drainage and Leachate Production

Leachate production occurred from both control plots and appears to be closely related to the snowmelt from the winters of 1984-1985 (above average snowfall) and 1986-1987 (record snowfalls during January and February). No leachate was produced from the control plots during the winter of 1985-1986. Observation of a figure showing precipitation with time indicates that the winter of 1985-1986 had considerably less precipitation than the winters before and after. One of the improved plots did not produce any leachate or lateral flow during the course of the study while the other improved plot produced both lateral drainage and leachate. This may be due to the improved plot which produced no drainage having a greater biomass of vegetation (and therefore greater evapotranspiration) than the plot that did produce drainage (1245 g/m^3 compared to 847 g/m^3). One of the improved plots did produce some lateral drainage in mid-February of 1985. Lateral drainage was again observed in this improved test plot in mid-February of 1987. The capillary barrier functioned for approximately three weeks but "...finally failed (the soil above the gravel finally attained saturation with this extremely heavy snowmelt, allowing water to pass into the lower drain in the plot)..." about three weeks after lateral drainage was observed. The leachate production was substantially less for this improved plot than the control plots.

Leachate production from both of the control plots during the duration of the study was approximately 11 cm. Leachate production from the one improved plot that produced leachate was approximately 2 cm during the duration of the study and lateral drainage from this same plot was approximately 3 cm.

The authors caution utilizing the absolute drainage values obtained from the study due to the potential for boundary effects from the lysimeters. However, the relative comparison of the two cover designs should be appropriate.

Runoff

No runoff was measured for any of the plots during the course of this study.

Evapotranspiration

Evapotranspiration was estimated by utilizing the water balance equation. Evapotranspiration estimates for the period of August 13, 1894 through September 4, 1987, were estimated at 152 cm and 155 cm for the control plots (87% and 89% of total precipitation) and 170 cm and 165 cm (98% and 95% of total precipitation) for the improved plots.

4.7 LAS CRUCES, NEW MEXICO, Gee et al., 1994

A long term lysimeter study has been performed at a site near Las Cruces, New Mexico in the Chihuahuan desert. The lysimeter was constructed from September 1982 through May 1983. Approximately 52% of the precipitation in this area falls between July and September. The mean annual precipitation is 230 mm and the average potential pan evaporation is 2390 mm. Snow is rare. Vegetation is sparse with creosote bush being the dominant species.

The configuration of the lysimeter is:

2.44 m diameter highway culvert
6 m deep

Soils:

The lysimeter was backfilled with a loamy fine sand. The backfill was placed in approximately 13 cm thick layers from September, 1982 through May, 1983. The average bulk density (dry?) of the soil was 1.67 Mg/m^3

Vegetation:

The soil surface was kept bare.

Monitoring:

Soil Moisture (neutron probe)
Soil Suction

The soil moisture content was monitored approximately every month from September, 1983 through July, 1992. During this period there was a one year gap in moisture monitoring from April, 1988 through April 1989.

Soil suction was monitored from October, 1987 through July, 1992.

Precipitation

The average annual precipitation was 338 mm during the course of the study with the maximum annual precipitation recorded in 1894 at 385 mm and the minimum annual precipitation of 250 mm being recorded in 1990.

Results

The wetting front moved down at a rate of approximately 2 m/year decreasing to approximately 0.5 m/year by 1989. The wetting front reached the bottom of the lysimeter in the spring of 1988. From the spring of 1988 through the summer of 1991 the soil moisture content did not change significantly and was relatively constant from a depth of approximately 3 m to the wetting front ranging from approximately 13% to approximately 18% (volumetric). Volumetric moisture contents in the upper approximately 1 m varied from approximately 24% to approximately 16% with time. Higher than normal precipitation (176 mm) occurred form late 1991 through early 1992 which resulted in increases in moisture content at the bottom of the lysimeter.

Water storage increased steadily from an initial value of 260 mm in 1984 until mid-1987 when it reached a relatively constant value of 850 mm with some seasonal fluctuations "...presumably due to evaporation..." noted.

In July of 1989 a vacuum pump and collection bottles were installed at the bottom of the lysimeter to prevent water from ponding there. The vacuum pump applied a suction of approximately 200 cm of water and initiated drainage from the soil. An average drainage rate of approximately 0.08 mm/day was measured until the spring of 1991 when the pump failed. After the pump was replaced the average drainage rate increased to 0.44 mm/day.

Over the course of the study an average of 25% of the total precipitation was either stored in the soil or drained through the profile. This value varied considerably from a low of -19% to a high of 45%. The low value was stated to be associated with ponding water at the bottom of the lysimeter as the vacuum system failed and the high value was stated to be associated with initial conditions "...when water was being stored in dry soil under above normal precipitation conditions."

Neutron probe studies on vegetated, undisturbed soils in the vicinity of this lysimeter test "...clearly indicated that deep drainage in vegetated, undisturbed Berino soils did not occur. The lack of deep drainage ... is attributed to the presence of native plants (mainly creosote bush) and their removal of water by transpiration."

4.8 MOJAVE DESERT NEAR BEATTY, NEVADA, Gee et al., 1994

Lysimeter tests were performed in an area near Beatty, Nevada. The configuration of the test trenches are described under Andraski, 1990 in this report. The mean annual precipitation for the area is 104 mm and the mean annual potential pan evaporation is 1900 mm. Approximately 70% of the precipitation falls between the months of October through April. Gee et al. reported on the first three years of a five year study. This study looked at four systems:

Vegetated, natural soil profile,
unvegetated, natural soil profile, and
two unvegetated test trenches

The vegetated, natural soil profile was established in 1983. The unvegetated, natural soil profile and the test trenches were established in 1987.

Vegetation

Natural vegetation is sparse and dominated by creosote bush. Studies of creosote bush in the Mojave desert indicate a normal rooting depth of less than two meters with extensive lateral spreading. There were no detailed root measurements made at the study site.

Precipitation

The precipitation recorded at the site were:

1987 (September - December)	56 mm
1988	104 mm
1989	14 mm
1990	32 mm

Monitoring

The following parameters were monitored and reported in this reference (additional parameters were monitored and are summarized in other reports):

- soil moisture (neutron probe)
- soil suction (thermocouple psychrometer)
- precipitation

Soil moisture was monitored monthly and after precipitation events of 5 mm or greater. Monitoring began on October, 1987 for the trenches and the vegetated, natural soil profile. Monitoring began on September, 1988 for the unvegetated, natural soil profile.

Results

The soil moisture increase through March of 1988 was greatest for the vegetated, natural soil and moisture depletion was approximately 30% less for the vegetated, natural soil profile than for the trenches (Gee et al., 1994). This may be due to different soil types, different hydrologic properties of compacted and natural soils, and a higher hydraulic conductivity in the vegetated soil due to biologic processes. From March through June of 1988 water depletion was greater for the vegetated, natural soil profile than for the trenches. The vegetated soil averaged 0.6 mm/day moisture depletion (ranged from approximately 0.4 mm/day to 0.8 mm/day) while the trenches averaged 0.3 mm/day (ranged from 0.1 mm/day to 0.5 mm/day). By the end of November, 1988, soon after the "wet" season, the soil moisture storage for the vegetated, natural soil profile had decreased below it's initial amount while the soil moisture in storage for all three nonvegetated areas remained above their initial amounts. It is interesting to note that when comparing the natural, undisturbed soils, the unvegetated soil had substantially more moisture in storage than the vegetated soil.

Conclusions

The authors state that "Vegetation had a substantial effect on the depletion of water that accumulated at depth in the root zone." Soil suction in the root zone showed significant increases during 1988 and 1989 while the soil suction in the nonvegetated plots remained relatively constant through 1990 and were less than for the vegetated soils.

The authors state that they found no evidence for "...significant drainage from the upper 1.25 m of soil at either [trench] site." based upon their observation of relatively steady moisture contents. However, they conclude by stating, "... water storage increases in the disturbed, nonvegetated sites persisted during the 3.3-yr. period reported here, thus increasing the quantity of water available for deep percolation. In contrast, water that accumulated in the undisturbed, vegetated profile was rapidly depleted by plant transpiration."

4.9 HANFORD, COLD DESERT OF THE COLUMBIA BASIN, WASHINGTON, Gee et al., 1994

This study was started in 1971 and consisted of two, deep lysimeters. The average annual precipitation for the site is 162 mm and the average annual potential pan evaporation is 1600 mm. Approximately 73% of the precipitation falls between the months of October and April. Snowfall averages 355 mm (27 mm of water equivalent) and comprises approximately 38% of the precipitation that falls between the months of December and February.

Configuration

Two lysimeters were installed for this study, they were 3 m wide and 18 m deep. One was closed at the bottom and the other was left open at the bottom. This reference presented only the results for the lysimeter with the closed bottom.

Soil Type

Monofill

The lysimeter was filled with a loamy sand; 87% sand, 10% silt, 3% clay

Monitoring

Monitoring reported in this report consisted of:

soil moisture (neutron probe), and
precipitation

Monitoring began in early 1972 and continued on a routine basis for approximately seven years. In 1985 after about eight years of limited monitoring, the soil within the lysimeter was cored to determine moisture contents. Monitoring began again in January of 1988 after reconditioning the surface to bare ground (see discussion below) and continued until July of 1991.

Vegetation and Surface Conditions

Vegetation was present by 1974 and by 1978 "...a substantial amount of annual weeds (primarily russian thistle, *Salsola kali* L.) were growing on the surface." (Gee et al., 1994). On January of 1988 the top rim of the lysimeter was found beneath approximately 20 cm of soil and the soil surface had become vegetated with grasses, weeds and a perennial forb. All of the plants were removed at this time and soil removed to expose approximately 5 cm of the rim of the lysimeter. Moisture monitoring resumed for over three years with the surface of the lysimeter maintained as bare ground along with two adjacent sites. It should be noted that the two adjacent sites consisted of monitoring the native soil profile and not a soil that had been removed and replaced as the soil in the lysimeter had. One of the adjacent sites was dominated by cheatgrass and the other was dominated by sagebrush. In March of 1991 vegetation was allowed to naturally reestablish in the surface of the lysimeter. The new vegetation was primarily russian thistle.

Results

Gee et al., 1994 stated, "Interpretation of the water content profiles obtained for 1972 through 1976...indicate that if water was moving into the lysimeter, it was doing so very slowly. Below the 5-m depth the water content stayed relatively constant at [6% volumetric]."

When the lysimeter had bare ground at the surface (January 1988 through March 1991) as much as 150 mm more water was stored in the lysimeter soils than in the adjacent vegetated soils. The increase in soil moisture was associated primarily with winter precipitation. When the vegetation was allowed to reestablish at the surface, "...water removal was rapid." Other studies at Hanford resulted in "...limited..." drainage through a silt loam

Capillary Barrier underlain by resistive barrier

From the top down:

150 mm topsoil; uncompacted clay loam to silty clay loam
610 mm high silt clay; $K_{sat} < 1x10^{-7}$ cm/sec
30 mm sand
610 mm high silt clay; $K_{sat} < 1x10^{-7}$ cm/sec

Monitoring

The following parameters were monitored:

runoff
percolation
soil moisture (neutron probe)
Precipitation
air temperature
relative humidity

The plots were monitored for four years.

Results

A figure is presented by Benson and Khire (1995) indicating a total precipitation of approximately 265 cm. The largest component of the water balance was evapotranspiration, approximately 85% of total precipitation for plots RB1 and RB2. Evapotranspiration was not measured for the capillary barrier. The barriers produced similar amounts of percolation, 4.8%, 3.6% and 4.6% of total precipitation for RB1, RB2 and the capillary barrier respectively. It should be noted that the upper clay layer in the capillary barrier became cracked and "...allowed rapid infiltration of water into the sand layer; however the sand layer removed a large fraction of the infiltrating water via lateral flow." (Benson and Khire, 1995). The lower clay layer did not desiccate and percolation through it did not increase to a higher rate like the upper clay layer, rather, percolation through the lower layer remained constant at approximately 4.6% of the total precipitation.

Runoff for all three plots also appeared similar at between a 8% and 11% of total precipitation.

4.12 LOS ALAMOS, NEW MEXICO, Benson and Khire, 1995

Benson and Khire (1995) describe a study that was performed at the Los Alamos site in New Mexico. The study incorporated four different cover designs.

Configuration

The test plots were 1 m x 10 m in plan and were constructed with slopes of 5%, 10%, 15%, and 25%.

The cover designs tested consisted of:

Conventional

From the top down

150 mm loam topsoil; comprised of organic matter, sand and aged sawdust
760 mm tuff
300 mm gravel
660 mm coarse sand

EPA-Recommended

610 mm loam topsoil
300 mm medium sand
610 mm clay/tuff mix; $K_{sat} < 1 \times 10^{-7}$ cm/sec
300 mm gravel
50 mm coarse sand

Loam Capillary Barrier

610 mm loam topsoil
760 mm fine sand
300 mm gravel
200 mm coarse sand

Clay-Loam Capillary Barrier

610 mm clay loam topsoil
760 mm fine sand
300 mm gravel
200 mm coarse sand

Monitoring

The test plots were monitored for:

runoff
lateral drainage
percolation
soil water storage

Monitoring was performed for 15 months.

Results

A figure is presented by Benson and Khire (1995) indicating a total precipitation of 53 cm. It does not state on the figure the slope of the test plots from which the data was derived. The largest component of the water balance was evapotranspiration, approximately 52% of total precipitation was lost as evapotranspiration from the conventional design while approximately 70% to 75% of total precipitation was lost to evapotranspiration from the other designs. "Analysis of the data showed that all of the test sections produced percolation, and that the EPA-recommended resistive barrier and the loam capillary barrier produced the largest quantity of percolation (8.5% and 7.4% of precipitation, respectively). The clay-loam capillary barrier produced the least amount of lateral flow (0.7% of precipitation), the greatest amount of overland flow (6.2% of precipitation) and the least amount of percolation (0.7%). The superior performance of the clay-loam capillary barrier is attributed to the lower saturated hydraulic conductivity afforded by the clay-loam surface layer." (Benson and Khire, 1995).

It appears that the clay-loam's superior performance may be attributed to it's higher runoff, however, there was not enough detailed data to determine this conclusively. Additionally, little was mentioned regarding the conventional design's apparently low percolation rate as evidenced by a graphical presentation of the results. The percolation of the conventional design appears to be of the same order as the clay-loam capillary barrier even though it had the lowest evapotranspiration (approximately 52% of total precipitation) and very little runoff. The low percolation must have been due to it's relatively high lateral flow (approximately 10% of total precipitation) and probably a higher percentage of moisture in storage in the tuff layer, although this parameter was not discussed in the reference.

4.13 EAST WENATCHEE, WASHINGTON, Benson and Khire, 1995

A study was performed at a landfill site near East Wenatchee, Washington of two landfill cover designs. Benson and Khire, 1995, present a summary of the results of the study. The average annual precipitation for the area is approximately 230 mm.

Configuration

30 m x 30 m in plan

Capillary Barrier

Slope; 2.5H:1V

150 mm Uncompacted Silt; $K_{sat} = 2.7 \times 10^{-4}$ cm/sec
750 mm Sand; $K_{sat} = 2.9 \times 10^{-3}$ cm/sec

Prescriptive Resistive Barrier

Slope; 2.8H:1V

150 mm Uncompacted Clayey Silt; $K_{sat} = 4.5 \times 10^{-5}$ cm/sec

600 mm Compacted Silty Clay; $K_{sat} = 2.2 \times 10^{-7}$ cm/sec

Results

Total precipitation reported on a graph of the results was 53 cm. Evapotranspiration was the major component of the water balance comprising approximately 65% of the total precipitation for both designs. Benson and Khire, 1995 reported, "...the capillary barrier has been more effective than the resistive barrier in restricting percolation ... Percolation from the capillary barrier has been 0.6% of precipitation, whereas percolation from the resistive barrier has been 4.4% of precipitation." Runoff was similar for both of the test plots at approximately 15% of the total precipitation.

Results with respect to the effect of snow during this study were similar to the results of other studies but also provide greater insight into the effect of snow. During the winter of 1992-1993 and 1993-1994 "... approximately the same amount of precipitation was recorded...". During the winter of 1992-1993, 1.68 m of snow accumulated on the test section. In contrast, during the winter of 1994-1995 only 0.09 m of snow accumulated at the cover surface and "...little precipitation was stored on the surface as snow. Instead, water was applied to the test section as light rains, or snows that quickly melted." . The result on cover performance was that during the early spring of 1993 when the snow melted, "...the fine grained layer became saturated and rapid flow occurred through the coarse grained layer. Subsequently a large pulse of percolation occurred." (It should be noted that by observation of the graph of results presented in this reference, the capillary barrier still out performed the resistive barrier with respect to percolation during this time period). During early spring of 1995, "...the fine grained-layer became nearly saturated, but the quantity of infiltration did not overwhelm the storage capacity of the fine-grained layer. Consequently, percolation from the cover was nearly imperceptible." (It should be noted that by observation of the graph of results it appears that the resistive barrier produced significant amounts of percolation during this same time period).

Benson and Khire, 1995 also reported that desiccation cracking and biointrusion occurred in the resistive barrier. Analysis of monitoring data indicated that these features may be providing preferential flow paths for water to flow through the cover design. The capillary barrier did not exhibit these same features.

With respect to vegetation, Benson and Khire, 1995, reported that generally the resistive barrier had a "..better stand of vegetation...". They also stated, "...the predominant vegetation on both test sections consists of a mixture of native species rather than the species that were seeded. This suggests that it may be difficult to implement a cover seeded with vegetation selected to maximize evapotranspiration unless the species is native to the area."

Note that there seems to be some confusion as to the dates, however, observation of the graphs seems to substantiate the conclusions.

4.14 CAPILLARY BARRIER STUDY, Stormont, 1995

Stormont, 1995 performed a study of the effectiveness of layering and sloping in a capillary based cover design to enhance lateral drainage and minimize percolation. In a brief summary of research reviewed by Stormont he states that a 1.5 m thick soil layer over lying a non-sloping capillary break was successful in removing three times the average annual precipitation near Hanford, Washington (52 cm). At Idaho Falls, 1.6 m soil layer was capable of storing 37 cm of precipitation. With respect to the design of capillary barriers, a capillary barrier will remain effective as long as the combined effects of evapotranspiration and lateral diversion exceed the rate of infiltration of water such that the fine grained layer stays sufficiently dry to prevent break through into the underlying coarse layer. "Depending upon the climate and thickness of the fine layer, evaporation and transpiration may remove sufficient water to prevent failure, and the capillary barrier need not be sloped for lateral diversion." (Stormont, 1995).

Stormont (1995) reviewed the results of some previous field studies of capillary barriers and in those which resulted in measurable percolation he states that "...these capillary barriers did not laterally divert sufficient water to prevent breakthrough over their relatively short lengths (10 m to 3 m). These short [effective] diversion lengths are a consequence of the relatively low hydraulic conductivity of the fine-grained soils compared to the infiltration rate during stressful periods."

Configuration

Two different capillary barriers were tested. Both of them had the same general configuration.

Above ground wooden boxes
7.0 m x 2.0 m in plan
1.2 m high

Slope: Surface flat, terraced to prevent runoff
Layer interfaces at 5% for lateral (interlayer) flow

The bottom of the box was constructed so that water that broke through the capillary barrier (percolation) could be collected every approximately 1 m. In this way percolation as a function of lateral drainage length could be determined. There were five different percolation collection zones.

The bottom approximately 25 cm of both designs was filled with gravel except for the downstream most 1 m which was filled with the fine grained soil so that lateral drainage from on top of the capillary barrier could be collected.

Provisions were made to minimize leakage of water along the sides of the box.

Homogeneous Capillary Barrier

From the top down;

90 cm fine grained soil
geotextile
25 cm gravel

Layered Capillary Barrier

From the top down;

20 cm fine grained soil
10 cm sand
20 cm fine grained soil
10 cm sand
20 cm fine grained soil
10 cm sand
geotextile
25 cm gravel

Soil properties:

Fine grained soil;
Silty Sand
mean particle diameter 0.11 mm, 30% finer than the No. 200 sieve.
$K_{sat} = 1.2 \times 10^{-4}$ cm/sec
Porosity approximately 40%

Sand;

uniform Sand
mean particle diameter 0.3 mm, 99% between 0.6 mm and 0.8 mm
K_{sat} = 2.1 x 10^{-2} cm/sec
Porosity approximately 40%

Gravel;

poorly graded, rounded
mean particle diameter approximately 2 cm
K_{sat} estimated at 10 cm/sec

Unsaturated soil properties for the sand and gravel were derived from laboratory testing. Properties for the gravel were taken from Fayer, et al. (1992). Observation of the hydraulic conductivity versus soil suction relationships indicate that the sand will behave as a capillary barrier to the overlying fine grained soil at suctions above approximately 40 cm of water. If the overlying fine grained soil reaches a moisture content such that the soil suction is less than approximately 40 cm, the sand should begin to act as a lateral drainage layer on top of the underlying fine grained soil layer. At approximately 1 cm of suction in the bottom sand layer, the water will break through into the underlying gravel.

Irrigation

Water was applied with a drip irrigation system at a rate just slow enough to prevent ponding. Sixty-five liters were added each day for 74 days. The resulting infiltration rate was equivalent to a flux rate of 1.8 x 10^{-5} cm/sec. The top of the box was covered with plastic to "...minimize evaporation of water, discourage plant growth, and prevent rainfall from contacting the soil." (Stormont, 1995).

Monitored

Percolation
Lateral Drainage
Soil Moisture Content (Frequency Domain Reflectometry)

Results

Lateral Drainage and Percolation

In the homogeneous design lateral drainage began at 43 days. Eventually water broke through the capillary barrier along it's entire length. The percolation rate increased with time while the lateral drainage rate remained relatively constant at approximately 7 liters per day. Total percolation recorded increased downslope, indicating that the capillary barrier was becoming progressively more saturated as the lateral drainage length increased.

In the layered capillary barrier design lateral drainage began on day 35 and increased rapidly to 35 liters per day by day 45 and then increased by approximately 0.5 liters per day until irrigation was stopped. About 1 liter was collected from the most downslope percolation drain. Lateral drainage accounted for approximately 87% of the daily infiltration.

The lateral drainage results seemed to correlate well with work that has been performed by others on the steady-state diversion lengths of capillary barriers.

Soil Moisture

The wetting front advanced to the gravel in the homogeneous design in 24 days. In the layered design, the wetting from advanced to the bottom most sand layer in 24 days. Moisture contents at the lower depths of the fine grained soils in the layered design were generally lower than in the homogeneous design. By the end of water application, the moisture content of the deep fine grained soil in the homogeneous design had dropped, presumably due to breakthrough and drainage from the bottom of this layer.

Conclusions

"The layered design is much more effective in laterally diverting water than the homogeneous design. At a constant infiltration rate of about 0.5 cm/day, all but 1% of the water which moved out of the fine gained layer was laterally diverted beyond the 6 m length of the capillary barrier." (Stormont, 1995). Most of the lateral diversion was accomplished by the bottom sand layer. At lower infiltration rates, the upper sand layers will most likely "...create capillary barriers with the overlying soil layers and impede the downward movement of water." (Stormont, 1995).

"The very short diversion length of the homogeneous profile (<2 m) is consistent with other tests of capillary barriers, and is a consequence of the relatively low hydraulic conductivity of the [fine grained] soil compared to the infiltration rate." (Stormont, 1995). The lower portion of the soil saturates and water breaks through because the hydraulic conductivity is too low for effective lateral drainage.

The steady-state solutions for diversion length of capillary barriers appear to correlate well. These solutions may prove useful in cover design if they can be modified to account for non-steady state, cyclic conditions.

"The experiments ... indicate that capillary barriers can be designed to increase their diversion [lateral drainage] capacity ... Designing capillary barriers with substantial lateral diversion capacity to complement their ability to store and evapotranspirate soil moisture may increase the useful applications of this alternative barrier technology." (Stormont, 1995).

4.15 EASTERN WASHINGTON, Waugh et al., 1994

Waugh et al., 1994, investigated the effect of mixing gravel into the upper portion of the soil rather than placing the gravel on the surface as in a gravel mulch. They theorized that by mixing small sized gravel into the soil surface they would be able to take advantage of the positive aspects of a gravel mulch (enhanced erosion protection and near surface moisture storage for plant growth), and minimize the negative aspects of a gravel mulch (potential for deep infiltration and reduced evaporation). Research referenced in Waugh, et al., 1994, indicates that; (1) small gravel (< 15 mm) have greater surface area to volume ratios and therefore yield less sediment from overland flow and wind [erosion] "... than admixtures or surface mulches consisting of large gravel cobbles ...", (2) evaporation is higher from admixtures than from thick surface mulches, and (3) protective veneers form again on admixtures if disturbed unlike thin mulches which they imply are not as prone to self repair.

A field study was initiated in 1986 with the following objectives:

- (I) Compare plant cover on soils with and without gravel admixtures;
- (ii) measure the interactive effects of precipitation amount, vegetation, and gravel admixture concentrations on soil water content and storage; and
- (iii) measure temporal changes in admixture morphology under these conditions.

The study was performed near Hanford in south eastern Washington. The area lies within the rain shadow of the Cascade mountains. The annual precipitation is approximately 160 mm with a historical range of 80 mm to 270 mm. A typical year is characterized by three seasons; October through January which is a moisture accumulation period during which more than 50 % of the annual precipitation falls, February through May which is a period of moisture depletion during which approximately 30 % of the annual precipitation falls and June through September which is a moisture stress period when the temperatures average approximately 25° C and most plants are dormant.

Configuration

A total of 36 different plots were evaluated. The plots were constructed in groups of six. Gravel admixture, vegetation and precipitation treatment were varied on the plots as described below.

Gravel Admixture

Gravel admixtures of 0 %, 22 % and 38 % (by weight) were evaluated. The gravel was mixed into the upper approximately 12 cm of soil.

Vegetation

Both bare soil and surface vegetation consisting of perennial species were tested.

Precipitation

Both ambient and twice average precipitation levels were applied to the test plots.

Three replicates of each combination of gravel admixture, vegetation and precipitation were constructed and monitored.

The overall dimensions of each group of six plots was 10 m x 15 m with each individual plot being 5 m x 5 m. Each group of six plots contained all three different gravel admixture conditions and vegetation combinations. All plots within a group received either ambient precipitation or twice average precipitation. Additional water (needed to achieve the twice average precipitation amount) was applied with an above ground irrigation system.

Soil

The soil used in the study was a silt loam.

Gravel

The gravel ranged in size from 50 mm to 100 mm.

Plot Preparation

The upper approximately 10 cm of soil was graded into a low perimeter berm. The remaining upper approximately 1 m of soil was ripped in both directions and then the surface was disced and harrowed. Gravel admixture was applied by spreading over the surface and rototilling in. The admixture was compacted using a cultipacker.

It appears that the plots may have been constructed with an approximately 1.5 % slope but there was no definitive statement.

Vegetation

Vegetation consisted of five grasses and four shrubs.

Grasses consisted of:
- Siberian wheatgrass
- Thickspike wheatgrass
- Indian rice grass
- `Canbar' canby bluegrass
- `Covar' sheep fescue

Shrubs consisted of:
- Big sagebrush
- Spiny hopsage
- Gray rabbitbrush
- Antelope bitterbrush

Monitoring

Soil Moisture; Neutron probe, 300 cm deep, monthly from October 1986 through October 1990.

Plant Canopy Cover; June of 1987, 1988, 1989, 1990 and 1992.

Gravel Concentration; On bare plots, once at the beginning of the study (June, 1987) and once at the end of the study (June, 1992).

Results

Vegetation

"Gravel admixture amendments had no effect on plant cover or species composition at any time during the 5-yr. study." It should be noted that this is in contrast to the results of studies where the gravel was placed at the surface of the soil and not mixed in (Warren at al., 1996, Nyhan et al., 1990).

Plant cover and species were, however, influenced by precipitation amount and also varied with time. Siberian and thickspike wheatgrass persisted beyond the first growing season only on plots receiving twice average rainfall. On plots receiving ambient precipitation wheat grass cover dropped from 19 % in 1987 to 2.5 % in 1988 and had "...all but disappeared by 1990."

Invasion of the plots by cheatgrass and russian thistle was "...well underway by the first growing season". Invasion by cheatgrass and russian thistle was not influenced by precipitation amount. Cheatgrass became well established the first year and steadily increased each year after. Russian thistle cover lagged behind that of cheatgrass by a year, peaked in 1989 and then dropped to less than 5% between 1990 and 1992 when the cheatgrass was gaining dominance.

Soil Water

Vegetation and the presence of gravel admixture had the most effect on the upper 30 cm of soil. The concentration of gravel, however, appeared to have no effect on the near surface moisture content. Bare surfaced plots "...consistently retained about 2 vol. % more water than ..." bare surfaced plots with no gravel admixture. Bare surfaced plots showed a consistent increase in soil moisture to a depth of 225 cm over the course of the four year study. When observed through time, the soil moisture data from the bare surfaced plots indicate a wetting front moving deeper with time.

In contrast, the vegetated plots showed a consistent decrease in soil moisture content from approximately 30 cm below the ground surface down to approximately 125 cm below the ground surface indicating that plants extracted moisture down to at least that depth. At depths of approximately 175 cm and deeper, moisture contents varied little during the study. "Overall, with vegetation present, gravel amendments had no effect on root-zone water storage."

An interesting deviation from this trend was noted in the twice average precipitation plots during the spring of 1990. During this time water application "...exceeded the prescribed level by an unknown amount..." but by observation of the precipitation versus time graphs, it appears that it was significant. During this time the highest soil water storage was observed in the vegetated plots without gravel (196 mm) as compared to vegetated plots with gravel and the bare surfaced plots (both at approximately 150 mm).

All plots showed cyclical variations of soil moisture content with the seasons in the upper 30 cm to 45 cm. "Seasonal peaks in bare plot water storage appeared as plateaus with relatively little summer drying...". Vegetated plots showed significant reductions in soil moisture during the summer drying period. This is an indication that transpiration of water by plants has a greater influence on soil moisture than evaporation.

Gravel Concentration Changes

Gravel exposed at the surface was "...significantly greater for the 38 wt. % treatment than for the 22 wt. % treatment for the first year of the study." By 1992 the differences in surface exposure between the two initial concentrations was not significant converging at approximately 70 %. Gravel surface exposure was not influenced by precipitation level. Gravel concentrations were approximately 4 % higher in the upper 2 cm than at the lower depths.

Summary

"These findings contrast sharply with a companion study of surface gravel mulches." A lysimeter study using the same soil type, gravel size, gravel amount and precipitation but with the gravel placed as a 15 cm layer on the surface measured greater water storage and drainage in profiles with the thick gravel mulch. This comparison may not be valid, however. If the soil in the lysimeter were recompacted to a different density or even with a different type of compaction equipment, the soil moisture characteristics would not have been the same.

Evaluation of back calculated evapotranspiration data indicates that wheatgrass extracted water more rapidly and to lower moisture storage levels than the cheatgrass. "This can be attributed in part to contrasts in the seasonal water extraction patterns of the grasses."

5.0 SUMMARY AND CONCLUSIONS

Based upon the review of the literature there are several items that can be summarized that are of significance to Nevada.

1. The results of field studies indicate that properly designed and evaluated alternative cover systems for municipal solid waste landfills in Nevada can perform satisfactorily.

2. Patterns of precipitation are critical in the performance of an alternative landfill cover. Concentrations of precipitation at certain times of the year (e.g. a high percentage of total annual precipitation typically occurs over a relatively short amount of time) and high snow accumulations may require special considerations in the design.

   Typically, the field studies indicated that soil moisture increased during the late fall and early spring and then decreased during the late spring and summer. This pattern may vary with precipitation and climate (Anderson et al., 1987 and 1993, Benson and Khire, 1995, Wenatchee, Washington).

3. Evapotranspiration was consistently the major component of the water balance in the field studies (other than precipitation).

4. Also consistent in the field studies was that bare soil did not show the seasonal variation of soil moisture content in the upper portion of the cover that the vegetative covers did. The seasonal variation of soil moisture in vegetated covers typically consisted of an increase in soil moisture in the late fall through early spring and decreases in soil moisture from late spring through summer.

5. Monitoring of vegetated covers typically showed a depth below which the soil moisture remained relatively constant throughout the year, indicating that water was not infiltrating below that depth. In contrast the bare surfaced covers typically resulted in steady increases of soil moisture with depth, with time, indicating deep percolation of water. The depths of evapotranspiration and magnitude of evapotranspiration will vary somewhat depending upon the amount of soil water available. That is, some field studies indicate higher magnitudes of ET than others, but, there may have been more soil moisture available to begin with and the lower bound of soil suction (and associated soil moisture content) may be relatively consistent. However, the field studies indicate depths of ET in the 1.25 m to 2.0 m range and magnitudes of ET of over/up to 366 mm (Anderson et al., 1987, 1993). It should be noted that climate, precipitation patterns, vegetation type, vegetation density and soil type will all affect ET.

6. The alternative cover design concepts that will most likely prove both technically and economically effective are:

a. A monofill design;

This design will be most effective in areas that do not receive considerable accumulations of snow. The surface of the monofill should incorporate a gravel mulch to provide additional erosion protection and assist in establishing vegetation. However, gravel admixtures may also prove effective (Waugh et al., 1994). The critical aspects of a monofill design are; vegetation (the importance of vegetation cannot be over stated) and proper selection of thickness.

Benson and Khire, 1995 state that, "The necessary thickness [of a monofill cover] is a function of the type of precipitation received, the unsaturated hydraulic properties of the soil, and the rate at which water can be removed by evapotranspiration. Monolayer barriers are constructed from silty sands, silts and clayey silts and are cost-effective when large quantities of fine grained soil requiring little processing are available on site."

Indications of the effect of soil type on the performance of a cover system in arid and semi-arid environments can be found in Gee et al., 1994 and Benson and Khire, 1995, Los Alamos.

b. A Capillary/Resistive Barrier;

This design may be required in areas that receive considerable snow accumulations. Conceptually the design consists of three layers; a top layer designed and constructed the same as for a monofill, a capillary break, and an underlying low permeability compacted soil liner. The capillary break will serve several functions; (1) it will act as a barrier to the downward migration of water out of the bottom of the monofill, (2) if the monofill soil reaches a high enough moisture content to allow break through of water, it will act as a lateral drainage layer on top of the low permeability soil liner (an analysis technique and guidance is provided by Ross, 1990; Steenhuis et al., 1991; and Stormont, 1995 in which for sloping covers, an effective diversion length before breakthrough can be estimated), and (3) it will assist in maintaining the moisture content of the compacted soil liner by inhibiting evaporation of water.

It is hoped that with this liner system, the requirements of the low permeability soil liner will not have to be as stringent as is typical for a "classic" compacted soil liner. There is a relatively simple leachate apportionment model (Sharma and Lewis, 1993; Wong, 1977;

and Lentz, 1981) that is suitable for hand calculation that may be able to be used to quickly check this design based upon the result of a computer model's flow out of the bottom of the top soil layer, the hydraulic conductivity of the capillary barrier, the hydraulic conductivity of the compacted soil liner, and the slope of the surface of the soil liner.

Goode, 1986, provide comments with respect to the selection of capillary barrier materials. The critical aspect of a capillary barrier is the relationship between the unsaturated hydraulic conductivity/moisture content characteristics of the overlying fine grained soil and the capillary break material.

The draw backs to this cover system are that the compacted soil liner may be susceptible to biointrusion and it may be costly to construct depending upon the availability of materials. However, it must be realized that areas that receive considerable snow accumulations are going to be more costly to close.

c. Capillary Barrier

A third option for an alternative cover design is the straight capillary barrier. Stormont, 1995, summarizes the concept of a capillary barrier, "A capillary barrier remains effective if the combined effects of evaporation, transpiration, and lateral diversion equals or exceeds the infiltration from precipitation events, thereby keeping the fine layer sufficiently dry so that appreciable breakthrough into the coarse layer does not occur. Depending upon the climate and thickness of the fine layer, evaporation and transpiration may remove sufficient water to prevent failure, and the capillary barrier need not be sloped for lateral diversion." The results of the field studies summarized in this report indicate that pure capillary barriers have a tendency to fail, and seem to be more sensitive to the uncertainties that we are forced to design with. There may be a "middle" climate, between the dry southern portion of the state and the wetter, colder northern portion of the state where pure capillary barriers may be appropriate.

It is evident from a review of the available literature that the performance of a landfill cover in arid and semi-arid environments is a complex, synergistic relationship between climate (total precipitation and pattern of precipitation), surface treatment (gravel admixture, gravel mulch), vegetation, thickness of soil layer(s), hydraulic properties of soil layer(s) and the geometrics of the cover (slopes, length of slopes etc.). In the evaluation of a landfill cover in an arid or semi-arid environment it is critical that the interrelationship of all of these elements be understood and evaluated. For the overall performance of a proposed cover we recommend performing a computer model of the cover using the Hydrus-2D model. Details of this model and it's application are presented in a separate report. It is obvious that the computer model will not be any more representative than the input.

With respect to the soil(s) used in the design, the saturated hydraulic conductivity is required as input into many unsaturated infiltration analyses. However, it should be realized that the saturated hydraulic conductivity is used only as a "scaling factor" in the analysis. The relationship between a soil's unsaturated hydraulic conductivity and moisture content is the soil characteristic that needs to be evaluated. It is the writer's opinion that evaluating a soil based upon it's saturated hydraulic conductivity can be very misleading.

A critical issue that still needs to be resolved within the geotechnical industry as a whole is the development of a landfill cover design procedure for arid and semi-arid environments. It is the writer's opinion that such a procedure can, and should, be based upon laboratory and field testing. It is currently envisioned that these procedures can be developed similarly to the procedures developed by Dr. David Daniel at the University of Texas at Austin for compacted clay liners. With respect to laboratory testing, detailed procedures for determining the moisture retention characteristics and/or unsaturated hydraulic conductivity characteristics of liner system soils need to be developed and standardized. Due to the complex nature of this type of testing and data evaluation, it will be prudent to consider different levels of required laboratory testing and data analysis based upon a particular site's level of risk for contamination. Another interesting parallel with "classic" low permeability compacted soil barrier design may be amending with pozzolans or diatomaceous earth to enhance a soils unsaturated hydraulic characteristics.

In addition to laboratory testing, it is the writer's opinion that field construction quality assurance (CQA) methods and procedures also need to be developed. Field verification of design assumptions with respect to the soil's unsaturated hydraulic characteristics was noticeably absent from the field studies reviewed for this report. It is common knowledge that a soil's unsaturated hydraulic characteristics are dependent upon the soil's density and texture. Therefore, it stands to reason that the degree of compaction and the means of placing and compacting the soil will affect the liner system's performance. Currently it is anticipated that the disc infiltrometer (Ankeny et al., 1991; Nachabe and Illangasekare, 1994) may provide a means of testing soils in-place to verify design assumptions.

6.0 EVALUATION PROCEDURE

Taking into account the literature and field studies reviewed for this report, the following evaluation procedure is presented based upon the EPA's recommended evaluation procedure described earlier.

I recommend maintaining the same general framework as the EPA procedure, e.g. examining or evaluating specific items in a series of steps. Rather than using the 36 steps provided by the EPA, the procedure has been simplified and tailored to Nevada's needs resulting in 26 steps.

The Nevada procedure maintains ten of the eleven main review items listed by the EPA. The review items in the Nevada procedure are:

1. Examine Soil Test Data
2. Examine Climate Data
3. Evaluate Composition
4. Evaluate Thickness
5. Evaluate Placement
6. Evaluate Configuration
7. Evaluate Drainage
8. Evaluate Vegetation
9. Evaluate Post-closure Maintenance
10. Evaluate Contingencies Plan

The first two items are related to the materials and conditions at the particular site, items 4 through 8 are related to the characteristics of the particular cover design under evaluation and items 9 and 10 are related to postclosure care issues.

The 26 evaluation steps are presented below with recommendations for implementation with respect to arid and semi-arid covers in Nevada.

TEST DATA REVIEW (Steps 1-3)

<u>Step 1</u> Review Field Sampling of Soils

The objective of this task is to establish that the applicant has satisfactorily documented the physical characteristics, volume and spatial distribution of the soil types that are proposed for use in the cover.

This should be accomplished by reviewing a plan view of test pits and/or borings in coordination logs of the test pits and/or borings within the proposed borrow area. Changes in soil and material type should be indicated on the test pit/boring logs. Sample locations should be indicated on the logs. Results of laboratory testing should be easily traceable to a particular sample as indicated on the logs.

A decision must be made as to whether or not the borrow area has been adequately characterized.

<u>Step 2</u> Check Adequacy of Soil Testing Program

At the present level of understanding I recommend that, as a minimum, the following laboratory tests be performed to characterize the proposed cover soils:

Sieve Analysis
Atterberg Limits
Specific Gravity
Laboratory Compaction
Saturated Hydraulic Conductivity

It should be noted that the saturated hydraulic conductivity is not used directly to calculate infiltration and downward migration of moisture. The saturated hydraulic conductivity is used in conjunction with parameters from the moisture retention function of the soil in order to estimate the unsaturated hydraulic conductivity at varying soil moisture contents.

Ideally a moisture-retention curve would be generated for each material type, however, the test is time consuming and few, if any, geotechnical firms in Nevada have the capability to perform the test. Additionally, there are some outstanding issues regarding the test, i.e. the effect of oversize particles etc. that still need to be resolved. However, criteria must be established upon which the decision to require a moisture-retention curve can be made. The criteria should be based upon the risk associated with the site, the maximum precipitation, the proposed design and the results of preliminary studies. There are procedures for estimating the moisture-retention characteristics of a soil based upon index testing that may be used for preliminary studies and for low risk projects.

The results of the laboratory testing should be checked against the input to models and analyses. For example, based upon the results of laboratory compaction and specific gravity tests, and a specified field compaction requirement, the porosity used in any modeling or analyses should be checked. Additionally, saturated hydraulic conductivity and moisture-retention testing should be verified to have been performed at the appropriate dry density.

Step 3 Check Soil Volumes Available

There should be enough information obtained from the site investigation and presented in the design report to allow verification that sufficient quantities of borrow materials are available to construct the proposed design.

CLIMATOLOGICAL REVIEW (Steps 4-6)

Step 4 Examine Precipitation Records

The design report should contain data on the precipitation that is being used for design of the cover. The source of the precipitation information should be given.

The results of the field studies indicate that the distribution of precipitation throughout the year is critical in the evaluation of the performance of an alternative landfill cover. Specifically, for arid and semi-arid regions, the majority of the precipitation typically occurs during a relatively short time period from fall through early spring. This pattern must be reflected as accurately as is practical in the input to the model. Snow accumulation is especially critical. For regions that expect snow, estimates as to the maximum accumulation of snow should be made as well as a detailed discussion of how snow was handled by the model.

Step 5 Examine Evapotranspiration Estimates

The EPA states that "...it [evapotranspiration] must be regarded as a major factor in cover design." The results of the field studies that are summarized in this report indicate that evapotranspiration plays a major, if not the major, role in the water balance for a landfill cover.

Estimates of evapotranspiration are typically made by the model used, based, of course, upon the input of the user. Due to the fact that evapotranspiration plays such a dominant role in the performance of an alternative landfill cover design, it may be prudent to require that the applicant provide detailed information on how the model estimates evapotranspiration, the required input to the model and a summary of the results of the model with respect to evapotranspiration. This information should include as a minimum:

Type(s) of vegetation assumed, i.e. the target plant community,

How and why that plant community was selected,

Proposed procedures to establish the target plant community on the cover, The root parameters used in the model,

Plant density parameters used, and

Temporal (seasonal) provision made within the model,

Summary of evapotranspiration with time; both monthly and, cumulative totals and as a percentage of total precipitation. These results can be compared to the results of the field studies to provide the evaluator with an indication as to whether the results are reasonable.

Step 6 Examine Design Storms

The cover design should consider not only average precipitation but also higher intensity, shorter duration events and appropriate periods of sustained precipitation.

With respect to deep infiltration, the worst cases appear to be snowmelt (as previously discussed) and multiple, closely spaced storms or storms of long duration. Closely spaced storms and storms of long duration that cause infiltration and are spaced close enough together in time that the soil moisture is not evapotranspirated out before the next storm occurs can result in deep percolation. These do not necessarily need to be large storms, therefore, a statistical evaluation of frequency, duration and recurrence of smaller storms may need to be evaluated as well.

COVER MATERIALS COMPOSITION (Step 7)

Step 7 Evaluate Composition

The manual presents a table that provides a ranking of Unified Soil Classification System (UCS) soil types to performance of cover functions. The functions considered in the table include:

Trafficability; go/no-go, stickiness, slipperiness
Water Percolation; impede, assist
Gas Migration; impede, assist
Fire Resistance
Erosion Control; water and wind
Dust Control
Reduce Freeze Action; fast freeze, saturation
Crack Resistance
Side Slope; stability, seepage, drainage
Discourage Burrowing
Impede Vector Emergence
Discourage Birds
Support Vegetation
Future Use; natural, vegetation

The procedure checks a soil's suitability by establishing it's strengths and weaknesses for it's intended function by means of a rating system. Less favorable rankings generally indicate that special features need to be incorporated into the design to mitigate material shortcomings. The manual states that the reviewer needs to exercise good judgement in applying this method.

With respect to Nevada's requirements, this step should be applied in a site specific manner, incorporating past performance histories of landfill covers in Nevada. A copy of the EPA table is provided in Appendix B of this report.

THICKNESS EVALUATION (Steps 8-10)

The EPA states that cover thicknesses greater than the regulatory minimums may be required based upon the results of an evaluation of one or more of the following factors:

Coverage
Infiltration
Gas Migration
Trafficability and Support Requirements
Freeze/Thaw or Dry/Wet Cycles
Cracking
Differential Settlement and Off-set
Membrane Protection
Vegetative Requirements

These items should be applied to Nevada as described below.

It should be noted that one of the most critical aspects of an arid/semi-arid alternative landfill cover is it's thickness. In general the cover should be thick enough to store the required amount of water for eventual evapotranspiration back to the atmosphere. Details of this issue are presented in Step 9.

<u>Step 8</u> Evaluate Coverage

Within this step the EPA provides what they term "...a reasonable criterion of adequacy for coverage over irregular waste...". Their criteria is:

$$T>2R$$

where T is the cover thickness and R is the relief. Relief is determined by measuring the difference in elevation between the high point and low point of irregularities over an area which is approximately equal to the size of the equipment that will be used to place the material.

It is anticipated that alternative cover design thicknesses will be thicker than this requirement based upon water storage criteria. If it is not, this seems to be a reasonable requirement for a minimum thicknesses.

<u>Step 9</u> Evaluate Thickness for Infiltration

In general, for Nevada, the thickness of the cover will depend upon which type of alternative design is proposed. For monolithic covers, the thickness will be determined by the amount of water that needs to be stored. It should be noted that there is most likely a maximum depth below which evapotranspiration will not draw moisture out. This may be a difficult depth to determine due to the fact that some plants may have a tendency to extend their roots deeper if there is water available at depth.

It is recommended that it be within this step that the evaluation of the cover with respect to deep percolation be performed either by review of the applicant's model output or by performance of a model by the evaluator.

<u>Step 10</u> Consider Freeze/Thaw and Dry/Soak

This step is primarily concerned with freezing and desiccation. For Nevada's requirements, this step will be important if a compacted soil resistive barrier is utilized within the design. The cover above the soil liner should be thicker than the frost depth for the area to protect it from freezing. The cover should also be thicker than the depth of moisture extraction to minimize drying of the compacted soil liner by evapotranspiration. The depth of moisture extraction may be estimated from the results of modeling and field studies.

PLACEMENT EVALUATION PROCEDURE (Steps 11-14)

After selection of materials and thicknesses of layers, proposed construction procedures are evaluated.

<u>Step 11</u> Evaluate Cover Compaction

The details provided by the EPA for this step are out of date and inappropriate for Nevada's application.

It is the writer's opinion that compaction of alternative cover soils do need to be addressed. There should be some correlation between the soil parameters used in the model and the anticipated soil densities in the field. If a moisture-retention test is performed it should be performed at the same soil matrix density as anticipated in the field. If unsaturated properties are estimated, some correlation with anticipated void ratios and porosities should be made. Consideration should also be given to settlement, stability etc.

Step 12 Evaluate Internal Layering

The specifics provided in this step are generally related to a prescriptive standard type of design.

Layering of soil types is an option for some alternative cover designs, e.g. designs incorporating capillary barriers. If capillary barriers are used, verification of lateral drainage capacity above the capillary barrier should be made. This should be performed by the applicant and may have been assessed during modeling or handled separately utilizing alternate methods.

Step 13 Evaluate Top Soil

It is anticipated that topsoil at the site will be stripped and stockpiled prior to construction and that this topsoil will be used on the final cover.

Due to the fact that vegetation is so critical to the performance of alternative landfill covers, it is the writer's recommendation that individuals who specialize in this area be consulted. The applicant should submit the qualifications of the individual(s) that provided the recommendations for the topsoil.

There are two individuals on the UNR campus who appear to be knowledgeable in this area. It is hoped that there will be no, or minimal, need for application of fertilizers or conditioners to the vegetative layer.

Step 14 Review Proposed Construction Techniques

The EPA states, "The application should be carefully reviewed for the following general recommendations for layering (from the bottom up)..." The majority of the recommendations have to do with the prescriptive standard and compacted soil liner as a barrier layer and are not applicable to alternative cover designs.

There does not appear to be a history of construction of full scale alternative landfill covers from which to draw information from. As a minimum it is the writer's opinion that the following be included in the application:

Borrow Source Quality Control Requirements

Cover Soil(s) Material Specifications

Moisture Conditioning and Placement Requirements

Maximum Lift Thickness

Minimum Compaction Requirements

Quality Assurance Requirements

Vegetative Layer Placement (when applicable)

Seed Mixture Requirements (when applicable)

Seed Application Requirements and Quality Assurance (when applicable)

It is the writer's opinion that the quality control and quality assurance testing of the borrow soils should consist of as a minimum:

Sieve Analysis
Atterberg Limits
Specific Gravity
Laboratory Compaction
Field Density and Moisture Content

It should be noted that the writer is investigating a method to determine the soils unsaturated hydraulic conductivity in-situ that can be used as a construction quality assurance tool.

CONFIGURATION EVALUATION PROCEDURE (Steps 15 and 16)

These evaluation procedures are concerned primarily with erosion and infiltration

<u>Step 15</u> Evaluate Erosion Potential

If erosion is considered an issue there are numerous methods available to evaluate erosion potential including the Revised Universal Soil Loss Equation (RUSLE) which is used by UMTRA. The evaluation should also consider past performance of landfill covers in Nevada.

It should be noted that the less conservative a design is with respect to erosion the more rigorous the monitoring and maintenance should be.

<u>Step 16</u> Evaluate Surface Slope Inclination

The EPA generally discusses the relationship of increased slope and reduced infiltration vs erosion. They provide some rules of thumb for slope inclination that may or may not be applicable to Nevada:

- Slopes of 4(Horizontal):1(Vertical) are generally stable

- 2:1 slopes are the steepest upon which vegetation can be established and maintained with favorable soil conditions (low erodibility, adequate moisture holding capacity, [nutrients])

- 3:1 slopes are the steepest upon which a stable vegetative community can be maintained in less than ideal soil conditions

- 4:1 slopes or flatter slopes are optimum for vegetation stability

DRAINAGE EVALUATION PROCEDURE (Steps 17 - 19)

The recommended procedures are basically the same as presented by the EPA.

<u>Step 17</u> Check Overall Drainage System

The applicant's documentation should be reviewed to establish that surface runoff and adjacent surface water issues have been thoroughly addressed. A review for obstacles that may cause ponding or excessive erosion should be made. Particular attention be paid to the toes of slopes where slopes may need to be excessively steep.

<u>Step 18</u> Evaluate Ditch Design

Review for adequate hydraulic capacity and erosion protection where needed.

<u>Step 19</u> Evaluate Culvert Design

Standard procedures are used to assess adequacy of culverts where needed.

VEGETATION EVALUATION PROCEDURE (Step 20)

As previously mentioned, vegetation is a critical aspect of the performance of an alternative landfill cover design. The EPA states that rapid establishment of vegetation requires careful attention to soil type, nutrient and pH levels, climate, species selection, mulching and seeding time.

Based upon the results of many of the field studies presented in this report and the comments in Caldwell and Reith, 1993, it is evident that trying to prevent native species of plants from establishing on the cover will most likely require considerable maintenance. The goal for landfill covers in Nevada is to minimize maintenance, particularly in the rural areas. It is recommended to concede that native species of plants will invade the cover and to therefore, target a local, native plant community and to incorporate that community into the design.

The evaluator should review the credentials and experience of the individual(s) that provided the vegetation recommendations. It is highly recommended that individuals within the State of Nevada that are experts in the field of revegetation be consulted to assist in the evaluation of applications.

A review of the vegetation of a landfill cover should include, but not necessarily be limited to, the following items as listed in the EPA procedure:

- Evaluate the Proposed Soil's Suitability for Vegetation
- Evaluate the Proposed Soil's pH Level
- Evaluate Nitrogen and Organic Matter Contents of the Proposed Soil
- Evaluate other Nutrient Contents of the Proposed Soil
- Evaluate the Target Species Selection
- Evaluate Time of Seeding
- Evaluate Seed and Surface Protection

The EPA recommends the use of a mulch for temporary protection against large temperature and moisture fluctuations and rapid degeneration from wind and water erosion. It should be understood that applying surface mulches has the potential to increase infiltration and, if there is not enough evapotranspiration, the potential for deep percolation.

MAINTENANCE EVALUATION PROCEDURE (Steps 21 - 23)

The amount of conservatism in the design with respect to erosion will effect the level of maintenance that may be required. It is hoped that the alternative covers will be relatively maintenance free, however, some maintenance must be expected.

<u>Step 21</u> Evaluate the Design/Maintenance Balance

The EPA recommends that a check be made to see that there is a balance between the design and the proposed monitoring, maintenance and repair. Many factors such as climate, waste type, soil, vegetation etc., are involved in evaluating this balance. Little specific guidance is offered by the EPA.

This task will most likely be based upon the past performance of covers in similar climates within Nevada.

Step 22 Evaluate Maintenance of Vegetation

As previously mentioned, it is recommended that a native plant community be targeted as the vegetation for the cover. Therefore, this step should be used to evaluate the applicant's proposed methods of establishing and maintaining the target plant community until it becomes self-sustaining.

Step 23 Evaluate Provisions for Condition Surveys

The requirements should be site specific. Provisions should be made for documentation during the site visits and record keeping.

This step should follow established protocols and include such items as:

Plant types that have become established on the cover

Plant Density

Condition of Slopes

Notes of any rill or gully development

Notes regarding the development of armoring, if present

CONTINGENCY PLAN EVALUATION PROCEDURE (Steps 24)

Step 24 Evaluate the Plan for Erosion and Vegetation Damage Repair

The plan should generally follow the guidelines presented by the EPA but incorporate local performance history into the evaluation procedure.

The EPA states that long term maintenance helps to avoid erosion problems. However, unusual climate conditions and shortcomings in the design may cause excessive damage to the cover at times due to such events as excessive winds or water even in well maintained covers. One important factor that needs to be considered is the future source of soil to implement repairs if and when they are needed. Additionally, provision should be made for redesign of the cover, or certain areas of the cover, should the original design result in inadequate performance.

It is the intent that the vegetation be as selfsustaining as possible and to minimize the amount of maintenance and repair. However, contingency plans need to be formulated to reestablish the vegetation in the event that vegetation becomes damaged or dies out.

Step 25 Evaluate the Plan for Drainage Renovation

Drainage ditches should be maintained including repairing damage caused by unexpected erosion and, cleaning ditches and cutting brush as required to maintain hydraulic capacity.

Step 26 Evaluate Provisions for Other Cover Deterioration

Plans for repair due to other types of cover deterioration should be provided. Other types of damage to the cover may include such things as excessive root penetration, cracking, freezing, seepage and slope instability. The effect of damage will need to be assessed in combination with the type of cover proposed, for example, deep root penetration may not be a concern in a monolithic type of cover whereas it may be of major concern in a cover design that incorporates a compacted soil liner.

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Appendix A - Field Study Summary Tables

Table 1 - Summary of Field Studies Reviewed

Table 2 - Summary of Liner Systems, Materials and Precipitation Application

Table 3 - Summary of Results

TABLE 1 - SUMMARY OF FIELD STUDIES REVIEWED

LOCATION	REFERENCE	CLIMATE	OBJECTIVES
Eastern Washington-1 (Hanford)	Fayer, et al., 1992	≈52% of precipitation between Nov. and Feb. of that ≈40% as snow Also see Gee et al., 1994	Primarily to assess an infiltration model but presents usefull infiltration data.
Southeastern Idaho (INEL)	Anderson et al., 1987 Anderson et al., 1993	Cold Desert Rangeland Mean Annual Precipitation 221 mm (8.7 in.) ≈36% between April and June	Designed to assess the potential for using vegetation to prevent water from infiltrating through a cover.
Northern Utah (Hill Air Force Base)	Warren et al., 1996	Average annual precipitation of 51 cm (20.1 in.) ≈40% of precipitation falls as snow (182 cm)	Measure water balance and erosion to determine the effectiveness of different cover designs in an area where a high percentage of precipitation falls as snow.
North-central New Mexico (Los Alamos)	Nyhan et al., 1990		Compare performance of a "conventional" cover with an improved design.
South-Central New Mexico (Las Cruces)	Gee et al., 1994	Average annual precipitation 230mm (9.1 in.) ≈52% precipitation falls between July and September Snow is rare	Assess deep infiltration into a single cover design.
Mojave Desert (near Beatty, Nevada)	Gee et al., 1994	Average annual precipitation 104 mm (4.1 in.) ≈70% of precipitation falls between October and April	Assess infiltration in four different systems.

TABLE 1 - SUMMARY OF FIELD STUDIES REVIEWED

LOCATION	REFERENCE	CLIMATE	OBJECTIVES
Eastern Washington-2 (Hanford)	Gee et al., 1994	Average annual precipitation 162 mm (6.4 in.) ≈73% of the precipitation falls between October and April Average snowfall 27 mm (1.1 in.) and is ≈38% of the precipitation between Dec. and Feb.	Assess infiltration into a single design.
Germany (Near Hamburg)	Benson and Khire, 1995	Average annual precipitation 800 mm (31.5 in.)	Assess performance of three different cover designs
Southern Wisconsin (Near Milwaukee)	Benson and Khire, 1995	Average annual precipitation 800 mm (31.5 in.)	Assess performance of three different cover designs.
North-central New Mexico (Los Alamos)	Benson and Khire, 1995		Assess the performance of four different cover designs.
Central Washington (Near East Wenatchee)	Benson and Khire, 1995	Average annual precipitation 230 mm (9.1 in.)	Assess the performance of two different cover designs.
Eastern Washington-3 (Hanford)	Waugh et al., 1994	See Gee et al., 1994	Assess the affect of a gravel admixture in contrast to a gravel mulch, on vegetation, erosion, and over all cover performance.
Capillary Barrier Study	Stormont, 1995	Not Applicable	Study the difference between the performance of standard capillary barrier and a capillary barrier designed to enhance lateral drainage. Water was applied at a flux rate of approximately 1.8×10^{-5} cm/sec.

TABLE 2 - SUMMARY OF LINER SYSTEMS, MATERIALS AND PRECIPITATION APPLICATION

LOCATION	LINER SYSTEM and SURFACE CONDITION (from the top down)	CONFIGURATION	MOISTURE APPLICATION
Eastern Washington-1 (Hanford)	**Surface Condition**: Nonvegetated **Liner System (Capillary):** 1.5 m silty loam 5 cm of 20/30 sand (>90% between 0.25 mm and 1 mm) 5 cm of No. 8 sand (>90% between 1 mm and 2 mm) 5 cm of 1 cm gravel 10 cm of 2 cm gravel 15 cm of 4 cm to 5 cm railroad ballast ≈ 1 m of basalt rip rap	Total of eight lysimeters: 6 were cylindrical, ≈1.93 m diam. x 2.93 m deep 2 were rectangular 1.5 m x 1.5m in plan, 1.7 m deep	Two cylinders and one rectangular at ambient precipitation Two cylinders and one rectangular at twice the recorded ambient precipitation Two cylinders had water applied until break through
Southeastern Idaho (INEL)	**Surface Condition:** Two plots each vegetated with a single species of either crested wheatgrass, great basin wild rye, streambank wheatgrass, or Wyoming big sagebrush Two plots maintained as bare soil **Liner System (Monolithic):** Single soil type consisting of 26% sand, 54% silt, and 20% clay Compacted in layers with a front end loader, bulk density 1.4 g/cc (87.4 pcf)	Total of ten plots 10.7 m x 3 m in plan, 2.4 m deep	1984 - 1986 ambient precipitation 1987 - 1988 one plot of each species was irrigated to simulate wetter conditions. Additional water ranged from 366 mm (14.4 in) to 600 mm (23.6 in.) annually.

TABLE 2 - SUMMARY OF LINER SYSTEMS, MATERIALS AND PRECIPITATION APPLICATION

LOCATION	LINER SYSTEM and SURFACE CONDITION (from the top down)	CONFIGURATION	MOISTURE APPLICATION
Northern Utah (Hill Air Force Base)	**Surface Condition:** All surfaces seeded with a mixture of native grasses. LA-2 was also transplanted with two shrubs. **Liner Systems (1-Monolithic, 1-Resistive, 2-Capillary):** Typical Soil Cover (Control) Consisted of 90 cm of local topsoil. The following properties were reported for the topsoil: Sandy Loam $K_{sat} = 5.3 \times 10^{-5}$ cm/sec Volumetric Moisture Content at Saturation = 30% Modified EPA RCRA Cover 120 cm of local topsoil Geotextile 30 cm sand drainage layer 60 cm bentonite amended compacted barrier layer with the following reported properties: Clay loam $K_{sat} = 3.4 \times 10^{-6}$ cm/sec Volumetric Moisture Content at Saturation = 50%	The top surface and all layers sloped at 4%. 5 m x 10 m in plan (fiberglass swimming pools)	All exposed to ambient precipitation for the duration of the experiment.

TABLE 2 - SUMMARY OF LINER SYSTEMS, MATERIALS AND PRECIPITATION APPLICATION

LOCATION	LINER SYSTEM and SURFACE CONDITION (from the top down)	CONFIGURATION	MOISTURE APPLICATION
Northern Utah (Cont.)	**Liner Systems:** (Cont.) LA-1 A capillary barrier design incorporating a gravel which consisted of: Approximately 1 cm gravel mulch covering 70% to 80% of the cover surface 150 cm of local topsoil Geotextile 30 cm of approximately 1 cm diameter washed gravel (capillary break) LA-2 A capillary barrier design which was the same as LA-1 except that it had different vegetation as described above.		

TABLE 2 - SUMMARY OF LINER SYSTEMS, MATERIALS AND PRECIPITATION APPLICATION

LOCATION	LINER SYSTEM and SURFACE CONDITION (from the top down)	CONFIGURATION	MOISTURE APPLICATION
North Central New Mexico (Los Alamos)	**Surface Condition:** All plots received 60% to 70% cover with gravel mulch (<2cm in diameter) All plots vegetated with blue grama and western wheatgrass **Liner Systems (Monolithic, Capillary):** Control Design, 20 cm of topsoil 108 cm of crushed tuff Improved Design (capillary barrier): 71 cm of topsoil geotextile 46 cm gravel (5 mm - 10 mm diameter) 91 cm cobble (10 cm - 30 cm) biointrusion layer 38 cm crushed tuff	3.0 m x 10.7 m in plan 0.5% slope of the surface 5% lateral slope at the interface of the topsoil and the capillary barrier	Ambient precipitation other than "minor" amounts applied the first 4 months to establish vegetation.
South Central New Mexico (Las Cruces)	**Surface Condition:** Bare soil. **Liner System (Monolithic):** Monolithic , loamy fine sand backfilled in 13 cm thick lifts. Average bulk density 1.67 g /cc (104.2 pcf)	Cylindrical 2.44 m diameter, 6 m deep	Ambient precipitation

TABLE 2 - SUMMARY OF LINER SYSTEMS, MATERIALS AND PRECIPITATION APPLICATION

LOCATION	LINER SYSTEM and SURFACE CONDITION (from the top down)	CONFIGURATION	MOISTURE APPLICATION
Mojave Desert (Near Beatty, Nevada)	**Surface Conditions:** Vegetated natural soil profile Unvegetated, natural soil profile Two unvegetated test trenches **Liner Systems:** Not Applicable		Ambient precipitation
Eastern Washington-2 (Hanford)	**Surface Condition:** Varied from bare soil to vegetated with naturally occurring plants. **Liner System (Monolithic):** Loamy sand; 87% sand, 10% silt, 3% clay.	Cylindrical, 3 m in diameter, 18 m deep.	Ambient precipitation

TABLE 2 - SUMMARY OF LINER SYSTEMS, MATERIALS AND PRECIPITATION APPLICATION

LOCATION	LINER SYSTEM and SURFACE CONDITION (from the top down)	CONFIGURATION	MOISTURE APPLICATION
Germany (Near Hamburg)	**Surface Conditions:** Not reported **Liner Systems (Resistive):** Compacted Soil Cover 750 mm of topsoil Geotextile 250 mm lateral drainage layer 600 mm compacted clay 200 mm drainage layer Composite Liner 750 mm of topsoil Geotextile 250 mm Lateral drainage layer Geomembrane 600 mm compacted clay 200 mm drainage layer Extended Capillary Barrier 750 mm of topsoil Geotextile 250 mm Lateral drainage layer 400 mm compacted clay Geotextile 600 mm fine sand 250 mm drainage layer	10 m x 50 m in plan Slopes of 4% to 20%.	Ambient precipitation

TABLE 2 - SUMMARY OF LINER SYSTEMS, MATERIALS AND PRECIPITATION APPLICATION

LOCATION	LINER SYSTEM and SURFACE CONDITION (from the top down)	CONFIGURATION	MOISTURE APPLICATION
Southern Wisconsin (Near Milwaukee)	**Surface Condition:** Vegetated **Liner System (Resistive, Capillary/Resistive):** Resistive Barrier (RB1) 150 mm topsoil; uncompacted clay loam to silty clay loam 1200 mm high silt clay; $K_{sat} < 1x10^{-7}$ cm/sec Resistive Barrier (RB2) 450 mm topsoil; uncompacted clay loam to silty clay loam 1200 mm high silt clay; $K_{sat} < 1x10^{-7}$ cm/sec Capillary Barrier underlain by resistive barrier 150 mm topsoil; uncompacted clay loam to silty clay loam 610 mm high silt clay; $K_{sat} < 1x10^{-7}$ cm/sec 30 mm sand 610 mm high silt clay; $K_{sat} < 1x10^{-7}$ cm/sec	All test plots constructed with a 3H:1V slope.	Ambient precipitation.

TABLE 2 - SUMMARY OF LINER SYSTEMS, MATERIALS AND PRECIPITATION APPLICATION

LOCATION	LINER SYSTEM and SURFACE CONDITION (from the top down)	CONFIGURATION	MOISTURE APPLICATION
North-Central New Mexico (Los Alamos)	**Surface Condition:** Vegetated **Liner Systems (Resistive, Capillary):** Conventional 150 mm loam topsoil, comprised of organic matter, sand and aged sawdust 760 mm tuff 300 mm gravel 660 mm coarse sand EPA-Recommended 610 mm loam topsoil 300 mm medium sand 610 mm clay/tuff mix; $K_{sat} < 1 \times 10^{-7}$ cm/sec 300 mm gravel 50 mm coarse sand Loam Capillary Barrier 610 mm loam topsoil 760 mm fine sand 300 mm gravel 200 mm coarse sand Clay-Loam Capillary Barrier 610 mm clay loam topsoil 760 mm fine sand 300 mm gravel 200 mm coarse sand	1 m x 10 m in plan 5%, 10%, 15% and 25% slopes	Ambient Precipitation

TABLE 2 - SUMMARY OF LINER SYSTEMS, MATERIALS AND PRECIPITATION APPLICATION

LOCATION	LINER SYSTEM and SURFACE CONDITION (from the top down)	CONFIGURATION	MOISTURE APPLICATION
Central Washington (Near East Wenatchee)	**Surface Condition:** Vegetated **Liner System (Capillary, Resistive):** Capillary Barrier 150 mm Uncompacted Silt; $K_{sat} = 2.7 \times 10^{-4}$ cm/sec 750 mm Sand; $K_{sat} = 2.9 \times 10^{-3}$ cm/sec Prescriptive Resistive Barrier 150 mm Uncompacted Clayey Silt; $K_{sat} = 4.5 \times 10^{-5}$ cm/sec 600 mm Compacted Silty Clay; $K_{sat} = 2.2 \times 10^{-7}$ cm/sec	Capillary Barrier @ 2.5H:1V Prescriptive Resistive Barrier @ 2.8H:1V	Ambient precipitation

TABLE 2 - SUMMARY OF LINER SYSTEMS, MATERIALS AND PRECIPITATION APPLICATION

LOCATION	LINER SYSTEM and SURFACE CONDITION (from the top down)	CONFIGURATION	MOISTURE APPLICATION
Eastern Washington-3 (Hanford)	**Surface Condition:** Gravel admixture @ 0%, 22%, and 38% by weight, mixed into the upper ≈ 12 cm of soil. The gravel ranged in size from 50 mm (2 in.) to 100 mm (4 in.). Both bare soil and vegetated with perennial species plots were tested. **Liner System (Monolithic):** The upper ≈ 10 cm (4 in.) of soil was removed and graded into a low perimeter berm. The remaining upper ≈ 1 m of soil was disced and harrowed. After the gravel admixture was mixed in , the soil was compacted with a cultipacker.	Six plots 10 m x 15 m divided into six 5 m x 5 m plots. May have been @ a 1.5% slope.	Ambient and twice average precipitation.

TABLE 2 - SUMMARY OF LINER SYSTEMS, MATERIALS AND PRECIPITATION APPLICATION

LOCATION	LINER SYSTEM and SURFACE CONDITION (from the top down)	CONFIGURATION	MOISTURE APPLICATION
Capillary Barrier Study	**Surface Condition:** Bare soil and covered with plastic to minimize evaporation and prevent plant growth. **Liner Systems (Capillary):** Homogeneous Capillary Barrier 90 cm fine grained soil geotextile 25 cm gravel Layered Capillary Barrier 20 cm fine grained soil 10 cm sand 20 cm fine grained soil 10 cm sand 20 cm fine grained soil 10 cm sand geotextile 25 cm gravel Soil properties: Fine grained soil: Silty Sand mean particle diameter 0.11 mm, 30% finer than the No. 200 sieve. $K_{sat} = 1.2 \times 10^{-4}$ cm/sec Porosity approximately 40% Sand; uniform Sand mean particle diameter 0.3 mm, 99% between 0.6 mm and 0.8 mm $K_{sat} = 2.1 \times 10^{-2}$ cm/sec Porosity approximately 40% Gravel; poorly graded, rounded mean particle diameter approximately 2 cm K_{sat} estimated at 10 cm/sec	Above ground wooden boxes 7 m x 2 m in plan, 1.2 m high. Top surface flat, layers sloped at 5% for lateral drainage.	Water was added at a rate just slow enough to prevent ponding. The resulting infiltration rate was ≈equivalent to a flux rate of 1.8×10^{-5} cm/sec.

TABLE 3 - SUMMARY OF RESULTS

LOCATION	PRECIPITATION	RUNOFF	Evapotran-spiration	LATERAL DRAINAGE	PERCOLATION	DEPTH OF MOISTURE EXTRACTION	REMARKS
Eastern Washington-1 (Hanford)	Ambient; 12.8 cm (5.04 in.) first year, 26 cm (10.23 in.) total Twice ambient; 22.5 cm (8.86 in.)first year, 49 cm (19.29 in.) total			N/A	None None		
Southeastern Idaho (INEL)		Assumed negligible	>366 mm	N/A	No evidence for vegetated plots.	1.2 m to 2.2 m	Results dependant upon plant type.
Northern Utah (Hill Air Force Base)		LA covers, ≈1% RCRA and Control, ≈3%	LA covers, 85% to 86% RCRA ,71% Control, 82%	LA covers, 6% - 10% RCRA, 21%	LA covers, 12% - 15% RCRA, <1% Control, 20%		Net moisture increase on RCRA cover due to CCL increase in moist.
North-Central New Mexico (Los Alamos)	Total during study (Aug. 1984 - Sept. 1987) 173.72 cm	None from any of the plots	Improved, 95% - 98% Control, 87% - 89%	Improved (only from one), 3 cm	Improved (only from one), 2 cm Control, 11 cm	Control plots down to ≈1 m	Gravel mulch substantially increased plant cover.
South-Central New Mexico (Las Cruces)	Average annual during study 338 mm (13.3 in.)						The wetting front advanced at of 2m /year decreasing to 0.5 m/yr. Got break through in ≈5 yrs. Measurements in nearby vegetated, undisturbed clearly indicated that deep drainage did not occur.

TABLE 3 - SUMMARY OF RESULTS

LOCATION	PRECIPITATION	RUNOFF	Evapotran-spiration	LATERAL DRAINAGE	PERCOLATION	DEPTH OF MOISTURE EXTRACTION	REMARKS
Mojave Desert (Near Beatty Nevada)	1987; 56mm (2.2 in.) 1988; 104mm (4.1 in.) 1989; 14mm (0.6 in.) 1990; 32mm (1.3 in.)		Initially ≈30% less for vegetated. Afterward, ≈0.6 mm/day for vegetated, ≈0.3 mm/day for bare soil		No evidence for significant percolation below 1.25 m		Water storage continually increased in the nonvegetated sites for the duration of the study. In contrast, water that accumulated in the undisturbed, vegetated profile was rapidly depleted by plant transpiration.
Eastern Washington-2 (Hanford)				None	See remarks	Below 5 m water contents remained relatively constant.	When the lysimeter had bare ground as much as 150 mm (5.9 in.) more water was stored in the soils. When vegetation was allowed to reestablish water removal was rapid. When silt loam was covered with gravel and kept free from vegetation, deep drainage occurred. With vegetated <u>sand</u> filled lysimeters above normal precipitation resulted in 20% to 50% deep drainage.

TABLE 3 - SUMMARY OF RESULTS

LOCATION	PRECIPITATION	RUNOFF	Evapotran-spiration	LATERAL DRAINAGE	PERCOLATION	DEPTH OF MOISTURE EXTRACTION	REMARKS
Germany (Near Hamburg)	Annual; 80 cm (31.5 in.) Total; 249 cm (98 in.)	≈ 2%	60% - 70%	30% - 40%	≈ 0% for all.		
Southern Wisconsin (Near Milwaukee)	Annual; 79 cm (31.1 in.) Total; 265 cm (104.4 in.)	Similar for all three at ≈ 8% - 11%	RB1 and RB2 ≈85% CB not measured		RB1; 4.8% RB2; 3.6% CB; 4.6%		It should be noted that the upper clay layer in the CB design became cracked and allowed rapid infiltration into the underlying sand layer. The sand later was able to remove a large portion of that water via lateral flow.
North-Central New Mexico (Los Alamos)	Annual; 47 cm (18.5 in.) Total; 53 cm (20.9 in.)	Clay-Loam Cap, 6.2% Others less.	Conventional ≈ 52% Others at ≈70% to 75%	Clay-Loam Cap, 0.7% Others ≈9%	EPA Rec. 8.5% Loam Cap. 7.2% Clay- Loam Cap. 0.7% Conv. ≈0.7%		The superior performance of the clay-loam capillary barrier was attributed to it's lower saturated hydraulic conductivity.

TABLE 3 - SUMMARY OF RESULTS

LOCATION	PRECIPITATION	RUNOFF	Evapotran-spiration	LATERAL DRAINAGE	PERCOLATION	DEPTH OF MOISTURE EXTRACTION	REMARKS
Central Washington (Near Wenatchee)	Annual; 23 cm (9.1 in.) Total; 53 cm (20.9 in.)	≈ 15% for both designs	≈65% for both designs		Cap. 0.6% Resis. 4.4%		Winters of '92-'93 and '93-'94 had similar amounts of precipitation. In '92-'93 ≈ 1.7 m of snow accumulated. In '93-'94 ≈0.1 m of snow accumulated and the rest of the precipitation was as light rain or snow that quickly melted. During spring of '93 a large pulse of percolation occurred. During the spring of '94 the fine grained layer became nearly saturated but did not exceed it's storage capacity. It was also noted that desiccation cracking and biointrusion occurred in the resistive barrier.

TABLE 3 - SUMMARY OF RESULTS

LOCATION	PRECIPITATION	RUNOFF	Evapotran-spiration	LATERAL DRAINAGE	PERCOLATION	DEPTH OF MOISTURE EXTRACTION	REMARKS
Eastern Washington-3 (Hanford)						Vegetated; 1.25 m with little moisture variation below 1.75 m. Bare Surfaced; Consistent moisture increase to a depth of 2.25 m during the course of the study.	
Capillary Barrier Study	≈0.5 cm/day (0.2 in./day)	Homogeneous Capillary Barrier Design: Lateral drainage began at 43 days. Eventually water broke through the capillary barrier along it's entire length. The percolation rate increased with time while the lateral drainage rate remained relatively constant at ≈ 7 liters 1.8 gallons) per day. Total percolation increased downslope indicating that the capillary barrier was becoming progressively more saturated as the lateral drainage length increased. Layered Capillary Barrier Design: Lateral drainage began on day 35 and increased rapidly to 35 liters (9.2 gallons) per day. About one liter was collected from the most downslope percolation drain. Lateral drainage accounted for ≈ 87% of the daily infiltration.					

Appendix B - Report titled:

"Summary of Survey of Practitioners and Regulators with respect to the Design and Evaluation of Landfill Covers in Arid and Semi-arid Environments"

B.1 Questionnaire: Practitioners

B.2 Questionnaire: Regulators

B.3 Practitioners Response

B.4 Regulators Response

SUMMARY OF SURVEY OF PRACTITIONERSAND REGULATORS WITH RESPECT TO THE DESIGN AND EVALUATION OF LANDFILL COVERS IN ARID AND SEMI-ARID ENVIRONMENTS

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Prepared For:

The State Of Nevada
Department of Conservation and Natural Resources,
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1.0 INTRODUCTION

This report presents the results of the survey that was carried out to asses the current state of practice for landfill closure design and evaluation in arid and semi-arid environments. The survey was performed by means of questionnaires that were sent to practitioners and regulators in the western United States. A total of 28 questionnaires were distributed; 19 to practitioners and 9 to state regulatory agencies. Two of the organizations classified as practitioners were the Uranium Mill Tailings Remedial Action (UMTRA) project group and Sandia National Laboratories (SANDIA). Although these two organizations are not concerned with municipal solid waste (MSW) they were included in the survey due to their extensive research and experience with waste cover systems in arid and semi-arid environments. Fifteen responses were received with practitioners in the states of New Mexico, Arizona and California and regulatory agencies from the states of Utah, Washington, Colorado and California responding. The questionnaires that were distributed are attached in Appendix A. The diversity of opinions and approaches to landfill closure strategies in arid and semi-arid environments is reflected in the different responses to the questions, and at times, different interpretations of the questions contained in the questionnaire. Section 2 of this report contains a summary of the answers to the questions presented. A conclusion is presented in section 3 of this report summarizing the writers thoughts and opinions based upon the review of the responses, numerous telephone conversations that were held during the course of this work and experience gained as a consultant in the containment industry.

It should be noted that reference to "practitioners" and "regulators" in this report should be understood to be practitioners and regulators that responded to the questionnaires. Transcripts of the responses are attached as Appendix B to this report. All responses are identified by state to maintain anonymity.

This report is a portion of Phase I of work being performed under NDEP Interlocal Contract Number DPE96-026 for the State of Nevada, Division of Environmental Protection, Solid Waste Branch. Work that will follow includes a summary of our literature search on past and current research into alternate landfill closure technologies in arid and semi-arid environments and presentation of an infiltration model to use to evaluate landfill closure designs in Nevada.

2.0 RESPONSE SUMMARY

2.1 Regulatory Aspects

Solid Waste Management Plan

All practitioners stated that the state in which they practice has an EPA approved Solid Waste Management Plan. UMTRA, which is a Federally funded Department of Energy (DOE) project, is regulated by the Nuclear Regulatory Commission (NRC) not the EPA and therefore the question did not apply.

Regulators stated that they either had an EPA approved Solid Waste Management Plan (California and Colorado), had submitted a plan and had not heard whether it was approved or disapproved (Washington), or had submitted a plan that was never given approval (Utah).

Prescriptive Standards

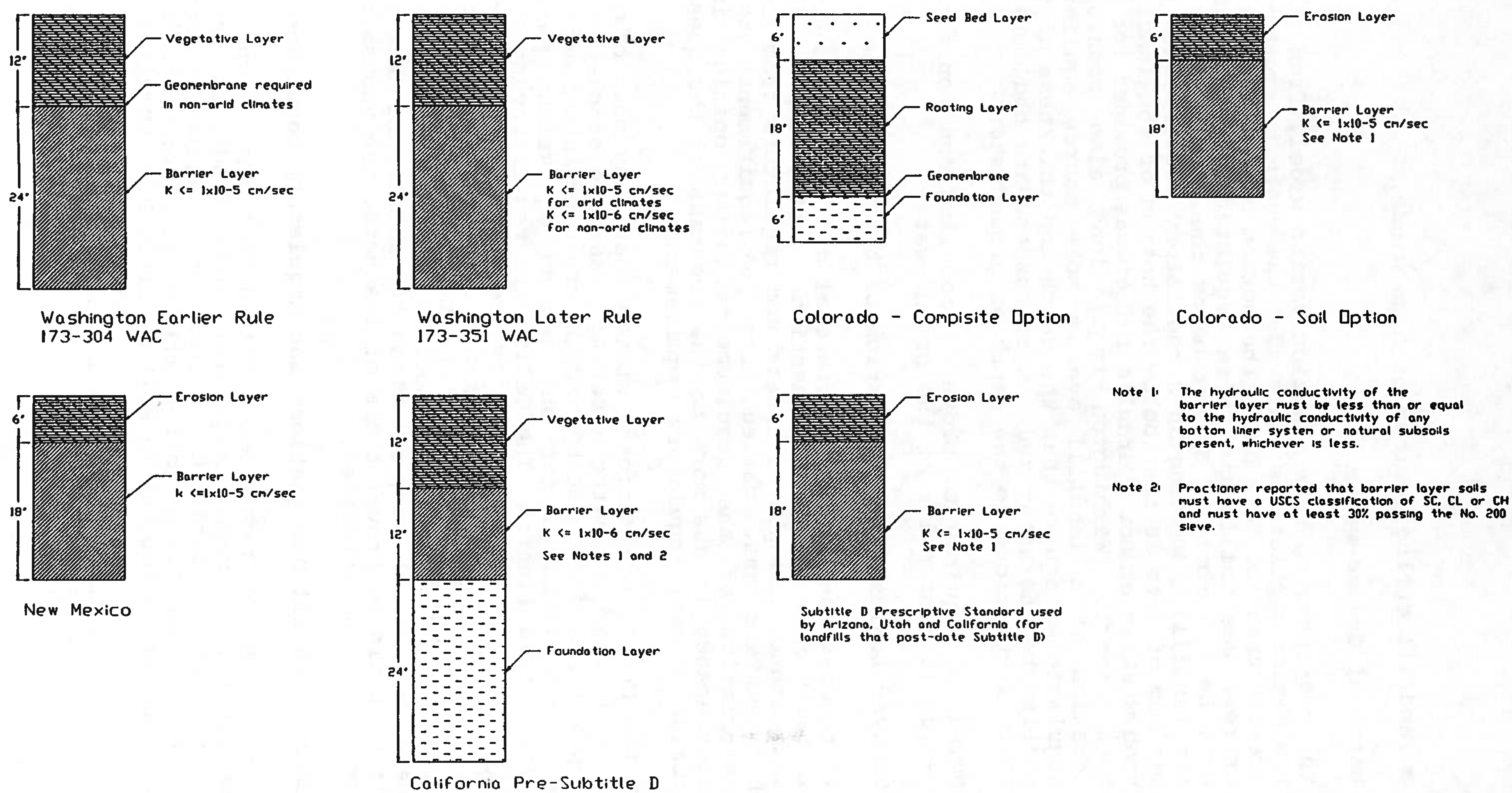
The prescriptive standards for landfill cover systems reported were generally in accordance with 40CFR258, herein after referred to as Subtitle D. There are some differences in requirements of hydraulic conductivities and layer thicknesses and in the requirements for facilities in place before Subtitle D came into effect. The Washington regulatory agency pointed out that they have different cover requirements for arid and non-arid regions of the state. The prescriptive standard cover systems that were described are presented in Figure 1. Also included in Figure 1 are the writers interpretations of States prescriptive standards based upon a review of available regulations.

Regulatory Aspects of Climate, Depth of Ground-water, and Geohydrological Characteristics of the Vadose Zone

Some respondents stated simply that these issues are covered in the regulations which generally emulate Subtitle D. Some of the respondents addressed each item individually, those comments are summarized below. Most of the responses were with respect to siting of new landfills and do not necessarily apply directly to closure of existing landfills. Some practitioners do, however, appear to evaluate these items in the process of designing an alternate closure design for an existing landfill.

Climate

Most of the respondents stated that the only reference to climate in the regulations is with respect to the small landfill designation. There were also general comments that climate is referred to in regulations with respect to design, evaluation and requirements for control of runon and run-off. One regulatory agency also made mention of regulations governing the operation of



MSW Landfill Cover Prescriptive Standards

Figure 1

a landfill during periods of high winds.

Depth of Ground-water

The responses to this question varied widely from state to state. New Mexico regulations state that the depth to ground-water must be greater than 100 feet below the bottom of the landfill. The other extreme was California whose regulations state that groundwater must be a minimum of 5 feet below the bottom of the waste within the landfill. Washington's regulatory requirements varied from a minimum of 5 to 10 feet below the bottom of the landfill depending upon whether or not hydraulic relief was provided for on top of the base liner. Washington regulations also prohibit/discourage location of a landfill over a sole source aquifer. Colorado regulations require that the depth and thickness of the uppermost aquifer be characterized. Most respondents had some reference in their regulations to the depth of groundwater.

UMTRA is required to prove by modeling and monitoring that the design is protective of the ground-water.

Geohydrological Characteristics of the Vadose Zone

In general there was a substantial difference between respondents in their approach to this question. Different practitioners in the same state, and practitioners and regulators from the same state had answers that varied from no requirements to a detailed description of the requirements. Our opinion is that this discrepancy is due more to the openness of the question than to confusion over regulatory requirements.

A New Mexico practitioner stated that they must characterize the site geology including a boring plan with samples collected to a depth of 100 feet. Geohydrologic characteristics determined at the site are required for determining equivalent performance for alternative liners. The California regulatory agency stated the geohydrological characteristics are considered in siting and design of landfills. Colorado's regulatory agency requires characterization of the thickness, stratigraphy, lithology, hydraulic conductivity and porosity of the vadose zone in order to develop a ground-water detection and monitoring network. However, in determining travel times of leachate, the vadose zone is often assumed to be saturated.

Small Landfill Designations and Regulatory Requirements

All of the MSW respondents stated that their regulations made a distinction between large and small landfills except for one California practitioner. California's regulatory agency stated, however, that they follow the distinction implemented by the federal regulation set in RCRA Subtitle D. UMTRA and SANDIA have no difference between large and small landfills due to the nature of the waste with which they are working. Colorado's regulatory agency also provide distinction between landfills in their annual registration fees which are based upon yearly volumes.

Regulatory Monitoring Requirements for Small Landfill Facilities

Each state had different requirements for monitoring of small landfills. Arizona practitioners stated that small landfills in their state had no monitoring requirements. New Mexico practitioners stated that monitoring is required, but it is substantially less for small landfills, and that suspension of groundwater monitoring may be approved for any size landfill. Colorado's regulations require ground-water monitoring, but the monitoring requirement may be waived for small landfills meeting specified site conditions (Ref. Section 1.5.3). California has equal monitoring requirements for all landfills.

More Stringent Levels of Containment

According to most practitioners a more stringent level of containment then the prescriptive standard is not typically required. A California practitioner stated that in southern California the prescriptive standard is usually the base level of enforcement, but that routinely practitioners are held to a higher standard even though it is generally a more arid area of the State.

Most of the regulators that responded stated that they hold the practitioners to a higher standard only under certain circumstances, such as if the landfill is to be a commercial landfill (operated for profit) where the site warrants, if there is evidence that the prescriptive vegetative layer thickness is not adequate protection against frost penetration, in situations were environmental impact has already been significant or where there is a potential for an immediate impact to public health and safety.

2.2 Infiltration Modeling and Climate

Infiltration Modeling

All practitioners in municipal solid waste (MSW) that responded stated that they use the Hydraulic Evaluation of Landfill Performance (HELP) model to estimate infiltration through a landfill cover. Other models that were mentioned were Leachum, UNSAT-2, SUTRA, SEEP/W, SIGMA/W and hand calculations using the method described by McWhorter and Nelson.

The most commonly seen model by the regulators is the HELP model. Colorado made mention of one consultant who has developed a spreadsheet program which has been used to model infiltration.

Regulatory Model Requirement

All of the practitioners stated that no specific model was required by the states in which they practice, but there was a consensus that the HELP model was the most widely used among the practitioners.

All but one of the regulatory agencies stated that they required no specific model for estimating infiltration through a landfill cover. Washington's Chapter 173-351 specifically requires the use of the HELP model or equivalent.

HELP Model Input Variables Regarding Soils, Waste, Vegetation, Precipitation, and Evapotranspiration

The most common response from the practitioners was that they use site specific information when available, but most of the time the HELP model guidance documentation and default values are used to determine input variables. Commonly modification of initial moisture contents and saturated hydraulic conductivities were made from the default values. Most of the practitioners used conservative values to maximize leachate generation and seepage. A few of the practitioners estimate values based on experience or available published data for similar situations. In general, it appears that most practitioners utilized the default HELP values in one form or another. Only one practitioner mentioned budget constraints limiting the amount/type of site specific soil testing performed, however, I believe that it is most likely a common consideration in all projects. UMTRA and SANDIA responded that they perform laboratory testing to determine soil input variables. UMTRA uses the Department of Agriculture's RETC program to interpret the moisture-retention test results and provide the specific parameters necessary for infiltration modeling.

The practitioners rely heavily on the NOAA historical records for climatoligical data. The average precipitation for each project is taken from the nearest NOAA weather station.

Evapotranspiration is typically estimated using the guidelines developed by the HELP model as site specific evaporation and transpiration data is typically rare. One practitioner mentioned the use of pan evaporation data.

Regulatory agencies responded that they have no specific guidelines for development of input variables. Generally the only requirement is that the variables used be as site specific as possible and justifiable.

Typical Values used for Annual Average Precipitation and Evapotranspiration Potentials

Ranges of typical average annual precipitation and average annual evapotranspiration that were reported are presented in the table below by State.

State	Average annual Precipitation, in.	Average annual Evapotranspiration, in.
Utah	8 - 12	Not Reported
Washington	15 - 50 with some areas as low as 6	Not Reported
Colorado	< 10 - > 25	35 - 65 based upon limited data
Arizona	9 - 13	40 - 70
California	20 - 65[1] 5 - 18 <10 - >80	20 - 45[1] 5 - 13.5 <4 - >100
UMTRA	5 - 12	> 40 to > 200
SANDIA	approx. 8	Not Reported

[1] Within practitioners area of practice

Micro-climates

The general comment from both practitioners and regulators is that micro-climates are not specifically addressed but that the most site specific data available is used.

2.3 Hydrogeology

According to all the practitioners the hydrogeology of a site is one of the most, if not the most, important characteristic of a landfill location. The hydrogeologic characteristics that practitioners mentioned as being relevant included hydraulic conductivities of vadose soils, depth to ground-water, quality of the ground-water, gradient and velocity of ground-water and the manner in which the ground-water flows (fracture flow, simple aquifer flow etc.). One practitioner mentioned that varying degrees of success were achieved in negotiating reduced closure requirements based upon ground-water quality and HELP modeling.

According to all of the regulators the hydrogeology must be determined for any proposed landfill location. For all areas the depth to groundwater is one siting criteria. In Washington landfills are discouraged from locating over a sole source aquifer, also regulations in Washington, state that there must be a 1,000 foot buffer zone from the active landfill area to any down gradient water supply well unless it can be demonstrated that the hydraulic travel time in the first useable aquifer is more than 90 days. Hydrogeology is considered in Washington when evaluating a landfill's arid status and associated proposal to not incorporate a base liner. California regulations consider hydraulic conductivity as a siting criteria (Article 3, Section 2530).

Geochemical Attenuation

Practitioners that responded to this question were split on this subject; two responded no, two responded that they have considered geochemical attenuation but that regulatory acceptance was not favorable, one responded that attenuation is sometimes considered depending upon project requirements, and two practitioners responded yes. Both positive responses were from practitioners in Arizona. It seems as though geochemical attenuation considered alone does not provide a strong enough case for regulatory agencies to allow alternate containment strategies. One of the positive responds added that geochemical attenuation was typically evaluated in the vadose zone through laboratory testing and analysis, specifically for clayey layers or fine grained rock units which lie beneath, and down gradient of the landfill cell.

From the regulatory perspective; Utah does not require geochemical attenuation but will consider it on a site specific basis and Washington and Colorado both consider geochemical attenuation. In Washington, geochemical attenuation is considered during fate and contaminant modeling when considering a MSW landfill design with out a liner in an arid area (Chapter 173-351 WAC). The California regulatory agency responded that attenuation of contaminants is addressed in various parts of Article 5, Chapter 15.

2.4 Design Specifications

Specific Design Elements

In general, the practitioners and regulators responded that certain design elements are required by regulation (prescriptive standard) but that alternate designs can be proposed. One evaluation criteria mentioned for comparison of alternate designs was a performance standard (e.g. MCL's at the property line).

Features Used to Minimize Infiltration (e.g. liners, capillary breaks, lateral drainage layers, etc)

All respondents stated that barrier layers (compacted soil liners, geomembranes or composite liners) are used to minimize infiltration. Several practitioners mentioned that geosynthetic clay liners (GCL's) are becoming quite popular. Lateral drainage layers have been used by all the practitioners that responded. Capillary breaks were used by four of the practitioners that responded (including UMTRA and SANDIA). One practitioner responded that they have not as of yet used capillary breaks but was of the opinion that the technology was promising. Another practitioner stated that it was their opinion that "... capillary breaks are not as practical in the field as they are in the lab."

Both the California regulatory agency and practitioner stated that thick monofills were being used as covers. The hydraulic conductivity of the monofill soils were reported to be in the 10^{-4} to 10^{-5} cm/sec range.

Consideration of Potential Infiltration Through a Cover or Consideration of Potential for Infiltrated Water to Migrate Out of the Containment System as a Whole

Practitioners typically consider the system as a whole but at times will consider only infiltration through the cover, for example, when evaluating different cover designs or depending upon the scope-of-work for which they were retained. There seemed to be a general consensus that the entire containment system should be evaluated to assess the potential impact upon the ground-water.

The regulatory agencies generally consider the system as a whole with protection of ground-water being the bottom line.

In a somewhat different context of the question, Washington's regulatory agency responded that they "...do not tie the design of the cover to the nature of the bottom liner...a standard cover design is simpler to administer and does not reward the landfill owner that has no bottom liner or a substandard liner with a lesser cover design than the owner with a higher quality [bottom] liner."

Vadose Zone Monitoring

Vadose zone monitoring is not required in Utah and is required under certain circumstances in Colorado, California, and Washington. For example it is required in Washington for the case of a landfill in an arid region operating without a liner and in California in cases of deep ground-water or fractured bedrock.

Methods Used and Frequency of Measurements

Two methods used for vadose zone monitoring were reported; pan lysimeters (Washington) and wet/dry wells (Colorado). Both of these methods are monitored quarterly and water from the wells are sampled if present.

The wet/dry wells are designed and installed so that they will intercept any leakage from the containment structure based upon a qualitative analysis of the facility type and design and the geology and hydrogeology of the site.

Criteria for Acceptable Performance Based Upon Vadose Zone Monitoring

Washington's regulatory agency stated that any evidence of leachate or waste constituent detected in the vadose zone that violates or could be expected to violate the performance standard would be used to trigger certain regulatory action.

Surface Erosion

All respondents mentioned the use of vegetation (or at least the incorporation of a vegetative soil layer) to minimize erosion. Other common features used to minimize surface erosion include control of runon and run-off, minimizing slopes as much as practical, contouring slopes, ditches and berms, rip-rap and gravel mulches.

Cover Stability

Cover stability is not always performed by all of the practitioners. One practitioner does not perform detailed slope stability analysis because the covers slopes are limited under regulations in the area of practice to 25 percent. While most of the others use one of the slope stability programs that are on the market such as PCstabl, STABL 5, etc. The slopes are also often analyzed for erosion stability. Some practitioners use limiting velocity and tractive force methods for determining the erosion stability, while another practitioner stated that they use the program RUSLE.

Regulatory agencies typically require proof that the slopes of the cover are stable under static and seismic loading. The type of analysis is not specific in most cases.

Potential for Gas Generation

The Colorado, Washington and Utah regulatory agencies responded that they do not require an assessment of gas generation potential. California requires that all new landfills monitor for landfill gas migration.

Most practitioners responded that landfill gas is typically not an issue in arid climates and is not evaluated for in design. Gas monitoring seemed to be fairly common. The California practitioner responded that gas generation is typically assessed. One practitioner made a statement that landfill gas is more of a consideration in a cover design that incorporates a geomembrane rather than a soil barrier.

It was mentioned that new Federal air quality regulations may have an impact on the current state of practice regarding landfill gas.

Performance and Monitoring Data

All of the practitioners collect groundwater monitoring data and most collect gas monitoring data. A California firm gathers post closure data and enters it into a site specific data base to determine overall performance.

Regulatory agencies typically receive monitoring data from the owner/operators on varying schedules.

2.5 Cost and Public Acceptance

Cost of Compliance with Regulations

Generally, the cost of compliance was reported to be much more of an issue with small, rural communities than with the larger metropolitan communities. The cost of implementing regulations and fulfilling the monitoring requirements is especially critical for landfills servicing smaller communities that do not fall under the small landfill designation. Landfills that are operated by municipalities as not full profit operations have also had difficulty implementing regulatory requirements due to cost considerations. It was reported that due to political motivations they are not always able to pass the full cost of compliance on to the consumer and may also be faced with funding restrictions that limit their ability to comply with the regulations.

Based upon the responses that were received it appears that the states of Washington and New Mexico have taken a proactive position on the cost of compliance. It was reported that in New Mexico many rural municipalities and counties formed regional solid waste authorities to combine resources for "... cost-effective, integrated solid waste management solutions." Also, the New Mexico legislature approved $10 million in grant funds targeted for integrated waste management planning, landfill development and closure, and recycling programs. Loans for solid waste programs are also available through the New Mexico Finance Authority.

The state of Washington inacted regulations in 1985 the got many counties and cities looking at the economics of "...continuing the operation of small, poorly run, badly located and designed landfills." The state had matching funds available that helped fund public landfill closures. At the time Subtitle D came into effect it was not such a major issue because many cities and counties had switched to larger, private regional sites whose economies of scale helped to absorb the cost of compliance with the federal regulations.

Delays to Design and Construction Due to the Cost of Regulatory Compliance

There was no definitive consensus on this subject. Many of the practitioners felt that it is an issue but were not able to give specifics. One practitioner stated that it can take up to two years for the permit review process and that the trade off between the cost of permitting and design features that may be controversial must be considered. A regulator's response (from a different state however) to this issue is that the delays are due in part to the complexity of new designs and site conditions and to alternative designs that take more time to review.

One practitioner stated that there are several instances where the construction of a new cell or closure of an existing landfill has been delayed due to cost considerations. It is particularly common for landfills that started operation in the 1970's and require closure in the early 1990's to not have had enough time to generate the money required for closure. It appears that it is common for a landfill to defer closure for as long as possible utilizing a number of "stalling tactics" such as accepting only inert waste to out right refusal to close due to lack of funds.

It was also mentioned that some landfills are delaying implementation of monitoring requirements due to cost considerations.

General Opinion and Response of Public and Local Officials to Regulatory Compliance

Based upon a review of the responses it is apparent that different communities have dramatically varying responses to regulatory compliance. Some communities are very environmentally sensitive and want to comply with every regulatory requirement while others seek to reduce their financial obligation by trying to obtain approval of regulatory exemptions.

Generally, the more rural areas are less receptive to regulations then larger metropolitan areas. This difference in acceptance seems to be primarily cost driven (larger communities can absorb the costs much easier by economies of scale) but it also appears that there may also be a general resistance to regulation in the more rural areas. It was stated that some local governments (Board of Supervisors) will not authorize the solid waste managers to implement the regulations and challenge the State's authority to require them to implement an across-the-board minimum standard.

There was also a general comment that owners and operators are often faced with multiple agencies regulating a landfill resulting in excessive amounts of paperwork and reporting.

Regulators responded that they are often faced with individuals or groups who feel that the current regulations are too stringent and groups of people or individuals who feel that the regulations are not stringent enough.

3.0 CONCLUSION

Based upon the writer's review of the responses, the numerous telephone conversations that were held during the course of this work and his own experience, the following, admittedly somewhat biased opinions are offered:

- There needs to be some assistance given to small rural communities in resolving their solid waste management issues. This should be approached with a win-win attitude from all parties concerned. The most critical first step to this end should be educating the local governing boards and operators. Potential topics that may be covered can include the history and intent of current regulations, the provision for alternate designs that exists in the current regulations and the work that is currently being performed with respect to alternate cover design and evaluation methodologies. People should be cautioned that alternate covers may not provide adequate containment in all situations.

- While the work that is in progress is to develop a methodology to evaluate alternate cover designs, there should be a criteria to which the results of the evaluation can be applied. This criteria may be in the form of a maximum infiltration, maximum leachate generation potential or, based upon some type of risk assessment of potential impacts upon ground-water and the environment.

- In the development of these procedures, there needs to be a distinction made between evaluation requirements for existing landfills and the requirements for proposed new designs.

B.1 Questionnaire: Practitioners

Questionnaire: Practitioner

Regulatory Aspects:

Does your state have an approved Solid Waste Management Plan?

What is/are the prescriptive standard(s) for landfill cover systems in your area of practice?

What, if any, references do the regulations in your area of practice make to:

Climate?
Depth to groundwater?
Geohydrologic characteristics of the vadose zone?

Do the regulations in your area of practice make any distinctions between large and small landfills?

If so, what is the distinction, and what differences are there in regulatory requirements?

Does your state have regulatory monitoring requirements for small landfills?

Are you typically held to a higher standard than the prescriptive standard by the regulatory authority?

If so, why?

Infiltration modeling and climate:

What methods do you use for estimating infiltration through a landfill facility?

Do states in your area of practice require the use of a specific modeling method?

If so, which models?

If not, what model have you used?

If you use the HELP model how have you developed the input variables regarding soils, waste, vegetation, precipitation, and evapotranspiration?

What are typical values used for annual average precipitation and evapotranspiration potentials?

Do you take into account micro-climates within a geographic area?

Hydrogeology:

Do you consider the hydrogeology of an area proposed as the location of a landfill site?

Do you consider geochemical attenuation of contaminant transport?

Design Specifications:

Do states in your area of practice require specific design elements such as soil barriers, geomembranes, geosynthetic clay liners or combinations of these elements?

What design features do you use to minimize infiltration? (e.g. liners, capillary breaks, lateral drainage layers, etc.)

Do you consider only the potential for infiltration through a cover or do you consider the potential for infiltrated water to migrate out of the containment system as a whole? (Do you consider the benefits of leachate collection systems, base liners, etc.?)

What features do you employ to minimize surface erosion?

What method do you use to analyze cover stability?

Do you assess the potential for gas generation?

If so, are there performance criteria and what mitigation measures are specified or used?

Do you collect or acquire performance or monitoring data?

Cost and Public Acceptance:

To what extent has the cost of compliance with the regulations become an issue in your state?

Have the design or construction of any landfill facilities been delayed due to cost considerations related to regulatory compliance?

What is the general opinion and response of the public and local public officials to regulatory compliance?

B.2 Questionnaire: Regulators

Questionnaire: Regulator

Regulatory Aspects:

Does your state have an approved Solid Waste Management Plan?

What is the prescriptive standard for landfill cover systems in your state?

What, if any, references do the regulations make to:

Climate?
Depth to groundwater?
Geohydrologic characteristics of the vadose zone?

Does your state make regulatory distinctions between large and small landfills?

If so, what is the distinction, and what differences are there in regulatory requirements?

Does your state have regulatory monitoring requirements for small landfills?

Do you sometimes require more stringent levels of containment than the prescriptive standard?

If so, why and under what criteria?

Infiltration modeling and climate:

Does your state specify a particular model for estimating infiltration through a landfill facility?

If so, what model do you recognize?

If not, what model has been used by designers in you state?

Does you state have guidelines regarding the development of input variables with respect to soils, waste, vegetation, precipitation, and evapotranspiration?

What are typical values of annual average precipitation and evapotranspiration potentials for your state?

Do you take into account micro-climates within a geographic area?

Hydrogeology:

Does your state consider the hydrogeology of an area proposed as the location of a landfill site?

Does your state consider geochemical attenuation of contaminant movement?

Design Specifications:

Does your state require specific design elements such as the use of soil barriers, geomembranes, geosynthetic clay liners or combinations of these elements?

What features are typically used in your state to minimize infiltration? (e.g. liners, capillary breaks, lateral drainage layers, etc.)

Does your state consider only the potential for infiltration through a cover or do you consider the potential for infiltrated water to migrate out of the containment system as a whole? (Are the benefits of leachate collection systems, base liners, etc. considered?)

Does your state require vadose zone monitoring?

> If so, what type of methods are used and how often are measurements required?
>
> What are the criteria for acceptable performance?

What features does your state require to minimize surface erosion?

In your state what is a typical cover stability analysis procedure?

Does your state require assessment of the potential for gas generation?

> If so, are there performance criteria and what mitigation measures are specified or used?

Does your state collect or acquire performance or monitoring data?

Cost and Public Acceptance:

To what extent has the cost of compliance with the regulations become an issue in your state?

Have the design or construction of any landfill facilities been delayed due to cost considerations related to regulatory compliance?

What is the general opinion and response of the public and local public officials to regulatory compliance?

B.3 Practitioners Response

QUESTIONNAIRE RESULTS - PRACTITIONERS

REGULATORY ASPECTS

Does your state have an EPA approved Solid Waste Management Plan?

New Mexico-1:

New Mexico has EPA regulatory approval for the New Mexico Solid Waste Management Regulations (20 NMAC 9.1) adopted by the Environmental Improvement Board and enforced by the New Mexico Environment Department Solid Waste Bureau. New Mexico has a Solid Waste Management Plan drafted in accordance with the New Mexico Solid Waste Act (1991); however, this plan deals with waste reduction and regionalization efforts and is not subject to EPA approval.

New Mexico-2:

Yes, New Mexico is approved.

Arizona-1:

Yes, they adopted Subtitle D by reference to get approval.

Arizona-2:

Yes, the State of Arizona (through the Arizona Department of Environmental Quality, or ADEQ) is approved by the U.S. EPA to administer the EPA Subtitle D solid waste criteria and regulations.

California-1:

Yes, California has an EPA approved Solid Waste Management Plan.

California-2:

No response

UMTRA:

We are a federal DOE project. We have a separate law (PL95-604). Our regulator is NRC in place of EPA.

SANDIA:

Yes

What is/are the prescriptive standard(s) for landfill cover systems in your area of practice?

New Mexico-1:

EIB/SWMR-4 contains standard cover design requirements including:

6-inch erosion layer capable of sustaining vegetation, 18-inch infiltration barrier layer of soil with a saturated hydraulic conductivity of less than $1x10^{-5}$ cm/sec.

Slopes between 2 and 25 percent

For lined facilities, the liner becomes the standard cover design unless an alternative design may be demonstrated to achieve equivalent performance.

New Mexico-2:

18 inch infiltration layer with saturated K of $1x10^{-5}$ cm/sec; 6 inch erosion layer, gas vents, top slope of 2-5%, side slopes of 4:1.

Arizona-1:

Same as subtitle D; equivalents are being proposed such as GCL's and monolithic covers.

Arizona-2:

The prescriptive standards for municipal solid waste (MSW) landfill cover systems are in accordance with Subtitle D criteria.

California-1:

Title 23 California Code of Regulations, Chapter 15 prescriptive standards require a one-foot thick vegetative soil cover over a one-foot thick $1x10^{-6}$ cm/sec (or equal to the permeability of the bottom liner or underlying natural geologic materials, whichever is less) clay layer over a two-foot thick foundation layer. The root depth of the vegetative layer may not exceed the overall thickness of vegetation in the layer. Clay materials used in the barrier layer must be class SC, CL, or CH and have at least 30% of the material passing the number 200 standard sieve. Foundation layer material may consist of refuse or other waste or contaminated soils provided the material can be compacted to provide a firm and unyielding layer for construction of the barrier layer.

California-2:

No Response

UMTRA:

We have a set of prescriptive standards agreed to by our regulator, see enclosed "Technical Approach Document".

SANDIA:

Subtitle D: 2 feet of soil, 18 inches barrier layer (1 x 10^{-5} cm/sec, Subtitle C: 2 feet topsoil over 1 foot drainage layer (>$1x10^{-2}$ cm/sec) over geomembrane, (40 mil min.) over 2 feet compacted clay ($1x10^{-7}$ cm/sec) or approved equal.

What, if any, references do the regulations in your area of practice make to climate, depth to ground-water, geohydrological characteristics of the vadose zone?

Arizona-2:

Again, considering the adherence to Subtitle D content, reference in the regulations to climate, depth to groundwater and hydrogeological characteristics of the vadose zone relate to the definition of a small landfill (serving a community having annual precipitation less than 25 inches), and the factors which must be considered for an approved design other than the prescriptive design.

California-2:

No response

Climate?

New Mexico-1:

Climate is a factor in performance evaluations of liners, leachate collection systems, and covers.

Small landfill exemptions are available in areas that receive less than 25 inches of annual precipitation.

Precipitation rates are a qualitative factor in the regulators' determination of ground-water monitoring requirements.

New Mexico-2:

Small landfill exemption at locations with less than 25 inches [precipitation] per year.

Arizona-1:

None except for small landfills.

California-1:

None.

UMTRA:

Our standards refer to climate, PMF etc.

SANDIA:

No

Depth to Groundwater?

New Mexico-1:

Depth to ground-water at landfills must exceed 100 feet.

New Mexico-2:

Can't locate at site with depth to water of 100 feet or less.

Arizona-1:

None specifically.

California-1:

High ground-water levels must be a minimum of five feet lower than the bottom of waste within the landfill cell.

UMTRA:

We have to prove by modeling and monitoring that our designs are protective of the ground-water.

SANDIA:

Nothing formal

Geohydrological characteristics of the vadose zone?

New Mexico-1:

The regulations require characterization of the site geology including a boring plan with sample collection to a depth of 100 feet below the deepest fill area.

Geohydrological characteristics of the site are considered in determining the equivalent performance of alternative liners. Less stringent liners may be allowed if it can be adequately demonstrated that ground-water quality will be protected at favorable site locations.

New Mexico-2:

None

Arizona-1:

None

California-1:

None.

UMTRA:

We also have to monitor the vadose zone.

SANDIA:

Nothing formal

Do the regulations in your area of practice make any distinction between large and small landfills?

New Mexico-1:

Small landfills accepting less than 20 tons per day were allowed a longer time frame to comply with ground-water monitoring requirements: until October 1995 if less than two miles to drinking water intake, and until October 1996 if more. Small landfills may also be exempt from liner design requirements. To receive these exemptions, a community must also have no other practicable waste management alternative.

New Mexico-2:

Yes

Arizona-1:

Yes

Arizona-2:

The distinction between large and small landfills is that of Subtitle D; i.e. a small landfill receives less than 20 tons per day of MSW. The differences in regulatory requirements for large versus small landfills are those presented in Subtitle D (exemption from Design Criteria and Groundwater Monitoring); otherwise, the Subtitle D regulatory requirements for small landfills are followed.

California-1:

No.

California-2:

No response

UMTRA:

No differences, all sizes the same.

SANDIA:

No but future legislation may make a distinction - to be decided.

If so, what is the distinction, and what differences are there in regulatory requirements?

New Mexico-2:

Small < 20 tpd, Large > 20 tpd

Arizona-1:

Exactly that allowed by 40CFR258

Does your state have regulatory monitoring requirements for small landfills?

New Mexico-1:

Yes, as noted above. A suspension of ground-water monitoring requirements may be approved for any size landfill.

New Mexico-2:

Yes, but requirements substantially less for small landfills.

Arizona-1:

No, at least not yet.

Arizona-2:

Our experience has been that ground-water monitoring for small landfills is not required by the state.

California-1:

Yes, all landfills have equal monitoring requirements.

SANDIA:

Yes

Are you typically held to a higher standard than the prescriptive standard by the regulatory authority? If so, why?

New Mexico-1:

20 NMAC 9.1 contains requirements that exceed federal standards in some respects; for example the ground-water monitoring requirements are more extensive. The regulators want extensive detail in landfill permit applications, but the requirements generally follow regulatory requirements.

New Mexico-2:

No

Arizona-1:

Not in Arizona.

Arizona-2:

Typically we have not been held to a higher standard than the Subtitle D prescriptive standards.

California-1:

Within Northern California the minimum prescriptive standard is usually the base level of enforcement, you are not routinely required to maintain a higher standard. In Southern California, where the climate is more arid, there appears to be a tendency to more routinely require a higher standard. Generally speaking most engineering consultants recognize and agree that the prescriptive standard California uses is not appropriate for long term performance in an arid climate.

California-2:

No response

UMTRA:

The NRC, our regulator, often holds us to higher standards based on their personal experience and feelings. They justify those additional requirements as "Best Management Practices".

SANDIA:

No

INFILTRATION MODELING AND CLIMATE:

What methods do you use for estimating infiltration through a landfill facility?

New Mexico-1:

HELP modeling is required in New Mexico to evaluate seepage through landfill covers and liners and to estimate leachate generation rates for the design of leachate collection and disposal systems.

MULTIMED modeling is required for estimates of leachate seepage through the vadose zone and potential ground-water impacts.

New Mexico-2:

Usually HELP model.

Arizona-1:

Primarily the HELP model.

Arizona-2:

We typically use the HELP model, SEEP/W and the McWhorter-Nelson simplified method to estimate infiltration. We have in our possession, but have not yet used, the SoilCover Ver. 1.0 model from the University of Saskatchewan.

California-1:

A water balance analysis is typically performed to estimate infiltration to the facility, most commonly the HELP model, Version 3.0 is used.

California-2:

HELP Model.

California-3:

I have utilized the HELP model to model infiltration at all of our landfill closure sites.

SANDIA:

HELP

Do states in your area of practice require the use of a specific modeling method? If so, which models?

New Mexico-2:

HELP used but not specifically required.

Arizona-1:

No

Arizona-2:

The State of Arizona does not require a specific modeling method.

California-1:

Although a specific modeling method is not required by regulation, the HELP Model, Version 3.0 is the most commonly used method.

California-2:

No response.

UMTRA:

We have to prove the model is validated.

SANDIA:

Prefer HELP

If not, which models have you used?

California-1:

HELP Model, Version 3.0, HELP Model, Version 2.0, and Leachum.

UMTRA:

We use UNSAT2, SUTRA, HELP, SEEP/W and SIGMA/W

If you use the HELP model how have you developed the input variables regarding soils, waste, vegetation, precipitation and evapotranspiration?

New Mexico-1:

Typical values are used from the HELP guidance documentation. Site-specific soil laboratory test results are used when possible. Parameters are selected to be conservative to maximize leachate generation and seepage. Information is sometimes sought from the HELP model author.

New Mexico-2:

Depends on site and availability of existing data.

Arizona-1:

We use site specific soil data when available. Often defaults (with modifications of permeability and initial moisture contents) are used.

Arizona-2:

Regarding our use of the HELP model, we usually attempt to estimate soil and waste properties from available published data and our experience with similar materials; occasionally, we will utilize default values. Vegetation input data is usually limited to selecting "bare ground" or "poor grass" default cases. Precipitation data utilized is site specific from available records. Evapotranspiration data is either site specific (rare), is estimated from available published data for site(s) of similar climate, or stored data for a city of similar climate is utilized with adjustment to the temperature data and growing season limits.

California-1:

In some cases the default soil, waste and vegetation information included in the HELP Model are used for modeling purposes. In other situations, where site specific information is available, this information is manually inserted into the model and used for the simulation. Precipitation and evapotranspiration as well as temperature data are manually adjusted for site specific conditions to the nearest default station listed in the program and then the synthetic weather generator is used to provide temperature, precipitation and evapotranspiration information for the site conditions.

California-2:

Grain-size-analysis, bulk density, laboratory perm. testing, HELP Model estimates modified using anticipated trash conditions. Precipitation from nearby rain gauges, evapotranspiration from defaults in HELP Model and pan evaporation rates.

California-3:

Our approach is to obtain as much site specific data as possible. We typically perform site walks and use gathered information in the HELP modeling. If budgets allow, soil samples are collected and analyzed for the HELP model parameters. Climatological data is obtained from County specific records or NOAA monitoring stations. The specific location of the site is also considered and data is adjusted if necessary. When is site specific data is available, the HELP defaults are used [when site specific data is not available].

UMTRA:

We've done laboratory testing and we use the Dept. of Agriculture's RETC program.

SANDIA:

Most practicing engineers use the defaults if available. For my project I used specific real data.

What are typical values used for annual average precipitation and evapotranspiration potentials?

New Mexico-1:

Annual precipitation must be based on NOAA historical records from the nearest weather station. Evapotranspiration potentials utilize HELP default values since site-specific data are generally unavailable.

New Mexico-2:

Depends on site, they vary greatly within New Mexico.

Arizona-1:

Average annual precipitation taken from NOAA weather data, evapotranspiration guidelines used from HELP.

Arizona-2:

Typical values of annual precipitation are in the range of 9 to 13 inches; typical values of evapotranspiration may be 40 to 70 inches.

California-1:

Average annual precipitation within my area of practice ranges from a low of approximately 20 inches per year to a high of 65 inches per year. Evaporation potentials range from approximately 20 inches per year to approximately 45 inches per year. Evapotranspiration potential data is not known.

California-2:

Precipitation; 5 - 18 inches. Evapotranspiration; 5 - 13.5 inches.

UMTRA:

Typical precipitation 5" -12" per year, ET >40" to >200" per year.

SANDIA:

Avg. annual precip. approx. 8 inches

Do you take into account micro-climates within a geographic area?

New Mexico-1:

The best available climatic information is used for any site.

New Mexico-2:

Depends on if we have site specific data.

Arizona-1:

No. Data available from the nearest city is typically used.

Arizona-2:

We do not consider micro-climates in our use of the HELP model except as they may be reflected in site specific climatic data.

California-1:

To the extent that site specific climatology data is available, micro-climates are considered when performing infiltration modeling. In situations where site specific data is not available, general regional data is first used and then modified as appropriate by available localized climatological information.

California-2:

Generally no, unless local data are available.

UMTRA:

Yes

SANDIA:

No.

HYDROGEOLOGY

Do you consider the hydrogeology of an area proposed as the location of a landfill site?

New Mexico-1:

The regulations require consideration of hydrogeology. The depth to ground-water must be at least 100 feet and the ground-water gradient and velocity must be characterized.

New Mexico-2:

Absolutely, regulations have siting criteria.

Arizona-1:

Yes.

Arizona-2:

Yes, the hydrogeology of a proposed landfill site is a critical consideration and merits intensive investigation.

California-1:

The hydrogeological geology of the area is most likely the single most important aspect to be considered when looking at a proposed landfill siting study. Of particular concern is the depth to ground-water, quality of ground-water, the manner in which ground-water flows (fractured flow situation or simplified aquifer flow), and geological properties (i.e. permeabilities of vadose soils).

California-2:

Yes, use MULTIMED

California-3:

The hydrogeology of a site is always a consideration when making management decisions. At many of our small, rural sites, ground-water is of poor quality. We have had varying degrees of success in negotiating with the CIWMB and RWQCB reduced closure requirements based on the results of HELP models and the local ground-water quality. Ground-water quality is a major factor in decision making when available.

Nevada:

We have used an initial investigation to evaluate the suitability of a site as a municipal solid waste landfill. This initial investigation involved:

test pitting to evaluate the surface soils at the site;

rotary drilling to establish depths to ground-water, ground-water flow direction, hydraulic gradient, and to determine the subsurface stratigraphy of the site;

geologic mapping to identify surface faulting or unstable areas; and

sample testing.

UMTRA:

Absolutely yes.

SANDIA:

Yes

Do you consider geochemical attenuation of contaminant transport?

New Mexico-1:

No, geochemical attenuation is not considered. When modeling contaminant transport using a model such as MULTIMED, conservative assumptions are made to maximize the potential for contaminant transport, so sorption and degradation are not considered.

New Mexico-2:

Sometimes, but depends on site, complexity etc, of project. It's not required.

Arizona-1:

Yes.

Arizona-2:

Yes, we typically evaluate the attenuation characteristics of the vadose zone through laboratory testing and analysis, specifically any clayey layers or fine-grained rock units which may lie beneath and down-gradient of the landfill cell.

California-1:

In past efforts to apply geochemical attenuation factors to contaminant transport within California, the Regional Water Quality Control Board has not been receptive to such modeling techniques. The Regional Water Quality Control Board tends to act in a very black and white mode any leakage from the facility will impact ground-water.

California-2:

Used MULTIMED with little or no geochemical attenuation.

Nevada:

[Have] used the EPA Hydraulic Evaluation of Landfill Performance (HELP) model in conjunction with the Multimedia Exposure Assessment Model (MULTIMED), developed by the EPA. The HELP (version 3.04) computer model simulates the movement of water across, into, through, and out of landfills. The effects of surface storage, snowmelt, runoff, infiltration, evapotranspiration, vegetative growth, soil moisture storage, unsaturated vertical drainage, and leakage through soil are taken into account by the model, resulting in an estimate of leakage rates from the bottom landfill layer to the underlying soil. MULTIMED, version 1.01, simulates the transport and transformation of contaminants released from a waste disposal facility into the environment. The model can be used as a technical and quantitative management tool to address the problem of the land disposal of chemicals in the environment. MULTIMED utilizes analytical and semi-analytical solution techniques to solve the mathematical equations describing flow and transport.

UMTRA:

Yes, although it is very difficult to support a case for ground-water protection solely on geochemical attenuation.

SANDIA:

No

DESIGN SPECIFICATIONS

Do states in your area of practice require specific design elements such as soil barriers, geomembranes, geosynthetic clay liners or combinations of these elements?

New Mexico-1:

The regulations include design requirements for a standard composite liner consisting of a FML overlying 2 feet of compacted clay. Alternative designs may be approved, and geosynthetic clay liners are common in New Mexico as a substitute for the compacted clay. These have the advantage of not desiccating in the arid climatic conditions. Cover design requirements were mentioned above.

New Mexico-2:

Yes

Arizona-1:

No, subtitle D prescriptive liner or approved design meeting performance standards (MCL's at property line).

Arizona-2:

The State of Arizona prescriptive design requirements include soil barriers and geomembranes.

California-1:

Title 23 California Code of Regulations, Chapter 15 requires a soil barrier as well as other soil barrier components within the final cover as well as liner systems for landfills. These requirements are superseded by Subtitle D requirements for liner systems (composite liner with two-feet of clay) as well as the cover requirements which basically reflect the liner system requirements.

California-2:

Yes.

UMTRA:

Our regulator expects certain design elements such as a rip rap erosion barrier, sand filter layer, radon/infiltration barriers, frost protection barriers, etc., but they don't specifically require them.

SANDIA:

Yes, see question 2 above. GCL's are becoming very popular here.

What design features do you use to minimize infiltration? (e.g. liners, capillary breaks, lateral drainage layers, etc)

New Mexico-1:

Liners consist of single FMLs or composite designs with lateral drainage layers for leachate collection. Covers are typically comprised of soil only and not FML's, since excellent seepage reduction performance may be demonstrated in arid climates. Such cover designs utilize a capillary break in the sense that the soils provide a moisture storage layer to promote evapotranspiration.

A dry-barrier design was utilized for a mixed (hazardous/radioactive) waste landfill. This patented technology uses air-flow through a coarse layer to remove leakage from below a liner system. Dry barriers may also be utilized in cover designs to enhance performance.

New Mexico-2:

Composite liners (24 inches compacted clay and 30 or 60 mil HDPE).

Arizona-1:

Mostly liners and lateral drainage layers, capillary breaks aren't as practical in the field as they are in the lab!

Arizona-2:

All of the listed features are utilized in design to aid in minimizing infiltration.

California-1:

The most common feature selected to minimize cover infiltration is the type of material used in the barrier layer. If infiltration is of paramount concern, either a thicker section of clay, a geomembrane or GCL, or a composite cover system (geomembrane over clay-GCL) is recommended. In regions of high, short duration rainfall lateral drainage layers are often included to allow a flow path for water and to reduce infiltration as well as slope saturation-stability concerns. My firm has not yet applied a capillary break to a final cover system. However, preliminary reports on this system's performance as well as the basic conceptual model appear to be promising. Other final cover approaches that have been used that have been effective include a three to four foot thick monofill cover. The monofill cover is usually constructed of a higher permeability soil ranging in the 10^{-4} to 10^{-5} cm/sec range and allows for a more substantial vegetative environment with root systems up to two feet. This results in reduced erosion problems, reduced desiccation problems, improved repair methods, and long term performance that more closely matches the initial model conditions. This approach is particularly effective in rural communities where the potential to impact ground-water is less; gas infiltration is not as much of a concern and capital funds available for multi-layered systems are not as readily available.

California-2:

Liners and lateral drainage layers.

Note: No further responses from this source.

California-3:

We have designed FML, GCL, and CCL in the past year. The choice of these liners is typically driven by economic and regulatory issues. GCL liners have become our liner system of choice when a cheap soil source is not available. Simplicity of installation and minimal QA/QC requirements make GCL very attractive for both liner installation and closure projects. Slope stability is always a concern when specifying a GCL at landfills with steep side slopes and site specific stability is a must. FML liners are always the fall back liner when all other choices are exhausted. We have also worked to get native soil covers approved in rural, arid areas (Lassen and Modoc Counties).

UMTRA:

Lateral drainage layers, capillary breaks, vegetation, clay or bentonite amended infiltration barriers have all been used at one time or another but not all together.

SANDIA:

All

Do you consider only the potential for infiltration through a cover or do you consider the potential for infiltrated water to migrate out of the containment system as a whole? (Do you consider the benefits of leachate collection systems, base liners, etc)

New Mexico-1:

Seepage through both covers and liners is considered. Progressive simulations are conducted using HELP to examine seepage potentials throughout the life of a landfill cell from initial opening through post-closure. The liner and cover system must be designed to prevent the "bathtub" effect after closure.

New Mexico-2:

Both, potential affect to GW is bottom line.

Arizona-1:

Depends upon the situation, whether we're doing a cover design, liner design, groundwater model, or leachate collection design.

Arizona-2:

In the course of design, we also consider the potential for migration of leachate out of the landfill cell; i.e., LCRS's and bottom liners are considered and utilized in design.

California-1:

When an infiltration model is used to evaluate comparative final cover options only the performance the final cover is considered. If the infiltration model is being used to determine overall leachate production and to determine the quantities that require treatment, given a potential cover system-liner system combination in the overall system's modeled and in the impacts of leachate collection as well as potential re-circulation are considered.

UMTRA:

We consider the system as a whole.

SANDIA:

Only the cover.

What features do you employ to minimize surface erosion?

New Mexico-1:

Establishment of vegetation is the primary means to minimize erosion. Post-closure maintenance of cover erosion is also expected. Gravel mulch is effective in arid climates to minimize erosion and also to aid in establishment of vegetation.

New Mexico-2:

Revegetation, runon/run off control.

Arizona-1:

Vegetation, slopes, surface armor in desert areas.

Arizona-2:

Surface erosion protection measures include vegetation, rip rap, cement-stabilized alluvium (soil-cement), contour grading, diversion channels, ditches and berms, and similar features.

California-1:

The most critical elements used to minimize surface erosion include: (1) minimization of slopes, when appropriate; (2) increasing the vegetative layer cover thickness to allow deeper root vegetation; (3) use of native vegetative species that have proven drought tolerance capabilities; (4) placement of cut-off and collection ditches at more frequent intervals to minimize run-off lengths (use of benches or similar activities); (5) use of rock or cobble material within the vegetative layer to provide greater resistance to erosion as well as animal burrowing.

California-3:

Erosion control is typically achieved through the use of geosynthetics and a well established vegetative cover. We try to avoid use of concrete and asphalt in our designs. Landfill settlement makes maintenance of concrete and asphalt covers a significant post closure cost issue. We have specified the use of either rip-rap or erosion control blankets depending on the flow velocities in the drainage structures. These structures are "low tech" and easy to repair.

UMTRA:

Rip rap layers and vegetation

SANDIA:

Vegetation, gravel mulches

What methods do you use to analyze cover stability?

New Mexico-1:

Detailed cover slope stability calculations are generally not performed for soil covers, since slopes are limited under the regulations to 25 percent. If FMLs are used in a cover design, a more extensive cover stability analysis is needed; however, alternative soil covers without FMLs are generally allowed in New Mexico.

New Mexico-2:

Not sure what you mean by "stability" seismic? or what?

Arizona-1:

RUSLE

Arizona-2:

Cover stability is usually analyzed using PC STABL for overall stability and interlayer stability, and regime theory, limiting velocity or tractive force methods for analysis of stability of cover materials against erosion and transport.

California-1:

Typical slope frictional models are used to analyze the stability of cover soils or veneered cover soil components on final cover slopes. If the general integrity of the slope is a concern, a slope stability analysis performed using a variety of available programs is utilized to determine the overall stability of the slope for the final cover profile or as it may be the liner profile. Where critical, site specific soil information as well as geosynthetic-soil interface testing is performed and utilized for modeling purposes.

UMTRA:

For slope stability we use the STABL5 program, for erosion stability see "Technical Approach Document".

SANDIA:

No response

Do you asses the potential for gas generation?

New Mexico-1:

Gas generation is limited in arid landfills and is not examined in detail during design. Methane is generally allowed to escape passively through the soil cover, which allows significant gas fluxes because the cover soil has a very low moisture content. Venting systems are generally not needed since low permeability covers are not utilized.

Methane monitoring is required at the perimeter of the landfill to ensure against off-site migration and on site buildings must be monitored for explosive methane levels.

New air quality regulations recently promulgated under 40 CFR 9, 51, 52, and 60 will require future designs to consider gas generation in more detail for larger landfills that must comply with the new requirements.

New Mexico-2:

Yes, methane.

Arizona-1:

Not typically in arid areas unless there is a problem.

Arizona-2:

The potential for gas generation is not usually specifically analyzed. The performance criteria are as presented in Subpart C of Subtitle D (Explosive Gases Control). Mitigation measures usually consist of gas monitoring wells for detection and a collection system tied to the wells, if necessary.

California-1:

Yes, typically gas generation is assessed either by performing a gas generation calculation considering the age, type, composition, and moisture content of the refuse or by performing specific perimeter migration monitoring and surface emissions monitoring to evaluate the potential release of gases in the landfill.

California-3:

Gas generation is always a concern for landfills receiving FML caps. Active gas collection systems are usually installed at landfills with capacities over 1,000,000 tons. Passive venting systems are used at smaller landfills. The requirements of local Air Boards also greatly influences the configuration of gas systems. The requirement of the new EPA landfill gas regulations should have a big impact on gas management outside of California where air regulations are not as strict.

UMTRA:

Yes, radon gas is our major concern see "Technical Approach Document".

SANDIA:

No

If so, are there performance criteria and what mitigation measures are specified or used?

New Mexico-2:

Vents, piping, barriers etc., but no prescriptive requirements.

California-1:

Title 14 California Code of Regulations has established on-site methane and perimeter methane migration levels of 1.25% and 5%, respectively. Until the adoption of the EPA NSPS and EG requirements these were used as a specific control criteria for establishing a need for landfill gas collection destruction systems. Additional, local air districts have adopted specific requirements typically based upon size of the facility and surface emission. However, these requirements vary greatly across the state.

Do you collect or acquire performance or monitoring data?

New Mexico-1:

Ground-water monitoring is the most common means of gathering data to assess landfill performance with respect to ground-water impacts. Vadose zone monitoring is also performed through collection of soil samples and installation of lysimeters to collect pore fluids from beneath landfills. Leachate volumes are recorded and leachate chemical quality is tested.

New Mexico-2:

Just methane and groundwater monitoring as required in regulations.

Arizona-1:

Yes, sometimes.

Arizona-2:

Yes, we do collect monitoring data for gas monitoring wells.

California-1:

Postclosure monitoring services are provided by my firm and the data is entered into a site specific data base to determine overall performance. On a more general level, as data become available through my firm and other consultants a generic data base is being prepared that assess the overall performance of a variety of cover systems. In the case of GCL's, my firm has performed laboratory large scale permeability/desiccation recovery testing as well as field desiccation/insitu moisture content/moisture recovery testing to better understand the long term field performance of GCL's and final cover systems. This testing has resulted in a general understanding that within California's Central Valley environment, GCL's do not release all the moisture as was once expected and thus do not result in the dried out clumped bentonite particles that could result in increased infiltration during initial storm events.

UMTRA:

Yes, from monitoring wells, settlement plates, and geophysical analysis.

SANDIA:

Yes, see papers.

COST AND PUBLIC ACCEPTANCE

To what extent has the cost of compliance with the regulations become an issue in your state?

New Mexico-1:

In New Mexico, many rural municipalities and counties have formed regional solid waste authorities to combine their resources for cost-effective, integrated solid waste management solutions. Larger communities appear to be able to fund their solid waste management programs through taxing authority and increases in disposal rates.

The New Mexico Legislature approved $10 million in grant funds that are currently being distributed to government entities that were selected in a proposal process implemented by the New Mexico Environment Department. The money will go to fund integrated waste management planning, landfill development and closure, and recycling programs. Loans for solid waste programs are also available through the New Mexico Finance Authority.

New Mexico-2:

Big issue for small landfills.

Arizona-1:

Don't know, obviously it's a concern to owners/operators.

Arizona-2:

It is believed that the cost of compliance with landfill regulations has become an issue within Arizona particularly with regard to operators (both private owners and municipalities) of existing landfills in semi-rural areas which don't qualify as small landfills, in that implementation of the design criteria and adherence to groundwater monitoring requirements (specifically, the cost of well installation and monitoring for a laundry list of chemical constituents) can become prohibitively expensive.

California-1:

The cost of compliance is a critical issue when it comes to compliance with regulations for municipalities who are not operating on a full profit basis, the cost becomes a direct pass-on to the consumer and quite often due to political reasons of local governing boards will not allow the cost to be passed on or will limit the ability of the operators to fully comply with the programs due to funding restrictions. In many cases this results in the need for an alternative program to be developed which meets the intent of the regulatory requirements but may not specifically follow the protocols established. For larger companies that specialize in waste management and disposal, the cost of compliance becomes an immediate impact to their bottom line and thus, they are resistant to implement programs until the last possible minute and usually look for some type of alternative or minimized action to meet the regulatory requirements.

California-3:

Cost is always a concern in landfill projects. This is especially true with regards to landfill closure. The major problem we see today is lack of adequate closure and postclosure funding. Many local and private operators did not put enough money into closure funds during operations prior to the implementation of Subtitle D. Subtitle D has forced many landfills to close early. As a result, there is less cash flow to fund closure. Many clients have resorted to stalling tactics to avoid closure. These tactics range from keeping a landfill open by accepting only inerts (effectively extending some landfill lives indefinitely) to outright refusal to proceed with closure due to lack of funding.

UMTRA:

Don't know.

SANDIA:

Majority want change, but need data to show alternative comparisons with standard covers.

Have the design or construction of any landfill facilities been delayed due to the cost of regulatory compliance?

New Mexico-1:

Regulatory compliance costs are substantial for new and existing landfills. The permit review process generally takes two years, including the required public hearing process. The regulator's initial review of a landfill permit application is taking more than six months, followed by a series of responses to additional requirements. Landfill design must consider financial trade-offs between permitting costs and design features that may be controversial.

New Mexico-2:

Don't know.

Arizona-1:

Not directly.

Arizona-2:

I do not know of any specific instances in which design or construction of a landfill was delayed due to the cost of regulatory compliance, however, I believe there have been numerous landfills which were closed and/or converted to transfer stations.

California-1:

There are several instances where construction of a new landfill cell or closure of a landfill has been delayed due to cost considerations. This is particularly common with landfills that have started operation in the 70's and have required closure in the early 90's and have not had the adequate number of years to provide the finance mechanisms to obtain moneys to support the cost of closure. As a result, these moneys must be obtained from general funds or other source mechanisms. For smaller, rural communities, it is fairly common to defer closure for as long as possible after the site has stopped operation in order to minimize the immediate impact of these construction costs.

UMTRA:

In New Mexico, many of the municipal landfills have delayed environmental monitoring due to cost considerations.

SANDIA:

Yes, but I don't know details.

What is the general opinion and response of the public and local officials to regulatory compliance?

New Mexico-1:

Various communities differ substantially with regard to public opinion and the ability of local governments to finance solid waste management efforts. Some communities want to meet every regulatory requirement and emphasize environmental protection, while other communities are interested in reducing their financial obligations by seeking approval of regulatory exemptions. The degree of community support or opposition to new landfills is highly variable. In general, New Mexico's rural character allows landfill siting with minimal public opposition. Waste disposal rates in New Mexico remain well below national averages, and the cost of regulatory compliance is not a highly publicized issue.

New Mexico-2:

They comply grudgingly, compliance is especially difficult in the rural counties with low population.

Arizona-1:

Most generally believe in the necessity for rules and understand the importance of compliance. By the same token, owners/operators do not readily agree to anything that could be above and beyond the minimum regulatory requirements.

Arizona-2:

No response is offered.

California-1:

The opinion of local public officials is somewhat varied dependant upon if they are in rural areas or a more metropolitan region. Rural regions generally consider required compliance to be a state bugging into local affairs. Quite often what the state or federal government considers to be a low end cost can be a substantial burden to a small rural county that has a very small tax base. As a result, the board of supervisors will not authorize the local solid waste managers to implement programs and will often challenge the state's authority to require them to implement programs applying what they consider to be a common sense rule in terms of providing what you absolutely need to have rather than applying an across the board minimum standard. In larger metropolitan regions the cost of compliance is more easily distributed over a large base and generally there appears to be a greater level of public acceptance for higher costs and more of a demand for improved protection and safety of facilities. Again this is somewhat contrary to the nature of rural counties. Many of the individuals that live in rural counties are there to escape the impact of large costs and public systems being applied to them and instead prefer to have a much more fend for yourself type of attitude.

California-3:

Overall the opinion of the landfill operator is that there is over regulation. Most operators do not oppose environmental compliance and the general intent of the regulation. The primary opposition is found in the use of multiple agencies to regulate the landfills and the amount of paperwork that is required to comply with the regulation. Smaller operators do not have the expertise to understand and comply with regulations. This is especially true for small, rural facilities. The current regulations treat small and large landfills in a similar fashion. Unfortunately many local public agencies cannot afford to comply.

UMTRA:

Don't know.

SANDIA:

Based upon our public involvement (1000+ stakeholder groups), the public and regulators are anxious for improvement in landfill cover technologies, particularly when it comes to cost and performance.

B.4 Regulators Response

QUESTIONNAIRE RESULTS - REGULATORS

REGULATORY ASPECTS

Does your state have an EPA approved Solid Waste Management Plan?

Utah:

Utah submitted a state solid waste plan to EPA but the plan was never given approval. Utah has conducted a solid waste planning effort in 1992 but that plan was never submitted to EPA.

Washington:

We prepared and submitted the "Washington State Solid Waste Management Plan, January, 1991" to the EPA, who has neither approved or disapproved the document.

Colorado:

Yes.

California:

California is an authorized state for implementing the RCRA subtitle D Municipal Solid Waste Landfill requirements.

California-2:

Yes, California is an approved state as of October 1, 1993. United States Environmental Protection Agency (USEPA) has determined that existing California regulations are functionally equivalent to Federal Subtitle D Municipal Solid Waste (MSW) regulations. The approval was based upon the California Code of Regulations, Title 23, Division 3, Chapter 15, Discharges of Wastes to Land (Chapter 15); and State Water Resources Control Board (SWRCB) Resolution No. 93-62 Policy for Regulation of Discharge of Municipal Solid Waste (SWRCB 93-62). Also, Title 14, Division 7, California Integrated Waste Management Board (CIWMB) contains non-water quality requirements for landfills.

What is the prescriptive standard for landfill cover systems in your state?

Utah:

Utah has used the federal rules to define cover requirements.

Washington:

We have two sets of landfill standards:

Chapter 173-304 WAC passed in 1985 which is used for all landfills except municipal landfills. It sets a prescriptive cover standard of two feet of soil having a maximum permeability of $1x10^{-6}$ cm/sec for non-arid areas; and a prescriptive standard of two feet of soil having a maximum permeability of $1x10^{-5}$ cm/sec for arid areas of the state. An arid area is defined as an area having less than twelve inches of precipitation per year. Both designs must be topped with six inches of vegetative cover.

Chapter 173-351 WAC passed in 1993 which uses the prescriptive federal standards of 30/60 mil geomembrane underlain with two feet of soil having a maximum permeability of $1x10^{-5}$ cm/sec permeability and topped with a one foot vegetative layer for non-arid areas; and a prescriptive standard of two feet of soil having a maximum permeability of $1x10^{-5}$ for arid areas of the state. The arid design must also be topped with a one foot vegetative layer.

Colorado:

Soil Design - 18 inch infiltration layer, permeability of less than or equal to that of the bottom liner system or natural subsoils, or permeability no greater than $1x10^{-5}$ cm/sec, whichever is less. An erosion control layer of six inches, or greater, that is capable of sustaining native plant growth.

Composite Design - six inch soil foundation layer; geomembrane barrier layer with a minimum of 30 mil thickness; 18 inch soil rooting layer; six inch soil seed bed layer.

California:

We implement the prescriptive standard contained in

Subtitle D. For sites that predate the RCRA Subtitle D regulations, the prescriptive standard is 2 feet of foundation layer, 1 foot of a minimum $1x10^{-6}$ cm/sec barrier layer or equal to permeability of any bottom liner or natural geologic materials whichever is less, and a 1 foot vegetative layer.

California-2:

See Chapter 15, Article 8, and Title 14, §17225 for landfill cover systems.

What, if any, references do the regulations make to climate, depth to ground-water, geohydrological characteristics of the vadose zone?

California:

All of these are considered in siting and design of landfills in California. The specifics of each of these factors depends on the classification of the waste being disposed of in a particular landfill. We would refer you to the California Code of Regulations, Article 3, Section 2530 (attached).

California-2:

These issues are addressed in Article 3 of Chapter 15 (Waste Management Unit Classification and Siting).

Climate?

Utah:

The only reference to climate is in the small landfill definition which is the same as the federal definition.

Washington:

See response to 1.a above; we have similar bottom liner requirements that vary from arid to non-arid areas in both sets of regulations.

Colorado:

Facilities must cease operations during periods of high wind warnings defined as sustained winds of 40 mph or gusts of 55 mph or greater to persist for one hour or longer.

Facilities must control run-on and run-off from the peak discharge from the 25-year, 24-hour storm event during active life, and control and the water volume from the 100-year, 24-hour storm event both during the active life and post-closure.

Climatic factors must be considered during the liner design phase of proposed facilities.

Depth to Groundwater?

Utah:

Utah rules have siting criteria for new landfills that include depth to groundwater.

Washington:

Both regulations have siting criteria that require at least 10 feet of separation between the bottom of the lowest liner and the seasonal high level of the ground-water. The distance can be reduced to 5 feet for liners having an engineered hydraulic gradient control system.

Colorado:

The depth to and thickness of perched zones and uppermost aquifers are required data in the engineering design and operations report. The regulations specifically prohibit placement of waste into groundwater.

Geohydrological characteristics of the vadose zone?

Utah:

No reference in the Utah rules.

Washington:

Not directly, but we do have a siting criteria that prohibits locating a landfill above sole source aquifer as designated by EPA under the Safe Drinking Water Act. See also response to question 4.a., below.

Colorado:

The thickness, stratigraphy, lithology, hydraulic conductivity, porosity and effective porosity of the vadose must be characterized in the process of developing a ground-water detection monitoring network. Engineering design and operation reports typically contain an estimate of the time of travel for leachate to migrate off-site, assuming worst case scenario of failure of the liner system. However, the usual approach to this calculation assumes saturated conditions in the vadose zone.

Does your state make regulatory distinction between large and small landfills?

Utah:

Yes, Utah has adopted the federal distinction of under 20 tons per day and allows exemption from the design requirements. Gas monitoring and ground-water monitoring are currently required but the ground water requirement will be removed to conform with the exemption for small landfills recently passed by Congress.

Washington:

The earlier regulation, ch. 173-304 WAC, has a 200,000 cubic yard threshold, below which the need for a liner and leachate collection system is evaluated on a case-by-case basis; the later regulation, ch. 173-351 WAC, has a 100 ton per day threshold for allowing existing landfills to close, meeting only the cover design requirements. The state has no very small municipal landfills that would otherwise be exempted from ground-water monitoring under the 20 tpd threshold.

Colorado:

Yes.

California:

Since we are an authorized state for implementing RCRA Subtitle D, we follow the distinctions contained in the federal regulations.

California-2:

Chapter 15 contains minimum requirements and provides for more stringent requirements if necessary. Requirements are determined on a site-specific basis and may be modified at the discretion of the appropriate Regional Water Quality Control Board (RWQCB). There are nine RWQCB's (see enclosed map), which are the State agencies having responsibility for direct oversight of water quality.

If so, what is the distinction, and what differences are there in regulatory requirements?

Colorado:

In Colorado, the solid waste program is primarily funded through annual registration fees and technical review fees. The annual registration fee is based on the amount of waste disposed annually. The fee ranges from $6,000 per year for facilities accepting 600,000 or more cubic yards per year, to $250 per year for facilities accepting less than 10,000 cubic yards.

Does your state have regulatory monitoring requirements for small landfills?

Colorado:

Yes. All landfills are subject to standard monitoring requirements. However, for small landfills, i.e. those that accept an annual aggregate average of less than 20 tpd, a waiver may be granted for the design and ground-water monitoring requirements. If such a waiver is granted, it is done in consultation with the local governing body having authority and additional, site-specific conditions must exist as described in section 1.5.3 of the regulations.

Do you sometimes require more stringent levels of containment than the prescriptive standard? If so, why and under what criteria?

Utah:

For commercial landfills (those that are operated for a profit) the standards may be increased where the site warrants.

Washington:

Yes (presumably you are referring to cover systems), in response to evidence that the one foot vegetative layer is not adequate protection against frost penetration in colder parts of the state.

Colorado:

No.

California:

Situations where there is already significant environmental impacts or there is the potential for an immediate impact to public health and safety might require containment that is more stringent than the prescriptive standard.

California-2:

Yes, see above comment.

INFILTRATION MODELING AND CLIMATE:

Does your state require a particular model for estimating infiltration through a landfill facility? If so, what model do you recognize?

Utah:

No specific model is required but the HELP model is generally used.

Washington:

Chapter 173-304 WAC does not; chapter 173-351 does.

The HELP model or equivalent.

Colorado:

No, we do not.

California:

California landfill regulations are based on performance standards and do not contain specific models for estimating infiltration into the landfill. The HELP model is a commonly used infiltration model.

California-2:

None is specified, however, the HELP model is widely used.

If not, what model has been used by designers in your state?

Colorado:

The most commonly used model is the HELP model. At least one consultant has developed a Lotus spreadsheet which that firm has used to model infiltration.

Does your state have guidelines regarding the development of input variables with respect to soils, waste, vegetation, precipitation and evapotranspiration?

Utah:

No guidelines are used. Each model must show the variables used and justify why each is used.

Washington:

No.

Colorado:

Only in that the data be as site specific as possible. For example, for constructed portions of the landfill cross section (liner and cover barrier layers, etc.), initial moisture contents for the infiltration model should be the same as those specified for construction (i.e., optimum moisture plus or minus 2%). Also, site specific meteorological data should be used if such data is available.

California-2:

No, however, the HELP model has default values for soil type, rainfall data, etc.

What are typical values used for annual average precipitation and evapotranspiration potentials for your state?

Utah:

8 to 12 inches of precipitation per year and evapotranspiration would be from weather data for the site.

Washington:

Western Washington, 50 inches; Eastern Washington 15 inches (although significant parts of eastern Washington are below 12 inches and some parts as low as 6 inches of annual precipitation).

Colorado:

Average annual precipitation ranges from less than 10 inches in more arid areas to over 25 inches in mountain climates. Available data on annual evapotranspiration are limited, but generally range from 35 inches to 65 inches. More specific information is available through the state meteorologist office at Colorado State University in Fort Collins, Colorado.

California-2:

There is considerable variation in average precipitation and evapotranspiration. Mean annual precipitation in California ranges from less than 10 inches to greater than 80 inches. Evapotranspiration ranges from less than four inches to greater than 100 inches.

Do you take into account micro-climates within a geographic area?

Utah:

This data would be used only if the site had specific weather data.

Washington:

Other than the less than 12 inches of precipitation definition of "arid", there are not any other climatic distinctions made in either regulation.

Colorado:

Only if micro-climates are reflected in site specific meteorological data, and such data are available and used in the model.

California-2:

Proposed landfill sites are evaluated on a site-specific basis as much as possible. The best available data is used. See Article 9, Chapter 15.

Does your state consider the hydrogeology of an area proposed as the location of a landfill site?

Utah:

Depth to ground-water is one siting criteria for new landfills.

Washington:

Yes. Landfills are discouraged from locating over sole source aquifers in Washington state, although there are ways to demonstrate that a landfill will not impact such an aquifer in each regulation. There are also requirements in each regulation for a 1000 foot buffer zones from the active area to any down gradient water supply well, unless an owner or operator can demonstrate that the hydraulic travel time in the first useable aquifer is more than 90 days. Also hydrogeology is considered when considering whether to allow a landfill to be constructed in an arid area (see response 4.a. below).

Colorado:

Yes.

California:

Site permeability is considered in the siting criteria for landfills. We would refer you to California Code of Regulations, Article 3, Section 2530 (attached).

California-2:

Hydrogeology is assessed as required in Chapter 15, Article 5 and Article 9.

Does your state consider geochemical attenuation of contaminant movement?

Utah:

Utah rules do not require this consideration but it may be used on a site specific basis.

Washington:

Geochemical attenuation is considered during fate and contaminant modeling when considering whether to allow a municipal landfill to be constructed without a liner in an arid area under ch. 173-351 WAC. This approach is not spelled out in ch. 173-304 WAC, however.

Colorado:

Yes.

California-2:

Yes, attenuation of contaminants is addressed at various points in Article 5 (Water Quality Monitoring and Response Programs for Waste Management Units) of Chapter 15; e.g., Subsection 2550.4(d).

DESIGN SPECIFICATIONS

Does your state require specific design elements such as soil barriers, geomembranes, geosynthetic clay liners or combinations of these elements?

Utah:

The standard design in the Utah rules is a composite liner. However, alternatives are allowed where the permittee can show that the design is protective of the ground-water.

Washington:

Yes. (The following describes the bottom liner requirements; landfill cover design elements are described in response to 1.b above.) Both regulations have prescriptive designs but allow alternative designs that are engineering equivalents of the prescriptive liner design. The older rule, ch. 174-304 WAC, specifies four feet of soil having a maximum permeability of no more than $1x10^{-7}$ cm/sec or a composite liner of 50 mils geomembrane on top of two feet of soil having a permeability of no more than $1x10^{-6}$ cm/sec. The municipal landfill rule, ch. 173-351 WAC, specifies the EPA standard design of 30/60 mil geomembrane over two feet of soil having a permeability of no more than $1x10^{-7}$ cm/sec. Please note that landfills located in arid zones are not required to have any liner:

Under ch. 173-351 WAC, if the owner or operator can demonstrate through the use of a fate and contaminant transport model that the ground-water standards will be met at the point of compliance;

under ch.173-304 WAC, if the owner or operator installs and performs vadose zone monitoring.

Colorado:

Yes.

California:

California landfill regulations are based upon performance standards, with a specific prescriptive design but with allowance for engineered alternatives that meet certain criteria.

California-2:

Yes, design elements are covered in Article 4 of Chapter 15 (Summarized in Table 4.1), and SWRCB Resolution No. 93-62 (Liners and LCRS for MSW landfills) which provides requirements for implementation of Chapter 15 and Federal MSW Regulations by RWQCBs.

What features are typically used in your state to minimize infiltration? (e.g. liners, capillary breaks, lateral drainage layers, etc)

Utah:

Composite liner or siting where the ground-water will not be impacted.

Washington:

Liners are most typically used to minimize infiltration through covers and in landfill bottom liners.

Colorado:

The design standard required by our Solid Waste Regulations includes a cover consisting of 6 inches of growth medium underlain by 18 inches of low permeability soil, and a liner consisting of 12 inches of leachate drainage material underlain by 36 inches of low permeability soil. The maximum allowable coefficient for the cover barrier layer is 1×10^{-5} cm/sec or the coefficient of permeability for the liner (whichever is lowest), and the maximum allowable coefficient for the liner is 1×10^{-7} cm/sec.

California:

Containment systems for both liners and covers will utilize designs incorporating individually or in combination clay, geosynthetics, GCL's, and in some cases relatively thick (5 feet or greater), low permeability (10^{-5}) monolithic soil covers.

California-2:

Primarily surface drainage control and final cover systems as explained in Article 4 and Article 8 of Chapter 15.

Does your state consider only the potential for infiltration through a cover or do you consider the potential for infiltrated water to migrate out of the containment system as a whole? (Do you consider the benefits of leachate collection systems, base liners, etc)

Utah:

Infiltration is considered but the impact on ground-water is the most important factor.

Washington:

We did not adopt the EPA standards that try to tie the design of the cover to the nature of the bottom liner installed (the "bathtub" effect). A standard design is simpler to administer and does not reward the landfill owner that has no bottom liner or a substandard liner with a lesser cover design than the owner with a higher quality liner.

Colorado:

We consider the performance of the containment system as a whole.

California:

Current design standards are based on the concept of "dry tombing" solid waste. Therefore, base liners and leachate collection and treatment systems are typically required.

California-2:

The cover is required to minimize infiltration. Releases from the base liner are generally not allowed (See Article 3). Base liners and LCRS are required per Chapter 15 and SWRCB Resolution No. 93-62. The possible presence of construction water (water released from a compacted clay liner) and infiltrated precipitation contained in an LCRS is typically considered, where appropriate.

Does your state require vadose zone monitoring?

Utah:

No

Washington:

No, except in the case of arid landfill operating without a liner in ch. 173-304 WAC.

Colorado:

Yes, in certain circumstances.

California:

Yes; we would refer you to California Code of Regulations, Article 3, Section 2550.11.

California-2:

See Title 23, §2550.11. Vadose zone monitoring is not generally required. Primary monitoring is provided by ground-water monitoring wells. In certain cases (deep ground-water, shallow fractured bedrock), vadose zone monitoring is required to supplement ground-water monitoring and the containment system as an early warning of releases from the unit.

If so, what types of methods are used and how often are measurements required?

Washington:

I have attached a copy of our Technical Interpretative Memorandum that specifies the design of a pan lysimeter for vadose zone monitoring beneath non-municipal arid landfills; quarterly monitoring is required.

Colorado:

At smaller MSW facilities where the depth to ground-water and other conditions warrant, we allow the installation and monitoring of wet/dry wells. These wells usually penetrate a short distance past the bottom of the waste containment. The wells are monitored quarterly, and are sampled if water is present.

What are the criteria for acceptable performance?

Washington:

WAC 173-304-460(3)(c)(iv)(B) specifies that "any evidence of leachate or waste constituents detected in the vadose zone that violates or could be expected to violate the performance standard of WAC 173-304-460(2)" would be used to trigger certain regulatory actions.

Colorado:

The criteria for acceptable performance are that the wet/dry wells be designed and installed so that they will intercept any leakage from the containment structure. This criteria is based on a qualitative analysis of the facility type and design and the geology and hydrogeology at the site.

What features does your state require to minimize surface erosion?

Utah:

Erosion is minimized through the proper contouring and through the maintenance of a plant or other suitable cover.

Washington:

Ch. 173-304 WAC requires cover slopes to be between 2 and 33 percent in addition to six inches of vegetative cover over the infiltration layer; and
Ch. 173-351 WAC requires a vegetative layer of 12 inches (but no slope requirements).

Colorado:

During the design stage, facilities with long slopes at 4H:1V or steeper, are usually required to perform an analysis of soil loss using the Universal Soil Loss Equation. If the predicted loss exceeds 2 tons/acre/year, changes in the reclamation plan or the design are required. During operations and closure, inspections of the final cover to determine performance and resistance to erosion are required. If problems are observed, corrective actions are implemented.

Also, storm water management plans are required for most facilities. These plans require some means of controlling erosion and sampling site runoff for suspended sediment.

California:

Final grading performance standards require that runoff velocities be maintained at levels that minimize surface erosion. In addition, a vegetative layer is also required to be an integral part of the final cover design.

California-2:

Surface erosion potential is addressed in Chapter 15, Article 4, §2540 and typically utilizes features such as drains, berms, ponds, etc.

In your state what is a typical cover stability analysis procedure?

Utah:

Permittee must demonstrate that a cover is stable under static and seismic load.

Washington:

The use of friction angles from laboratory shear tests and appropriate factors of safety has been reported but this author is not certain as to whether it is typical for our state. Seismic analysis slope stability during foundation liquefaction has also been performed because most of Washington has threshold ground accelerations that have a 90 percent or greater expectation of exceeding 0.10 g for a 250 year quake (the EPA threshold).

Colorado:

Stability analyses are generally not required for site with final slopes 4H:1V or less that are built in seismically stable areas. For sites that propose steeper final slopes, are in seismic hazard zones or where slope failure would cause significant property damage or loss of life, some type of stability analysis is usually required. The type of analysis and the level of detail are site specific. The method of analyses generally includes a computer based iterative method of slices that determines the lowest factor of safety [of a] circular failure surface.

California:

Current regulations require slope stability analyses be conducted for all slopes in excess of 3:1. Landfill owner/operators must demonstrate that a 1.5 pseudostatic factor of safety exists. If this factor of safety cannot be achieved, a deformation analyses is required to demonstrate that the proposed slope geometry is stable.

California-2:

Performance standards are in Article 2. Slope stability requirements are presented in §2595, Article 9, Chapter 15, under "Geology". Exact procedures are not specified. The analytical method chosen depends on preference of individual designers.

Does your state require assessment of the potential for gas generation? If so, are there performance criteria and what mitigation measures are specified or used?

Utah:

No

Washington:

No.

Colorado:

No, we do not.

California:

Yes, all "new" landfills are required to monitor for landfill gas migration. If landfill gas is detected at 5% at the landfill boundary or at 1.25% in on site structure, than the owner/operator will be required to implement landfill gas control. Both active and passive systems have been installed.

California-2:

Yes, the CIWMB, in Title 14, has specific criteria for landfill gas, as well as the Air Quality Management Districts.

Does your state collect or acquire performance or monitoring data?

Utah:

Yes

Washington:

Ground-water information is submitted yearly to jurisdictional health departments across the state. The department does not have a centralized ground-water data base for all solid waste landfills. Combustible gas measurement and leachate quality are not routinely reported to the jurisdictional health departments nor to the state.

Colorado:

Yes. Generally, ground-water and explosive gas monitoring data are provided to us for each facility on a quarterly basis.

California:

The owner/operator is required to submit both landfill gas and ground-water monitoring data to the appropriate regulatory agencies.

California-2:

California landfills are extensively monitored as a matter of routine. Some monitoring involves assessment of performance of the containment systems under both static and dynamic conditions. For examples, see Article 5, Water Quality Monitoring, and Article 8, Closure and Post-Closure Maintenance of Chapter 15.

COST AND PUBLIC ACCEPTANCE

To what extent has the cost of compliance with the regulations become an issue in your state?

Utah:

Cost is a factor that we must consider in the permitting decision and it is always a concern for the permittee at small landfills.

Washington:

Costs were much more of an issue in 1985 when chapter 173-304 WAC was passed; many cities and counties had to look at the economics of continuing the operation of small, poorly run, badly located and designed landfills. Several larger landfills were entering corrective action that helped accelerate their decisions. Our department had matching grant monies available that also helped fund public landfill closures. The later landfill standards, chapter 173-351 WAC, were not as controversial, because they were handed down from EPA and many cities and counties had switched to larger private regional sites whose economies of scale helped to absorb the costs of the standards.

Colorado:

The response to the cost of compliance with the regulations has varied throughout the state. In the front range, urban, metro area, the public is less involved with the cost of waste disposal. In some areas, waste disposal costs are buried in municipal utility bills and community dumpsters are available. In other areas, individuals contract with private waste haulers who usually charge what the market will bear. The majority of urban residents have never been to a landfill. Landfills are owned and operated by large international corporations e.g. Waste Management, BFI, and Laidlaw all have facilities serving the front range urban corridor. For these communities, the cost of compliance is a concern of industry rather than the citizenry.

In contrast, many of the rural communities have reacted quite strongly to the cost of compliance with the regulations. In many of these communities several generations of families have lived in the same place for a hundred or more years. Solid waste disposal was an individual responsibility. In many communities, waste minimization by combustion was common-place, until very recently. Very small communities, of two to three hundred people had their own landfill. Now, a population that small cannot afford to have a landfill which complies with the regulations. For many of these communities, the cost of compliance has been an extremely important issue.

California:

The cost of compliance has always been an issue in California. However, the impacts to the "small" landfills is much greater in large part to the economies of scale. The larger landfills are constantly challenging the regulations but for the most part accept them as the cost of doing business.

California-2:

Although, the SWRCB is aware of the cost of compliance to some degree, we do not keep track as a rule. RWQCBs are given the option of considering alleged excessive costs by allowing alternative designs as explained in Article 1, §2510, Chapter 15.

Have the design or construction of any landfill facilities been delayed due to the cost of regulatory compliance?

Utah:

Not that I am aware of.

Washington:

The 1985 standards had a four year compliance schedule for meeting the standards of ch. 173-304 WAC; many landfills were granted a two year extension to allow for increased tipping fees to pay for proper closure of older landfills. This has not been the case for remaining landfills affected by the newer rules, ch. 173-351 WAC because effective dates are pretty much spelled out in the federal rules.

Colorado:

Yes.

California:

There have been situations where construction of new landfills have been delayed due to regulatory compliance. However, this may also be due in part to the complexity of the proposed designs and site conditions for new landfills. These designs are proposed as alternatives to the prescriptive standards which take more time to review. In addition, proposed landfill designs may also be influenced by the "NIMBY" attitude of the concerned public.

California-2:

The SWRCB does not compile this type of information. As indicated above, RWQCBs do consider cost issues at individual landfill sites during the permitting process.

What is the general opinion and response of the public and local officials to regulatory compliance?

Utah:

Most officials see the need for proper management of solid waste and are willing to meet the rules when they are informed and educated on the benefits and the liability risks on noncompliance.

Washington:

In general the public seems to have accepted long haul of municipal solid waste because it's out-of-sight, out-of-mind. Recycling and waste reduction issues are far more important to the general public than landfill compliance, unless a new landfill or a landfill expansion is being proposed near their home, or they live along transport routes, etc. Local public officials seemed to have accepted the idea that landfilling, a necessary component of the waste management system, must be done in an environmentally safe manner.

Colorado:

Opinions about the solid waste regulations vary throughout Colorado. They span from the realm of possible responses from, "the regulations are too stringent" to "the regulations are not stringent enough". At the present, we have not collected data which would allow a definitive answer to the is question.

California:

Depending on the landfill and the area where the respondent is located, the opinions would vary from too much to inadequate regulatory compliance. Several of the agencies responsible for the regulation of landfills are governed by Boards that are sometimes politically influenced by the public, the landfill industry or local governments.

California-2:

Although the SWRCB is sensitive to compliance issues, we do not routinely monitor public opinion in regard to existing regulatory requirements. SWRCB structure does provide a means for concerned individuals or groups to present a case against RWQCB decisions or orders. Cases are considered on their merits through a process of appeal to the SWRCB. The SWRCB conducts an extensive evaluation of public opinion by requesting comments and conducting public hearings whenever new regulatory requirements are proposed.