2.0 GEOTECHNICAL STABILITY

The reclamation plan and its supporting documents must contain geotechnical information, design details, and construction considerations related to the proposed disposal site and to all materials associated with the reclamation design, including soil and rock cover, foundation materials, contaminated materials, and other materials, for any zones (liners, filters, or capillary breaks). Standard review plan Chapter 2.0 establishes the procedures for NRC staff to conduct and document the review of geotechnical stability aspects of reclamation plans for mill tailings impoundments, amendments to the approved reclamation plans, or license termination.

2.1 Site and Uranium Mill Tailings Characteristics

2.1.1 Areas of Review

The staff should review information presented in the reclamation plan on the geotechnical aspects of the regional and site geology and stratigraphy, the geotechnical characteristics of the uranium mill tailings and other materials designated for stabilization, and borrow area material characteristics. "Other materials" are contaminated soil from site cleanup operations, tailings from other sites accepted for disposal at this site, and any contaminated materials from mill decommissioning activities to be disposed of at this site. This review should cover exploration data, sampling and laboratory techniques, test results, descriptions of physical properties, and static and dynamic geotechnical engineering parameters of the materials, as well as discussions of ground-water conditions (e.g., perched, confined, or unconfined) for all critical subsurface strata at the site, including information on the fluctuations of the hydraulic head. Review of the ground-water information should be coordinated with the review of information on ground-water resources protection, as described in standard review plan Chapter 4.0. Review of geologic, stratigraphic, and seismologic information should be coordinated with the review of the geology and seismology information as described in standard review plan Chapter 1.0. Borrow area restoration plans should be evaluated.

2.1.2 Review Procedures

The information to be reviewed depends on whether the proposed tailings disposal is below grade, either in mines or specially excavated pits, or in above ground impoundments. The reviewer should focus on the appropriateness of the site characterization for the proposed tailings disposal scheme. The reviewer should examine the site stratigraphy and evaluation of engineering properties of the underlying materials at the site, uranium mill tailings, other materials, and borrow materials to determine if appropriate methods were properly used in characterizing the materials.

The reviewer should examine the following specific descriptive information to determine its adequacy for characterizing the site and for supporting the evaluations of reclamation system performance:

(1) Site stratigraphy, based on borings and other investigations conducted to determine the type, location, and thickness of underlying materials.

(2) Regional and site-specific seismologic information to determine the potential for impact on the geotechnical stability of the site and site structures.

(3) Stratigraphy specifying type, location, and thickness of borrow material and other materials designated for stabilization in the tailings disposal cell.

(4) *In situ* testing programs and procedures conducted to determine the engineering properties of underlying materials at the site, borrow area material, other materials, and tailings.

(5) Sampling programs conducted to obtain laboratory samples for determination of engineering properties of borrow materials, underlying materials at the site, other materials, and tailings.

(6) Laboratory testing used to determine the engineering properties of borrow materials, underlying materials at the site, other materials, and tailings.

(7) Physical and engineering properties of borrow materials, underlying materials at the site, other materials, and tailings.

(8) Records of historical ground-water-level fluctuations at the site, to the extent that they are available.

The reviewer should evaluate methods used to characterize the site to ensure that they comply with generally accepted standards, such as those of the American Society for Testing and Materials and those which are commonly used in the geotechnical engineering profession. Areas to be examined in this respect include the *in situ* and laboratory testing programs, sampling techniques, and analyses for determining the physical and engineering properties of materials at the site. Field investigations and laboratory testing procedures not commonly used in the geotechnical engineering profession will be reviewed in detail.

Staff determination of compliance should be based in part on professional judgment, considering the complexity of the site subsurface conditions.

2.1.3 Acceptance Criteria

The site characterization information constitutes part of the input data needed for analysis and design of the tailings impoundment facility. The site characterization will be acceptable if it provides the needed input for the design and analysis of the disposal facility and meets the following criteria:

(1) The site stratigraphy is described in sufficient detail to provide an understanding of the site-specific subsurface features, including structural features and other characteristics of underlying soil and rock.

(2) Information on regional and local faults and seismicity, as obtained from field data, published literature, and historical records is presented in sufficient detail to effectively incorporate that information into a geotechnical stability analyses. (Note: This aspect of the review should be coordinated with the geology and seismology review performed in accordance with standard review plan Chapter 1.)

(3) Sampling scope and techniques are appropriate and sufficient to ensure that samples collected are representative of the range of *in situ* soil conditions, taking into consideration variability and uncertainties in such conditions within the site.

(4) For all soils that might be unstable because of their physical or chemical properties, locations and dimensions are identified and the properties have been documented.

(5) Investigations (including laboratory and field testing) are conducted using appropriate standards published by the American Society for Testing and Materials or the International Society for Rock Mechanics and are sufficient to establish the static and dynamic engineering parameters of borrow materials, other materials, tailings, and underlying soil and rock materials at the site (NRC, 1978, 1979).

(6) A detailed discussion of laboratory sample preparation techniques is presented, when standard procedures are not used.

For critical laboratory tests, details such as how saturation of the sample was determined and maintained during testing, or how the pore pressures changed are provided. A detailed and quantitative discussion of the criteria used to verify that the samples were properly taken and tested in sufficient number to define the critical soil parameters for the site is presented. In the case of tailings material (e.g., license amendment reviews), the evaluations of its strength and settlement characteristics are presented in detail.

(7) Parameter values are presented to enable evaluation of properties of mill tailings, borrow materials, other materials, and underlying soil and rock, including the following:

(a) Compressibility and rate of consolidation

(b) Shear strength, including, for sensitive soils, possible loss of shear strength resulting from strain-softening

(c) Liquefaction potential

(d) Permeability

(e) Dispersion characteristics

(f) Swelling and shrinkage

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(g) Long-term moisture content for radon barrier material

(h) Cover cracking

(8) Soil stratigraphy and relevant parameters that are used in the geotechnical evaluations (settlement, stability, liquefaction potential, etc.) are discussed in detail.

(9) Records of historical ground-water-level fluctuations at the site as obtained from monitoring local wells and springs and/or by analysis of piezometer and permeability data from tests conducted at the site are presented in sufficient detail to effectively incorporate the information into geotechnical stability analyses. (Note: This aspect of the review should be coordinated with the hydrogeologic characterization review performed according to standard review plan Chapter 4.0.)

The information should be sufficient to provide the required input for the design of the facility and to enable the reviewer to assess compliance with the regulatory requirements, such as site features contributing to waste isolation; facility location with respect to an active fault; and reasonable assurance of control of radiological hazards to be effective for 1,000 years to the extent reasonably achievable, and in any case, for at least 200 years.

2.1.4 Evaluation Findings

If the staff review as described in standard review plan Section 2.1 results in the acceptance of the characterization of the site and uranium mill tailings sufficient to support a conclusion regarding the geotechnical stability of the site, the following conclusions may be presented in the technical evaluation report:

The staff has completed its review of the geotechnical characteristics of the site and uranium mill tailings at the ________________ uranium mill facility. This review included an evaluation using the review procedures in Section 2.1.2 and the acceptance criteria outlined in Section 2.1.3 of this standard review plan.

The licensee has acceptably described the geotechnical characteristics of the site and uranium mill tailings based on sampling techniques that are acceptable, and will ensure that a representative range of *in situ* soil conditions will be examined. Unstable soils have been identified. Investigations and analyses have used acceptable standards and practices. Laboratory sample preparation and testing techniques are appropriately described and include: (1) compressibility and rate of consolidation, (2) shear strength, (3) liquefaction potential, (4) permeability, (5) dispersion characteristics, (6) swelling and shrinkage, and (7) physical properties. Records of historic ground-water-level fluctuations are presented to allow effective incorporation into geotechnical stability analyses.

On the basis of the information presented in the application and the detailed review conducted of geotechnical the characteristics of the site and uranium mill tailings at the _______________ uranium mill facility, the NRC staff concludes that the geotechnical characterization of the site and uranium mill tailings and associated conceptual and numerical models provide an acceptable input which, along with other information such as results of design analysis, will enable the staff to make a finding on the demonstration of compliance with the following criteria in Appendix A to 10 CFR Part 40: (1) Criterion 1, which relates to the site features that contribute to the permanent waste isolation characteristics of the site; (2) Criterion 3, which states the primary option for disposal of tailings is placement below grade, either in mines or specially excavated pits (if applicable for the site); (3) Criterion 4(e), which requires that the impoundment not be located near a capable fault on which a maximum credible earthquake, larger than one that the impoundment could reasonably be expected to withstand, might occur; (4) Criterion 5(G)(2), relating to the permeability characteristics of the site; and (5) Criterion 6(1), which requires reasonable assurance of control of radiological hazards to be effective for 1,000 years to the extent reasonably achievable, and in any case for at least 200 years.

2.1.5 References

American Society for Testing and Materials Standards:

D 420, “Guide for Investigating and Sampling Soil and Rock.”

D 421, “Practice for Dry Preparation of Soil Samples for Particle-Size Analysis and Determination of Soil Constants.”

D 422, “Method for Particle-Size Analysis of Soils.”

D 653, “Terminology Relating to Soil, Rock, and Contained Fluids.”

D 854, “Test Method for Specific Gravity of Soils.”

D 1140, “Test Method for Amount of Material in Soils Finer Than the No. 200 Sieve.”

D 1452, “Practice for Soil Investigation and Sampling by Auger Borings.”

D 1586, “Method for Penetration Test and Split-Barrel Sampling of Soils.”

D 1587, “Practice for Thin-Walled Tube Sampling of Soils.”

D 2113, “Practice for Diamond Core Drilling for Site Investigation.”

D 2166, “Test Method for Unconfined Compressive Strength of Cohesive Soil.”

D 2216, “Method for Laboratory Determination of Water (Moisture) Content of Soil, Rock and Soil-Aggregate Mixtures.”

D 2217, “Practice for Wet Preparation of Soil Samples for Particle-Size Analysis and Determination of Soil Constants.”

D 2487, “Test Method for Classification of Soils for Engineering Purposes.”

D 2488, "Practice for Description and Identification of Soils (Visual-Manual Procedure)."

D 2573, "Test Method for Field Vane Shear Test in Cohesive Soils."

D 3441, "Method for Deep, Quasi-Static, Cone and Friction-Cone Penetration Tests of Soil."

D 3550, "Practice for Ring-Lined Barrel Sampling of Soils."

D 4221, "Test Method for Dispersive Characteristics of Clay Soil by Double Hydrometer."

D 4318, "Test Method for Liquid Limit, Plastic Limit, and Plasticity Index of Soils."

D 4647, "Test Method for Identification and Classification of Dispersive Clay Soils by the Pinhole Test."

D 4750, "Test Method for Determining Subsurface Liquid Levels in a Borehole or Monitoring Well (Observation Well)."

NRC. Regulatory Guide 1.132, "Site Investigations for Foundations of Nuclear Power Plants." Rev. 1. Washington, DC: NRC, Office of Standards Development. March 1979.

NRC Regulatory Guide 1.138, "Laboratory Investigations of Soils for Engineering Analysis and Design of Nuclear Power Plants." Washington, DC: NRC, Office of Standards Development. April 1978.

2.2 Slope Stability

2.2.1 Areas of Review

The staff should examine exploration data, test results, slope characterization data, design details, and static and dynamic analyses related to the stability of all natural and manmade earth and rock slopes whose failure, under any of the conditions to which they could be exposed throughout the period of regulatory interest, could adversely affect the integrity of the slopes or embankments. This review should also include examination of static and dynamic materials properties, test and design methods, pore pressures within and beneath the embankment, and the design seismic coefficient. Information on the design seismic event should be obtained from results of the review completed using standard review plan Chapter 1.0. The review will focus on (i) the design of the impoundment during operation when a large volume of tailings liquor would be present and (ii) the stability of the impoundment over the long term.

2.2.2 Review Procedures

The reviewer should examine data gathered from site investigations, such as borings: maps; laboratory and field tests; soil profiles; site plans; results of seismic investigations; permeability tests; and static, dynamic, or pseudostatic stability analyses to determine whether the assumptions and analyses used in the reclamation plan are conservative. The degree of conservatism required depends on the type of analysis used, the variability and uncertainty in the values of the parameters considered in the slope stability analysis, the number of borings, the sampling program, the extent of the laboratory testing program, and the resultant safety factor. For instances in which safety factors are low, the reviewer should ensure that reasonable ranges of soil properties have been considered. Other factors, such as flood conditions, pore pressure effects, possible erosion of soils, and seismic amplification effects, should be conservatively assessed. The design criteria and analyses should be reviewed to ascertain whether the techniques employed are appropriate and represent commonly accepted methods [e.g., U.S. Army Corps of Engineers (1970b)].

The reviewer should examine the spatial variability of the measured properties to ensure that it has been adequately defined. The reviewer should also examine slope characterization data to ensure that nearby slopes, the failure of which could adversely affect the stability of impoundments, have been properly characterized.

The reviewer should determine whether the static and dynamic stability analyses demonstrate that there is an adequate factor of safety against failure.

The reviewer should examine the slope stability analysis to determine that an appropriately conservative approach has been used and that adverse conditions to which the slope might be subjected have been considered. The reviewer should confirm that the static analyses include calculations using appropriate assumptions and methods to assess the following:

(1) Uncertainties and variations in the shape of the slope, the boundaries and parameters of the several types of soils within the slope, the forces acting on the slope, and the pore pressures acting within and beneath the slope.

(2) The failure surface corresponding to the lowest factor of safety.

(3) The effect of the assumptions inherent in the method of analysis used.

The reviewer should ensure that the analysis is conservative and that possible failure modes have been considered, including evaluation of the effect of the maximum credible earthquake, or the appropriate design criteria found acceptable in standard review plan Section 1.4. The reviewer will also verify that the impoundment will not be located near a capable fault on which a maximum credible earthquake larger than that which the impoundment could reasonably be expected to withstand might occur.

The reviewer should be aware that no single method of analysis is applicable for all stability assessments. Therefore, no single method of analysis is recommended. If the staff review indicates that questionable assumptions have been made or that non-standard or inappropriate methods of analysis have been used, the staff may model the slope in a manner consistent with the data and perform an independent analysis.

The reviewer should verify that disposal cell slopes will be relatively flat after final stabilization to minimize the potential for erosion and to provide a conservative factor of safety. In evaluating the slope, the reviewer will focus on determining if the slopes are 5 horizontal to 1 vertical (5h:1v) as required by 10 CFR Part 40, Appendix A, Criterion 4(c). If slopes steeper than 5h:1v are proposed, the reviewer must evaluate these steeper slopes as an alternative to the requirements of Criterion 4(c). In conducting a review of steeper slopes, the reviewer must evaluate the acceptability of the steeper slope using the applicable criteria in this standard review plan and determine if there is an acceptable economic basis and an equivalent level of protection available to justify an alternative to 10 CFR Part 40, Appendix A, Criterion 4(c). The reviewer should evaluate whether a full self-sustaining vegetative cover can be placed over the tailings pile, primarily to reduce the wind and water erosion to negligible levels. If a vegetative cover is not suitable for the site conditions, the reviewer should verify that an appropriate rock cover has been provided. This verification should be coordinated with the review using standard review plan Chapter 3.0.

Because dams at operating facilities, or dams that continue to hold water after the cessation of operations, are also subject to the National Dam Safety Program Act of 1996, the reviewer should determine if the dam is classified as a structure with low hazard potential or high hazard potential. If the dam is classified as high hazard, the reviewer should evaluate the emergency action plan for the facility.

2.2.3 Acceptance Criteria

The analysis of slope stability will be acceptable if it meets the following criteria:

(1) Slope characteristics are properly evaluated.

   (a) Cross sections and profiles of natural and cut slopes whose instability would directly or indirectly affect the control of radioactive materials are presented in sufficient number and detail to enable the reviewer to select the cross sections for detailed stability evaluation.

   (b) Slope steepness is a minimum of five horizontal units (5h) to one vertical unit (1v) or less. The use of slopes steeper than 5h:1v is considered an alternative to the requirements in 10 CFR Part 40, Appendix A, Criterion 4(c). When slopes steeper than 5h:1v are proposed, a technical justification should be offered as to why a 5h:1v or flatter slope would be impractical and compensating factors and conditions are incorporated in the slope design for assuring long-term stability.

   (c) Locations selected for slope stability analysis are determined considering the location of maximum slope angle, slope height, weak foundation, piezometric level(s), the extent of rock mass fracturing (for an excavated slope in rock), and the potential for local erosion.

(2) An appropriate design static analysis is presented.

(a) The analysis includes calculations with appropriate assumptions and methods of analysis (NRC, 1977). The effect of the assumptions and limitations of the methods used is discussed and accounted for in the analysis. Acceptable methods for slope stability analysis include various limit equilibrium analysis or numerical modeling methods.

(b) The uncertainties and variability in the shape of the slope, the boundaries and parameters of the several types of soils and rocks within and beneath the slope, the material properties of soil and rock within and beneath the slope, the forces acting on the slope, and the pore pressures acting within and beneath the slope are considered.

(c) Appropriate failure modes during and after construction and the failure surface corresponding to the lowest factor of safety are determined. The analysis takes into account the failure surfaces within the slopes, including through the foundation, if any.

(d) Adverse conditions such as high water levels from severe rain and the probable maximum flood are evaluated.

(e) The effects of toe erosion, incision at the base of the slope, and other deleterious effects of surface runoff are assessed.

(f) The resulting safety factors for slopes analyzed are comparable to the minimum acceptable values of safety factors for slope stability analysis given in NRC Regulatory Guide 3.11 (NRC, 1977).

(3) Appropriate analyses considering the effect of seismic ground motions on slope stability are presented.

(a) Evaluation of overall seismic stability, using pseudostatic analysis or dynamic analysis, as appropriate (U.S. Army Corps of Engineers, 1977; NRC, 1977). Alternatively, a dynamic analysis following Newmark (1965) can be carried out to establish that the permanent deformation of the disposal cell from the design seismic event will not be detrimental to the disposal cell. The reviewer should verify that the yield acceleration or pseudostatic horizontal yield coefficient necessary to reduce the factor of safety against slippage of a potential sliding mass to 1.0 in a “Newmark-type” analysis has been adequately estimated (Seed and Bonaparte, 1992).

(b) An appropriate analytical method has been used. A number of different methods of analysis are available (e.g., slip circle method, method of slices, and wedge analysis) with several variants of each (Lambe and Whitman, 1979; U.S. Army Corps of Engineers, 1970b; NRC, 1977; Bromhead, 1992). Limit-equilibrium analysis methods do not provide information regarding the variation of strain within the slope and along the slip surface. Consequently, there is no assurance that the peak strength values used in the analysis can be mobilized simultaneously along the entire slip surface unless the material shows ductile behavior (Duncan, 1992). Residual strength values should be evaluated if mobilized shear strength at some points is less than the peak strength. The reviewer should ensure that appropriate conservatism has been incorporated in the analysis using the limit equilibrium methods. The limit equilibrium analysis methodologies may be replaced by other techniques, such as finite element or finite difference methods. If any important interaction effects cannot be included in an analysis, the reviewer must determine that such effects have been treated in an approximate but conservative fashion. The engineering judgment of the reviewer should be used in assessing the adequacy of the resulting safety factors (NRC, 1983a,b).

(c) For dynamic loads, the dynamic analysis includes calculations with appropriate assumptions and methods (NRC, 1977; Seed, 1967; Lowe, 1967; Department of the Navy, 1982a,b,c; U.S. Army Corps of Engineers, 1970a,b, 1971, 1972; Bureau of Reclamation, 1968). The effect of the assumptions and limitations of the methods used is discussed and accounted for in the analysis.

(d) For dynamic loads, a pseudostatic analysis is acceptable in lieu of dynamic analysis if the strength parameters used in the analysis are conservative, the materials are not subject to significant loss of strength and development of high pore pressures under dynamic loads, the design seismic coefficient is 0.20 or less, and the resulting minimum factor of safety suggests an adequate margin, as provided in NRC Regulatory Guide 3.11 (NRC, 1977).

(e) For pseudostatic analysis of slopes subjected to earthquake loads, an assumption is made that the earthquake imparts an additional horizontal force acting in the direction of the potential failure (U.S. Army Corps of Engineers, 1970b, 1977; Goodman, 1989). The critical failure surface obtained in the static analysis is used in this analysis with the added driving force. Minimum acceptable values for safety factors of slope stability analysis are given in Regulatory Guide 3.11 (NRC, 1977).

(f) The assessment of the dynamic stability considers an appropriate design level seismic event and/or strong ground motion acceleration, consistent with that identified in Chapter 1 of this review plan. Influence of local site conditions on the ground motions associated with the design level event is evaluated. The design seismic coefficient to be used in the pseudostatic analysis is either 67 percent of the peak ground acceleration at the foundation level of the tailings piles for the site or 0.1g, whichever is greater.

(g) If the design seismic coefficient is greater than 0.20g, then the dynamic stability investigation (Newmark, 1965) should be augmented by other appropriate methods (i.e., finite element method), depending on specific site conditions.

(h) In assessing the effects of seismic loads on slope stability, the effect of dynamic stresses of the design earthquake on soil strength parameters is accounted for. As in a static analysis, the parameters such as geometry, soil strength, and hydrodynamic and pore pressure forces are varied in the analysis to show that there is an adequate margin of safety.

(i) Seismically induced displacement is calculated and documented. There is no universally accepted magnitude of seismically induced displacement for determining acceptable performance of the disposal cell (Seed and Bonaparte, 1992; Goodman and Seed, 1966). Surveys of five major geotechnical consulting firms by Seed and Bonaparte (1992) indicate that the acceptable displacement is from 15 to 30 cm [6 to 12 in.] for tailings piles. The reviewer should ensure that this criterion is also augmented by provisions for periodic maintenance of the slope(s).

(j) Where there is potential for liquefaction, changes in pore pressure from cyclic loading are considered in the analysis to assess the effect of pore pressure increase on the stress-strain characteristics of the soil and the post-earthquake stability of the slopes. Liquefaction potential is reviewed using Section 2.4 of this review plan. Evaluations of dynamic properties and shear strengths for the tailings, underlying foundation material, radon barrier cover, and base liner system are based on representative materials properties obtained through appropriate field and laboratory tests (NRC, 1978, 1979).

(k) The applicant has demonstrated that impoundments will not be located near a capable fault on which a maximum credible earthquake larger than that which the impoundment could reasonably be expected to withstand might occur.

(4) Provision is made to establish a vegetative cover, or other erosion prevention, to include the following considerations:

(a) The vegetative cover and its primary functions are described in detail.

This determination should be made with respect to any effect the vegetative cover may have on reducing slope erosion and should be coordinated with the reviewer of standard review plan Chapter 3.

If strength enhancement from the vegetative cover is taken into account, the methodology should be appropriate (Wu, 1984).

(b) In arid and semi-arid regions, where a vegetative cover is deemed not self-sustaining, a rock cover is employed on slopes of the mill tailings. If credit is taken for strength enhancement from rock cover, the reviewer should confirm that appropriate methodology has been presented.

The design of a rock cover, where a self-sustaining vegetative cover is not practical, is based on standard engineering practice. Standard review plan

Chapter 3 discusses this item in detail.

(5) Any dams meet the requirements of the dam safety program if the application demonstrates the following:

(a) The dam is correctly categorized as a low hazard potential or a high hazard potential structure using the definition of the U.S. Federal Emergency Management Agency.

(b) If the dam is ranked as a high hazard potential, an acceptable emergency action plan consistent with the Federal Emergency Management Agency guide (U.S. Federal Emergency Management Agency, 1998) has been developed.

(6) The use of steeper slopes as an alternative to the requirements in 10 CFR, Part 40, Appendix A, will be found acceptable if the following are met:

(a) An equivalent level of stabilization and containment and protection of public health, safety, and the environment is achieved.

(b) A site-specific need for the alternate slopes is demonstrated.

2.2.4 Evaluation Findings

If the staff review as described in standard review plan Section 2.2 results in the acceptance of the slope stability, the following conclusions may be presented in the technical evaluation report:

The staff has completed its review of the slope stability at the _______________ uranium mill facility. This review included an evaluation using the review procedures in Section 2.2.2 and the acceptance criteria outlined in Section 2.2.3 of this standard review plan.

The licensee has acceptably described the slope stability evaluation by (1) providing cross sections and profiles of natural and cut slopes in sufficient detail and number to represent significant slope and foundation conditions; (2) placing tailings below grade or in demonstrably safe above-grade disposal facilities; (3) ensuring that slope steepnesses are five horizontal (5h) to one vertical (1v) or less or by providing technical justification for a different slope ratio; (4) providing measurements of static and dynamic properties of soil and rock using standards such as those established by the American Society for Testing and Materials, International Society of Rock Mechanics, NRC, or the U.S. Army Corps of Engineers; (5) selecting locations for slope stability analyses while considering the location of maximum slope angle, slope height, weak foundation, the extent of rock mass fracturing, and the potential for local erosion; and (6) describing vegetative cover and its primary functions in detail. Where the licensee has proposed use of steeper slopes as an alternative to the requirements of 10 CFR Part 40, Appendix A, Criterion 4(c), the staff has evaluated the licensee's demonstration that steeper slopes would result in economic savings and also ensure the long-term stabilization of the tailings with a level of protection equivalent to that required in 10 CFR Part 40, Appendix A, Criterion 4(c). Therefore, the use of steeper slopes complies with the alternates requirement in

10 CFR Part 40, Appendix A.

The static loads analysis is acceptable and includes (1) appropriate uncertainties and variabilities in important rock/soils parameters; (2) consideration of appropriate failure modes; (3) a discussion of the effect of the assumptions inherent in the method of analysis used; (4) consideration of adverse conditions, including flooding, with appropriate safety factors; and (5) the effects of toe erosion, incision of the base of the slope, and other deleterious effects of surface runoff.

The dynamic and pseudostatic analyses are acceptable and include (1) calculations with appropriate assumptions and methods; (2) treatment of important interaction effects in a conservative fashion; (3) an accounting of the dynamic stresses of the maximum credible earthquake on soil strength parameters; (4) for pseudostatic analyses of slopes subjected to earthquake loads, consideration of the added driving horizontal force acting in the direction of a potential failure; (5) determination that possible permanent deformation sustained in the slope from a maximum credible earthquake will not damage the effectiveness of the disposal cell; (6) determination that the magnitude of seismically induced displacement does not exceed 15 to 30 cm [6 to 12 in.]; (7) a selection of appropriate design-level seismic events or strong ground motion accelerations; (8) evaluations of local site conditions; (9) evaluations of the potential for liquefaction and the effect of pore pressure increase on the stress-strain characteristics of the soil and post-earthquake stability of the slopes; (10) evaluations of the dynamic properties and shear strength of the tailings, underlying foundation, radon barrier cover, and base liner system; and (11) design of a self-sustaining vegetative or rock cover that is consistent with commonly accepted engineering practice.

On the basis of the information presented in the application and the detailed review conducted of the slope stability at the ______________ uranium mill facility, the NRC staff concludes that the slope stability and associated conceptual and numerical models pertaining to design of the impoundments provide an acceptable input to demonstration of compliance with the following criteria in 10 CFR Part 40, Appendix A: Criterion 4(c), which provides requirements for the long-term stability of the embankment and cover slopes for tailings; Criterion 4(d), which requires establishment of a self-sustaining vegetative cover or employment of a rock cover to reduce wind and water erosion to negligible levels, that individual rock fragments are suited for the job, and that the impoundment surfaces are contoured to avoid concentrated surface runoff or abrupt changes in slope gradient; Criterion 4(e), which requires that the impoundment not be located near a capable fault on which a maximum credible earthquake larger than that which the impoundment could reasonably be expected to withstand might occur; Criterion 5(A)(5), which requires the structural integrity of slopes (dikes) to prevent massive failure of the dikes; and Criterion 6(1), which requires that impoundment designs providing reasonable assurance of control of radiological hazards to be effective for 1,000 years to the extent reasonably achievable, and in any case for at least 200 years.

2.2.5 References

American Society for Testing and Materials Standards:

D 2850, “Test Method for Unconsolidated, Undrained Compressive Strength of

Cohesive Soils in Triaxial Compression."

D 3080, "Method for Direct Shear Test of Soils Under Consolidated Drained Conditions."

D 4767, "Test Method for Consolidated-Undrained Triaxial Compression Test on Cohesive Soils."

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Goodman, R.E. and H.B. Seed. "Earthquake-Induced Displacements in Sand Embankments." *ASCE Journal of the Soil Mechanics and Foundations Division*. Vol. 92, No. SM2. March 1966.

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———. Regulatory Guide 1.138, “Laboratory Investigations of Soils for Engineering Analysis and Design of Nuclear Power Plants.” Washington, DC: NRC, Office of Standards Development. April 1978.

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Seed, H.B. “Slope Stability During Earthquakes.” *ASCE Journal of the Soil Mechanics and Foundations Division.* Vol. 93, No. SM4. 1967.

Seed R.B. and R. Bonaparte. “Seismic Analysis and Design of Lined Waste Fills: Current Practice. Stability and Performance of Slopes and Embankments--II, Volume 1.” Proceedings of a Specialty Conference. R.B. Seed and R.W. Boulanger, eds. Geotechnical Special Publication No. 31. New York, New York: American Society of Civil Engineers. 1992.

U.S. Army Corps of Engineers. “Earthquake Design and Analysis for Corps of Engineer Dams.” ER1110-2-1806. U.S. Department of the Army, Office of the Chief of Engineers. April 1977.

———. “Soil Sampling.” Engineering Manual EM1110-2-1907. Department of the Army, Office of the Chief of Engineers. March 1972.

———. “Instrumentation of Earth and Rockfill Dams.” Engineering Manual EM1110-2-1908, Part 1 and 2. Department of the Army, Office of the Chief of Engineers. August and November 1971.

———. “Laboratory Soil Testing.” Engineering Manual EM1110-2-1906. Department of the Army, Office of Chief Engineers. November 1970a.

———. “Engineering and Design Stability of Earth and Rock Fill Dams.” Engineering Manual EM1110-2-1902. Department of the Army, Office of the Chief of Engineers. 1970b.

U.S. Federal Emergency Management Agency. “Federal Guidelines for Dam Safety: Emergency Action Planning for Dam Owners.” Washington, DC: U.S. Federal Emergency Management Agency. 1998.

Wu, T.H. “Effect of Vegetation on Slope Stability, "Soil Reinforcement and Moisture Effects on Slope Stability.” Transportation Research Record 965. National Research Council, Transportation Research Board. 1984.

2.3 Settlement

2.3.1 Areas of Review

The staff should review the methods and results of testing and analyses conducted to estimate deformation of subsurface materials and uranium mill tailings. This should include examination of material properties and thicknesses of compressible materials, factors used in stress calculations, calculated pore pressures within and beneath the embankment, resulting total and differential settlement of the tailings surface under both static and seismic conditions, and the effects of such settlements on the radon barrier layer of the cover of the disposal cell and erosion protection layer. Liquefaction and associated settlement are addressed in standard review plan Section 2.4. One of the purposes of this review is to determine if the licensee has an acceptable method for determining if tailings consolidation is sufficient to allow the placement of a radon barrier.

2.3.2 Review Procedure

The reviewer should examine the assessments of the magnitudes and distributions of settlement of the disposal cell and the analyses of the potential for cracking of the radon barrier from tensile strains in order to determine the adequacy of the design.

The reviewer should confirm that clay layers and slime in the tailings pile and foundations have been considered in the assessment of both immediate and long-term settlement.

In reviewing the assessment of settlements, the reviewer should give particular attention to the identification and thicknesses of compressible soil layers within the tailings and in the foundation. Settlement should be calculated at several locations within the disposal cell to enable a determination of the overall settlement pattern of the disposal cell cover. The locations for settlement calculations should be selected considering the presence of sand/slime tailings and foundation materials. The tailings are expected to be a hydraulically placed material comprised of interspersed sand and slime tailings. The following specific items should be reviewed to determine the acceptability of the assessment of the magnitudes and distribution of settlement:

(1) The analysis of immediate settlement of tailings surfaces, considering rebound from excavation and settlement from instantaneous compression of underlying materials and the tailings pile. The computation of incremental tailings loading and the width of the loaded area, as well as the determination of the undrained modulus and Poisson’s ratio should be examined. Calculations of the settlement of hydraulically placed tailings should be examined.

(2) The analysis of consolidation settlement from delayed compression (caused by pore-pressure dissipation) of underlying materials and the tailings pile.

The calculation of settlement should be reviewed to ensure that each compressible soil layer within or underneath the tailings pile is considered and is assigned proper thickness and that the appropriate level of stress change is applied at the mid-depth of the soil layer.

(3) The estimate of the time at which the primary consolidation settlement of the tailings will be essentially complete. Generally, the radon barrier and disposal cell cover may be placed only after the settlement of tailings is essentially complete.

(4) The analysis of secondary settlement from long-term creep.

(5) The distribution of settlement magnitudes for assessment of differential settlement.

(6) Evaluation of the potential for cracking of the radon barrier layer as a result of long-term settlement of the cover.

2.3.3 Acceptance Criteria

The analysis of tailings settlement will be acceptable if it meets the following criteria:

(1) Computation of immediate settlement follows the procedure recommended in NAVFAC DM–7.1 (Department of the Navy, 1982). If a different procedure is used, the basis for the procedure is adequately explained.

The procedure recommended in NAVFAC DM–7.1 (Department of the Navy, 1982) for calculation of immediate settlement is adequate if applied incrementally to account for different stages of tailings emplacement. If this method is used, the reviewer should verify that the computation of incremental tailings loading and the width of the loaded area, as well as the determination of the undrained modulus and Poisson's ratio, have been computed and documented.

Settlement of tailings arises from compression of soil layers within the disposal cell and in the underlying materials. Because compression of sands occurs rapidly, compression of sand layers in the disposal cell and foundations must be considered in the assessment of immediate settlement. However, the contribution of immediate settlement to consolidation settlement cannot be ignored. Clay layers and slime undergo instantaneous elastic compression controlled by their undrained stiffness as well as long-term inelastic compression controlled by the processes of consolidation and creep (NRC, 1983a).

(2) Each of the following is appropriately considered in calculating stress increments for assessment of consolidation settlement:

(a) Decrease in overburden pressure from excavation

(b) Increase in overburden pressure from tailings emplacement

(c) Excess pore-pressure generated within the disposal cell

(d) Changes in ground-water levels from dewatering of the tailings

(e) Any change in ground-water levels from the reclamation action

(3) Material properties and thicknesses of compressible soil layers used in stress change and volume change calculations for assessment of consolidation settlement are representative of *in situ* conditions at the site.

(4) Material properties and thicknesses of embankment zones used in stress change and volume change calculations are consistent with as-built conditions of the disposal cell.

(5) Values of pore pressure within and beneath the disposal cell used in settlement analyses are consistent with initial and post-construction hydrologic conditions at the site.

(6) Methods used for settlement analyses are appropriate for the disposal cell and soil conditions at the site. Contributions to settlement by drainage of mill tailings and by consolidation/compression of slimes and sands are considered. Both instantaneous and time-dependent components of total and differential settlements are appropriately considered in the analyses (NRC, 1983a,b,c).

The procedure recommended in NAVFAC DM–7.1 (Department of the Navy, 1982) for calculation of secondary compression is adequate.

(7) The disposal cell is divided into appropriate zones, depending on the field conditions, for assessment of differential settlement, and appropriate settlement magnitudes are calculated and assigned to each zone.

(8) Results of settlement analyses are properly documented and are related to assessment of overall behavior of the reclaimed pile.

(9) An adequate analysis of the potential for development of cracks in the radon/infiltration barrier as a result of differential settlements is provided (Lee and Shen, 1969).

2.3.4 Evaluation Findings

If the staff review, as described in standard review plan Section 2.3, shows that the settlement has no impact on the integrity and functionality of the radon barrier and disposal cell cover, then the following conclusions can be presented in the technical evaluation report. If the settlement impacts the cell cover integrity, then the licensee will be required to revise the design to ensure the functionality of the cell cover before a technical evaluation report can be prepared.

The staff has completed its review of the settlement at the _______________ uranium mill facility. This review included an evaluation using the review procedures in Section 2.3.2 and the acceptance criteria outlined in Section 2.3.3 of this standard review plan.

The licensee has acceptably described settlement by presenting computations following the procedure recommended in NAVFAC DM–7.1 (Department of the Navy, 1982) or by explaining the technical merit for an alternate procedure. Material properties, thickness, and load increments used to calculate settlement are representative of site conditions. The applicant has acceptably considered each of the following: (1) decrease in overburden pressure from excavation, (2) increase in overburden pressure from emplaced tailings, (3) excess pore-pressure generated within the tailings disposal cell, (4) changes in ground-water levels from dewatering of the tailings, and (5) changes in ground-water levels from reclamation actions. Pore pressures within and beneath the disposal cell/embankment are consistent with initial and as-built hydrologic site conditions. Methods used to determine settlement are appropriate for the tailings embankment and soil conditions at the site. The results of the settlement analyses are properly documented. The tailings embankment has been subdivided acceptably into assessment zones with appropriately assigned settlement magnitudes. The settlement data provide information to assess the possibility of surface ponding or sudden change of gradient caused by settlement. An acceptable analysis for the development of cracks in the radon/infiltration barrier is provided.

On the basis of information presented in the application and the detailed review conducted of the characteristics of the settlement at the ______________ mill facility, the NRC staff concludes that the settlement and associated conceptual and numerical models present information needed to demonstrate compliance with 10 CFR Part 40, Appendix Ae. Criterion 6(1), which requires that impoundment designs provide reasonable assurance of control of radiological hazards to be effective for 1,000 years to the extent reasonably achievable, and in any case for at least 200 years.

2.3.5 References

American Society for Testing and Materials Standards:

D 2435, “Test Method for One-Dimensional Consolidation Properties of Soil.”

D 4719, “Test Method for Pressuremeter Testing in Soils.”

Department of the Navy. 1982. *Soil Mechanics.* NAVFAC DM–7.1. May 1982.

Lee, K.L. and C.K. Shen. “Horizontal Movements Related to Subsidence.” *ASCE Journal of Soil Mechanics and Foundations Division*. Vol. 95, No. SM1. 1969.

NRC. 1983a. NUREG/CR–3204, “Consolidation of Tailings.” Washington, DC: NRC. 1983a.

———. NUREG/CR–3199, "Guidance for Disposal of Uranium Mill Tailings: Long-Term Stabilization of Earthen Cover Materials." Washington, DC: NRC. 1983b.

———. NUREG/CR–3397, “Design Considerations for Long-Term Stabilization of Uranium Mill Tailings Impoundments.” Washington, DC: NRC. 1983c.

2.4 Liquefaction Potential

2.4.1 Areas of Review

The staff should review the analysis of the liquefaction potential of subsurface, pile, and embankment materials, and the associated test and data interpretations. Consequences of the liquefaction of subsurface soils and/or uranium mill tailings affecting the settlements within and stability of the disposal cell and the erosion protection layer should also be reviewed. Design features or mitigation actions that address liquefaction potential should be examined. The effect of settlements not induced by liquefaction is considered in standard review plan Section 2.3 and is also considered in standard review plan Section 2.4.3.

2.4.2 Review Procedures

The reviewer should examine the analysis of liquefaction potential by studying the results of geotechnical investigations and *in situ* tests such as standard penetration, cone penetration, piezocone, density, and strength tests as well as boring logs, laboratory classification test data, water table measurements, perched water zones, and soil profiles, to determine if any of the site soils or the tailings pile material could be susceptible to liquefaction.

If it is determined that there may be soils susceptible to liquefaction beneath the site or in the tailings pile, the reviewer should examine the adequacy of site exploration programs, the laboratory test program, and the analyses. Where global liquefaction potential exists, the reviewer should determine that it has been mitigated or eliminated. Minor or local liquefaction potential should be accounted for in settlement analyses.

The reviewer should compare the liquefaction potential analysis in the reclamation plan to an independent study performed by the staff, if necessary.

2.4.3 Acceptance Criteria

The analysis of the liquefaction potential will be acceptable if the following criteria are met:

(1) Applicable laboratory and/or field tests are properly conducted (NRC, 1978, 1979; U.S. Army Corps of Engineers, 1970, 1972).

(2) Data for all relevant parameters for assessing liquefaction potential are adequately collected and the variability has been quantified.

(3) Methods used for interpretation of test data and assessment of liquefaction potential are consistent with current practice in the geotechnical engineering profession (Seed and Idriss, 1971, 1982; National Center for Earthquake Engineering Research, 1997). An assessment of the potential adverse effects that complete or partial liquefaction could have on the stability of the embankment may be based on cyclic triaxial test data obtained from undisturbed soil samples taken from the critical zones in the site area (Seed and Harder, 1990; Shannon & Wilson, Inc. and Agbabian-Jacobsen

Associates, 1972).

(4) If procedures based on laboratory tests combined with ground response analyses are used, laboratory test results are corrected to account for the difference between laboratory and field conditions (NRC, 1978; Naval Facility Engineering Command, 1983).

(5) The time history of earthquake ground motions used in the analysis is consistent with the design seismic event.

(6) If the potential for complete or partial liquefaction exists, the effects such liquefaction could have on the stability of slopes and settlement of tailings are adequately quantified.

(7) If a potential for global liquefaction is identified, mitigation measures consistent with current engineering practice or redesign of tailings ponds/embankments are proposed and the proposed measures provide reasonable assurance that the liquefaction potential has been eliminated or mitigated.

(8) If minor liquefaction potential is identified and is evaluated to have only a localized effect that may not directly alter the stability of embankments, the effect of liquefaction is adequately accounted for in analyses of both differential and total settlement and is shown not to compromise the intended performance of the radon barrier. Additionally, the disposal cell is shown to be capable of withstanding the liquefaction potential associated with the expected maximum ground acceleration from earthquakes. The licensee may use post-earthquake stability methods (e.g., Ishihara and Yoshimine, 1990) based on residual strengths and deformation analysis to examine the effects of liquefaction potential. Furthermore, the effect of potential localized lateral displacement from liquefaction, if any, is adequately analyzed with respect to slope stability and disposal cell integrity.

2.4.4 Evaluation Findings

If the staff review, as described in standard review plan Section 2.4, results in the acceptance of the licensee liquefaction potential analysis and conclusions on the impact on the performance of the disposal cell, the following conclusions may be presented in the technical evaluation report:

The staff has completed its review of the liquefaction potential at the _____________ uranium mill facility. This review included an evaluation using the review procedures in standard review plan Section 2.4.2 and acceptance criteria outlined in Section 2.4.3 of this standard review plan.

The licensee has acceptably evaluated liquefaction potential based on results from properly conducted laboratory and/or field tests. The methods used for interpretation of test data are consistent with current practice. Where global liquefaction is identified, mitigation measures or redesign of tailings ponds/embankments are proposed and the new design provides reasonable assurance that the liquefaction potential has been eliminated or mitigated. In the case of minor/local liquefaction potential, its effect is accounted for in the analysis of both differential and total settlement and is shown not to compromise the intended performance of the radon barrier and erosion protection.

On the basis of the information presented in the application and the detailed review conducted of the liquefication potential at the ______________ uranium mill facility, the NRC staff concludes that the results of evaluation of liquefaction potential and associated conceptual and numerical models present input to a demonstration of compliance with the following criteria in 10 CFR Part 40, Appendix A: Criterion 4(c), which provides long-term stability requirements for the slopes of the tailings embankment and cover; and Criterion 6(1), which requires that impoundment designs povide reasonable assurance of control of radiological hazards to be effective for 1,000 years to the extent reasonably achievable, and in any case for at least 200 years.

2.4.5 References

American Society for Testing and Materials Standards:

D 3999, “Test Method for the Determination of the Modulus and Damping Properties of Soils Using the Cyclic Triaxial Apparatus.”

D 4015, “Test Method for Modulus and Damping of Soils by the Resonant-Column Method.”

Ishihara, K. and M. Yoshimine. “Evaluation of Settlements in Sand Deposits Following Liquefaction During Earthquake.” *Soil Foundations*. Vol. 32, No. 1. Japanese Society of Soil Mechanics and Foundation Engineering. 1990.

National Center for Earthquake Engineering Research. “Proceedings of the NCEER Workshop on Evaluation of Liquefaction Resistance of Soils.” T.L. Youd and I.M. Idriss, eds. Technical Report No. NCEER 97-002. Buffalo, New York: State University of New York. 1997.

Naval Facility Engineering Command. “Soil Dynamics, Deep Stabilization, and Special Geotechnical Construction. NAVFAC DM–7.3. Alexandria, Virginia: Department of the Navy. 1983.

NRC. Regulatory Guide 1.132, “Site Investigations for Foundations of Nuclear Power Plants.” Rev. 1. Washington, DC: NRC, Office of Standards Development. March 1979.

———. Regulatory Guide 1.138, “Laboratory Investigations of Soils for Engineering Analysis and Design of Nuclear Power Plants.” Washington, DC: NRC, Office of Standards Development. April 1978.

Seed, H.B. and I.M. Idriss. “Ground Motions and Soil Liquefaction During Earthquakes.” Earthquake Engineering Research Institute. *Engineering Monograph*: 5. 1982.

Seed, H.B. and I.M. Idriss. “A Simplified Procedure for Evaluating Soil Liquefaction Potential.” *Journal of Soil Mechanics and Foundation Division.* Vol. 97, No. SM 9. pp. 1,249–1,274. 1971.

Seed, R.B. and L.F. Harder. “SPT-Based Analysis of Cyclic Pore Pressure Generation and Undrained Residual Strength.” Proceedings of the H. Bolton Seed Memorial Symposium. Berkeley, California: University of California, May 10–11. pp. 351–376. 1990.

Shannon & Wilson, Inc. and Agbabian-Jacobsen Associates. “Soil Behavior Under Earthquake Loading Conditions: State-of-the-Art Evaluation of Characteristics for Seismic Responses Analyses.” Washington, DC: U.S. Atomic Energy Commission. 1972.

U.S. Army Corps of Engineers. “Soil Sampling.” Manual EM 1110-2-1907. March 1972.

———. “Laboratory Soil Testing, Engineering.” Manual EM1110-2-1906. November 1970.

2.5 Disposal Cell Cover Engineering Design

2.5.1 Areas of Review

The staff should review information presented on disposal cell cover engineering design. including field exploration data, laboratory test results, design details, and construction and installation considerations pertinent to the geotechnical aspects of design and any associated geomembranes (i.e., disposal cell configuration and thickness, compaction requirements, gradations, permeability, and dispersivity).

2.5.2 Review Procedures

The reviewer should examine the disposal cell design and engineering parameters to assess the geotechnical aspects of the disposal cell cover. Specific aspects of the review should consider the following items:

(1) Determination that an adequate quantity of the specified borrow material has been identified at the borrow source.

(2) Confirmation that placement density, specific gravity, moisture content, dispersivity, and shrinkage properties used in the disposal cell design have been determined by suitable laboratory testing so that long-term stability standards will be met. (Note that

permeability issues are discussed separately in standard review plan Section 2.7.)

(3) Confirmation that appropriate measures for controlling the effects of erosion, surface water flows, and vegetative deep root penetrations have been taken.

(4) Verification that the particle size gradation of the disposal cell cover material, bedding layers, other layers in the cover, and the rock layer are compatible to ensure stability against particle migration during the period of regulatory interest.

(5) Determination that the disposal cell has been designed to accommodate the effects of anticipated freeze-thaw cycles.

(6) Assessment, if bentonite amendment to the radon barrier material of the disposal cell cover is proposed, of whether supporting discussions define appropriate laboratory testing and field procedures associated with evaluating amended materials.

(7) Determination if the cracking potential of the disposal cell has been adequately addressed. Cracking from both settlement and shrinkage should be evaluated using standard review plan Section 2.3.

(8) Assessment of the acceptability of plans for installation and use of any geomembranes.

(9) Confirmation that the information used in the disposal cell cover design appropriately reflects the staff findings on the information reviewed using standard review plan Chapters 1.0, 2.0, 3.0, and 4.0.

Note that hydraulic conductivity aspects of the disposal cell cover design are assessed using standard review plan Section 2.7 and that review of the disposal cell design features is addressed in standard review plan Sections 2.2, 2.3, and 2.4. Review of the radon attenuation aspects of the disposal cell design is addressed in standard review plan Chapter 5.0.

2.5.3 Acceptance Criteria

The assessment of the disposal cell cover design and engineering parameters will be acceptable if it meets the following criteria:

(1) Detailed descriptions of the disposal cell material types [e.g., Unified Soil Classification System (Holtz and Kovacs, 1981)] and/or soil mixtures (e.g., bentonite additive) and the basis for their selection are presented.

An analysis is included demonstrating that an adequate quantity of the specified borrow material has been identified at the borrow source. The information on borrow material includes boring and test pit logs and compaction test data.

The soils that are considered suitable include the Unified Classification System Classes CL, CH, SC, and CL-ML, with desirable characteristics and limitations as listed in Table 3-1 of the “Construction Methods and Guidance for Sealing Penetrations in Soil Covers” (Bennett and Homz, 1991; Bennett and Kimbrell, 1991). The preferred material for the low-permeability layers is inorganic clay soil. This soil should be compacted to a low saturated hydraulic conductivity of at least 1×10^{-7} cm/sec. For drainage layers, cobble types GW, GP, SP, and SW are recommended, with GW and GP being the preferred types (Bennett, 1991).

Measures for resisting cracking, heaving, and settlement, and providing protection from burrowing animals, root penetration, and erosion over a long period of time are described.

(2) A sufficiently detailed description of the applicable field and laboratory investigations and testing that were completed, and the material properties (e.g., permeability, moisture-density relationships, gradation, shrinkage and dispersive characteristics, resistance to freeze-thaw degradation, cracking potential, and chemical compatibility, including any amendment materials) are identified (U.S. Army Corps of Engineers, 1970, 1972; Fermulk and Haug, 1990; NRC, 1978, 1979; Lee and Shen, 1969; Spangler and Handy, 1982).

(3) Details are presented (including sketches) of the disposal cell cover termination at boundaries, with any considerations for safely accommodating subsurface water flows.

(4) A schematic diagram displaying various disposal cell layers and thicknesses is provided.

The particle size gradation of the disposal cell bedding layer and the rock layer are established to ensure stability against particle migration during the period of regulatory interest (NRC, 1982).

(5) The effect of possible freeze-and-thaw cycles on soil strength and radon barrier effectiveness is adequately considered (e.g., Aitken and Berg, 1968).

If the region experiences prolonged freezing, the disposal cell cover may be affected by the freeze-thaw cycle. During freezing, ice crystals and lenses can form in the soil, causing heaving. On the other hand, during melting and thawing, the soil may lose its bearing capacity because of development of supersaturated conditions (Spangler and Handy, 1982). Major factors affecting growth of ice in soil are the temperature below the freezing point, the capillary characteristics of the soil, and the presence of water. The reviewer should check whether the soil is susceptible to frost heave, considering that uniformly graded soils containing more than 10 percent of particles smaller than 0.02 mm and well-graded soils with more than 3 percent of particles smaller than 0.02 mm are susceptible (Holtz and Kovacs, 1981; Spangler and Handy, 1982). After many freeze-thaw cycles, the soil may become a loose collection of aggregates with significantly reduced overall strength.

(6) A description is given (with sketches) of any penetrations (e.g., monitoring wells) through the disposal cell system, including details of penetration sealing and disposal cell cover integrity. Bennett and Kimbrell (1991) suggest methods for seal design that are acceptable.

(7) An adequate analysis is presented of the potential for development of cracks in the disposal cell cover as a result of differential settlement and shrinkage. Note that cracking issues associated with settlement are discussed in standard review plan Section 2.3.3.

(8) An adequate description of the geomembranes and their major properties (e.g., physical, mechanical, and chemical) is provided if low permeability geomembranes are proposed as a part of the disposal cell cover. Methods for installation of the membranes in accordance with the manufacturer's recommendations are discussed. The shear strength of the interface between compacted clay and geomembranes used in the stability analyses under both static and dynamic loads is noted. The expected service life of the geomembrane is analyzed.

(9) Information on site characterization, slope stability, settlement, and liquefaction used in the disposal cell cover design appropriately reflects the Licensee's evaluation, and therefore, constitutes inputs that would contribute to the demonstration of disposal cell design compliance with the regulations.

2.5.4 Evaluation Findings

If the staff review as described in standard review plan Section 2.5 results in the acceptance of the disposal cell cover design, the following conclusions may be presented in the technical evaluation report:

The staff has completed its review of the disposal cell cover design at the _______________ uranium mill facility. This review included an evaluation using the review procedures in Section 2.5.2 and acceptance criteria outlined in Section 2.5.3 of this standard review plan.

The licensee has acceptably defined the disposal cell cover design by presenting detailed descriptions of the disposal cell material types and/or soil mixtures, including the basis for their selection. The applicant has identified an adequate quantity of the specified borrow material at the borrow source. An acceptable schematic diagram displaying various disposal cell layers and thicknesses is provided. A description of the applicable field and laboratory investigations and testing is provided, including identification of material properties. The properties of the cover materials have been measured properly using standards such as American Society for Testing and Materials, NRC, or U.S. Army Corps of Engineers. Details (including sketches) have been provided of (1) disposal cell termination boundaries; (2) penetrations, including sealing and disposal cell integrity; and (3) geomembranes and their physical, mechanical, and chemical properties. Methods of installation for the membranes have been discussed and the expected service life has been justified. The analysis of the potential for development of cracks in the disposal cell cover is acceptable.

On the basis of the information presented in the application and the detailed review conducted of the disposal cell cover design at the ________________ uranium mill facility, the NRC staff concludes that the disposal cell engineering parameters and associated conceptual and numerical models are acceptable and provide input to demonstration of compliance with the following criteria in 10 CFR, Part 40, Appendix A: Criterion 4(c), which provides requirements for the embankment and cover slopes for tailings; and Criterion 6(1), which requires that impoundment design provide reasonable assurance of control of radiological hazards to be effective for 1,000 years to the extent reasonably achievable, and in any case, for at least 200 years.

2.5.5 References

American Society for Testing and Materials Standards:

D 75, “Practice for Sampling Aggregates.”

D 4992, “Practice for the Evaluation of Rock To Be Used for Erosion Control.”

Aitken, G.W. and R.L. Berg. “Digital Solution of Modified Berggren Equation to Calculate Depths of Freeze or Thaw in Multi-layered Systems.” Special Report 122. Hanover, New Hampshire: Cold Regions Research & Engineering Laboratory. 1968.

Bennett, R.D. NUREG/CR–5432, “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.” Vol. 1. Washington, DC: NRC. 1991.

Bennett, R.D. and R.C. Homz. NUREG/CR–5432, “Recommendations to the NRC for Soil Cover Systems Over Uranium Mill Tailings and Low-Level Radioactive Wastes: Laboratory and Field Tests for Soil Covers.” Vol. 2. Washington, DC: NRC. 1991.

Bennett, R.D. and A.F. Kimbrell. NUREG/CR–5432, “Recommendations to the NRC for Soil Cover Systems Over Uranium Mill Tailings and Low-Level Radioactive Wastes: Construction Methods for Sealing Penetrations in Soil Covers.” Vol. 3. Washington, DC: NRC. 1991.

Fermulk, N. and M. Haug. “Evaluation of *In Situ* Permeability Testing Methods.” *ASCE Journal of Geotechnical Engineering.* Vol. 116, No. 2. pp. 297–311. 1990.

Holtz, R.D. and W.D. Kovacs. *An Introduction to Geotechnical Engineering.* Englewood Cliffs, New Jersey: Prentice-Hall. 1981.

Lee, K.L. and C.K. Shen. 1969. “Horizontal Movements Related to Subsidence.” *Journal of Soil Mechanics and Foundation Division.* Vol. 95, No. SM–1. New York, New York: American Society of Civil Engineers. 1969.

NRC. NUREG/CR–2684, “Rock Riprap Design Methods and Their Applicability to Long-Term Protection of Uranium Mill Tailings Impoundments.” Washington, DC: NRC. 1982.

———. Regulatory Guide 1.132, “Site Investigations for Foundations of Nuclear Power Plants.” Rev. 1. Washington, DC: NRC, Office of Standards Development. March 1979.

———. Regulatory Guide 1.138, “Laboratory Investigations of Soils for Engineering Analysis and Design of Nuclear Power Plants.” April 1978. Washington, DC: NRC, Office of Standards

Development. April 1978.

Spangler, M.G. and R.L. Handy. *Soil Engineering*. New York, New York: Harper and Row. 1982.

U.S. Army Corps of Engineers. “Soil Sampling.” Engineering Manual EM1110-2-1907. March 1972.

———. “Laboratory Soil Testing.” Engineering Manual EM1110–2–1906. November 1970.

2.6 Construction Considerations

2.6.1 Areas of Review

The staff should review information on the geotechnical aspects of reclamation construction. These aspects should include details such as the sequence and schedule for construction activities, material specifications and placement procedures, and quality control aspects of the construction procedures. The geotechnical aspects of the planned construction operations should be reviewed to identify any deviations from standard engineering practice for earthworks, including measures to protect against erosion and provisions for a vegetative cover, if appropriate.

2.6.2 Review Procedures

The reviewer should determine if all the tailings and contaminated materials at the site can be placed within the configuration of the proposed stabilized pile. The construction sequence should be reviewed to verify the feasibility of achieving the intended final configuration of the tailings, particularly when tailings are to be relocated to new areas of the remediated pile, and to determine whether the schedule for completion is reasonable. The reviewer should also confirm that the construction schedule will allow the radon barrier to be completed as expeditiously as practical after ceasing operations.

The reviewer should examine material placement, placement moisture content (drying, if needed), placement density, and desired permeability to ensure that design specifications will be met. If mixing of the fine tailings (slimes) with sand tailings is proposed, the specifications to control the mixture and the determination of the engineering properties of this mixture should be examined for adequacy.

The reviewer should examine the proposed construction quality control program to verify that adequate provisions have been included to ensure that the construction will be in accordance with the NRC-approved reclamation plan. In particular, details of the proposed testing and inspection program, including the type and frequency of tests proposed, should be reviewed and compared with NRC guidance on testing and inspection.

Methods and schedules for emplacing the vegetative cover should be reviewed if necessary, to determine that they are reasonable, and that seeds for the planned vegetation are compatible with the local climate.

2.6.3 Acceptance Criteria

The analysis of construction considerations will be acceptable if the following criteria are met:

(1) Engineering drawings are at appropriate scales to completely and clearly show the design features (e.g., embankments, riprap, and channels).

(2) Sources and quantities of borrow material are identified, are shown to have been adequately characterized and quantified through field and laboratory tests, and are demonstrated to be adequate for meeting the geotechnical design requirements for the disposal cell (NRC, 1978, 1979). The background levels of contamination in the borrow materials, if any, are properly established.

(3) Methods, procedures, and requirements for excavating, hauling, stockpiling, and placing of contaminated and non-contaminated materials and other disposal cell materials are provided and are shown to be consistent with commonly accepted engineering practice for earthen works (Department of the Navy, 1982a,b; Denson, et al., 1987).

Material placement and compaction procedures are adequate to achieve the desired moisture content (drying, if needed) placement density and permeability. Recommendations made in NUREG/CR–5041 (Denson, et al., 1987) for gradation, placement, and compaction necessary to achieve design drainage rates and volumes, prevent internal erosion or piping, and allow for collection and removal of liquids, are acceptable. Compaction specifications include restrictions on work related to adverse weather conditions (e.g., rainfall, freezing conditions).

Specifications for controlling the mixture of fine tailings (slime) with sand tailings are consistent with commonly accepted engineering practice and testing programs for determination of engineering properties of this mixture.

(4) A plan for embankment construction is presented, that demonstrates embankments can be constructed in accordance with the design.

(5) Plans, specifications, and requirements for disposal cell compaction are supported by field and laboratory tests and analyses to assure stability and reliable performance.

(6) Testing and surveying programs to determine the extent of cleanup required are adequate. The contamination cleanup plan includes the method for determining the extent of the contaminated area and a confirmation program to demonstrate that the contaminated material has been removed. Details of the site cleanup (radiological aspects) are addressed in standard review plan Chapter 5.0.

(7) A plan for settlement measurement is provided that is satisfactory for producing representative settlement data throughout the area of the disposal cell. Settlement measurement stations are of sufficient coverage and are strategically placed to yield adequate information for determination of total, differential, and residual settlements. Monitoring monuments are designed to be durable. The reviewer should also determine

the reasonableness of the proposed monitoring frequency in accordance with NUREG/CR–3356 (NRC, 1983). In the past, the staff has determined that the final radon barrier may be emplaced once 90 percent of expected settlement has occurred.

(8) All tailings and contaminated materials at the site can be placed within the planned configuration of the stabilized pile.

(9) Procedures, specifications, and requirements for riprap, rock mulch, and filter production and placement are provided and are shown to be consistent with commonly accepted engineering practice and the design specifications (NRC, 1977, 1982).

(10) The construction sequence is described and demonstrated to be adequate to achieve the intended configuration for the tailings, particularly when tailings are to be relocated to new areas of the reclaimed pile. The proposed time to completion has been shown to be reasonably achievable, and the construction schedule provides for completing the radon barrier as expeditiously as practical after ceasing operations in accordance with an approved reclamation plan.

(11) The vegetation program or rock cover design is described and demonstrated to be adequate (Wu, 1984; NRC, 1982).

(12) Appropriate quality control provisions are provided to ensure that the construction will be in accordance with the reclamation plan. The descriptions of the methods, procedures, and frequencies by which the construction materials and activities are to be tested and inspected are reasonable and appropriate records will be maintained (NRC, 1983).

(13) Tailings are placed below grade, or the licensee has demonstrated that the above-grade disposal design provides reasonably equivalent isolation of the tailings from natural erosional forces. Tailings pile topographic features take into account wind protection and vegetation cover.

2.6.4 Evaluation Findings

If the staff review as described in this section results in the acceptance of the licensee proposed construction considerations, the following conclusions may be presented in the technical evaluation report.

The staff has completed its review of construction considerations at the _____________ uranium mill facility. This review included an evaluation using the review procedures in Section 2.6.2 and the acceptance criteria outlined in Section 2.6.3 of this standard review plan.

The licensee has acceptably described the construction considerations by (1) providing complete engineering drawings showing all design features; (2) describing sources and quantities of borrow material, including acceptable field and laboratory testing; and (3) identifying methods, procedures, and requirements for excavations, haulage, stockpiling, and placement of materials and demonstrating that all are consistent with accepted engineering practices for earthen works. An acceptable plan for embankment construction is provided. Disposal cell compaction plans are supported by field and laboratory tests that assure stability and performance. The licensee has an acceptable program to determine the extent of cleanup using appropriate testing and surveying programs. An acceptable plan for settlement measurement is provided, including (1) proper coverage and placement of settlement measurement stations, (2) durable monitoring monuments, and (3) reasonable monitoring frequencies. All tailings and contaminated materials have been demonstrated to fit within the planned configuration of the stabilized pile. Procedures, specifications, and requirements for riprap, rock mulch, and filters are provided and are shown to be consistent with commonly accepted engineering practices and design specifications. An acceptable construction sequence, including a reasonable time to completion, has been described. An acceptable vegetation program or rock cover design is proposed. Appropriate quality control provisions are in place to ensure that construction will be in accordance with the reclamation plan and that appropriate records will be maintained.

On the basis of the information presented in the application and the detailed review conducted of the construction considerations at the _______________ uranium mill facility, the NRC staff concludes that the construction considerations and associated conceptual and numerical models provide input to a demonstration of compliance with the following criteria in 10 CFR, Part 40, Appendix A: Criterion 4(c), which provides requirements for the embankment and cover slopes for tailings; Criterion 4(d), which requires establishment of a self-sustaining vegetative cover or employment of a rock cover to reduce wind and water erosion to negligible levels, that individual rock fragments are suited for the job, and that the impoundment surfaces are contoured to avoid concentrated surface runoff or abrupt changes in slope gradient; Criterion 6(1), which requires that impoundment designs provide reasonable assurance of control of radiological hazards to be effective for 1,000 years to the extent reasonably achievable, and in any case, for at least 200 years; and Criterion 6A(1), which requires that the radon barrier be completed as expeditiously as practical after ceasing operations in accordance with a Commission-approved reclamation plan.

2.6.5 References

American Society for Testing and Materials Standards:

D 698, “Test Method for Laboratory Compaction Characteristics of Soil Using Standard Effort.”

D 1556, “Test Method for Density and Unit Weight of Soil In Place by the Sand Cone Method.”

D 1557, “Test Method for Laboratory Compaction Characteristics of Soil Using Modified Effort.”

D 2167, “Test Method for Density and Unit Weight of Soil In Place by the Rubber Balloon Method.”

D 2922, “Test Methods for Density of Soil and Soil-Aggregate in Place by Nuclear Methods (Shouldow Depth).”

D 2937, “Test Method for Density of Soil in Place by the Drive Cylinder Method.”

D 3017, “Test Method for Water Content of Soil and Rock in Place by Nuclear Methods (Shouldow Depth).”

D 3740, “Practice for the Evaluation of Agencies Engaged in the Testing and/or Inspection of Soil and Rock as Used in Engineering Design and Construction.”

D 4253, “Test Methods for Maximum Index Density and Unit Weight of Soils Using a Vibratory Table.”

D 4254, “Test Method for Minimum Index Density and Unit Weight of Soils and Calculation of Relative Density.”

D 4643, “Test Method for Determination of Water (Moisture) Content of Soil by the Microwave Oven Method”

D 4718, “Practice for Correction of Unit Weight and Water Content for Soils Containing Oversize Particles.”

D 4914, “Test Methods for Density of Soil and Rock In Place by the Sand Replacement Method in a Test Pit.”

D 5030, “Test Method for Density of Soil and Rock in Place by the Water Replacement Method in a Test Pit.”

Denson, R.H., et al. NUREG/CR–5041, “Recommendations to the NRC for Review Criteria for Alternative Methods of Low-Level Radioactive Waste Disposal.” Washington, DC: NRC. 1987.

Department of the Navy. “Foundations and Earth Structures.” NAVFAC DM–7.2. May 1982a.

———. “Soil Dynamics, Deep Stabilization, and Special Geotechnical Construction.” NAVFAC DM–7.3. May 1982b.

NRC. NUREG/CR–3356, “Geotechnical Quality Control: Low-Level Radioactive Waste and Uranium Mill Tailings Disposal Facilities.” Washington, DC: NRC. 1983.

———. NUREG/CR–2684, “Rock Riprap Design Methods and Their Applicability to Long-Term Protection of Uranium Mill Tailings Impoundments.” Washington, DC: NRC. 1982.

———. Regulatory Guide 1.132, “Site Investigations for Foundations of Nuclear Power Plants.” Rev. 1. Washington, DC: NRC, Office of Standards Development. March 1979.

———. Regulatory Guide 1.138, “Laboratory Investigations of Soils for Engineering Analysis and Design of Nuclear Power Plants.” Washington, DC: NRC, Office of Standards Development. April 1978.

———. Regulatory Guide 3.11, “Design, Construction, and Inspection of Embankment Retention Systems for Uranium Mills.” Rev. 2. Washington, DC: NRC, Office of Standards Development. 1977.

Wu, T.H. "Effect of Vegetation on Slope Stability: Soil Reinforcement and Moisture Effects on Slope Stability." Transportation Research Record 965. National Research Council, Transportation Research Board. 1984.

2.7 Disposal Cell Hydraulic Conductivity

2.7.1 Areas of Review

The staff should review test results, calculations, the technical bases for disposal cell design hydraulic conductivity values, the field testing program, and the quality control program.

2.7.2 Review Procedures

The reviewer should examine the geotechnical design aspects of the disposal cell to ensure that the disposal cell cover component has a minimal hydraulic conductivity, to limit radon emissions from, and water infiltration into, stabilized mill tailings. The geotechnical reviewer should coordinate with the water resources protection reviewer (see standard review plan Chapter 4.0) to ensure that regulatory requirements for ground-water protection can be met by the proposed radon barrier.

The reviewer should verify that an adequate technical basis has been presented for the design hydraulic conductivity (K) value for the disposal cell cover. For any situation in which a $K<10^{-7}$ cm/sec is proposed by the licensee, the staff should verify that either a test fill program will be undertaken to verify the constructability to achieve the desired K value, or the reclamation plan narrative and accompanying analyses have adequately demonstrated the acceptability of the design K value, considering technical papers on this subject (e.g., Rogowski, 1990; Panno, et al., 1991; Benson and Daniel, 1990). If the reclamation plan acceptably demonstrates that field testing is not required, the reviewer should document the technical basis in the technical evaluation report. If field testing is required, the staff should ensure that the test fill specifications require that the hydraulic conductivity value be verified by in-place testing with double-ring infiltrometers or other approved methods.

The test reviewer should examine the test fill construction plan and verification program for adequacy, including such aspects as (1) use of proper procedures and equipment for placement and compaction operations; (2) verification of the material and thickness for the barrier test zone; (3) comparison of gradation, bentonite amendment, and moisture/density testing with specifications; (4) review of the quality control plan; and (5) review of the proposed construction schedule.

2.7.3 Acceptance Criteria

The analysis of disposal cell hydraulic conductivity will be acceptable if it meets the following criteria:

(1) A sufficient technical basis is provided for the design hydraulic conductivity (K) value for the disposal cell.

The hydraulic conductivity is minimized by compacting fine-grained soil for a sufficient depth above the stabilized tailings. Natural borrow soils having insufficient silt and clay content to effectively reduce the hydraulic conductivity of the barrier can be amended with bentonite for improved effectiveness. (Note that construction issues are discussed separately using standard review plan Section 2.6.)

(2) A field testing program adequate to verify the constructability of the disposal cell with a design hydraulic conductivity $K<10^{-7}$ cm/sec is provided unless the reclamation plan demonstrates that field testing is not required (Benson and Daniel, 1990; NRC, 1979).

To meet the U.S. Environmental Protection Agency (EPA) ground-water standards, designers of disposal cells for mill tailings sites are proposing increasingly smaller design hydraulic conductivity (K) values. It is not unusual for laboratory permeability test values to yield results of 10^{-8} to 10^{-10} cm/sec. Such tests are performed on compacted soil samples considered by the design engineer to represent the soil to be used for the disposal cell. However, several technical papers (Rogowski, 1990; Panno et al., 1991; Benson and Daniel, 1990) have raised serious questions concerning the exclusive use of laboratory testing for demonstrating hydraulic conductivity values in those cases in which a radon barrier K-value less than 10^{-7} cm/sec is specified. On the basis of these technical papers, field testing is necessary to confirm the radon barrier hydraulic conductivity, since construction operations and soil material variability can create preferred pathways, joints, seams, holes, and flaws that effectively increase the value of this parameter. Test results should take into consideration the variability and uncertainty in site conditions and material properties. The test results should be properly documented and available for inspection.

(3) An appropriate quality control program is followed for the field testing to determine hydraulic conductivity (NRC, 1983).

For all cases in which $K<10^{-7}$ cm/sec and the test fill program requirement has been defined, specifications and related documents (Remedial Action Inspection Plan, etc.) will require an adequate quality control program. An acceptable quality control program should contain mechanisms to ensure that as-built construction duplicates the test fill construction techniques on the cell barrier (NRC, 1983). The objective of the quality control program will be to provide assurance that uniform and high-quality construction of the cell barrier has been achieved. Records for implementation of the quality control program during the construction of the cell barrier should be properly maintained and available for inspection.

(4) A reasonable construction schedule is proposed. The proposed construction schedule should promote completion of the radon barrier as expeditiously as practical after ceasing operations in accordance with a written, Commission-approved reclamation plan.

2.7.4 Evaluation Findings

If the staff review as described in standard review plan Section 2.7 results in the acceptance of the disposal cell hydraulic conductivity, the following conclusions may be presented in the technical evaluation report:

The staff has completed its review of the disposal cell hydraulic conductivity at the _______________ uranium mill facility. This review included an evaluation using the review procedures in Section 2.7.2 and the acceptance criteria outlined in Section 2.7.3 of this standard review plan.

The licensee has acceptably evaluated the disposal cell cover materials hydraulic conductivity by providing a sufficient technical basis for the design K-value for the disposal cell. A field testing program adequate to verify the constructability of the disposal cell with a hydraulic design conductivity of $K<10^{-7}$ cm/sec is presented. The applicant followed an acceptable quality control program for the field testing to determine the hydraulic conductivity.

On the basis of the information presented in the application and the detailed review conducted of the disposal cell hydraulic conductivity at the _______________ uranium mill facility, the NRC staff concludes that the disposal cell hydraulic conductivity and associated conceptual and numerical models provide an acceptable input to the demonstration of compliance with the following criteria in 10 CFR Part 40, Appendix A: Criterion 4(c), which provides requirements for the embankment and cover slopes for tailings and Criterion 6(1), which requires that impoundment designs provide reasonable assurance of control of radiological hazards to be effective for 1,000 years to the extent reasonably achievable, and in any case, for at least 200 years.

2.7.5 References

American Society for Testing and Materials Standards:

D 2434. “Test Method for Permeability of Granular Soils (Constant Head).”

D 3385. “Test Method for Infiltration Rate of Soils in Field Using Double-Ring Infiltrometers.”

D 5093. “Test Method for Field Measurement of Infiltration Rate Using a Double-Ring Infiltrometer With a Sealed Inner Ring.”

Benson, C.H. and D.E. Daniel. “Influence of Clods on Hydraulic Conductivity of Compacted Clay.” *ASCE Journal of Geotechnical Engineering.* Vol. 116, No. 8. pp. 1,231–1,248. 1990.

NRC. NUREG/CR–3356, “Geotechnical Quality Control: Low-Level Radioactive Waste and Uranium Mill Tailings Disposal Facilities.” Washington, DC: NRC. 1983.

———. Regulatory Guide 1.132, “Site Investigations for Foundations of Nuclear Power Plants.” Rev. 1. Washington, DC: NRC, Office of Standards Development. March 1979.

Panno, S.V., et al. “Field-Scale Investigation of Infiltration Into a Compacted Soil Liner. *Ground Water.* Vol. 29, No. 6. pp. 914–921. 1991.

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Rogowski, A.S. "Relationship of Laboratory- and Field-Determined Hydraulic Conductivity in Compacted Clay Layer." EPA/600/S2–90/025. Cincinnati, Ohio: Risk Reduction Engineering Laboratory. 1990.