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NUREG/CR-5432
Vol. 1

Recommendations to the NRC for Soil Cover Systems Over Uranium Mill Tailings and Low-Level Radioactive Wastes

Identification and Ranking of Soils
for Disposal Facility Covers

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Prepared for
U.S. Nuclear Regulatory Commission

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Recommendations to the NRC for Soil Cover Systems Over Uranium Mill Tailings and Low-Level Radioactive Wastes

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for Disposal Facility Covers

Manuscript Completed: January 1991
Date Published: February 1991

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NRC FIN D1095

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ABSTRACT

The U.S. Army Engineer Waterways Experiment Station (WES) has provided recommendations to the U.S. Nuclear Regulatory Commission (NRC) for the selection, placement, compaction, testing, and acceptance of soils proposed to be placed in cover systems over uranium mill tailings and low-level radioactive wastes. The recommendations from WES are contained in three volumes of NUREG/CR-5432. Volume 1 identifies the various soil types and engineering properties that are needed to fulfill important soil cover functions. The identified soils are then ranked according to their capability to perform the low-permeability and filter and drainage functions. Volume 2 provides recommendations for conducting pertinent laboratory and field tests to ensure acceptable soil cover performance. Volume 3 covers recommendations from WES on proper field construction methods including guidance on quality control testing and inspections. Recommendations are given for sealing penetrations (e.g., observation wells) that are required to penetrate covers for environmental monitoring of disposal facility performance.

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Acknowledgements

This report provides recommendations developed under Interagency Agreement No. NMS-89-002, "Recommendations to the NRC for Laboratory Testing and Field Placement of Low Permeability Soils for Waste Covers," dated 1 May 1989, between the U.S. Nuclear Regulatory Commission (NRC) and the U.S. Army Engineer Waterways Experiment Station (WES).

The study was performed by personnel of the WES Geotechnical Laboratory (GL). Messrs. Ray Horz, Allen Kimbrell, and Larry Lynch contributed to the study and wrote task reports or sections of task reports. Their efforts and assistance were crucial in successfully completing this study. Mrs. Mary Anne Kirklin and Ms. Kathy Grant cheerfully and tirelessly contributed their proficient word processing skills to the effort of transforming rough drafts into camera-ready reports. Mr. Bennie Washington provided drafting support. Mr. David Bennett was the WES principal investigator.

The study was performed under the direct supervision of Mr. Jerry S. Huie, Chief, Rock Mechanics Branch (RMB), and under the general supervision of Dr. Don Banks, Chief, Soil and Rock Mechanics Division (S&RMD), within the Geotechnical Laboratory. Dr. William F. Marcuson III was Chief of GL. Dr. Robert W. Whalin was WES Technical Director and COL Larry B. Fulton was Commander and Director of WES during the study.

This study benefitted greatly from the review and advice offered by a formal independent peer review panel, convened to review and comment on each of the draft task reports and the conduct of the study in general. The panel was chaired by Dr. Paul Hadala, Assistant Chief, GL, WES. Other members included Dr. David Daniel, University of Texas, Austin, Texas and Dr. Steve Poulos, principal in GEI Consultants, Inc., Winchester, Massachusetts. Mr. Robert Landreth from EPA's Risk Reduction Laboratory in Cincinnati, Ohio arranged for informal review from his staff and participated in the panel review meeting held at WES on 5-6 June 1990. The panel members contributed a significant amount of time, effort, and much valuable insight from their many years of combined experience to make the study results more valuable and useful. The authors are very grateful for their enthusiastic support and advice.

Mr. Joseph Kane was the NRC Project Officer. He was an effective coordinator and arbitrator between the WES study team and the independent review panel, furnished pertinent background reports and information, and generally helped bring the study to a successful conclusion.

Volume 1: Identification and Ranking of Soils for Disposal Facility Covers

1.0 Introduction

1.1 Background

The regulations governing disposal of low-level radioactive wastes (LLW) and uranium mill tailings remedial action (UMTRA) wastes are summarized by Kane and Widmayer (1988). Emphasis in the Federal regulations (10 CFR Part 61 for LLW and 40 CFR Part 192 for uranium mill tailings) is on protection of public health and safety and protection of the environment from radiological and non-radiological hazards associated with the radioactive materials. The Uranium Mill Tailings Radiation Control Act of 1978 (UMTRCA) further requires US Nuclear Regulatory Commission (NRC) concurrence on selection and performance of proposed remedial actions proposed by the US Department of Energy (DOE) and with the licensing of long-term maintenance and surveillance of the uranium mill tailings disposal sites.

By regulation, low-level radioactive waste (LLW) disposal facilities are required to achieve long-term stability on the order of 300 to 500 years (10 CFR Part 61.44). Uranium mill tailings must be controlled and disposed in a manner that will ensure stability for up to 1000 years to the extent reasonably achievable, and in any case, for at least 200 years (40 CFR Part 192.02). In developing these regulations, the Environmental Protection Agency (EPA) called for designs that rely primarily on passive controls rather than active controls, which would require long-term active maintenance and restrictions on land use. Passive controls imply thick soil covers, below ground disposal, and high quality rock covers for erosion protection (Kane and Widmayer, 1989). The emphasis is similar for LLW as described in 10 CFR Part 61, Subparts C and D.

To address the regulatory requirements, NRC Division of Low-Level Waste Management and Decommissioning (LLWM) requested assistance from the U.S. Army Engineer Waterways Experiment Station (WES) in the development of recommendations for selection, placement, compaction, testing, and acceptance of soils for use in covers for low-level radioactive wastes (LLW) and uranium mill tailings wastes.

1.2 Objectives

These recommendations will be used by the NRC to develop regulatory guidance on criteria to be followed in the review of Uranium Mill Tailings Remedial Action (UMTRA) projects and LLW disposal facility license applications. These recommendations may also be useful to Agreement States, license applicants and others involved in LLW and uranium mill tailings waste disposal. These recommendations are not intended as a design manual, but may be useful to designers. The recommendations address selection of soils, test methods, and construction methods for waste covers. Sealing of cover penetrations was also addressed. Waste covers must satisfy long-term stability and environmental protection standards and must perform specific waste cover functions including:

1. Minimizing infiltration through the cover from precipitation and surface runoff or runoff.
2. Minimizing the contact of water with wastes, through removal of water as runoff before it infiltrates, through drainage layers after it infiltrates, and through the use of low permeability barriers around the wastes.
3. Minimizing surface erosion.
4. Minimizing differential settlement and subsidence of the cover, and more importantly, damage to the cover as a result of differential settlement and subsidence of the wastes or highly compressible foundation soils. (The second part of this function is much more difficult to ensure if covers are placed over unstable wastes.)
5. Limiting the radioactivity dose rate at the ground surface of the cover to acceptable levels.
6. Provide resistance to damage to the cover as a result of burrowing animals or root penetration (biointrusion).
7. Provide resistance to damage to the cover as a result of freezing and thawing.
8. Provide long-term stability over the covered wastes without the need for active maintenance.

It should be noted that long-term stability is achieved by satisfaction of the other functions listed over the long periods of time required by regulations. Therefore, satisfaction of long-term stability may be inferred from the rankings assigned to various soil classes for their performance of the other cover functions. Long-term stability was not evaluated as a separate function.

1.3 Scope

This study was divided into several tasks to accomplish the stated objectives. Under Task 1, soils that could be used in cover systems for LLW and uranium mill tailings were described and ranked, according to their potential performance of required cover functions. Rankings were justified by relating engineering behavior and typical values of important soil properties for various soil types to the properties and behavior required for satisfying the various cover functions. Soils were ranked according to performance of low permeability or radon barrier layer functions and filter and drainage layer functions. These layers must perform several functions to achieve the overall performance objectives, as listed in Tables 1-1 and 1-2 and described in Section 2. Soil additives or mixtures that would enhance performance of cover functions were also identified and described.

It is recognized that geomembranes, geotextiles, or other manufactured liner and cover materials may be effectively used in some cases to supplement or improve performance of soil covers. The acceptance of these manufactured materials for use in covers is a regulatory and technical issue that may be

addressed on a case-by-case basis. Effective use of these materials is encouraged, but the guidance provided in this report is for soil covers only.

It is further recognized that topsoil and vegetation at humid sites and riprap at arid sites are important protective features for low permeability soil layers. Extensive guidance for design and construction of riprap or armor stone layers is provided in the Technical Position, "Design of Erosion Protection Covers for Stabilization of Uranium Mill Tailings Sites" (USNRC, 1990). Guidance on design and construction of topsoil and establishment of vegetative layers is provided in NUREG/CR-3144 (Tucker, 1983); and in NUREG/CR-5041 (Denson et al., 1987). These protective cover features are not addressed in this report. The wastes are assumed to be in place and are not addressed in this study.

The cover components or layers that are addressed in this report are the low permeability or radon barrier layer and filter and drainage layers. Figures 1-1a. and 1-1b. show cross sectional views of two multi-layer waste cover conceptual designs. These concepts incorporate the various soil layers and engineered materials that may be used to satisfy long term cover requirements.

Under Task 2, laboratory and field test methods recommended for determining and verifying soil cover performance were described. This work included discussion of specific tests recommended for ensuring satisfactory performance of all important cover functions, and advantages and disadvantages of the test methods.

Recommendations for field construction methods were developed under Task 3, including methods for placement, compaction, and acceptance testing for low permeability and filter and drainage soil layers. Use of test fills and remediation of cover deficiencies were addressed.

Methods for sealing penetrations through the cover such as monitoring wells are described in Task 4. Under Task 5, all draft reports were reviewed by a panel of experts to ensure that technically sound, defensible recommendations had been made.

This report describes work completed under Task 1 of the study.

1.4 Approach for Task 1

In developing recommendations for selection of soils for UMTRA and LLW covers, it was apparent from the start that soil type recommendations by themselves are a necessary but incomplete part of the overall approach to selection, design, and construction of soil layers used in cover systems. The rankings assigned to various soil types were related to and justified by the discussions in the text of relevant engineering properties and behavior. Because some specific soil types may exhibit widely different properties, variable rankings were deemed appropriate in some cases.

A properly designed cover system must satisfy several functions that conflict to some extent. Satisfaction of some functions or cover requirements depends not only on the soil type used and its engineering properties but to a

COMPOSITION

PURPOSE

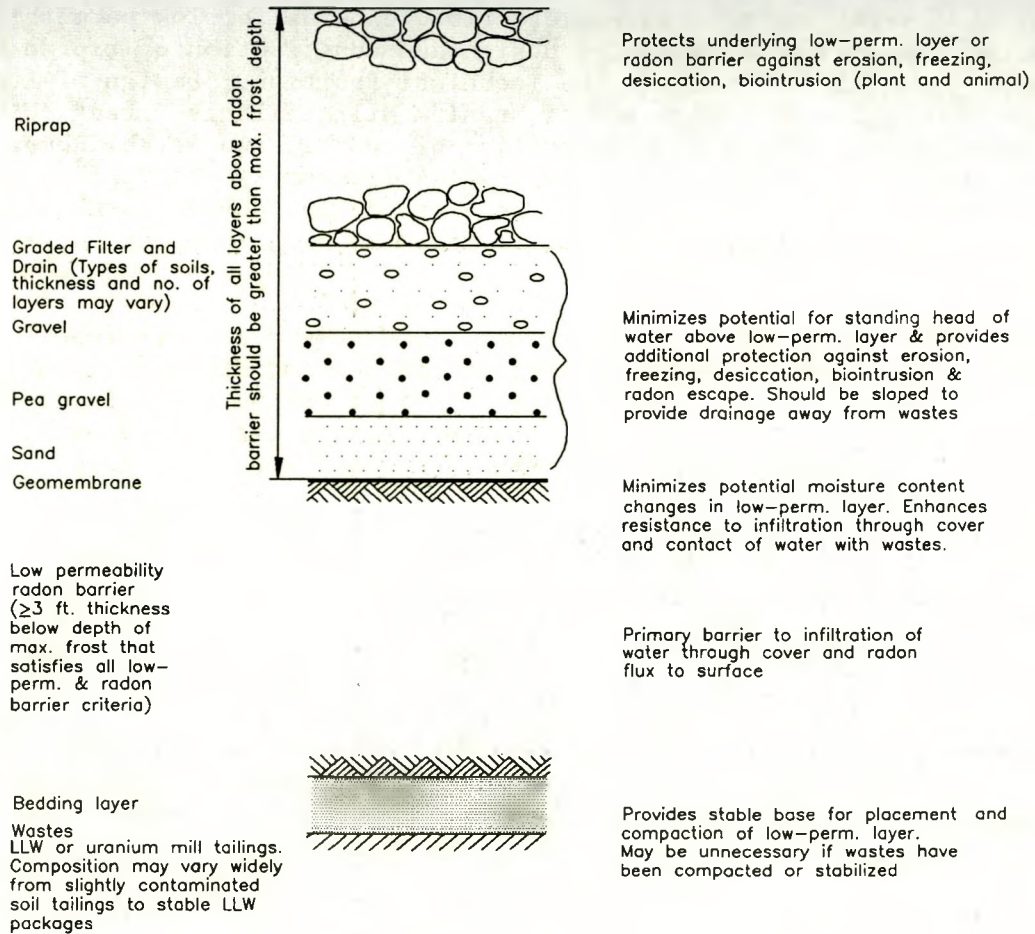


Figure 1-1a. Conceptual Design for Multi-Layer Waste Cover System with Riprap for Protection of Low-Permeability or Radon Barrier Layer

COMPOSITION

PURPOSE

Vegetation

Topsoil
(Thickness varies; typically ≥ 18 inches)

Graded Filter and Drain
(Types of soils, thickness and no. of layers may vary)
Sand (≥ 9 inches)

Pea Gravel (≥ 9 inches)

Gravel (≥ 9 inches)

Sand (≥ 9 inches)

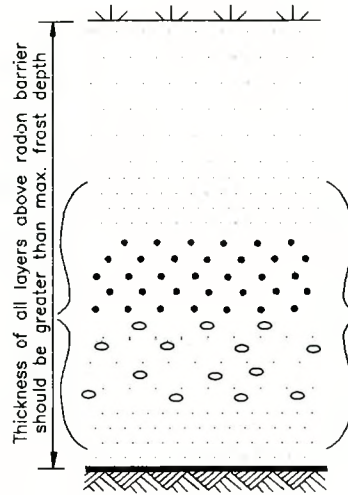
Geomembrane

Low permeability radon barrier
(≥ 3 ft. thickness below depth of max. frost that satisfies all low-perm. & radon barrier criteria)

Bedding layers

Wastes

LLW or uranium mill tailings. Composition and characteristics may vary widely from slightly contaminated tailings soil to stable LLW packages



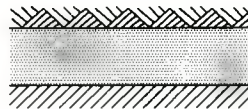
Provides resistance to erosion

Protects underlying low-perm. layer or radon barrier against erosion, freezing, desiccation, biointrusion (plant and animal). Helps reduce radon flux to surface.

Minimizes potential for standing head of water above low-perm. layer & provides additional protection against erosion, freezing, desiccation, biointrusion & radon escape. Should be sloped to provide drainage away from wastes.

Minimizes potential moisture content changes in low-perm. layer. Enhances resistance to infiltration through cover and contact of water with wastes.

Primary barrier to infiltration of water through cover and radon flux to surface



Provides stable base for placement and compaction of low-perm. layer. May be unnecessary if wastes have been compacted or stabilized

Figure 1-1b. Conceptual Design for Protection of Multi-Layer Waste Cover System with Topsoil and Vegetation for Protection of Low-Permeability or Radon Barrier Layer

larger extent on its proper location, placement, thickness, slope, and the properties of adjacent soils and other materials, including the wastes. In addition, some marginally satisfactory soils can be amended to improve their performance. Marginal soils may be screened or processed to remove debris and oversize material to enhance their performance.

Therefore, a multi-layer approach to cover design is recommended in which one layer complements and improves the performance of adjacent material layers and the entire cover. This approach allows the designer some flexibility in satisfaction of the various, sometimes conflicting requirements and avoids total reliance on any one material type or cover feature.

As mentioned previously, covers for LLW and UMTRA disposal sites must remain stable and perform the various functions satisfactorily over a period of 200 to 1,000 years, which is much longer than the design service life of most engineered structures. The cover materials must perform adequately without the need for active maintenance. Active maintenance is defined in 10 CFR Part 61.2 as: "any significant remedial activity needed during the period of institutional control to maintain a reasonable assurance that the performance objectives of paragraphs 61.41 and 61.42 are met. Such active maintenance includes ongoing activities such as the pumping and treatment of water from a disposal unit or one-time measures such as replacement of a disposal unit cover. Active maintenance does not include custodial activities such as repair of fencing, repair or replacement of monitoring equipment, revegetation, minor additions to soil cover, minor repair of disposal unit covers, and general disposal site upkeep such as mowing grass."

Stability is defined in 10CFR Part 61.2 as "structural stability." In this context, cover materials must remain physically and chemically stable, in essentially the same condition as when installed and resist major erosion, subsidence, differential settlement, cracking, volume change, frost damage, and infiltration. Therefore, as discussed in the introduction, the long-term stability requirement may be thought of as a time requirement for satisfactory performance of all primary cover functions. In addressing stability, consideration must be given to the impact on cover functions that may result from failure of components or features other than the cover, e.g., the subsidence of waste packages.

To rationally evaluate various types of soils, it was necessary to develop an objective basis for evaluation. In this study, the basis used for evaluation was a generally accepted group of cover functions, against which each soil type was ranked according to its performance in this function. The functional requirements of a cover system may seem somewhat conflicting if all functions must be satisfied by a single soil material type and gradation. For example, low hydraulic conductivity is a desirable characteristic of a cover soil for the function of minimizing infiltration, but low hydraulic conductivity is a disadvantage for promoting drainage. A multi-layer cover system offers some advantages in performance of the somewhat conflicting functions. Disadvantages of a multi-layer cover system in some cases may include higher material and construction costs due to limited availability of acceptable materials and added complexity in design, construction, and acceptance testing methods required to achieve desired results. In most cases, the positive attributes of the multi-layer soil cover system can be shown to outweigh the disadvantages.

Therefore, in developing the recommendations for cover materials in this study, cover functions have been divided according to those that would be best satisfied by low-permeability, fine-grained soils and those best satisfied by higher permeability coarse-grained soils. In this regard, Table 1-1 lists fine-grained soil types, using the Unified Soil Classification System (USCS), cover functions required of fine-grained soils, and the rankings of these soils in satisfying these functions. The ranking system is qualitative, with preferred, acceptable and unacceptable rankings assigned to each soil type for performance of each function. As mentioned previously, variable rankings were assigned to some soils for performance of particular functions because of the range of engineering properties and behavior that these soils may exhibit. Similarly, Table 1-2 lists coarse-grained soils according to the USCS, cover functions required of coarse-grained soils and the rankings of the soils in satisfying these functions. The ranking system is identical to that used for fine-grained soils. Some redundancy appears in the tables in both functional requirements and soil types, due to a natural overlap of the functions required of the covers and the performance of some soils.

2.0 Summary of Required Cover Functions

The various cover functions are briefly defined and described in the following paragraphs to help remove ambiguities that could result from the abbreviated descriptions used in the tables. For completeness, a brief summary is also given of the Unified Soil Classification System (USCS) in Appendix A.

2.1 Cover Functions for Fine-Grained Soils

2.1.1 Minimize Infiltration Through the Cover and Contact of Water with Wastes

This cover function is probably the most critical and together with minimizing dose rate are the key functions essential to good cover performance.

Infiltration is defined in Freeze and Cherry (1979) as: "entry into the soil of water made available at the ground surface, together with the associated flow away from the ground surface within the unsaturated zone." A slightly different definition is given in Glossary of Geology, (Bates and Jackson, 1987) as: "The flow of a fluid into a solid substance through pores or small openings, specifically the movement of water into soil or porous rock."

Hydraulic conductivity is the soil property of primary interest for evaluating potential for infiltration and can be measured directly by suitable laboratory and field tests. Hydraulic conductivity is dependent on such variables as a soil's porosity, pore size distribution, structure, and degree of saturation. For compacted soils, porosity and pore structure are greatly affected by the water content at which the soil is compacted, the compactive energy used, and to a lesser degree, by the method of compaction. Satisfaction of this cover function then requires in part, that a soil be selected and placed to minimize pore space and thereby minimize hydraulic conductivity. The rate of infiltration through soils compacted in the field in actual waste covers may be significantly greater than would be expected based on hydraulic conductivities of the soils as tested in the laboratory.

Table 1-1. Cover Functions and Rankings for Fine-Grained Soils
(P = Preferred, A = Acceptable, U = Unacceptable)

<u>Soil Type</u>	(1)	(2)	(3)	(4)	(5)	(6)	(7)
	Minimize Infil- tration through <u>Cover</u>	Limit Dose Rate at <u>Surface</u>	Minimize Surface <u>Erosion*</u>	Minimize Diff. Settlement & Subsidence <u>of the Cover</u>	Minimize Dam. to Cover as Result of Diff. Set- tlement & Subsidence of wastes or under- <u>lying material</u>	Minimize Shrink/Swell Potential & <u>Cracking</u>	Provide Resistance to Freeze- <u>Thaw</u>
Inorganic Clay (CL)	P	P	A to U	A	A to U	A	A
Inorganic Highly Plastic Clay (CH)	P to U	P to U	A	A to U	A to U	A to U	A
Clayey Sand (SC)	P to U	P to U	A	P	P to U	P to A	A to U
Inorganic Silty Clay (CL-ML)	P to A	P to A	A to U	A	A to U	P for Shrink/Swell P to U for Cracking	A to U
Inorganic Highly Plastic Silt (MH)	A to U	A to U	A to U	A to U	A to U	A to U	U
Inorganic Silt (ML)	A to U	A to U	U	A	A to U	P for Shrink/Swell A to U for Cracking	U
Silty Sand (SM)	U	U	A to U	P	A to U	P	A to U

Highly Organic soils are not listed in this table, as they are deemed to be unsatisfactory for use as low permeability cover materials. However, they may be used for top soil layers to support vegetation.

Engineering properties that influence the rankings assigned to these soil types are discussed in Section 3.

* These materials should be protected through the use of riprap or vegetation. Unprotected fine-grained soils provide marginal to poor erosion resistance.

Table 1-2. Cover Functions for Coarse-Grained Soils
(P = Preferred, A = Acceptable, U = Unacceptable)

(1) Soil Type (USCS Class.)	(2) Promote Drainage and Min. Contact of Water w/Wastes	(3) Min. Diff. Settle- ment & Subsid- ence of the cover	(4) Min. Dam. to Cover from Diff. Settl. & Sub. of Wastes or Underlying Materials	(5) Min. Shrink/ Swell Poten- tial	(6) Dis- courage Burrowing	(7) Min. Bio- intru- sion (Root Pene- tration	(8) Provide Resis- tance to Freeze/ Thaw
<u>Cobbles</u>	P	P	P	P	P	P	P
<u>Gravel</u>							
Well Graded (GW)	P	P	P	P	P	P	P
Poorly Graded (GP)	P	P	P	P	P	P	P
Silty Gravel (GM)	A to U	P to A	P to A	A to U	P	P to A	A
Clayey Gravel (GC)	U	P to A	P to A	A to U	P to A	P to A	A
<u>Sand</u>							
Well Graded (SW)	P to A	P	P	P	P	P to A	A
Poorly Graded (SP)	P to A	P to A	P	P	P	P to A	A
Silty Sand (SM)	U	A to U	P	A to U	P	A to U	A to U
Clayey Sand (SC)	U	A	P	A to U	P to A	A to U	A to U

Engineering properties that influence the rankings assigned to these soil types are discussed in Section 3.

This discrepancy has been attributed to macrofeatures that may be present in field scale soil layers that are not present in the comparatively small specimens sampled from the field and tested in the laboratory. These macrofeatures may result from desiccation and cracking, from improper placement and compaction, or settlement and subsidence.

It is therefore extremely important that the cover maintain its integrity, i.e. that cracking be minimized so that defects do not cause infiltration rates to be significantly higher than the intact cover would allow. It may be impossible to ensure long-term integrity of covers placed over unstable wastes or highly compressible foundation soils. Development of guidance on tolerable settlements and methods for minimizing settlements and the effects of these settlements on waste covers are important issues that should receive attention.

Regardless of the soil types used for the cover, the upper surface of each cover layer should be sufficiently sloped to promote runoff but not so steeply sloped as to cause or accelerate erosion. A minimum slope of 2 percent is typically needed for the upper surface of each layer for drainage. Likewise, the cover and each cover layer should be sufficiently thick to perform satisfactorily even if small defects occur during or after construction. A minimum thickness of 3 ft is recommended for the low permeability or radon barrier layer. A minimum thickness of 1 ft is recommended for the drainage layer.

2.1.2 Limit Dose Rate at Surface of Cover to Allowable Levels

As mentioned in Section 2.1.1, this cover function is of primary importance, together with the requirement for minimizing infiltration. All the other cover functions shown in Tables 1-1 and 1-2 actually help ensure that these first 2 cover functions are satisfied. The function is abbreviated as "limit dose rate at surface" in the tables. The criteria for acceptable levels of dose rate at the surface are given in 10 CFR Parts 20.105 and 61.52 (a)(6) for LLW and in 40 CFR Part 192 for inactive uranium processing sites.

The primary source of radioactivity from uranium mill tailings piles is radon gas (^{222}Rn) created from the radioactive decay of Radium (^{226}Ra) present in uranium mill tailings in small concentrations. If radon gas is able to diffuse through the cover to the surface before itself decaying then animals or humans may be exposed. Escape of particles of radioactive dust through cracks or holes in a soil cover may be eliminated by attention to the other aspects of cover performance such as prevention of erosion, cracking, and infiltration of water.

Procedures have been developed to predict the radon flux at the surface of multi-layered tailings covers based on properties of the tailings (e.g., radium concentration, porosity, degree of water saturation, and emanating power) and on the thickness, and diffusion coefficient of each of the various cover layers. These procedures are presented in A Handbook for the Determination of Radon Attenuation Through Cover Materials (Rogers and Nielson, 1981) and have undergone subsequent validation (Kalkwarf et al., 1984; Rogers and Nielson, 1984). The dominant factors affecting the diffusion coefficient of a given soil cover layer are that of porosity and degree of water saturation. A soil's porosity is dependent on soil type and on the

degree of soil densification that is achieved in construction. The degree of saturation in situ depends on soil type and varies with such factors as cover design, climate, depth of water table, and adjacent soil layers. Compaction and density tests may be performed to establish reasonable ranges of values for soil unit weight (density). These values, along with specific gravity can be used to calculate the ranges of porosities for proposed cover soils. Climatic and other data for a proposed site may be used in conjunction with suitable field data or predictive computer programs such as the HELP program (Schroeder et al., 1983) to estimate the long term degree of saturation of any given cover component. In addition to compaction tests, it may be necessary to perform swell tests on some cover materials to predict the ultimate equilibrium range of porosities. On the basis of predicted ranges of porosities and water saturation, radon diffusion coefficients may be calculated based on the empirical relationship between soil porosity, water saturation, and diffusion coefficient. More accurate evaluations of diffusion coefficient can be made based on laboratory tests.

It should be noted that degree of soil saturation can vary over a wide range due to climatic conditions and these variations will have a greater effect on the rate of radon diffusion than differences in soil porosities. While fine-grained soils often have greater porosity than coarse-grained soils, fine-grained soils have a lower air void space under typical drying conditions and clay soils typically maintain a higher degree of saturation under circumstances where the soil is above the water table. Therefore, relatively thick, dense layers of saturated, low permeability soils perform best in limiting dose rate at the surface for a given set of climatic conditions.

2.1.3 Minimize Surface Erosion

Surface erosion may be defined as the wearing away of land by wind, water, or glaciers. On a large scale, land forms such as the Grand Canyon and the Badlands are the results of erosion occurring over a large area and extensive period of time. The manifestations of erosion that are of concern in waste covers are not necessarily of such a grand scale. Minor erosion rills and gullies, unchecked, can grow and severely impair the performance of the cover. Wind erosion can reduce the thickness of unprotected covers and likewise impair performance. Therefore, covers must be designed and constructed to resist erosion by wind and water over long periods of time.

The design of an erosion resistant cover must take into account not only soil properties, but also disposal facility geometry, climate, vegetation, and operating procedures.

Erosion susceptibility increases with increasing storm intensity, drainage area, slope angle, and slope length for a given soil. Complete coverage with vegetation or a protective rock layer reduces erosion susceptibility.

For estimating erosion due to water, perhaps the most widely known and accepted soil loss prediction tool is the USDA universal soil loss equation (USLE) (Tucker, 1983). This equation has been used for agricultural erosion-control planning for more than a decade in the eastern states and is now also used to a limited extent in the western states, Hawaii, and several foreign

countries. Development of the equation has involved the analysis of the records from more than 10,000 plot-years of erosion studies at 42 research stations. The use and limitations of the USLE are discussed by Tucker (1983). While the USLE is helpful in assessing the relative capability of soils in resisting erosion, this method does not consider design storm events, nor does it take gully erosion into consideration which in most cases is the major factor in the design of a soil cover. The design of stable soil covers over wastes that are placed on slopes with shallow flow depths resulting from surface runoff should use the tractive force (or shear stress) method. In this method, the tractive force produced by the flow is compared for stability to the allowable tractive forces of the soil. This method therefore, minimizes the potential for gully formation and any subsequent enlargement. The tractive force method is discussed by Temple (1987) and in more general terms by Chow (1959). The NRC staff has developed a Technical Position (USNRC, 1990) on the design of erosion protection covers for stabilization of uranium mill tailings sites that recommends the tractive force method.

Wind erosion can be a serious problem in arid and semi-arid regions. Most studies of wind erosion and control measures have been aimed at agricultural lands. Some similarities, but also some significant differences exist between agricultural lands and waste disposal sites. Therefore, caution must be used when ranking soils for waste covers based on results of erosion studies on agricultural lands. Tucker (1983) discusses application of the wind erosion equation (WEE) and the factors involved in estimating erodibility. The equation is:

$$A' = f(K', C', L', T', V',)$$

where

A' = erosion in tons per acre per year

K' = a soil erodibility index

T' = a soil ridge roughness factor

C' = a climatic factor

L' = the field length along the prevailing wind erosion direction

V' = an equivalent quantity of vegetative cover

As implied by the factor definitions above, K' is the only factor directly related to soil properties and can be estimated using graphs given by Tucker. These graphs indicate that wind erodibility increases as grain size decreases. The factor T' is the amplitude of crop rows, and therefore, has no real meaning for waste covers. The other factors are related to climate, C'; geometry, L'; and vegetative cover V'.

Wind erosion can also be estimated using an equation developed by the U.S. Department of Agriculture and adopted by Isrealsen et al. (1980). The equation considers topography, local wind factors, surface roughness, vegetation cover, and a soil wind erodibility index which depends on the ability of the soil to form a natural crust in place and to form cohesive clods when disturbed. The test for determining the soil wind erodibility index requires a visual estimate of the relative areas covered by crust and uncrusted areas and determination of the percentage of dry soil retained on a No. 20 (0.84 mm) sieve. The value is determined in the field as follows:

Scoop up a 250 milliliter sample of the exposed surface soil. Allow the sample to air-dry, then sieve the dry sample with a 20-mesh sieve. Measure the volume of the material remaining on the screen and determine the percent remaining by volume. The value determined, along with the area of crusting is used get the soil loss in tons/acre/yr. (Isrealsen et al., 1980)

A soil surface can be considered non-erodible by wind if the surface materials consist of clods or particles at least 80 percent of which would be retained on a No. 20 sieve.

Another factor considered is surface roughness. A soil surface roughness factor is determined by measuring the height of undulations of the ground surface. The most severe case is that of a smooth surface. Presumably the surface of a newly constructed waste cover will be smooth or will have relatively small ridges. The mean height of the individual soil ridges or particle protrusions can be measured and used to determine a surface roughness factor.

In addition to surface roughness and particle size, the amount of vegetative cover has a bearing on wind erosion. The greater the amount of organic matter in terms of organic litter (undecayed vegetable matter), the lower will be the degree of wind erosion. For this purpose, the percent organic matter is determined as follows:

Obtain a sample of soil (to a 3-inch depth) plus litter, including standing litter and wash on a 20-mesh sieve. Dry and weigh the organic portion of the sample. Determine the percent by weight of organic matter in the surface 3 inches of soil. (Isrealsen et al., 1980)

From the above discussion, it can be concluded that if a surface mulch of gravel and sand with no more than 20 percent passing the No. 20 sieve is provided as the surface layer of a soil cover, wind erosion will be eliminated. The incorporation of vegetative cover can supplement the mulch to provide an extra measure of protection and promote soil drying by evaporation and transpiration.

Clays are not normally as erodible as fine sands or silts. However, in some areas of the United States, there exist clays which are nevertheless highly erodible by water. These soils are termed dispersive clays, and are characterized by relatively high levels of sodium cation attached to the clay particles. Dispersive clays normally deflocculate when exposed to water of low salt content, in contrast to aggregative clays which remain flocculated in the same soil-water system. Dispersive clays are highly erosive, generally have high shrink-swell potential, and have lower hydraulic conductivities than aggregated clays. Thus, dispersive clay soils that might otherwise be acceptable candidate soils for low permeability or radon barrier layers based on hydraulic conductivity requirements, should not be used if directly exposed to erosive forces. Tests used to evaluate soils for dispersivity are discussed in the Task 2 report.

From the foregoing summary, it can be concluded that coarse-grained soils are more resistant to both water and wind erosion than fine-grained soils. The erosion resistance of fine-grained soils is highly variable. Dispersive clays, silts, and very fine silty sands are highly erodible. Clays of high plasticity are less susceptible to erosion.

However, wind and water erosion of any unprotected soil covers could be serious over the long periods of concern for waste covers. Therefore, vegetation or rock covers are recommended for erosion protection of soil covers. Extensive guidance on selection and design of rock covers for erosion protection is provided in the Staff Technical Position Paper, "Design of Erosion Protection Covers for Stabilization of Uranium Mill Tailings Sites," (USNRC, 1990).

2.1.4 Minimize Differential Settlement and Subsidence

Differential settlement has been cited as the most common mechanism of LLW trench cover failure and has been referred to as an unavoidable consequence of current waste disposal practices (Cartwright et al., 1988). However, the term differential settlement was used to describe settlement, piping, and subsidence of the cover, presumably caused by large settlements and subsidence of unstable wastes. Differential settlement and subsidence as a result of compressibility of the cover itself and of the underlying wastes and foundation soils are discussed separately here to distinguish between relative magnitudes, causes, and consequences.

Differential settlement is the uneven settlement of a structure or the ground surface. Problems with differential settlement are usually associated with structural foundations built on deposits of soft or expansive soils of variable thickness or foundations built partly on fill and partly on natural ground or cut ground. Problems can be especially acute when foundation loads are unevenly distributed or when moisture conditions fluctuate. Differential settlement can also be a problem in collapsible soils, such as windblown silts. In compacted fills, uneven or differential settlements within the fill may result from poor construction quality control in placement and compaction, poor foundation preparation, or failure to remove organic material or debris. Highly plastic soils containing appreciable amounts of swelling clay minerals exposed to seasonal moisture changes can be especially troublesome. The time rate of consolidation is an important factor in estimating total and differential settlements. Fine-grained soils consolidate much more slowly than free-draining soils because of their low permeability. Practically all primary settlement of compacted coarse-grained soils occurs by the end of construction, so total and differential settlements within these layers are only minor concerns. Primary settlements of thick layers of clay may continue for several years after construction. Rates of settlement of these soils are strongly influenced by drainage conditions, thickness of the layer, and initial void ratio (porosity). Settlement rates decrease as layer thickness (drainage path length) increases and initial void ratio decreases. The presence of a drainage layer above and below a clay layer effectively reduces the time required for 100 percent primary settlement by a factor of four, because time rate of settlement is inversely proportional to the length of the drainage path squared. It is important to remember that only the time rate of settlements and not total settlement is affected by drainage path length.

A compacted fill (or waste cover) of relatively uniform thickness, placed over a stable base and subjected to relatively uniform load will settle differentially only if the fill material properties or placement moisture-density conditions vary with area or depth. Therefore, differential settlements within the layer and potential cracking of the cover can be minimized by enforcement of adequate construction quality control measures to ensure uniform moisture and density, uniform lift thicknesses and compactive effort and relatively uniform total fill thickness. Highly compressible soils underlying the proposed disposal site may require treatment or removal in some cases.

Differential settlement due to subsidence is usually a larger scale problem than differential settlement due to compression of cover materials. Subsidence is often associated with collapse of large voids such as solution cavities or underground mines. Subsidence or collapse upon wetting of certain soils such as windblown silts can occur without the presence of underlying voids or cavities. Water flowing through these generally unsaturated soils destroys the weak clay bonds and cementation by dissolving the calcium and other cementing agents, resulting in sudden volume decrease.

Collapsible soils that have been remolded and properly compacted are generally not as susceptible to collapse, unless they are compacted at moisture contents significantly less than optimum, or subjected to high loads. The loose, weakly-cemented structure of the natural soil matrix is destroyed by remolding and compaction when placement moisture contents are at or above optimum. However, these soils remain susceptible to piping and internal erosion and may require use of graded soil filters or synthetic filter fabric to prevent erosion. Concerns for subsidence due to site features would typically be addressed in the evaluation of geotechnical characteristics during site characterization studies.

With respect to tailings sites and LLW disposal sites, subsidence may occur as a result of settling and decay of wastes, of incomplete filling of voids within or between packages, or as a result of piping and internal erosion of wastes, cover materials, or underlying soils.

The keys to minimizing differential settlements and subsidence, then, are to require that the foundation be firm and stable, that waste forms remain stable and that void spaces that exist or may form in the wastes or cover be minimized. Guidance for filling void spaces between waste packages placed in LLW disposal facilities is given in Appendix A of the Standard Review Plan, SRP 4.3 (NUREG 1200). It should be noted that relatively thin soil covers placed directly over an unstable waste mass or highly compressible foundation soils cannot be expected to withstand large settlements of the underlying mass without damage to the cover. Differential settlement, subsidence, cracking, and increased infiltration of water through covers placed over unstable wastes may be expected as a logical consequence of such actions.

To summarize the issues and recommendations associated with differential settlement and subsidence of waste covers:

1. Significant differential settlement or subsidence as a result of self-compression of the cover is unlikely if good design and construction practice has been followed. This statement is true for

any soil that could be used for waste covers. Therefore the rankings assigned to various USCS classes are separated by minor differences in practical terms.

2. A soil cover, properly designed and constructed over a stable base, e.g. over stable waste packages, with minimum void spaces, and with those voids filled with free draining materials as called for in NUREG-1200, is unlikely to experience significant differential settlement or subsidence. This statement also is true for practically any soil that could be used for a waste cover.
3. Relatively thin soil covers cannot tolerate or accommodate large settlements or subsidence (on the order of several feet) of underlying materials, i.e. waste packages or compressible foundation soils, without damage or adverse impacts on important cover functions (e.g. minimize cracking and infiltration). Therefore, it is not recommended that relatively thin soil covers be placed over unstable wastes or highly compressible foundation soils.
4. Highly compressible foundation soils should be avoided, removed, treated, or compacted to reduce compressibility before wastes and covers are placed.
5. Wastes should be stabilized, and voids should be minimized, with these voids filled with materials of low compressibility before covers are constructed.
6. If covers are to be constructed over potentially unstable wastes, then thicker covers are preferable to thin covers and flexible layers are preferable to rigid or stiff layers so that the surface manifestations of the settlement of underlying materials and subsequent damage to the cover is minimized. In so far as possible, covers over unstable wastes should be designed and constructed to be "self-healing." One method of constructing a self-healing cover is through the use of widely graded soils. The wide distribution of particle sizes in these soils tends to result in redistribution of the mass to fill voids and cracks that may develop.

2.1.5 Minimize Shrink/Swell Potential and Cracking

Volume changes of soils, i.e. shrinking and swelling are a result of fluctuations in moisture content and the presence of swelling clay minerals. Cracking of the soil surface may result from desiccation and shrinkage or from large settlement or subsidence of underlying wastes or highly compressible foundation soils as discussed in the previous section. Cracking should be minimized or the integrity of the low permeability cover may be lost. Kleppe and Olsen (1985) found that the susceptibility of compacted clays to shrinkage and desiccation cracking increased with increasing placement moisture content, increasing PI, and increasing clay content. Dry density had little effect on desiccation cracking potential. They also reported that some sand and clay mixtures that are predominantly sands show very little shrinkage potential, and could be compacted to achieve very low hydraulic conductivity values.

Data presented in Winterkorn and Fang (1975) indicate that soils most susceptible to volume change are those with PI greater than 25, shrinkage limits less than 12, and colloid content (percent smaller than 0.001 mm) greater than 20.

Bara (1969) reported that swelling characteristics for an expansive clay used in a low embankment were significantly reduced when the clay was compacted on the wet side of optimum. Lower swelling pressures and magnitudes of swell are also reported in TM 5-818-4 (Depts. of the Army and Air Force, 1983) for soils compacted at moisture contents higher than optimum moisture content.

Lambe (1958) and Seed and Chan (1959) reported that effects of soil structure on swelling is opposite the effects on shrinkage. That is the dispersed soil structure characteristic of soils compacted on the wet side of optimum moisture content will shrink more than those compacted on the dry side, if allowed to dry. Soils compacted on the wet side can shrink more because they have more water in the double layers of the soil structure that can be given up.

The requirement of minimizing volume change or shrink/swell potential conflicts to some extent with the requirement for minimizing infiltration. That is, the clay minerals and other fines of a soil that promote low permeability also increase the potential for volume change. In fact, it is not unusual to add swelling clay minerals in the form of sodium montmorillonite to natural soils to reduce permeability. These conflicting requirements can be balanced and satisfied by proper placement of the low permeability natural or amended soil layers to minimize the potential for moisture change, and thereby minimize the potential for volume change. For example, the low permeability layer should be covered with a drainage layer, topsoil and vegetation or armor stone to minimize exposure to freezing, drying and wetting, and to provide a surcharge load that will counteract swelling pressures. The low permeability layer should be sufficiently thick that if some wetting or drying should occur, the integrity of the entire layer is not compromised. For this reason, layers less than 3 ft thick are not recommended.

Recommendations for placement moisture contents for low permeability soils used as waste covers are given in the Task 3 report.

2.1.6 Provide Resistance to Freeze-Thaw

Freeze-thaw problems may be divided into two categories: those problems that involve frost heave and migration of moisture and those problems that occur at constant water content and may result in significant changes in hydraulic conductivity after a few cycles of freezing and thawing.

The first category of freeze-thaw problems are typically associated with wet silty soils. Structures founded on these highly frost susceptible soils can experience damage as a result of heaving of ground surfaces during freezing. When the ground thaws, the zone nearest to the surface thaws first, this zone becomes oversaturated from the excess moisture trapped above the underlying frozen zone, and further damage may occur as the soil loses strength.

Clays are less susceptible to this category of freeze-thaw or frost heave damage than silts because of their low hydraulic conductivity and small amount of unbound water available to form ice lenses. Soils susceptible to frost heave require a source of water for significant heave damage to occur. However, a source of water is not a necessary condition for the second category of freeze-thaw problems, i.e. increases in hydraulic conductivity of clayey soils at constant moisture content that impair a cover's performance. Clay soils subjected to even a few cycles of freezing and thawing have exhibited large increases in hydraulic conductivity (Chamberlain and Gow, 1979; Chamberlain et al., 1990). The largest increases were reported for high plasticity clays and for soils under low confining stresses.

Repeated freezing and thawing may also have an effect on the long-term stability of cover side slopes. The loss of shear strength from seasonal frost action may result in slumping of side slopes and disruption of rip rap side slope erosion protection. In cases where the stability of side slopes may be compromised by a reduction in soil shear strength due to frost action, the effect of such action should be considered by performing freezing tests to determine the reduction in density and consequent reduction in strength that may occur. This effect can be expected to be greatest for silts and for clays of low plasticity used in the uppermost soil layer and in humid climates where near saturation conditions may exist in the top soil layer at the beginning of the freezing season.

For a given soil, potential for frost damage increases with placement moisture content, because more water is available. Frost susceptibility decreases with increasing density for a given soil, if the increased density results in lower hydraulic conductivity.

The rate of freezing affects the severity of frost heave and resulting damage. A quick freeze limits the growth of ice lenses, which require a continuing supply of water brought up by capillarity.

Criteria for frost heave susceptibility are presented in TM 5-818-4, based in part on work done by Casagrande (1931) and Riis (1948). The criteria are based on coefficient of uniformity and percentage of particles smaller than 0.02 mm. Soils that are susceptible to frost action are those with greater than 3 percent by weight of particles smaller than 0.02 mm and with C_u values greater than 5 for nonuniform soils or greater than 10 for uniform soils. C_u is defined as the ratio of D_{60} to D_{10} . TM 5-818-4 also provides rankings of USCS soil classes for frost susceptibility, compacted to 100 percent of Standard Proctor densities at optimum moisture contents.

The rankings assigned to various USCS soil classes in this report are considered to be good indicators of frost heave susceptibility. However, good engineering practice would be to place the radon barrier or low permeability layer below the depth of maximum frost penetration, regardless of the characteristics of the particular soil, to avoid potential adverse effects on hydraulic conductivity from freezing.

2.2 Cover Functions for Coarse-Grained Soils

2.2.1 Promote Drainage and Minimize Contact of Water with Wastes

The second part of this function is also listed under fine-grained soil cover functions along with minimizing infiltration. This apparent redundancy can be explained by considering the possible methods for minimizing contact of water with wastes. One method best satisfied by fine-grained soils as discussed in Section 2.1.1, is to minimize infiltration through the cover and thereby minimize the amount of water available that may come into contact with wastes. The other method is to promote drainage, so that water that does infiltrate may be quickly removed to minimize the time of contact with wastes. This part of the overall function is best achieved through the use of coarse-grained soils. Both minimization of infiltration and promotion of drainage are encouraged as complementary means to ensure satisfaction of the overall goal.

Criteria for design of filter and drainage systems have been recommended in NUREG/CR-5041 (Denson et al., 1987) and are only summarized here. The three primary design criteria are:

1. Prevent piping and internal erosion.
2. Provide adequate permeability and capacity for drainage.
3. Provide for collection, monitoring, and removal of water.

Only the second criterion directly addresses the function of drainage through a soil layer. The first criterion is often called the piping criterion and must be satisfied to protect adjacent finer-grained materials. The third criterion is based on the need to monitor and safely convey collected water to ensure satisfactory performance of the cover and other disposal facility features.

2.2.2 Minimize Surface Erosion and Provide Erosion Protection to Fine-Grained Soils

This cover requirement was discussed in Section 2.1.3. As mentioned in that section, chemically and physically stable coarse-grained materials and rock protection are best suited for resistance to erosion. Coarse-grained soils can be effectively used in single or multi-layer filter systems to protect adjacent fine-grained soils from internal erosion and piping.

2.2.3 Minimize Differential Settlement and Subsidence

This cover requirement was discussed under Section 2.1.4. Differential settlement and subsidence within the cover layer is usually not a problem with coarse-grained soils, placed over a stable base unless the materials are placed in a very loose or low density condition. However, even properly placed and compacted coarse-grained soil layers would be subject to damage from large settlements of underlying unstable wastes or highly compressible foundation soils. Therefore the relative rankings assigned to various USCS soil classes for this function are separated by minor differences in practical terms.

2.2.4 Minimize Shrink/Swell Potential

The requirement for minimizing volume change or shrink/swell was discussed in Section 2.1.5. Volume change is generally not a problem with coarse-grained materials, unless the coarse material contains appreciable amounts of swelling clay minerals in the form of fragments of rocks such as clay shales, pyrite, gypsum, or serpentine.

2.2.5 Discourage Burrowing Animals

Animal burrows can severely impair the performance of embankments and waste covers. The burrows provide preferential pathways for radon escape and water infiltration and seepage, and can lead to piping and erosion problems. Therefore, covers, or at least the surface cover layer, should be designed and constructed to minimize the potential for burrowing animals to establish colonies and impair the performance of the cover. The materials that discourage burrowing are those that are difficult to dig through such as dense compacted clay or soils that will not support a stable opening such as clean dry sand. In general the best materials for discouraging burrowing are rock, cobbles, and gravel.

2.2.6 Minimize Biointrusion (Root Penetration)

Deep-rooted vegetation can impair the performance of a cover in much the same way that burrowing animals do. Preferential pathways develop as the roots that have penetrated the cover decay, leaving open channels for infiltration of water and escape of waste gases. These channels can become enlarged due to concentrated seepage, piping and erosion and further deteriorate cover performance. Therefore, conditions that permit deep rooted vegetation should be discouraged, either through the use of selected cover materials that minimize or limit root penetration, through treatment of the surface, or through substitution of shallow-rooted vegetation. Shallow-rooted vegetation is also an effective means of protecting the surface from erosion and promoting evapotranspiration. However, establishing and maintaining vegetative covers in arid regions is difficult.

2.2.7 Provide Resistance to Freeze/Thaw or Frost Damage

The two categories of problems associated with this required cover function were discussed in Section 2.1.6. As pointed out in that section, coarse-grained materials are generally not susceptible to frost damage, but very fine sands, silty sands, and silty gravels may exhibit frost susceptibility if the water table is adjacent. This condition of closeness to the water table is extremely unlikely for a waste cover, and can be often discounted, because of favorable disposal facility site conditions and design features. It was noted in the section on fine-grained soils that relatively few cycles of freezing and thawing can cause large increases in hydraulic conductivity, especially in soils with initially low values of hydraulic conductivity. However, materials intended for drainage would not be adversely affected by freezing. The drainage characteristics of these soils would probably be unchanged. Therefore, drainage materials can be placed above the depth of maximum frost penetration and would protect underlying low permeability soil layers.

3.0 Discussion and Ranking of Soils According to Cover Function Performance

3.1 Selection of Soil Classification System

Any attempt to discuss and distinguish characteristics and performance of specific soil types must be based partly on arbitrary boundaries and definitions. Fortunately, the relevant boundaries and definitions have been established and largely accepted by the geotechnical engineering community. Differences of opinion exist and are expected to continue about which soil classification system is best for which purpose. The merits of various classification systems are not discussed or debated in this report. Rather, the Unified Soil Classification System (USCS) has been used because of its widespread acceptance for a broad range of applications and because it is the only soil classification system that has been standardized by ASTM. The USCS classification criteria and definitions are summarized in Appendix A. Classification of soils using the USCS are based on texture or grain-size, distribution of grain sizes, plasticity, and presence of organic material. The USCS was developed by Casagrande in 1948, modified in 1952, and was adopted by the Corps of Engineers in 1953 (Holtz and Kovacs, 1981). The system uses two-letter symbols as soil classes. The first letter gives the soil type, and the second letter is a modifier. Borderline soils are given dual classifications.

3.2 Fine-Grained Soils

Fine-grained soils are classified as clays (C), silts (M), or organic soils (O), and are distinguished from coarse-grained soils in the USCS as soils such that more than half of the material by weight passes through the openings in a No. 200 sieve. A No. 200 sieve has 0.074 mm openings. In Table 1-1, silty sands (SM) and clayey sands (SC) have been included with fine-grained soils because they do satisfy some fine-grained cover functions, even though the percentage by weight of particles finer than the No. 200 sieve openings is less than 50 percent. (These soils are also included in Table 1-2 for coarse-grained soils.) The fine-grained soils are subdivided according to Atterberg limits and the presence of organic material. Those soils with liquid limits less than 50 are classified as non-plastic or slightly plastic. The modifier used as the second letter in the classification of these soils is L for low plasticity. These soils include ML, CL, and OL, referring to slightly plastic inorganic silt, inorganic clays, and organic silts, respectively. Highly plastic soils have liquid limits greater than 50, and the modifier used as the second letter in the classification is H for high plasticity. These soils include MH, inorganic plastic silt; CH, inorganic plastic clay; and OH, organic, plastic silt. Silts and clays are distinguished by the "A-line" on the Plasticity Chart, a plot of Plasticity Index vs Liquid Limit. Plasticity Index, PI, is defined as the difference between the Liquid Limit (LL) and Plastic Limit (PL). The equation of the A-line is $0.73(LL-20)$. All silts plot below the A-line, all clays plot above the A-line. Borderline materials require a dual classification. One common borderline soil type is CL-ML, an inorganic, low plasticity, clayey silt. This material plots in the so-called hatched zone of the plasticity chart that lies to the left of the A-line and is bounded by lower and upper PI values of 4 and 7, respectively, and a lower bound LL of 12 and upper bound LL of 29. The final subdivision of fine-grained soils is based on the presence and extent of organic material. Organic silts or organic clayey silts OL and OH, respectively plot below the A-line and contain appreciable amounts of organic

materials. Peat, Pt, is highly organic. Visual tests useful in distinguishing fine-grained soils in the field are presented in Appendix A.

In the following paragraphs, each USCS fine-grained soil class is briefly defined, followed by its ranking as a cover material and justification of its ranking in performing each of the 7 fine-grained soil cover functions listed in Table 1-1. These functions were discussed in Section 2.1.

3.2.1 CL. Inorganic clays of low to medium plasticity, gravelly clays, sandy clays, or silty clays are classified CL. The LL of this soil is less than 50 and the PI falls between 7 and 38. A Plasticity Chart is shown in Appendix A for reference. This soil type is commonly referred to as a lean clay in reference to its low plasticity. CL soils possess practically all the good performance characteristics of highly plastic clay soils without the potential problems often associated with them. CL soils can be placed and compacted with far less difficulty than is encountered with CH and MH soils. Modification of placement moisture content is easier and clods break up more easily than is the case with CH. Hydraulic conductivity values less than or equal to 1×10^{-7} cm/sec can be achieved with soils compacted in the lab at or slightly above optimum moisture content with compactive effort equivalent to or greater than the Standard Proctor compaction test ASTM D 698 (Depts. of the Army and Air Force, 1983). Similar values can be achieved in covers constructed at disposal sites, but good construction practices and QA procedures are essential. Therefore, performance of this soil type in limiting infiltration through the cover and limiting dose rate at the surface of the cover is excellent and when properly compacted, this soil would be preferred for these 2 functions.

CL soils of medium plasticity are moderately susceptible to erosion; resistance would be expected to be slightly less than CH clays that possess higher plasticity. Therefore an acceptable ranking was assigned for erosion resistance of medium plasticity CL soils. Erosion resistance would be lower for low plasticity CL soils and would approach the poor resistance of an ML soil at the lowest plasticity range of 7. Therefore, an unacceptable ranking would be appropriate for very low plasticity CL soils.

The potential for differential settlement and subsidence within a compacted CL layer is slight to moderate. As mentioned in the preceding discussions, modification of moisture contents to achieve uniform levels is much easier for CL than for CH or MH soils. With proper construction, the end result is a more homogeneous fill with respect to moisture and density and less potential for large total and differential settlements. Therefore this soil was given an acceptable ranking for this function. However, large settlements of underlying wastes or highly compressible foundation soils could still result in damage to even properly compacted layers of CL soils.

For the reasons discussed in Sections 2.1.6, CL soils are moderately susceptible to frost heave damage. Hydraulic conductivity could be adversely affected by freezing, but is not as likely as for higher plasticity soils such as CH or MH soils, so a ranking of acceptable was assigned.

Because of the low plasticity and low occurrence of swelling clay minerals, the potential for shrink/swell of covers constructed of CL soils is low. Cracking of covers constructed of CL soils subjected to large

settlements of underlying wastes or highly compressible foundation soils could be expected, but as previously discussed, practically any soil cover would experience some distress from large settlements of underlying materials. CL soils would provide somewhat better resistance to cracking than some soils, so an acceptable ranking was assigned. Overall, the performance of lean clay of medium plasticity (CL) should be excellent, if properly placed and compacted as a waste cover. Its resistance to erosion and freeze-thaw damage can be improved by protective overlying layers and it is ranked preferred to acceptable in all other functions that fine-grained soils must perform.

3.2.2 CH. Inorganic clays of high plasticity (fat clays) are classified CH. The LL of CH is greater than 50, it plots above the A-line on the plasticity chart and its lower bound value of plasticity index (PI) is 22 and is often much higher. In fact the PI of sodium montmorillinite may exceed 1,000. Plastic clays have a high affinity for water. The so-called double layer of water surrounding each plate or clay particle can be 10 to 100 times larger than the particle itself. Very low permeabilities (in some cases as low as 1×10^{-8} cm/sec) can be achieved with covers constructed of CH soils, compacted at slightly above optimum moisture content. These soils are often used in embankment dam cores and levees. Fat clays are difficult to place and compact properly and therefore, great care and QA must be exercised to achieve desired results. CH is extremely sticky when wet and it is difficult to dry out. It is very stiff and it is difficult to break up the dry clods and uniformly add moisture prior to fill placement.

CH soils do however, make an excellent low permeability cover layer when constructed properly. Therefore preferred rankings were assigned for minimizing infiltration and for limiting the dose rate at the surface of the cover to acceptable regulatory levels.

Fat clays are moderately resistant to erosion due to their cohesive nature, but may be more susceptible when highly compacted, because infiltration is practically eliminated. Therefore, a ranking of acceptable was assigned to CH for minimizing surface erosion.

Subsidence on a large scale is generally not a consideration for plastic clays, but differential settlement can be a problem in thick layers. The differential settlement is often related to differences in natural or as placed moisture contents, seasonal fluctuations in moisture content, or uneven load distribution. As mentioned previously, modification and control of placement moisture contents are difficult with plastic clays. This difficulty can result in placement and compaction of hard dry clods and clumps surrounded by adjacent wetter, softer material. The result is unpredictable variations in strength, permeability, and compressibility. Therefore, a marginal ranking of acceptable to unacceptable was assigned to CH for minimizing differential settlement. It should be pointed out, though, that settlement of typical cover layers 2 to 6 ft thick would not generally be a major problem. Total and differential settlements are much larger concerns when the deposits exceed 20 ft in thickness, and when the layers are underlain by unstable wastes or highly compressible foundation soils.

The potential for volume change can be quite high with plastic clays, but it depends on the type and amount of clay minerals present. The affinity for water controls volume change potential. Clays that contain appreciable

amounts of swelling clay minerals such as sodium or calcium montmorillinite have very high volume change potential. However, if kaolinite is the predominant clay mineral, swelling pressure and volume change potential are low. Atterberg limits are good indicators of volume change potential. High values of LL and PI indicate high potential for volume change. The actual LL and PI of plastic clays varies widely. Therefore, a marginal ranking of acceptable to unacceptable was assigned to CH for shrink/swell potential.

Plastic clays are only slightly to moderately susceptible to frost heave. Low permeability and low percentage of non-plastic particles limits capillarity and the availability of water at the freezing surface. However, as discussed previously, hydraulic conductivity can be adversely impacted by even a few cycles of freezing even if no external source of water is available. Therefore, the low permeability layer should be overlain by a protective layer of topsoil or rock that would moderate temperature variations. An acceptable ranking is appropriate for CH soils for this function, if the CH soil layer is covered with a sufficient thickness of protective materials, so that its upper surface is below the depth of maximum frost.

The overall performance that can be expected of plastic clays for cover materials makes CH soils a preferred to acceptable choice because of excellent performance in the most important functions, i.e., minimizing infiltration and limiting the dose rate at the surface. Its fair to poor rankings in other functions can be improved to some extent through proper placement and compaction and use of overlying protective layers.

3.2.3 SC. SC soils were included in the list of fine-grained soils along with SM, because of their characteristics resulting from the percentage of fine particles present even though both of these soils classify as coarse-grained soils in the USCS. SC is a clayey sand or sand-clay mixture with at least 12 percent but less than 50 percent by weight of particles finer than a No. 200 sieve size. More than half of the coarse fraction (+ No. 200 sieve size) is smaller than the No. 4 sieve size (1/4 in.). The fine fraction may be slightly to highly plastic. The fine fraction (- No. 200 size) of this soil plots above the A-line of the Plasticity Chart and its PI is greater than 7.

The ability of SC to perform the two most important fine-grained cover functions, i.e. minimizing infiltration and limiting dose rate at the surface is highly dependent on the clay content percentage and the characteristics in the fine fraction. As mentioned, to be classified as an SC soil, one of the conditions that must be met is that the percentage of fines must be between 12 and 50 percent. If the percentage of fines is 30 percent or larger and an appreciable amount of the fines are clay minerals, then a properly compacted SC could be expected to have relatively low permeability, i.e. nearly as low as a CL. In this case, the SC soil would perform the two major functions very well and a preferred ranking for these two functions would be appropriate. If the percentage of fines is near the lower limit of 12 percent and only a small percentage of these fines are clay minerals, marginal to unsatisfactory performance would be expected and an unacceptable ranking may be appropriate. Of course, the actual performance would depend on placement and compaction controls, as well as actual grain size distribution and plasticity characteristics of the fine fraction. SC soils are fairly easy to work with;

adjustment of moisture content and proper placement and compaction are much less difficult than for fat clays or silts. Its performance under the best conditions would be expected to approximate that of a CL soil.

The performance of an SC soil for minimizing surface erosion would be expected to be good, unless an appreciable percentage of the soil was non-plastic silt. Therefore an acceptable ranking was assigned for this function. A preferred ranking was given for minimizing differential settlements and subsidence within the cover. As discussed previously, large settlements of underlying wastes could result in damage to a cover layer of SC soils but its resistance is better than some other soils, so a variable ranking of preferred to unacceptable was given for this function. Its ranking is preferred to acceptable for minimizing shrink/swell because its potential for volume change would be expected to be low. Frost susceptibility varies from slight to high, depending on the percentage of non-plastic fines and other factors discussed in Section 2.1.6, so a variable ranking of acceptable to unacceptable was given. Like other low permeability soils, it should be covered with a protective layer to minimize potential damage due to freezing or desiccation.

Overall, therefore, SC could be a very good cover soil if the percentage of fines and the percentage of clay minerals in the fine fraction is high.

3.2.4 CL-ML. This borderline soil carries a dual classification because it has characteristics of both CL, inorganic, lean sandy or gravelly clay or silty clay, and ML, inorganic silts and very fine sands, rock flour, silty or clayey fine sands, or clayey silts of low plasticity. Other soils such as SP-SM can carry dual classifications. CL-ML is discussed in this report because it is a fairly widespread soil in the US and has some very interesting behavioral characteristics. Windblown deposits commonly classify as CL-ML, CL, or ML soils. These deposits may be found in many parts of the US, including the middle and lower Mississippi River Valley, the arid areas of the northwest, and the western prairies. As might be expected, it ranks between CL and ML in its performance of fine-grained cover functions. Therefore, the rankings of this soil are not separately discussed here. The reader is referred to the discussions of CL and ML performance for justification of CL-ML rankings.

3.2.5 MH. Inorganic silts, micaceous or diatomaceous, fine sandy or silty soils or elastic silts are classified as MH. MH soils have an LL greater than 50 and plot below the A-line on the plasticity chart. Its lower bound value of PI is 22. MH soil was assigned an acceptable ranking for minimizing infiltration and limiting the dose rate at the surface. The high plasticity of the soil results in low permeability when properly compacted, and low permeability is the primary criterion for limiting infiltration and dose rate. Silts are susceptible to erosion, but plasticity increases its resistance somewhat over the non-plastic silt. Therefore, it was given a ranking of acceptable to unacceptable for erosion resistance.

Highly plastic silts are difficult to properly compact, and require precise control of moisture and very high compactive effort. Relatively large settlements can be expected for thick layers. If the settlements are uniform, adverse affects on cover performance are minor, but differential settlement can result if construction quality control is not emphasized and followed. Because of the difficulty in ensuring proper placement and compaction, a

marginally acceptable to unacceptable ranking was assigned to MH soils for minimizing differential settlement and subsidence.

As discussed in Section 2.1.6, silts are most susceptible to frost damage, if the other contributing factors are present, i.e. available water and freezing conditions. If water is available and the silt is unprotected by an overlying frost resistant layer in cold climates, frost damage can be expected. Therefore an unacceptable ranking is appropriate for freeze/thaw resistance, if the layer is not protected.

The potential for volume change depends on the extent of clay minerals in the silt, and was therefore ranked from acceptable to unacceptable with increasing percentage of swelling clay minerals present.

Overall, MH soils are not well suited as cover materials, but can be constructed to perform well as low permeability layers if extreme care and moisture control are exercised during placement and compaction. MH soils fare poorly with respect to the other functions. These other functions control, to a large extent, the long-term performance of the material and make it unlikely that MH would perform satisfactorily for the long periods of time required of covers at disposal sites. However, MH soils can be amended with additives to improve their workability and performance.

3.2.6 ML. Inorganic silts and very fine sands, rock flour, silty or clayey fine sands, or clayey silts with slight plasticity are classified as ML. ML soils plot below the A-line on the Plasticity Chart. Liquid limits of ML soils fall between 20 and 50, and the PI ranges from 0 to 22.

In general, low-plasticity silt, ML, is not a good choice as a cover soil by itself. If suitable cover soils cannot be found within reasonable distance and in sufficient quantities, ML soils can be amended with sodium montmorillonite or blended with soils of higher plasticity to bring performance up to acceptable levels. The performance of ML soils in the two most important cover functions, minimizing infiltration and limiting the dose rate at the surface, is expected to be marginal. Permeabilities less than about 1×10^{-6} cm/sec should not realistically be expected, and the actual permeability value could be much higher if extraordinary effort and care were not exercised during placement and compaction. An acceptable to unacceptable ranking was assigned to both of these functions. ML soils are highly susceptible to erosion. Evidence of erodibility is readily observed along the loess bluffs in the lower Mississippi River Valley. Silt content is the main factor influencing erodibility in the empirical charts developed by the Soil Conservation Service. Therefore an unacceptable ranking was assigned to ML soils for erosion resistance. For reasons discussed in Section 2.1.6, ML soils are also quite susceptible to frost damage, if freezing conditions and water are both present. Therefore it was given an unacceptable ranking. It is emphasized that a readily available source of water and freezing conditions are required for frost heave damage to actually occur, even with this highly susceptible soil, and these conditions are considered unlikely for properly designed facilities. Collapsible, windblown ML and CL-ML soils in loose natural deposits may be susceptible to subsidence, but in remolded fills compacted on the wet side of optimum water content, subsidence is not a significant concern. Therefore, an acceptable ranking was assigned for minimizing subsidence. Differential settlement of ML in properly compacted

fills is generally not a problem but, as with other soils, damage to the cover as a result of large settlements of underlying materials could be a serious problem. Volume change potential of ML is insignificant, due to its low plasticity, so a preferred ranking was assigned for the shrink/swell potential function.

Therefore, as mentioned in the previous paragraph, ML soils would be expected to provide marginally acceptable performance as a cover soil.

3.2.7 SM. Like SC, SM soils were included in the list of fine-grained soils because of borderline characteristics that result from the mixture of fine soil particles. SM is silty sand or a sand-silt mixture. The percentage of fines is at least 12 percent but less than 50 percent and the fines are predominantly non-plastic or only slightly plastic. The fine fraction would be expected to have behavior characteristics equivalent to an ML. The soil plots below the A-line on the Plasticity Chart and has a PI less than 4.

Its performance in minimizing infiltration and limiting dose rate at the surface would be expected to be unsatisfactory or marginal at best, and an unacceptable ranking was assigned. Because of its non-plastic fine fraction, resistance to erosion would be relatively poor. Its performance would improve as the percentage of fines decreased, so an acceptable to unacceptable ranking was given for this function.

Potential problems with differential settlement, subsidence, and volume change within the layer would not be expected ordinarily, so a preferred ranking was given for these functions. Again, resistance to damage of the cover as a result of large settlements of underlying materials would be insufficient to ensure satisfactory long-term performance. Frost susceptibility would be proportional to the percentage of non-plastic fines and other factors discussed in Section 2.1.6, so a variable ranking of acceptable to unacceptable was assigned.

Overall, the performance of SM soils as fine-grained soils used in a cover system would be expected to be poor to marginal at best, and it is not a recommended material.

3.2.8 Summary of Rankings of Fine-Grained Soils as Waste Cover Materials

The overall ranking of fine-grained soils as waste covers is weighted heavily in favor of high rankings in the two most important cover functions, i.e. minimizing infiltration through the cover and limiting dose rate at the surface of the cover. The other functions are important complementary requirements, but are not considered primary functions. Therefore, the best overall choice as a cover soil is CL and the worst is SM. The rankings, in order of best to worst are then:

1. CL
2. CH
3. SC
4. CL-ML
5. MH
6. ML
7. SM

These rankings are reflected in the order of listing in Table 1-1 and in the preceding Section 3.2. It should be emphasized that these rankings do not take into consideration the ease or difficulty of proper placement and compaction. If workability is an important consideration, CH and MH soils would rank near the bottom.

3.3 Coarse-Grained Soils

Less than 50 percent by weight of coarse-grained soils pass the No. 200 sieve. In Table 1-2, coarse-grained soils are listed from largest to smallest in general. Cobbles are listed first, though technically there is no description for cobbles in the USCS as a coarse-grained soil. Cobbles are listed in Table 1-2 because of their importance in protecting underlying soils from erosion and frost damage, and because of their performance in discouraging burrowing animals and biointrusion. Cobbles are defined as particles larger than 75 mm (3 in.) but smaller than 300 mm (12 in.) (Holtz and Kovacs, 1981). Gravels (designated by G) range in size from 4.75 to 75 mm, and sands (designated by S) range from 0.074 mm to 4.75 mm. Standard sieve numbers corresponding to these opening sizes are No. 200 (0.074 mm) and No. 4 (4.75 mm). (There is no standard sieve size with 75 mm or 300 mm openings.)

The coarse-grained soils are subdivided based on grain-size and grain size distribution, including the percentage of fines, i.e. materials passing the No. 200 sieve. The coefficient of uniformity, C_u , defined as the ratio of D_{60} to D_{10} , and the coefficient of curvature, C_c defined as the ratio of $(D_{30})^2$ to the product of D_{10} and D_{60} are used to further delineate well-graded from poorly-graded coarse-grained soils. The coefficient of uniformity is a misnomer in that the smaller the value of C_u , the more uniform is the gradation. For example, a soil with only one grain size would have a C_u value of 1. Typical C_u values might be 2 to 3 for beach sands, 15 for well-graded soils, or 400 to 500 for the core of an earth-rockfill dam with sizes ranging from stone to clay sizes. A soil with a coefficient of curvature of 1 to 3 would be considered well-graded if the C_u value of the soil was greater than 4 for gravels and 6 for sands (Holtz and Kovacs, 1981). The grain sizes in these ratios are the grain sizes at which the subscript percentage is finer. For example the value of D in the term D_{10} is the size corresponding to 10 percent passing, or 10 percent of the particles by weight, are smaller than D .

The final distinction in classification of coarse-grained soils is based on Atterberg limits of the fine fraction, i.e. liquid and plastic limit values. This distinction determines whether the modifying letter in sands (S) and gravels (G) is C for clay or M for silts. In the following paragraphs, each coarse-grained soil is defined, based on these distinguishing characteristics, and is then ranked according to its performance of each of the 8 listed coarse-grained cover functions.

3.3.1 Cobbles. As mentioned, the designation of cobbles is based on size only, i.e. particles between 75 and 300 mm. Inference or judgments about durability, i.e. physical and chemical stability of cobbles must be based on geologic history of the parent material and empirical evaluations. This statement is true for all soil sizes, but is most important for cobble and gravel sizes that are used to protect underlying materials from erosion and to

promote drainage. In the following evaluations, it is assumed that the materials that would be used are physically and chemically stable as demonstrated by testing and evaluation.

Cobble size material that is stable should perform all coarse-grained cover functions very well. This size material would be excellent for surface erosion protection and minimizing biointrusion and burrowing. Use of cobbles alone would certainly achieve good drainage but could allow piping and internal erosion of adjacent fine-grained soils if used as a subsurface drainage blanket. With these qualifications, a preferred ranking was assigned to cobbles for performance of all coarse-grained cover functions.

3.3.2 GW. Clean well-graded gravels, clean gravel-sand mixtures with less than 5 percent fines, and with a wide range in grain sizes, including all intermediate sizes are classified GW. More than half the material is retained on the No. 4 sieve size (i.e. is larger than 1/4 in.). The C_u value, D_{60}/D_{10} , is larger than 4, and the C_c value, $(D_{30})^2 / D_{10} \times D_{60}$ is between 1 and 3. The performance of GW would be good to excellent for all coarse-grained soil functions and a preferred ranking was assigned for all 8 functions.

3.3.3 GP. GP is distinguished from GW by its grain size distribution and C_u and C_c values. Like GW, GP soils contain less than 5 percent fines and more than 50 percent is larger than the No. 4 sieve opening. GP soils are poorly graded (well sorted), meaning that one size or a narrow range of sizes predominate the make-up of the soil and some particle sizes are missing.

GP soils should perform all coarse-grained cover functions very well, and a preferred ranking was assigned for all functions. The preferred ranking for minimizing surface erosion is justified because GP soils would protect underlying soils from erosion very well. However, piping and internal erosion of overlying fine-grained soils could occur if GP soils are used as a drainage layer without a graded filter. This potential can be checked for specific soils using well-established filter and drainage criteria as described in NUREG/CR-5041 (Denson et al., 1987).

3.3.4 GM. Silty gravels, or gravel-sand-silt mixtures comprise GM soils. Over half the particles by weight are larger than the No. 4 sieve opening and more than 12 percent by weight of particles pass the No. 200 sieve. The fine fraction is non-plastic or only slightly plastic. The Atterberg limits of the fine fraction plot below the A-line on the Plasticity Chart and the PI is less than 4.

GM soils are not as well suited for coarse-grained cover functions as the clean gravels (GW and GP) but should perform satisfactorily. The GM material could be screened to remove the objectionable fines if necessary to improve performance if more suitable native materials are not available. Permeabilities would be expected to be lower than desired for promoting drainage, but could be in the acceptable range, depending on climatic conditions, surface runoff, and fine-grained cover characteristics. If the saturated hydraulic conductivity of the fine-grained, low-permeability layer was 1×10^{-7} cm/sec, the hydraulic conductivity of the drainage layer should be at least 1×10^{-3} cm/sec. A silty gravel classified as GM could probably satisfy this criterion, and drainage rates would probably be acceptable in arid or semi-arid climates. Drainage rates through a layer with this value of

saturated hydraulic conductivity may be unacceptable in humid regions because of insufficient flow capacity or if the corresponding value of hydraulic conductivity for the low-permeability soil layer was not sufficiently less than the hydraulic conductivity of the drainage layer. Therefore, a marginally acceptable to unacceptable ranking was assigned for this function. The performance of GM soils for resisting erosion would be expected to be comparable but slightly less satisfactory than the performance of clean gravels. The non-plastic fines could be washed out, at which time the resulting clean gravel would have characteristics similar to GW or GP and would perform accordingly in protecting underlying fine-grained soil layers from erosion. Therefore, a preferred to acceptable ranking was assigned to GM for this function.

Subsidence and differential settlements within the cover are not significant concerns for GM or other gravels. However, large settlements of underlying materials could result in some damage to gravel or other drainage layers. Therefore, a preferred to acceptable ranking was assigned for resistance to settlements within the layer and acceptable to unacceptable ranking was given for resistance to damage from settlements of underlying materials. Likewise, volume change is not a problem with silty gravels, so a preferred ranking was assigned for this function. Burrowing animals could cause minor to moderate problems, and a variable ranking of preferred to acceptable was assigned to this function. Intrusion of deep-rooted plants into soils classified GM could be moderate to severe, so a variable ranking of acceptable to unacceptable was assigned to this function.

Susceptibility to frost damage is dependent on the percentage of non-plastic fines, and the existence of other conditions favorable to formation of ice lenses as discussed in Section 2.1.6. Capillarity would be expected to be low to moderate, even for a significant percentage of fines, so an acceptable ranking was assigned for this function.

Overall, silty gravel could be used for coarse-grained cover layers and would be expected to perform satisfactorily in arid regions. If processed to remove fines, its performance in all functions should be very good and these soils would then be suitable for sites in humid regions.

3.3.5 GC. Clayey gravels or gravel-sand-clay mixtures comprise soils classified as GC under the USCS. Like GM, GC soils have greater than 12 percent fines by weight and more than 50 percent of the particles by weight are larger than the No. 4 sieve opening. The Liquid Limit and Plasticity Index of the fine fraction of GC soils plot above the A-line and the PI is greater than 7. The fines may be slightly to highly plastic.

Drainage through GC soils is adversely affected by the fines. Actual impact is dependent on the percentage of fines and the plasticity of clay minerals in the fine fraction. More than about 15 percent by weight of fines would be expected to seriously impair drainage. Therefore, an unacceptable ranking was assigned to this function.

Clayey gravels would be expected to provide good protection from surface erosion and to underlying fine-grained soil layers. The ranking assigned to this function was preferred to acceptable.

Subsidence and differential settlement problems within a cover layer of GC soils would not be expected unless there was a high percentage of swelling clay minerals in the fine fraction. Therefore, a variable ranking of preferred to acceptable were assigned to this function. Damage to the drainage layer could occur as a result of large settlements of underlying materials so a ranking of acceptable to unacceptable was given for this function. Shrink/swell problems would not be expected so a ranking of preferred to acceptable was given for this function.

Compacted clayey gravels should provide good resistance to burrowing animals and a preferred to acceptable ranking was assigned for this function. Biointrusion of deep rooted vegetation may occur in soils classified as GC, so a variable ranking of acceptable to unacceptable was assigned to this function. Frost susceptibility is slight to moderate for clayey gravel and an acceptable ranking was assigned.

Therefore, the performance of clayey gravel would be good in almost all functions required of coarse-grained soils. However, the performance of this soil in what is considered to be the most important coarse-grained soil function, i.e. promoting drainage is only marginal. Properly weighted, the ranking of this function reduces the overall desirability and performance of clayey gravel as a coarse-grained cover material. However, like silty gravels, the clayey fines could be removed to greatly enhance its performance. Therefore, its overall performance is ranked marginally satisfactory without processing. This ranking could be upgraded to excellent if fines are removed.

3.3.6 SW. Sands are distinguished from gravels in the USCS by the percentage retained on or passing through the No. 4 sieve openings. More than 50 percent of the coarse fraction of the particles by weight must pass the No. 4 sieve for a soil to be classified as sand.

Well-graded sands and gravelly sands containing little or no fines (< 5 percent by weight) are classified SW. The well-graded designation, W, means that practically all intermediate sizes are represented in substantial amounts. The value of C_u must be greater than 6 and the value of C_c must be between 1 and 3 to distinguish SW from poorly graded sand, SP.

Excellent to good drainage characteristics are to be expected with well graded sands. Typical values for saturated hydraulic conductivity are in the range of 1 cm/sec to 1×10^{-3} cm/sec. Therefore a preferred to acceptable ranking was assigned for promoting drainage.

The relatively large, cohesionless particles of SW can be easily dislodged by rain, but water velocities and flow rates must be high to transport the particles significant distances. Therefore, overall performance in resisting surface erosion is very good and it was given a preferred ranking. Well-graded sand is typically an excellent choice as a filter and drainage layer beneath the low permeability layer, because it protects the overlying material against internal erosion and piping. A preferred ranking was assigned for this function. Subsidence, differential settlements, and volume change potential within the cover are not of concern with compacted well-graded sands. Well-graded sands are readily placed and compacted, and achievement of specified fill density is usually not difficult. Therefore, excellent or preferred rankings were given for these two functions. Again

large settlements of underlying materials could produce damage, but SW soils placed in relatively thick layers would be more resistant to damage than many other soils, so a preferred ranking was assigned to this function. Burrowing animals can easily dig through sands, unless the sands are cemented natural deposits. However, the burrows will not remain open and stable because of lack of cohesion unless the sand is damp. Damp sands exhibit apparent cohesion that would allow burrows to remain open. Therefore, a variable ranking of preferred to acceptable was assigned to this function. Similar rankings would apply to sands for resisting biointrusion of deep rooted vegetation. However, differentiation in this ranking is justified between clean sands and sands with significant fines. The clean sands don't offer a favorable environment for plant nourishment because of the lack of organic material and fines. Therefore, an acceptable ranking was assigned to SW soils for resisting biointrusion.

Frost susceptibility is not a problem for well graded sands and a preferred ranking was given for this function.

Overall SW is a very good choice as a coarse-grained cover layer, especially if protected by an overlying layer of larger material to enhance its resistance to erosion and deep-rooted vegetation.

3.3.7 SP. Poorly graded sands or gravelly sands with less than 5 percent by weight of fines, either predominantly one size or with some intermediate sizes missing, are classified SP in the USCS. This sand does not meet all the gradation requirements (eg. C_c and C_u) of SW soils.

Poorly graded sands typically have saturated hydraulic conductivity values comparable to but higher than well graded sands. Actual values may vary over a wider range than for well graded sands, depending on whether the predominant size is coarse, medium, or fine sands. Drainage characteristics are excellent to good and ranked accordingly, preferred to acceptable.

Erosion resistance of poorly graded sands would also vary over a wider range than well graded sands for the same reason as the variation in drainage characteristics, i.e. whether the predominant grain size is coarse, medium, or fine sand. Protection of adjacent or overlying soils from internal erosion and piping would not be as good as the protection provided by well-graded sands, because of the missing intermediate sizes. Therefore, a variable ranking of preferred to acceptable was assigned for resistance to erosion of poorly graded clean sand, SP. As was the case for SW, concerns about subsidence, differential settlement, and volume change potential would not be as serious for properly compacted poorly graded sand fills or for dense, natural deposits. Therefore, preferred rankings were given for these functions.

Poorly graded sands would provide little resistance to burrowing animals but the burrows would not remain stable and open unless the sand was damp so a preferred to acceptable ranking was given. Deep-rooted vegetation could also easily become established; the only deterrent is lack of organic matter and fines, and the resistance to biointrusion is ranked acceptable. Poorly graded sands are not frost susceptible so the ranking for frost resistance is preferred.

Overall, the performance of poorly graded sand, SP, would be expected to be nearly as good or better than well-graded sand and would be an excellent choice as a cover layer for all coarse-grained cover functions. As with SW soils, the performance of SP soils could be enhanced even further by provision of an overlying protective layer of cobbles or gravel to protect the SP soils from erosion, burrowing, and biointrusion.

3.3.8 SM. Silty sands and sand-silt mixtures with greater than 12 percent passing the No. 200 sieve are classified as SM, if the fine fraction plots below the A-line on the Plasticity Chart. The PI must be less than 4.

Silty sand, in general would be a marginal to poor choice as a soil for performing coarse-grained cover functions. Its drainage characteristics are poor, due to the high percentage of fines. Typical values of saturated hydraulic conductivity would be in the range of 1×10^{-4} cm/sec to 1×10^{-6} cm/sec. A typical value of 5×10^{-5} cm/sec is given in TM 5-818-4 for SM soils compacted to 100 percent of Standard Proctor density. Therefore, an unacceptable ranking is appropriate for its performance in promoting drainage. Its relatively poor resistance to erosion was discussed previously under fine-grained soil cover performance and a ranking of marginally acceptable to unacceptable was assigned.

Subsidence, differential settlement, and shrink/swell are not problems associated within layers of compacted silty sands. Subsidence or large settlements of underlying materials could occur and cause damage to cover layers of SM soils. Because of the low plasticity of the fine fraction, volume change potential is insignificant. Therefore, preferred rankings were given for resistance to settlement within the cover layer and minimizing volume change. The ranking assigned to minimizing damage to the cover as a result of large settlements of underlying materials was acceptable to unacceptable.

Burrowing animals and deep-rooted vegetation could become significant problems for unprotected surface layers of silty sand that contain enough fines or moisture to provide stable openings, so acceptable to unacceptable rankings were assigned for these functions.

Frost susceptibility could be a moderate to serious problem, if the environmental conditions favored the formation of ice lenses, and a variable ranking of acceptable to unacceptable was assigned to reflect this potential.

3.3.9 SC. Clayey sands and sand-clay mixtures are distinguished from silty sands according to the characteristics of the fine fraction. Both sands have at least 12 percent fines by weight, but the fine fraction of SC plots above the A-line on the Plasticity chart and the PI is at least 7. The clayey fines may be moderately to highly plastic. The percentage and plasticity of the fines has a very important impact on the engineering behavior of this soil.

Drainage characteristics of SC soils are poor. Hydraulic conductivity values may be almost as low as for CL, or nearly as high as very fine or silty sands, depending on the amount and plasticity of the clayey fines. Typical hydraulic conductivity for SC soils compacted to 100 percent of Standard Proctor density at optimum moisture content is given in TM 5-818-4 as 5×10^{-7} cm/sec. Therefore, an unacceptable ranking was assigned SC for its poor

drainage characteristics. Clayey sand would be expected to be fairly resistant to surface erosion. Clayey sands perform better than silty sands, because of the plasticity of the clayey fines, and an acceptable ranking was assigned for this function.

Clayey sand can be compacted with reasonable effort to minimize settlements. Differential settlements and subsidence would not be expected to be significant concerns within compacted layers of SC soils, so a preferred ranking was assigned. Of course, damage could result from large settlements of underlying materials and a ranking of A to U was assigned. Similarly, volume change potential is generally low, unless the fine portion includes a significant percentage of highly plastic swelling clay minerals. Therefore, a preferred to acceptable ranking is appropriate for this function.

Burrowing animals and deep rooted vegetation may have slightly more trouble becoming established than in silty sands, due to the higher plasticity and resulting higher strength and toughness of SC over SM. However, burrows and root channels would conceivably remain open long after being abandoned by the animals and long after the vegetation decayed. The long-term performance of SC would be poor in such cases and marginally acceptable to unacceptable rankings are assigned for these functions. Frost susceptibility is slight to high with SC soils so a variable ranking of acceptable to unacceptable was given for this function. In its natural state, SC soils may be a poor choice for performing coarse-grained soil functions, but may perform fine-grained soil functions quite satisfactorily. If SC soils were readily available at a disposal site, the fines could be separated from the natural soil by processing and the resulting clean sand would be expected to be an excellent material for performing coarse-grained soil functions. The clayey fines removed could be blended in with additional natural clayey sand to enhance its performance of fine-grained cover functions. In this way, this borderline material could be used as the raw material for different cover layers performing different functions satisfactorily. The resulting processed materials would probably classify as SP or SW and CL soils, respectively. Therefore, SC soils should not be ignored if sufficient quantities are available at or near the site, and more highly desirable coarse-grained soil types cannot be located within reasonable distance.

3.3.10 Summary of Coarse-Grained Soil Rankings

The most important coarse-grained soil functions are drainage, long-term stability, and erosion resistance. Erosion resistance should be evaluated based on both resistance of surface erosion of the material itself and the protection of adjacent materials. Practically all coarse-grained soils perform very well in minimizing subsidence and differential settlements within the layers if properly placed and compacted and are better than many other soils for resistance to damage as a result of large settlements of underlying materials. Practically all coarse-grained soils exhibit very little potential for volume change, with the possible exceptions of clayey sand, SC, and clayey gravel, GC. Resistance to freeze/thaw damage varies but is generally fair to excellent for all coarse-grained soils except for silty and clayey sands (SM and SC). The functional requirements of resistance to burrowing animals and deep-rooted vegetation are important but secondary requirements. These two functions are best accomplished by placement of a surface layer or layers of gravel, cobbles, or larger size stone. Therefore, in ranking soils for

performing coarse-grained cover functions, emphasis was placed on long-term performance in promoting drainage and resisting erosion. The benefits of using layers of different soils that perform certain functions best and/or protect other layers that perform these functions best should be emphasized. This multi-layered approach is highly recommended as a practical cost-effective design philosophy.

With these qualifications, the rankings of coarse-grained soils are:

1. Cobbles
2. GW
3. GP
4. SW
5. SP
6. GM
7. GC
8. SM
9. SC

It should be noted that the relative rankings of some of the soils listed consecutively above may be reversed or approximately equal. For example, depending on the actual engineering characteristics, the rankings of SP and GW may be approximately equal or reversed. This condition may also be true for some soils classified as GC and SM.

3.4 Amended Soils and Soil Mixtures

The addition of a material or materials to a soil to improve one or more engineering properties of that soil is referred to as stabilization. There are two types of stabilization; chemical stabilization and mechanical stabilization. Chemical stabilization is accomplished by adding materials such as cement, lime, fly ash, bitumen or a combination of these additives to a soil. Mechanical stabilization is accomplished by compaction or by blending additional aggregates, or a combination of both to the in-place material.

The use of additives or modifiers for improving engineering properties and behavior of marginal soils has increased steadily in the US since the 1950s, especially in the areas of highway and airfield construction. Soil additives have also been used to a lesser extent in earth embankments and foundations.

At some waste sites, suitable natural soils may be unavailable in sufficient quantities, or within reasonable hauling distances. Certain additives, modifiers, or mixtures may be considered as reasonable alternative solutions in these cases to improve the performance of marginal soils.

The potential applications and range of different additives or modifiers that may be considered are diverse. Detailed discussion of all possible additives or modifiers is beyond the scope of this study. In the following paragraphs, the most common modifiers and applications are summarized. Advantages and disadvantages of these additives or modifiers, with respect to waste cover applications are discussed. Guidance on the use of these additives is available and is cited, but this guidance has been developed primarily for airfield and highway construction. Direct application of this

guidance for design and construction of amended soils to be used in waste covers may be inappropriate and is not recommended.

Bentonite has been blended with selected soils to reduce hydraulic conductivity. This process has been widely used and has been proven to provide satisfactory performance. This process would be acceptable if construction operations were properly controlled and testing was performed that demonstrated achievement of required engineering properties.

Many questions remain about long-term durability and performance of soils amended with some additives (e.g. bituminous additives or mixtures). Until these questions are resolved, amended soils or soil additives should not be relied on as the primary or only means for satisfying long-term cover functions. They may be appropriately considered for enhancing performance of certain cover functions where natural soils would exhibit marginally satisfactory performance. A pertinent example would be the use of soil-cement for enhancing erosion protection.

The advantages and disadvantages of a specific stabilized soil will depend upon the soil that is to be stabilized or modified as well as the type and amount of additive being used to stabilize or modify the soil. Proper mixing and construction of the stabilized materials are also crucial in obtaining the desired characteristics.

The following paragraphs provide typical ranges for the amount of additive required for a particular soil and how that additive will affect the desired engineering properties. To further enhance soil engineering properties, more than one of the following additives can be added to stabilize a particular soil.

3.4.1 Addition of Cement to Soils for Enhancing Erosion Resistance

The addition of cement to a soil enhances durability and strength of the soil which improves resistance to surface erosion. Therefore, it may be appropriate to consider a well designed soil-cement, for erosion protection if other materials are not available for that purpose. The degree to which cement affects the soil properties will be dependent upon the quantity of cement added, the type of soil being stabilized and construction procedures used for stabilization.

Only the best combinations of uncontaminated, natural soils and cement should be used for this purpose. The most effective soils to stabilize using cement are sands, silty soils, and clayey soils with low to medium plasticity. It is difficult to achieve the proper dispersion of cement through the soil matrix of soils that are more plastic.

When cement is used to stabilize sandy soils, as classified in USCS, the Plasticity Index (PI) should be less than 30. Fine-grained soils should have a PI less than 20 and a Liquid Limit (LL) less than 40. Gravelly soils should have a minimum of 45 percent by weight passing the No. 4 sieve and a PI not greater than the value obtained using the following formula from TM 5-530 (U.S. Departments Army, Navy, and Air Force, 1971):

$$PI = 20 + [(50 - \text{fines content})/4]$$

Soils that contain low molecular weight organics, such as nucleic acid and dextrose, should not be stabilized using cement. These organic compounds act as hydration retarders, thereby reducing the strength of the stabilized soil. Sulfate-containing soils should not be used. If sulfate attack is likely, cement stabilized soils should not be used. In any case, sulfate soundness tests as described in ASTM C 88 should be conducted on the soil-cement to assure no significant losses, conservatively interpreted.

Freeze-thaw tests should be conducted if the material will be exposed to such conditions in the field. Freeze-thaw testing is described in TM 5-530 (U.S. Departments Army, Navy, and Air Force, 1971).

The typical range of cement required to stabilize coarse-grain soils is 4-7 percent by dry weight, while the typical range for fine-grain soils is 10-12 percent by dry weight. When stabilizing clays and silts, the smallest quantity of cement that can effectively produce the desired properties should be used to prevent shrinkage cracking.

A period of 7-10 days for curing will normally be required. Temperatures near or below freezing will greatly retard the hydration of cement; therefore, soil temperatures above 40°F (5°C) are recommended for construction. If cold weather conditions are encountered during construction, the stabilized soil must be protected using straw, hay or some other protective covering to prevent freezing during the cure period.

The optimum quantity of cement required to modify an engineering property of a soil should be determined in the laboratory. The specific criteria for laboratory testing will be dependent upon the type of soil being stabilized and the type of cement being used as the additive and the anticipated procedures for field placement. Cement stabilized soils routinely show increases in compressive strength of 250 to 2000 psi. The increase in compressive strength is dependent upon the soil type, the type of cement, cement content and construction procedures such as mixing, compaction and curing. In general, the higher the cement content the larger the compressive strength increase but with higher cement contents, longer cure periods will be required and shrinkage cracking potential will increase.

3.4.2 Addition of Lime to Soils

Calcium or magnesium oxides and hydroxides are the compounds normally referred to when the term lime is used. Several types and purity levels of lime are available for use in stabilization and consequently the chemical properties vary slightly. The most common types of lime used in stabilization are hydrated high calcium lime $\text{Ca}(\text{OH})_2$, monohydrated dolomitic lime $\text{Ca}(\text{OH})_2 \cdot \text{MgO}$, calcitic quicklime CaO , and dolomitic quicklime $\text{CaO} \cdot \text{MgO}$. Most types of lime, dehydrated dolomitic $\text{Ca}(\text{OH})_2 \cdot \text{Mg}(\text{OH})_2$ excluded, are acceptable for lime stabilization of soils. The properties of the soil that is to be stabilized will have a greater influence on the properties of the final product than the type of lime used. The type of waste being covered must be carefully considered before using quicklimes because they are highly caustic.

Lime effectively stabilizes fine-grained soils and is especially effective for high PI clays. However, it is difficult to properly mix lime into highly plastic clays, just as it is difficult to work with unmodified

highly plastic clays. To improve the durability or resistance to wear and weathering of a soil, 6-11 percent of lime by weight of the lime-soil mixture may be required while a reduction in PI may be accomplished by adding as little as 2 percent lime by weight. In general, if a quicklime is being used instead of a hydrated lime, then 25 percent less additive is required.

Lime stabilization affects the soil in one or more of three ways depending upon the soil type. First, the lime reacts with water in the soil and creates a drying effect, which is especially beneficial during construction periods when soils may become saturated. Secondly, lime causes flocculation in the soil which in effect changes the texture of a highly plastic soil to a silty texture. The change in texture increases the workability of the soil. If a highly plastic soil is to be stabilized with cement, lime may be added to the soil first to "coarsen" the soil texture. The change in texture allows the cement to be effectively mixed into the soil and react with the soil. Lastly, the lime can react with soil components, particularly alumina and silica, to form new chemical components that may provide improved strength and durability. The increase in strength is dependent upon the soil type and will generally range between 0-800 psi as measured in the unconfined compression test. The main difference between cement and lime stabilization is the amount and rate of strength gain. Lime stabilized soils will normally have lower strengths and gain strength at an appreciably slower rate than cement stabilized soils.

The addition of lime to a soil has potential advantages for waste coverings. The durability and strength of the stabilized soil will generally be increased which improves resistance to surface erosion, differential settlement and subsidence. Strength improvements gained through the use of lime aid in discouraging burrowing and will minimize biointrusion. The strength improvements are small as compared to the addition of cement; therefore, when strength improvement is required both lime and cement can be added to the soil. Some disadvantages may be associated with the use of lime as a soil additive. When large percentages of lime are mixed with the soil, the potential for shrinkage cracks is increased. The resistance to freeze-thaw cycles of lime-soil mixtures is dependent upon the initial unconfined compressive strength of the soil. Therefore, factors that influence the strength development; such as cure time, lime content, and density also influence freeze-thaw resistance. Addition of lime increases the mixtures' brittleness, which could result in increased cracking as a result of settlement of underlying materials.

Laboratory testing is required to determine the optimum lime content for a desired engineering property using specific soil types. Requirement criteria will depend on the desired engineering property improvement.

Lime stabilization requires a cure time of 7-10 days minimum and also requires warm weather to properly harden. Increases in strength and durability properties are obtained as the lime-soil mixture continues to cure in the same manner that concrete strength increases with time. The stabilized soil can be exposed to construction traffic after 10 days, but even after construction has ceased or the next layer has been placed, the lime-soil mixture will continue to cure.

Stabilization with lime-cement should not be conducted when the soil temperature is below 40°F (5°C). The soil must be protected from freezing conditions during the cure period if cold weather conditions are encountered.

3.4.3 Addition of Fly Ash to Soils

Fly ash and most pozzolanic materials, such as ground slag, are waste products from the combustion of coal that under certain conditions can react to form cementitious products. Because they are waste products, they offer economic advantages over cement products, but they also are not as uniform in size or chemical properties. Some fly ash materials are naturally cementitious and can be used directly to stabilize a soil. However, most fly ash materials require the addition of 1-2 percent of lime to aid in the pozzolanic reaction for strength gain.

Fly ash is generally used in stabilization as a filler to decrease air voids in a soil and/or to act as pozzolans which form a cementitious mass to increase strength. Lime and/or cement can be added to fly ash to provide a further increase in the strength of the soil. Fly ash reactivity is dependent upon the method of production of the fly ash and will often vary from one source to another. Laboratory testing is required to determine its reactivity and uniformity before it is used for stabilization.

Fly ash materials can be used to successfully stabilize coarse-grain soils that contain little or no fines. Coarse-grain soils that have less than 12 percent passing the No. 200 sieve and a PI of no greater than 25 for the minus 40 fraction (SW, SP, GW, and GP) are the most suitable. The particle size of fly ash minimizes its effectiveness as a filler material in fine-grain soils; however, when lime or cement is added to the fly ash, fine-grain soils can be effectively stabilized or modified. Typical ranges for lime-fly ash mixtures are 2.5-4 percent of lime and 10-15 percent of fly ash by weight of the total mixture. The typical range of cement is 0.5-1.5 percent, if it is added to the mixture to increase initial strength.

Lime-fly ash and cement-lime-fly ash stabilized soils have similar characteristic improvements as accomplished using cement or lime for stabilization. Strength and stability can be improved, differential settlement and subsidence is reduced, shrink/swell potential is reduced and an increase in freeze-thaw resistance can be accomplished using lime-fly ash. One potential advantage of fly ash mixtures is their ability to re-cement across cracks under some conditions. This self-generating mechanism is termed autogeneous healing. Lime-soil mixtures have this ability also but not to the extent of lime-fly ash-soil mixtures. Autogeneous healing means that lime-fly ash mixtures are not as susceptible to environmental deterioration and cracking as other materials that are not capable of "healing." The cure period and cold weather precautions are the same for fly ash stabilized soils as they are for cement or lime stabilized soils.

3.4.4 Addition of Bitumen to Soils

Bitumen stabilization of soils is usually accomplished using an asphalt cement, asphalt emulsion or asphalt cutback (liquid asphalt). Each one of these asphalt products has various classifications which distinguish characteristics of the stabilized material. Asphalt cements are graded or

divided by consistency or viscosity, while emulsions and cutbacks are graded or classified based on viscosity of the asphalt plus the curing time of the liquid. The main division or classification for cutbacks is the cure time; rapid-cure (RC), medium-cure (MC), and slow-cure (SC). Each one of the cure rates is further divided by the viscosity of the asphalt which is given in centistokes. For example, RC-250 is a rapid-cure cutback and the viscosity of the asphalt is 250 centistokes at 140°F (60°C). The cure time classifications for emulsions are rapid-setting (RS), medium-setting (MS) and slow-setting (SS). Emulsions also classified as cationic (possess a positive charge), anionic (possess a negative charge) or nonionic (do not possess a charge). For example a CSS-1, is a cationic slow-setting emulsion and a SS-1 is an anionic slow-setting emulsion. Nonionic emulsions are not generally used in the stabilization of soils. For in-place stabilization, either an asphalt emulsion or cutback may be used; however, due to environmental concerns, emulsions are preferred.

Bitumen can be used to stabilize most types of soils, but different types of bitumen will be required for different soil classifications. If the PI of the soil is above 10, lime will be required to reduce the PI before bitumen can effectively stabilize the soil. Cement can also be added to the soil at the same time the bitumen is added which will increase the early strength of the stabilized soil. A ratio of 1 to 5, cement to residual asphalt, is normally sufficient for early stiffness without making the soil too brittle.

The types of bitumen suggested for open-graded aggregates are rapid- and medium-curing liquid asphalts or cutbacks such as RC-250, RC-800 and MC-3000 or medium-setting asphalt emulsions such as MS-2 and CMS-2. For well-graded aggregates with little or no minus No. 200 material it is suggested that rapid- and medium-curing liquid asphalts, such as RC-250, RC-800 and MC-800, slow-curing liquid asphalts, such as SC-250 and SC-800, or medium- and slow-setting emulsions, such as MS-2, CMS-2, SS-1 and CSS-1 be used for stabilization. Medium-curing liquid asphalts, MC-250 and MC-800, slow-curing liquid asphalts, SC-250 and SC-800, and medium- and slow-setting emulsions, MS-2, CMS-2, SS-1, SS-1h, CSS-1, and CSS-1h, can be used to stabilize aggregates that contain a high percentage of minus No. 200 material. The typical range of residual asphalt cement used for modification or stabilization is 2-8 percent by weight. Soils that contain a higher percentage of minus No. 200 material will require a larger percentage of bitumen.

The addition of bitumen to a soil will generally enhance the desired engineering properties of the soil. Stability and durability can be increased; surface erosion is minimized; differential settlement and subsidence can be reduced; burrowing and biointrusion may be reduced; and infiltration and dose rate at the surface are reduced when bitumen is used. Bitumen usually will not affect the shrink/swell potential of a soil when used alone; however, lime can be added in conjunction with the bitumen if shrink/swell is a problem.

It should be noted however, that the benefits cited for addition of bitumen to soils may be short-lived. Long-term durability of bitumen and soil-bitumen mixtures is a serious concern. This concern should be addressed before bitumen is proposed for long-term performance in cover applications.

The optimum quantity of bitumen required to provide improvements in a given engineering property must be determined through laboratory testing. The addition of too much additive is more critical with bitumen stabilized soils than with cement, lime or fly ash stabilized soils. Too high of a bitumen content for a given soil will cause a decrease in soil stability.

Emulsified asphalt stabilization construction should not be started during periods of rain or when rain is expected. The rain water will dilute the emulsion and could cause it to be lost in runoff. The cure time for emulsion will increase when exposed to high humidity; but the addition of moisture to the soil may be required when hot, dry weather conditions are encountered during construction. Normal cure time for bitumen stabilized soils is 7-10 days.

3.4.5 Blending Soils

The purpose for blending soils is to decrease permeability and to improve gradation so that the blend is a better filter or barrier layer.

The likelihood of creating a partially skip-graded soil by blending is high. Skip gradation results in higher probability of non-uniformities within the layer, which in turn would interfere with its function as a filter or a barrier. Therefore, a great deal of caution should be used when blending soils that are to be applied in a cover that is intended to last 300 years.

If the blended soil is to be used as a filter, it should be prepared using techniques similar to those used in situ and then tested under high gradients to help assure that migration of fines through the filter does not occur.

One of the more common soils used in blending is the addition of clay to reduce hydraulic conductivity. Bentonite has been used successfully for modifying soils used in waste linings and in waste coverings.

The amount of bentonite required to decrease conductivity to a given value will be dependent chiefly on the soil to which it is to be added, the type of bentonite used, and the method of mixing and placement. If the bentonite is blended with a soil to make a low permeability barrier, it should be mixed using procedures that model field mixing. Then permeability tests should be performed at high gradients on a thin layer, with the same soil below as will exist in situ, to help assure that the low permeability will persist for long times. The test should be done long enough to permit several pore volumes to permeate the specimen. Short-term permeability tests have been found ineffective for soils used for waste linings because they do not allow sufficient time for the displacement of the pore liquid as would be encountered in the field.

The liquid used to permeate the bentonite-blended soil should be similar to the water that is expected to permeate the soil in situ. A range of water chemistries should be used to help observe potential effects on permeability.

In summary, soil bentonite mixtures may be used for low permeability barrier layers if extensive, careful testing of the hydraulic conductivity is done on the mixture to estimate (a) required compaction effort, water content,

and density; and (b) potential for migration of fines into the soil below at high gradients using various water chemistries.

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APPENDIX A
Unified Soil Classification System (USCS)

UNIFIED SOIL CLASSIFICATION
(Including Identification and Description)

Major Divisions	Group Symbols	Typical Names	Field Identification Procedures (Excluding particles larger than 3 in. and basing fractions on estimated weights)	Information Required for Describing Soils	Laboratory Classification Criteria						
1	2	3	4	5	7						
Coarse-grained Soils More than half of material is larger than No. 200 sieve size. More than half of material is smaller than No. 200 sieve size is about the smallest particle visible to the naked eye.	Gravels More than half of coarse fraction is smaller than No. 4 sieve size. (For visual classification, the 1/4-in. size may be used as equivalent to the No. 4 sieve size.)	GW	Well-graded gravels, gravel-sand mixtures, little or no fines.	Wide range in grain sizes and substantial amounts of all intermediate particle sizes.	For undisturbed soils add information on stratification, degree of compactness, cementation, moisture conditions, and drainage characteristics.	$C_u = \frac{D_{60}}{D_{10}} \text{ Greater than } 4$ $C_c = \frac{(D_{30})^2}{D_{10} \times D_{60}} \text{ Between } 1 \text{ and } 4$ <p>Not meeting all gradation requirements for GW</p>					
		GP	Poorly graded gravels or gravel-sand mixtures, little or no fines.	Predominantly one size or a range of sizes with some intermediate sizes missing.			Give typical name; indicate approximate percentages of sand and gravel, maximum size; angularity, surface condition, and hardness of the coarse grains; local or geologic name and other pertinent descriptive information; and symbol in parentheses.	<p>Atterberg limits below "A" line or PI less than 4</p> <p>Atterberg limits above "A" line with PI greater than 7</p>			
		GM	Silty gravels, gravel-sand-silt mixture.	Nonplastic fines or fines with low plasticity (for identification procedures see ML below).					$C_u = \frac{D_{60}}{D_{10}} \text{ Greater than } 6$ $C_c = \frac{(D_{30})^2}{D_{10} \times D_{60}} \text{ Between } 1 \text{ and } 3$ <p>Not meeting all gradation requirements for SM</p>		
		GC	Clayey gravels, gravel-sand-clay mixtures.	Plastic fines (for identification procedures see CL below).			<p>Example:</p> <p>Silty sand, gravelly; about 80% hard, angular gravel particles 1/8-in. maximum size; rounded and subangular sand grains, coarse to fine; about 15% nonplastic fines with low dry strength; well compacted and moist in place; alluvial sand; (GM).</p>	<p>Atterberg limits below "A" line or PI less than 4</p> <p>Atterberg limits above "A" line with PI greater than 7</p>			
		Sands More than half of coarse fraction is smaller than No. 4 sieve size. (For visual classification, the 1/4-in. size may be used as equivalent to the No. 4 sieve size.)	SW	Well-graded sands, gravelly sands, little or no fines.					Wide range in grain size and substantial amounts of all intermediate particle sizes.	<p>Example:</p> <p>Silty sand, gravelly; about 80% hard, angular gravel particles 1/8-in. maximum size; rounded and subangular sand grains, coarse to fine; about 15% nonplastic fines with low dry strength; well compacted and moist in place; alluvial sand; (SM).</p>	<p>Atterberg limits below "A" line or PI less than 4</p> <p>Atterberg limits above "A" line with PI greater than 7</p>
			SP	Poorly graded sands or gravelly sands, little or no fines.					Predominantly one size or a range of sizes with some intermediate sizes missing.		
	Sands with Fines (Appreciable amount of fines)	SM	Silty sands, sand-silt mixtures.	Nonplastic fines or fines with low plasticity (for identification procedures see ML below).	<p>Identification Procedures on Fraction Smaller than No. 40 Sieve Size</p> <p>Dry Strength (Crushing characteristics)</p> <p>Dilatancy (Reaction to shaking)</p> <p>Toughness (Consistency near PL)</p>	<p>Comparing Soils at Equal Liquid Limit Toughness and Dry Strength Increase with Increasing Plasticity Index</p>					
		SC	Clayey sands, sand-clay mixtures.	Plastic fines (for identification procedures see CL below).							
	Fine-grained Soils More than half of material is smaller than No. 200 sieve size. The No. 200 sieve size is about the smallest particle visible to the naked eye.	Silt and Clays Liquid limit is less than 50	ML	Inorganic silts and very fine sands, rock flour, silty or clayey fine sands or clayey silts with slight plasticity.	None to slight	Quick to slow	None	For undisturbed soils add information on structure, stratification, consistency in undisturbed and remolded states, moisture and drainage conditions.			
			CL	Inorganic clays of low to medium plasticity, gravelly clays, sandy clays, silty clays, lean clays.	Medium to high	None to very slow	Medium				
OL			Organic silts and organic silty clays of low plasticity.	Slight to medium	Slow	Slight					
Silt and Clays Liquid limit is greater than 50		MH	Inorganic silts, micaceous or diatomaceous fine sandy or silty soils, elastic silts.	Slight to medium	Slow to none	Slight to medium	<p>Example:</p> <p>Clayey silt, brown; slightly plastic; small percentage of fine sand; numerous vertical root holes; firm and dry in place; loess; (ML).</p>				
		CH	Inorganic clays of high plasticity, fat clays.	High to very high	None	High					
		OH	Organic clays of medium to high plasticity, organic silts.	Medium to high	None to very slow	Slight to medium					
Highly Organic Soils	Pt	Peat and other highly organic soils.	Readily identified by color, odor, spongy feel and frequently by fibrous texture.								

(1) **Boundary classifications:** Soils possessing characteristics of two groups are designated by combinations of group symbols. For example GW-GC, well-graded gravel-sand mixture with clay binder. (2) All sieve sizes on this chart are U. S. standard.

FIELD IDENTIFICATION PROCEDURES FOR FINE-GRAINED SOILS OR FRACTIONS
These procedures are to be performed on the minus No. 40 sieve size particles, approximately 1/64 in. For field classification purposes, screening is not intended, simply remove by hand the coarse particles that interfere with the tests.

Dilatancy (reaction to shaking)

After removing particles larger than No. 40 sieve size, prepare a pat of moist soil with a volume of about one-half cubic inch. Add enough water if necessary to make the soil soft but not sticky. Place the pat in the open palm of one hand and shake horizontally, striking vigorously against the other hand several times. A positive reaction consists of the appearance of water on the surface of the pat which changes to a livery consistency and becomes glossy. When the sample is squeezed between the fingers, the water and gloss disappear from the surface, the pat stiffens, and finally it cracks or crumbles. The rapidity of appearance of water during shaking and of its disappearance during squeezing assist in identifying the character of the fines in a soil. Very fine clean sands give the quickest and most distinct reaction whereas a plastic clay has no reaction. Inorganic silts, such as a typical rock flour, show a moderately quick reaction.

Dry Strength (crushing characteristics)

After removing particles larger than No. 40 sieve size, mold a pat of soil to the consistency of putty, adding water if necessary. Allow the pat to dry completely by oven, sun, or air-drying, and then test its strength by breaking and crumbling between the fingers. This strength is a measure of the character and quantity of the colloidal fraction contained in the soil. The dry strength increases with increasing plasticity. High dry strength is characteristic for clays of the CH group. A typical inorganic silt possesses only very slight dry strength. Silty fine sands and silts have about the same slight dry strength, but can be distinguished by the feel when preparing the dried specimen. Fine sand feels gritty whereas a typical silt has the smooth feel of flour.

Toughness (consistency near plastic limit)

After particles larger than the No. 40 sieve size are removed, a specimen of soil about one-half inch cube in size, is molded to the consistency of putty. If too dry, water must be added and if sticky, the specimen should be spread out in a thin layer and allowed to lose some moisture by evaporation. Then the specimen is rolled out by hand on a smooth surface or between the palms into a thread about one-eighth inch in diameter. The thread is then folded and rerolled repeatedly. During this manipulation the moisture content is gradually reduced and the specimen stiffens, finally loses its plasticity, and crumbles when the plastic limit is reached. After the thread crumbles, the pieces should be lumped together and a slight kneading action continued until the lump crumbles. The tougher the thread near the plastic limit and the stiffer the lump when it finally crumbles, the more potent is the colloidal clay fraction in the soil. Weakness of the thread at the plastic limit and quick loss of coherence of the lump below the plastic limit indicate either inorganic clay of low plasticity, or materials such as kaolin-type clays and organic clays which occur below the A-line. Highly organic clays have a very weak and spongy feel at the plastic limit.