LMS/SHP/S08254

Shiprock, New Mexico, Disposal Cell Internal Water Balance and Cell Conditions

February 2012

U.S. DEPARTMENT OF ENERGY | Legacy Management

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March 7, 2012

Distribution:

Subject: Transmittal of "Shiprock, New Mexico, Disposal Cell Internal Water Balance and Cell Conditions, February 2012" for the Shiprock, New Mexico, Uranium Mill Tailings Radiation Control Act (UMTRCA) Title I Site.

The enclosed document was prepared by the U.S. Department of Energy, Office of Legacy Management (DOE-LM) in response to concerns brought forth by the Navajo Nation related to the condition of the Shiprock disposal cell and the effectiveness of the cell cover design. This report is a technical evaluation related to the condition of the disposal cell, the effectiveness of the cover design, and the potential for the disposal cell to be a continuing source of groundwater contamination.

The main objectives of the report include a review and summary of the following:

- Mill site operational history for evidence of groundwater contamination from percolation of tailings fluids.
- Tailings material type, deposition patterns, and probable material locations that will affect drainage from the disposal cell.
- Past work performed on disposal cell water balance and seepage.

The report represents DOE-LM's ongoing commitment to evaluate site conditions at the Shiprock UMTRCA Title I Site. Although it does not offer recommendations or solutions, DOE-LM will continue to cooperate with the Navajo Nation on efforts that support the protection of human health and the environment at the site.

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Sincerely,

Deb Steckley
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Abbreviations

AEC	U.S. Atomic Energy Commission
AEP	air-entry permeameter
cm/s	centimeters per second
CSU	Colorado State University
DOE	U.S. Department of Energy
EPA	U.S. Environmental Protection Agency
ft	feet
ft^2	square feet
ft^3	cubic feet
HELP	Hydrologic Evaluation of Landfill Performance
JEG	Jacobs Engineering Group
LM	Office of Legacy Management
NECA	Navajo Engineering and Construction Authority
TPD	tons per day
UMTRA	Uranium Mill Tailings Remedial Action (Project)
VCA	Vanadium Corporation of America

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Executive Summary

The uranium- and vanadium-ore-processing mill near Shiprock, New Mexico, operated from 1954 until 1968. During milling operations, the solid material that remained after extraction of uranium and vanadium from the ore was conveyed in a slurry pipeline to two unlined ponds located just east of the mill. As the liquid in the ponds drained into the subsurface and evaporated into the atmosphere, the solids accumulated as tailings piles. Raffinate fluid was piped from the solvent extraction circuit to unlined, bermed ponds near the south tailings pile (Figure 1).

After the mill closed, the facility was decommissioned and razed, and by 1986 all mill buildings and contaminated soils on the site were encapsulated in a permanent disposal cell constructed on top of the two tailings piles. The disposal cell occupies approximately 77 acres and contains approximately 1.9 million cubic yards of contaminated materials.

This report was prepared by the U.S. Department of Energy (DOE) Office of Legacy Management in response to concerns brought forth by the Navajo Nation related to the functional condition of the Shiprock disposal cell, the effectiveness of the cell cover design, and the potential for the disposal cell to be a continuing source of groundwater contamination.

The total volume of water used to process the ore during the years of milling operations was estimated from historical records of mill production rates and reported percent solids in the slurry. Although the estimates contain considerable uncertainty, calculations indicate that between 50 million and 390 million gallons of milling-related fluids percolated into the subsurface during the operational life of the mill. These fluids resulted in legacy groundwater contamination in alluvial sediments and in the weathered upper portion of the underlying Mancos Shale at the site.

Several geotechnical investigations conducted between 1981 and the present have focused on determining moisture content in the disposal cell and cover and have attempted to evaluate the potential drainage rates from saturated and unsaturated tailings materials in the cell. Fine-grained tailings in the cell (slimes) that directly overlie native terrace deposits retain moisture and were saturated or nearly saturated during the investigations. The infiltration rate of moisture in the disposal cell cover is unknown and likely varies widely over the cover area from 4.76×10^{-8} centimeters per second (cm/s) to 1.19×10^{-4} cm/s. Saturated hydraulic conductivity values in the cover measured in a 2001 investigation using paired air-entry permeameters varied by four orders of magnitude.

The primary function of the disposal cell cover system is to mitigate the emanation of radon from the encapsulated tailings. Despite the movement of water through the cover, the cover remains protective, and the cover system is functioning as engineered and designed to mitigate radon.

The amount of contaminated water available to leach into the groundwater system is a function of percolation through the cover system and drainable moisture from tailings within the disposal cell and varies between 10^{-7} cm/s and 10^{-9} cm/s. Some volume of tailings fluid is draining from the cell. DOE and Knight Piésold Consulting, a contractor for Navajo Nation, cooperated in a joint effort to model this cell drainage. The 1.1×10^{-7} cm/s bounding estimate of the modeling equates to 4.85 gallons per minute over an area of 70 acres; which in turn equates to 1.1 inches per year, or approximately 20 percent of annual precipitation. However, this volume is very small compared to the minimum volume of 50 million gallons of milling-related water estimated to have percolated into the subsurface during the operation of the mill. Consequently, contamination will remain in subsurface sediments, and groundwater contamination will persist regardless of any contaminant contribution from the cell.

1.0 Introduction

A uranium- and vanadium-ore-processing mill operated near Shiprock, New Mexico, from 1954 to 1968. By September 1986, all tailings and associated materials at the former mill site were encapsulated in a disposal cell built on top of the two tailings piles that existed on the site. The cell occupies approximately 77 acres and contains 2,520,000 wet tons (approximately 1.9 million cubic yards) of contaminated materials, including contaminated materials from off-site vicinity properties. Groundwater in the area of the mill site was contaminated by uranium, nitrate, sulfate, selenium, and associated constituents as a result of the milling operations. The Uranium Mill Tailings Remedial Action (UMTRA) Ground Water Project was responsible for characterizing and remediating groundwater at the Shiprock site. In October 2003, responsibility for the UMTRA Ground Water Project sites, including Shiprock, was transferred to the U.S. Department of Energy (DOE) Office of Legacy Management (LM). LM now has responsibility for active groundwater remediation associated with the former processing site, as well as maintenance of the disposal cell at Shiprock, and must comply with applicable regulations.

The disposal cell and adjacent former mill site are on a terrace elevated about 75 feet (ft) above a floodplain of the San Juan River. An escarpment south of the river forms a boundary between the floodplain and the nearly flat terrace.

In March 2003, DOE initiated pump-and-treat remediation of groundwater at the Shiprock site, and contaminated groundwater is currently removed from the subsurface through extraction wells and interceptor drains. One objective of the remediation effort is to reduce the risk of exposure at seeps along the terrace by removing the terrace groundwater, thus drying up the seeps.

Concentrations of uranium, nitrate, sulfate, selenium, and other site constituents in groundwater beneath and adjacent to the disposal cell remain elevated after implementation of active pumping from the terrace. This report evaluates the likelihood that the disposal cell is a continuing source of contamination for groundwater. Also included is an estimate of seepage rates based on an analysis of transient drainage.

The objectives of this report include a review and summary of the following:

- Mill site operational history for evidence of groundwater contamination from percolation of tailings fluids (Section 3.0).
- Tailings material type, deposition patterns, and probable material locations that will affect drainage from the disposal cell (Section 4.0).
- Past work performed on disposal cell water balance and seepage (Section 5.0).

Section 6.0 presents the conclusions. Because of uncertainties in data, the report presents order-of-magnitude estimates to compare relative contributions to the groundwater plume.

2.0 Overview of Site Geology Adjacent to the Cell

The terrace deposits consist of a surface layer composed of fine-grained eolian sand and silt underlain by alluvial sandy gravels with cobbles ranging up to 12 inches in diameter. Thickness of the terrace material varies from approximately 5 ft to 15 ft along the escarpment paralleling the San Juan River and increases to around 45 ft toward the southwest portion of the site. The terrace deposits overlie a highly weathered and fractured erosional surface of Mancos Shale. The main body of the Mancos Shale consists of claystone and siltstone with lesser amounts of fine-grained sandstone and limestone. Thickness of the Mancos underlying the site is unknown but is estimated to be greater than a few hundred feet.

3.0 Mill Site History

Historical documents related to the Shiprock mill production and tailings deposition were reviewed to estimate the quantity of water used in production and determine probable locations of various types of materials in the stratigraphy of the tailings piles.

After the ore was crushed and processed, the remaining material (tailings), which consisted of fine-grained sand, silt, and clay, was mixed with water, transported as a slurry, and deposited. The resulting stockpiles of tailings and ponds where process water was deposited (raffinate ponds) on the mill site were unlined during the entire operational life of the mill, which was a standard industry practice at the time (i.e., there were no regulatory requirements to line the ponds). Thus, water used for slurry transport of tailings also freely percolated into the subsurface. Process fluids carrying heavy metals and other contaminants either evaporated or infiltrated directly into subsurface terrace deposits, and the contaminants likely sorbed onto native deposits. In 1960, the U.S. Public Health Service performed a water quality stream survey of the San Juan River below the Shiprock mill. A report from that survey provided the following information (USDHEW 1961):

> The portions of the ponded liquids which do not evaporate normally percolate into a 10 to 20 foot thick terrace gravel deposit which is underlain by Mancos Shale. These liquids then flow laterally over the shale to the edge of the bluff, where the shale outcrops from 10 to 20 feet above the narrow flood plain of the river. The major portion of the seepage appears in various gullies and washes where the alluvium has been eroded from the bluff.

The following historical timeline summary provides a basis for understanding the length of time water was used for slurry transport of tailings to the tailings ponds, which were constructed directly on the terrace deposits. The approximate volume of water used in the tailings slurry to transport solids is mentioned in the timeline when this information is available (historical information was obtained from Sullenberger 1993; USEIA 2010; Quinn 1957).

3.1 Timeline

August 1951	Navajo Uranium Company proposed construction of a uranium mill at Shiprock on Navajo Nation lands. The mill was designed to have a feed capacity of 300 tons per day (TPD). The U.S. Atomic Energy Commission (AEC) did not approve construction of the mill; however, AEC did approve creation of an ore-buying station (Sullenberger 1993; USEIA 2010).
January 1952	The ore-buying station opened. This facility may also be referred to as a 200 TPD Navajo Uranium Company Mill (see Sullenberger 1993, Chapter 6, "Navajo Indian Reservation Uranium Mills").
May 1952	Kerr-McGee Oil Industries, Inc. acquired Navajo Uranium Company ore-buying station and also acquired 75 percent interest in Navajo mining leases (Sullenberger 1993).
August 1953	Kerr-McGee signed a contract with AEC to build a uranium-ore-processing mill near the Shiprock ore-buying station. Construction began in fall 1953.
November 1954	The Shiprock mill started production at 300 to 400 TPD. Approximately 573,000 to 1,850,000 gallons of tailings fluids percolated into the subsurface annually at 40 percent tailings solids slurry. See Appendix A, Computation 3, "Shiprock Tailings and Raffinate Ponds Water Balance."
August 1960	Barren liquor (raffinate) was accidently released as a result of embankment failure at the raffinate ponds (see Figure 1). Fluids drained down Bob Lee Wash. Mill production was reported to be operating at 400 to 500 TPD.
March 1963	Vanadium Corporation of America (VCA) acquired the mill and operations. Figure 1 shows an oblique aerial photograph from July 1965 of the mill site, tailings ponds, and raffinate ponds.
August 1967	VCA merged with Foote Minerals.
May 1968	The mill closed. Total mill production from 1954 to 1968 is estimated to be 1.5 million tons of ore processed at 0.25 percent U_3O_8, producing 3,711 tons of yellowcake.
January 1973	Foote Minerals lease expired; Navajo Nation acquired Shiprock mill and tailings site. Navajo tribal chairman requested the U.S. Environmental Protection Agency (EPA) to assist in stabilizing tailings and decontaminating the site. Concurrently, the Navajo Nation government authorized the Navajo Engineering and Construction Authority (NECA) to use the mill and tailings site as a vocational school for training in the operation of heavy equipment.
April 1974	EPA completed site stabilization and characterization of off-site contamination.
October 1974	EPA provided the Navajo Nation with a decontamination plan and cost estimate. Meanwhile, NECA continued decontamination efforts by removing mill buildings, the entry road, parking lot, raffinate ponds, and ore-storage areas, placing material in the south tailings pile. NECA removed contaminated soil from areas surrounding the tailings piles and used the soil to construct containment dikes and a 6-inch cover on the south tailings pile.

	A sprinkler irrigation system was installed on the south tailings pile to mitigate dust problems; the water from this irrigation likely resulted in additional seepage.
March 1977	The Energy Research and Development Administration, predecessor agency of DOE, concluded that 80 percent of the EPA plan was complete. Incomplete items included installation of security fencing and cleanup of off-site contamination.
1978	The Shiprock mill was included in DOE's UMTRA Project.
1981	Colorado State University conducted a geotechnical site characterization of the tailings.
April 1985	UMTRA (DOE) Project contractors began decontamination of 15 off-site properties.
August 1985	Construction of the disposal cell began under the UMTRA Project.
February 1986	Decontamination of off-site properties was completed.
September 1986	Construction of the disposal cell was completed.
March 2003	DOE began pump-and-treat remediation on the terrace.

3.2 Uncertainty in the Production Rates

An uncertainty in the mill site history is the actual mill production rates. The volume of water calculated for use in slurry transport (see Appendix A, Computation 2, "Estimated Total Volume of Water Used in Mill Production") is based on the estimated total mill production published in historical reports. Differences in reported mill production rates range up to 100 tons per day, which could cause a difference in water volume of 20,700 gallons per day. Additionally, a 10 percent variation in solids content of the slurry could cause a variation of approximately 7,400 gallons per day.

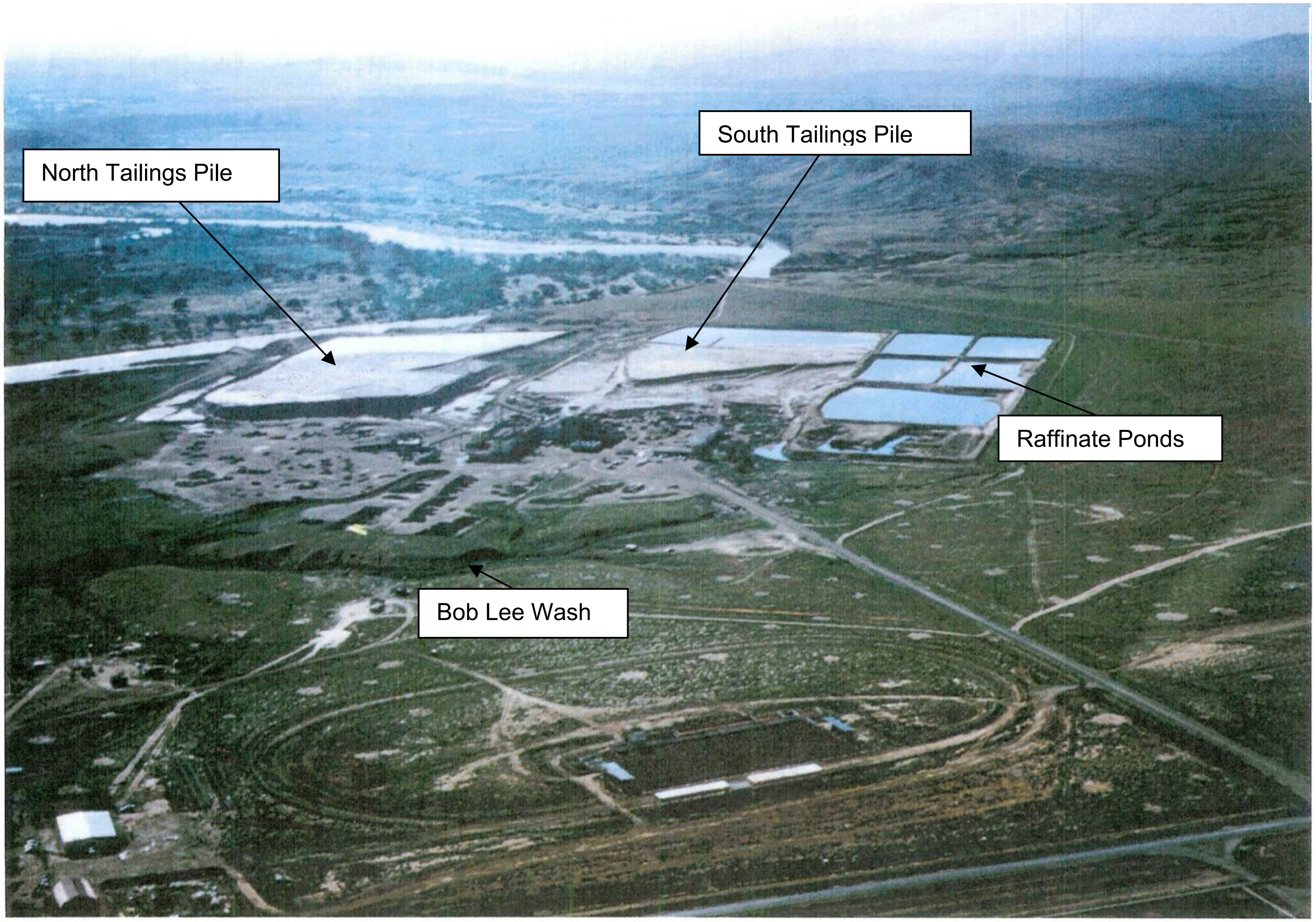


Figure 1. Oblique Aerial Photo of the Shiprock Mill Site in 1965, View Looking East
(Source of photo is unknown.)

4.0 Tailings Pile Stratigraphy

The tailings pile stratigraphy was evaluated to provide insight into the internal moisture conditions of the disposal cell and the cell's drainage potential. As moisture moves through the cell, different soil materials store moisture differently. Coarse-grained, clean sands and sands with minimal amounts of fine-grained material have an open network of pores that allows fluid to pass through connected flow channels relatively quickly. Saturated fine-grained material (slimes) and slimy sands have small, disconnected flow paths that do not allow fluids to pass freely. These materials store fluids for a relatively long period of time.

Stratigraphy was determined from (1) tailings characterization performed by Colorado State University (CSU) in 1981 (CSU 1985), (2) historical reports of initial remediation performed by NECA students, and (3) results from a piezocone investigation performed in 2001 (DOE 2002). The tailings stratigraphy is used to infer a depositional history, which is further used to infer location of sand and slimes deposits where geotechnical investigations were not performed.

Tailings slurries normally contain around 30 percent solids by weight; Quinn (1957) reported that the Shiprock tailings slurry may have reached 40 percent solids by weight. After the slurry was pumped to a tailings pond, the tailings were deposited as a single point discharge or through a series of spigots along the edge of the tailings pond. CSU (1985) mentions spigots as the most probable deposition method used at the Shiprock mill. After the slurry was discharged, the coarse sand particles dropped from suspension first, and the finer-grained particles (slimes) were carried farthest away from the discharge point. Slurry fluids drained into the subsurface and evaporated from the tailings ponds over time, resulting in the tailings ponds becoming tailings piles.

4.1 Deposition History and Sand/Slimes Locations

Two tailings piles, the south pile and north pile, were used during the mill operation at the Shiprock site. Figure 1 (source unknown) and Figure 2 (CSU 1985) show the general location and configuration of the tailings piles. The south pile was also known as the lower pile, and the north pile was known as the upper pile.

The south pile was the initial location for tailings deposition and was used into the 1960s. Although no mill records were available for review, photographs and locations of tailings deposition mentioned in various reports indicate that the south pile may have been used throughout the operation of the mill. The north pile was used for deposition from the mid-1960s until the mill ceased operation in 1968.

4.1.1 South Pile

At the time that CSU performed the 1981 geotechnical investigation, berms surrounded the south pile; these berms were presumably constructed by NECA during training activities for operation of heavy equipment. The berm construction material was surficial alluvial silty sands and gravels. Because of the NECA construction, it is difficult to establish a depositional sequence for the south pile; however, tailings appear to have been discharged by spigots from the north and west perimeters of the pile (CSU 1985). Results of widely spaced borings provide some evidence of slimes zones in the southeast portion of the impoundment and a greater concentration of sands along the north and west sides.

Results of the CSU investigation indicated that NECA construction had reworked the south pile to such an extent that any information of depositional history was erased. NECA consolidated windblown contamination from the terrace and the raffinate ponds in the south pile as part of operator training and also demolished mill buildings and parking lots and placed those materials in the south pile. After the extensive reworking, the pile is assumed to be a homogenous mixture of sand, sandy slimes, slimes, and construction debris. A thin soil cover was placed on top of the pile, and the pile/cover system was irrigated for an unknown period of time to suppress dust. The maximum period of irrigation is assumed to be from the mid-1970s (after the Navajo Nation took control of the site) to 1981 (when CSU personnel described the system).

4.1.2 North Pile

Field conditions evident during the CSU geotechnical investigation in 1981 suggest that the berms surrounding the tailings were constructed prior to tailings deposition. Locations of tailings sands and slimes indicate spigot deposition from the southern and western perimeter berms with frequent spigot movements. During late operations of the impoundment, discharge from the southwest corner of the impoundment is evident by a high mound of sands in that location. This deposition is also suggested by thick slimes deposits along the north and east portions of the impoundment. Between the high sand mound and slimes zones, the tailings consist of mixed alternating layers of sands and slimes.

4.2 Cross Sections from the CSU Geotechnical Investigation

Figure 2 (from CSU 1985) shows a plan view of the tailings piles in 1981. The figure also shows the locations of four interpretive cross sections (shown in red) of the tailings pile. Figures 3 through 6 show details of the cross sections, and Table 1 provides an explanation of the tailings material codes depicted on the individual cross sections.

As noted earlier, different soil materials have different moisture storage capacities. Therefore, the estimates of the locations and quantities of milling-related material types and their likely water content are critical in evaluating the water balance for the tailings in the disposal cell. These estimates are discussed further in Section 5.

4.3 Piezocone Investigation

In 2001, DOE conducted a screening-level piezocone investigation to determine internal moisture conditions within the Shiprock disposal cell (DOE 2002). A piezocone is an in situ geotechnical test tool that consists of an instrumented drill rod with a pointed tip, which is hydraulically pushed into the subsurface at a constant rate. During a piezocone sounding, also known as a cone penetration test, instruments record bearing pressure, sleeve resistance, and pore pressures. For the application at the Shiprock disposal cell, electrical resistivity was logged to assess in situ moisture conditions during the sounding (DOE 2002).

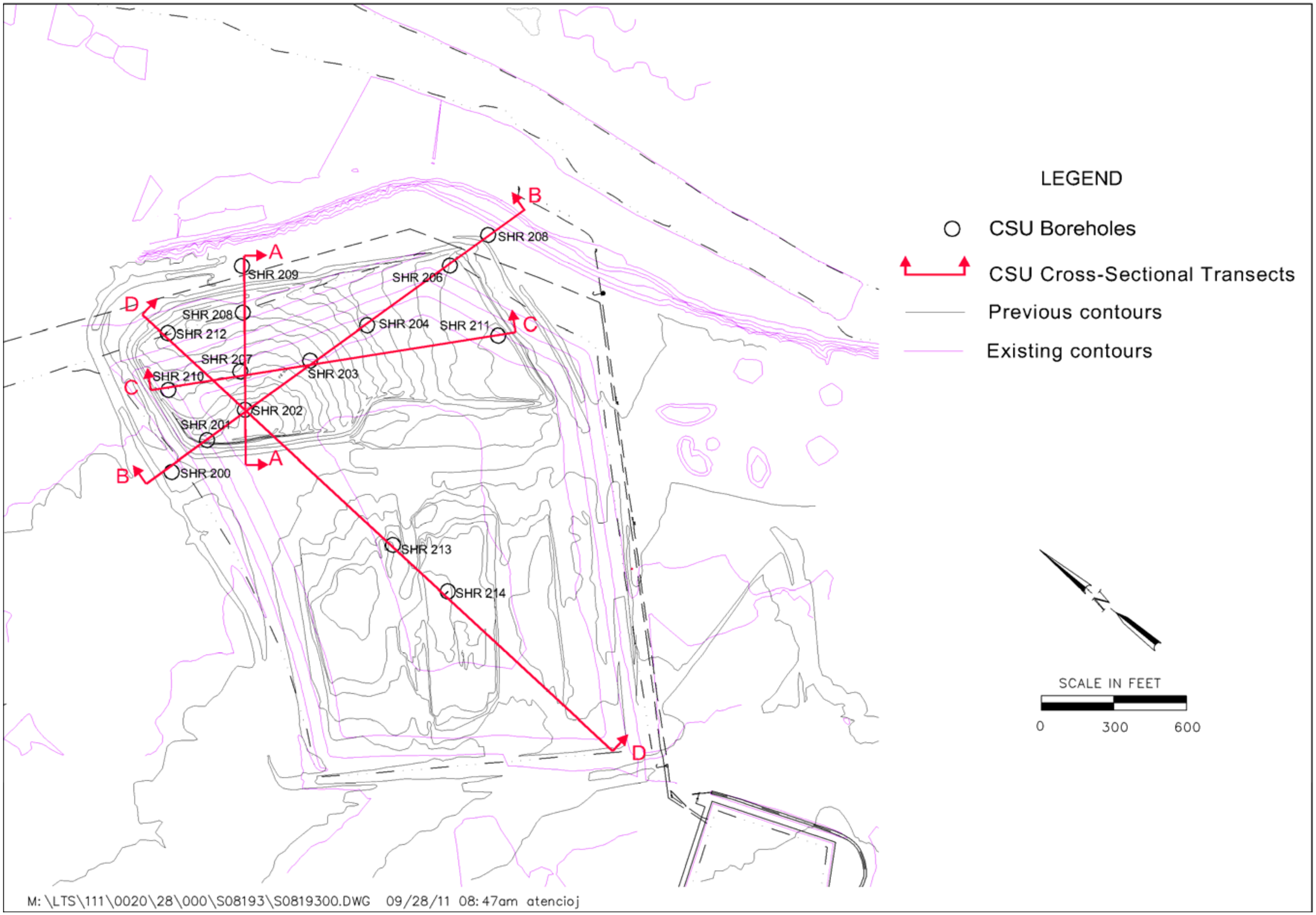
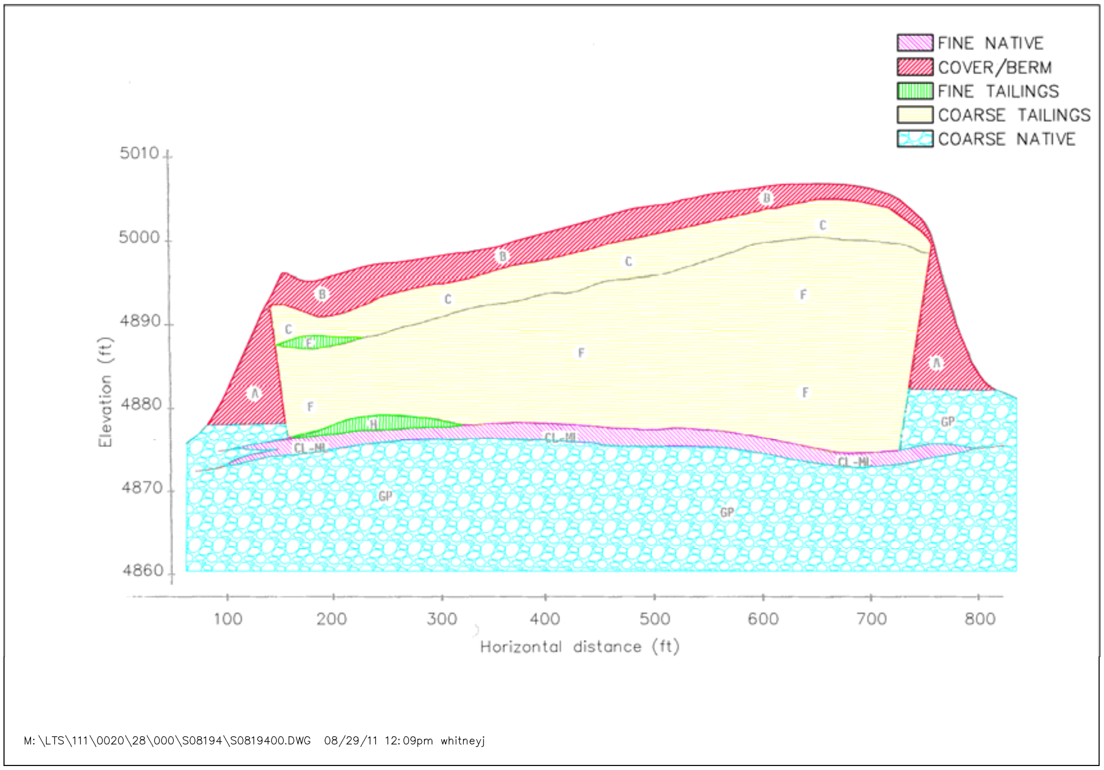
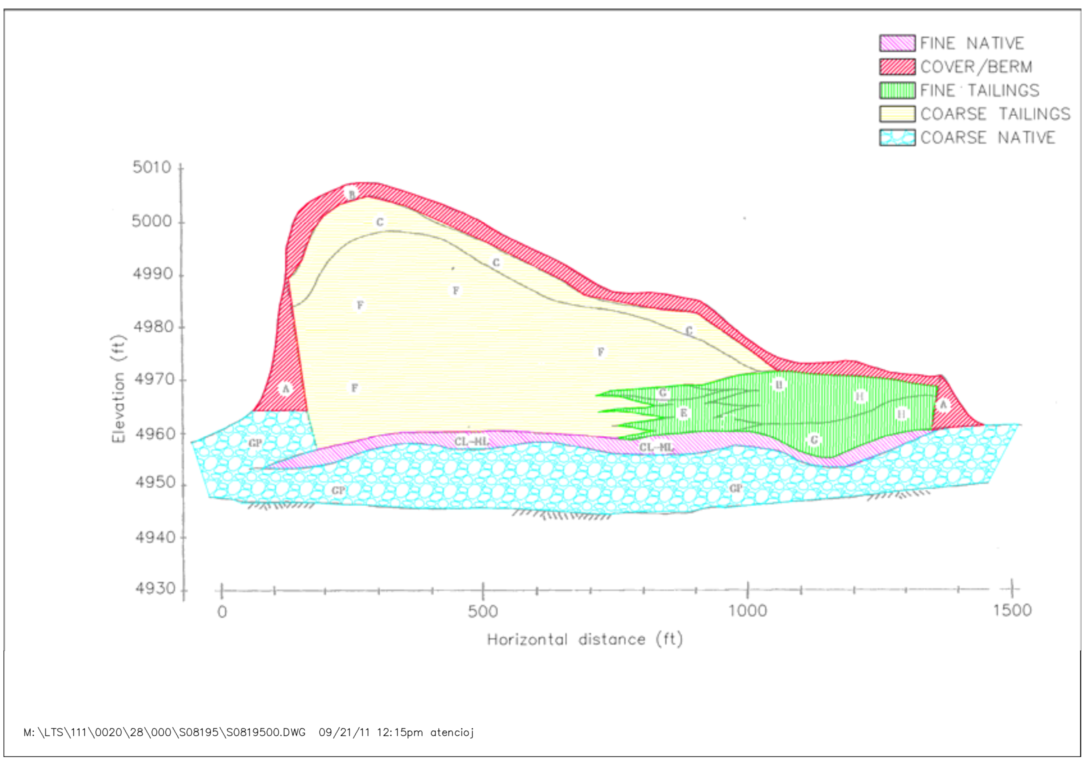


Figure 2. 1981 Cross-Section Locations at the Shiprock Tailings Piles



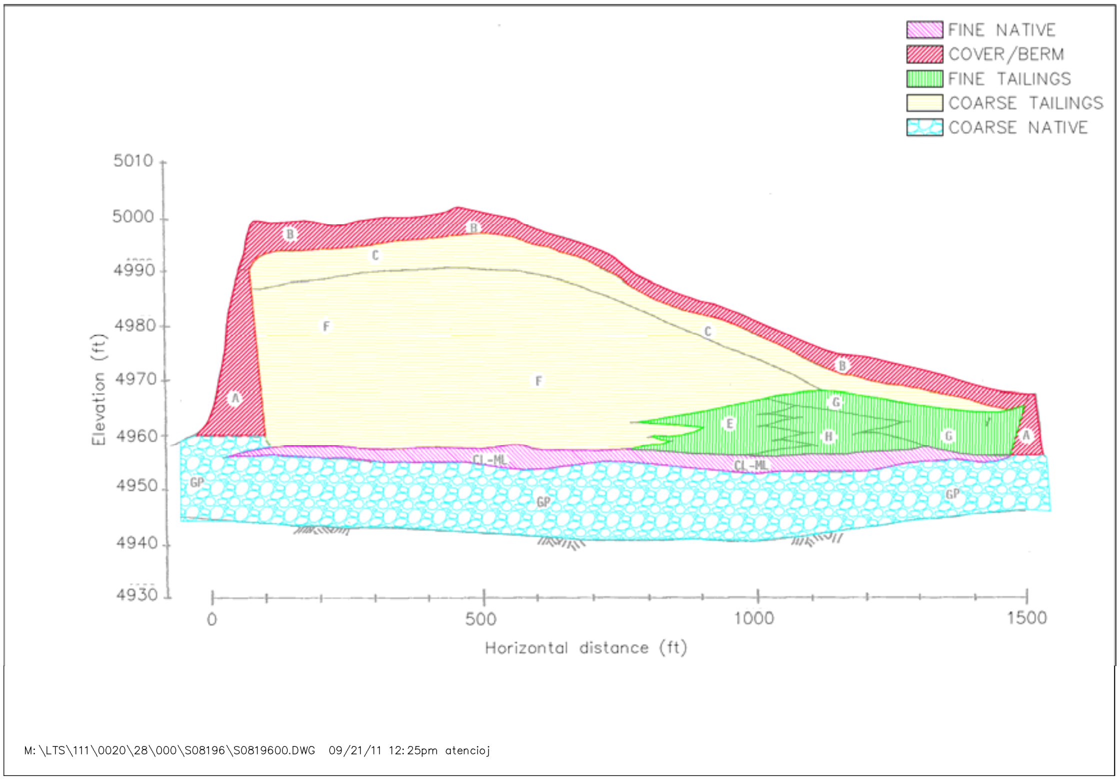
Source: CSU 1985

Figure 3. Cross Section A–A



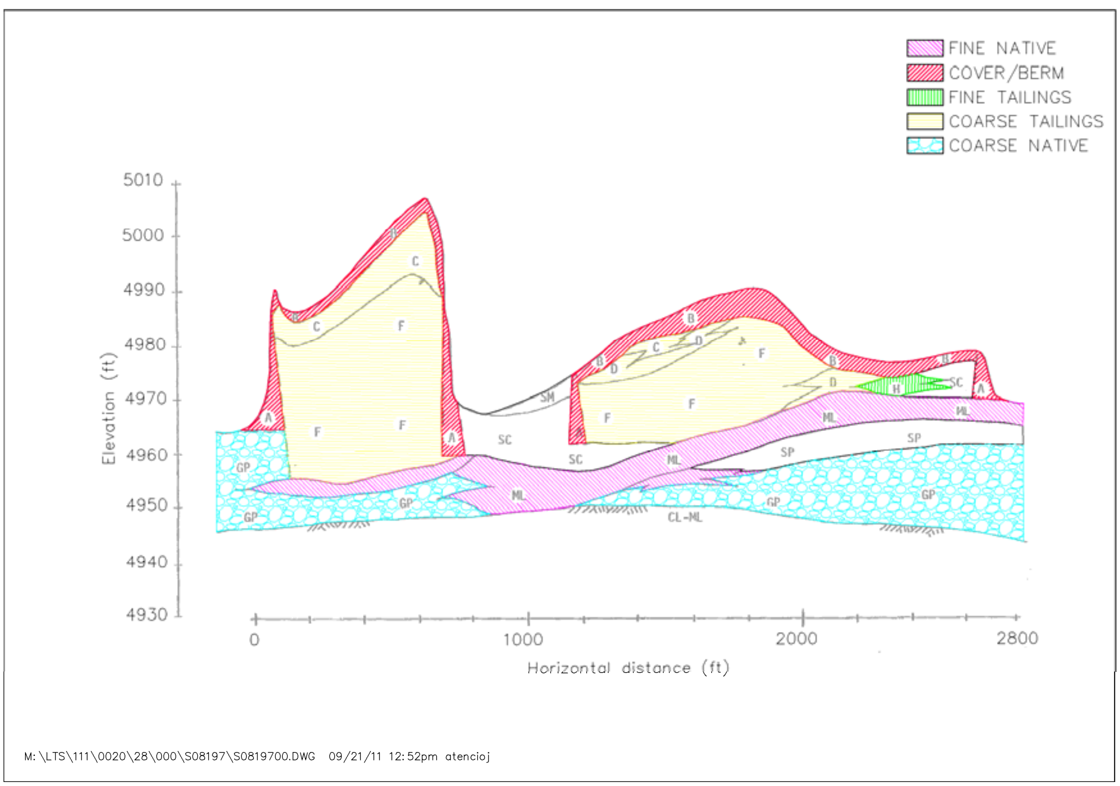
Source: CSU 1985

Figure 4. Cross Section B–B



Source: CSU 1985

Figure 5. Cross Section C–C



Source: CSU 1985

Figure 6. Cross Section D–D

Table 1. Key to Interpretive Cross Sections

Symbol	Description
Foundation Materials	
SM	Silty sand, brown, surficial
SC	Clayey sand, rusty brown
SP	Fine sand, tan
CL-ML	Silty clay to clayey silt, low to med. plasticity, brown
ML	Silt, low plasticity, golden brown
GP	Gravelly to silty sand, $CaCO_3$, rounded, terrace deposit
Tailings Materials	
C	Sand, fine, dry, gray
F	Sand, fine, dry, gray with layers of slimes
G	Clay, slimes, high plasticity, gray
H	Clayey silt, slimes, pink to white
E	Clayey sand, slimes, red-brown
D	Sand, fine, tan
Berm and Cover Materials	
A	Silty sand with gravel, brown
B	Gravelly sand to silty sand, pit run, light brown

Source: CSU 1985

4.3.1 Piezocone Results

A total of 29 soundings were attempted as part of the investigation. Piezocone refusal occurred on a very hard, dense layer of soil at the base (6.7 ft below the surface) of the cover layer across the southern two-thirds of the disposal cell. Thus, piezocone results could not be used to characterize cell materials in the southern area of the cell. Material characterization of this region relies on results from the CSU investigation (CSU 1985).

4.3.1.1 Cover Soils

Within the upper portion of soundings (within the approximately 6.7 ft cover) that met refusal across the southern two-thirds of the disposal cell, the cover soils were partially saturated at the time of the investigation (September 21–24, 2001). Zones of low bulk electrical resistivity, which indicate saturated conditions, occurred in five soundings in the cover layer. This information, coupled with the nearly saturated conditions found from results of neutron probe testing (discussed in Section 5.3), indicates that these zones could represent regions of preferential flow through the cover. Slimes underlying zones of preferential flow could result in the mounding of meteoric water (rain and snowmelt) if the local geometry allows for it (i.e., a depression exists in the upper surface of the slimes that would allow water to pond); otherwise, water will follow pathways of higher conductivity through the coarser material surrounding the slimes.

4.3.1.2 Cell Materials

The majority of materials in the cell are tailings consisting of sands and sandy slimes. Slimes are present along the north and northeastern portion in the disposal cell and directly overlie native alluvium. Thickness of slimes varies from 5 ft to approximately 20 ft and averages 13 ft. The piezocone investigation also showed that the slimes are saturated, as inferred from an excess pore pressure head of 5.5 ft, indicating that some consolidation is occurring. Overall, tailings materials are partially saturated. Saturated layers of tailings appear randomly throughout the disposal cell, indicating possible cover infiltration or residual moisture attained during final construction of the cell.

4.3.2 Cross Sections from the Piezocone Investigation

Figure 7 shows cross-section locations of the piezocone investigation and the estimated location of slimes, which were deposited directly on native terrace deposits. Based on best estimates of the depositional history, the basal slimes were deposited along north and east portions of the north pile and potentially along the eastern portion of the south pile. During final remediation, slimes were removed from the extreme north and east portions of the tailings pile. It is assumed that the slimes were placed either on top of existing slimes or in a swale between the north pile and the south pile to form the final cell geometry.

The area of slimes deposition is approximately 470,000 square feet (ft^2) (Figure 7). Assuming an average thickness of 13 ft, the volume of slimes in the disposal cell is approximately 6,110,000 cubic feet (ft^3).

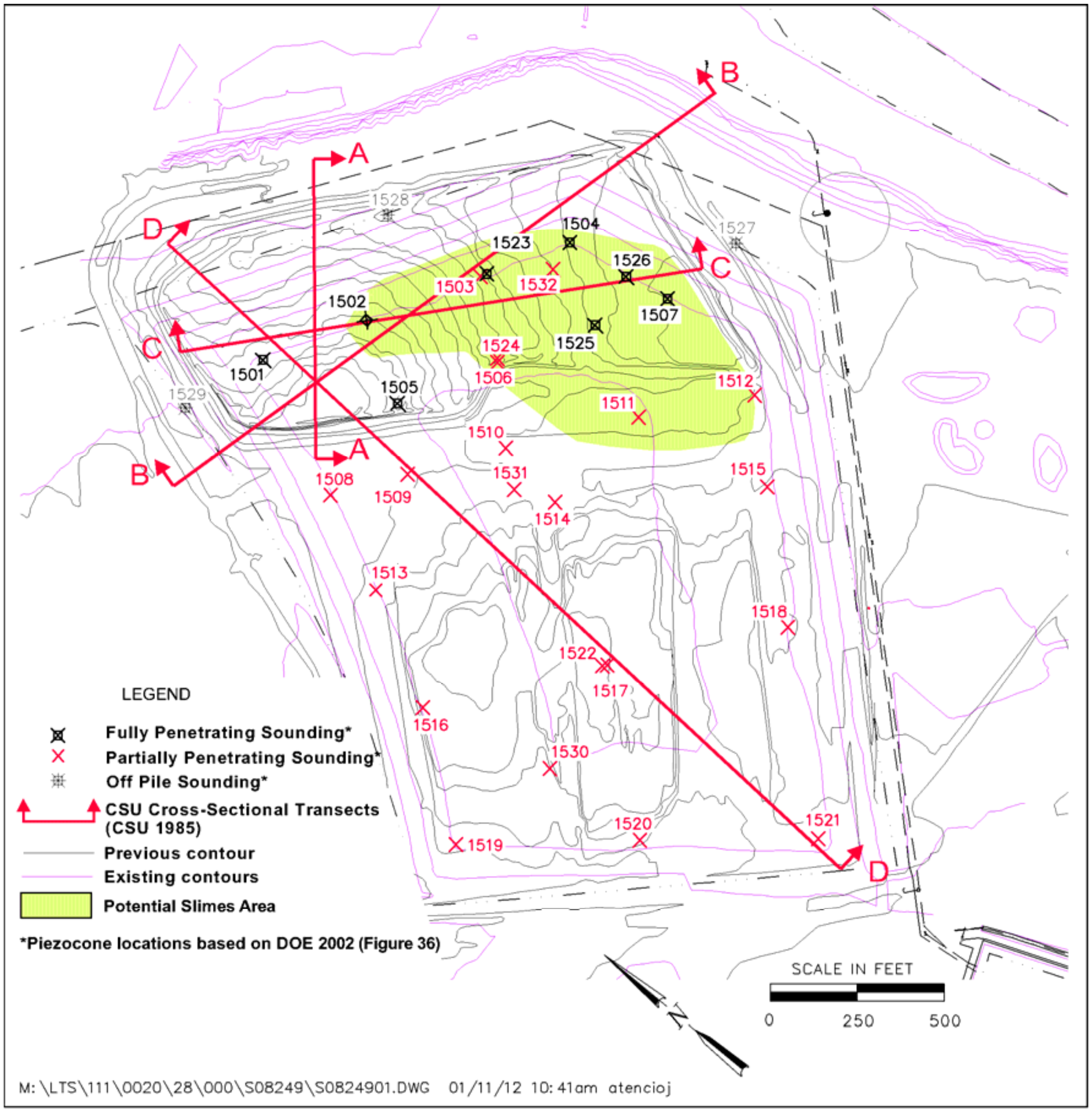
Figures 8, 9, and 10 present cross sections from the final disposal cell configuration. The figures show basal slimes and the south pile in sections B–B, C–C, and D–D. The locations of these cross-sections are the same as those shown as the CSU interpretive cross sections presented in Figures 4, 5, and 6, which are also shown in Figure 7 for reference.

5.0 Moisture Conditions: Internal Disposal Cell and Subsurface

Moisture within the disposal cell presents a continuing source of contamination as tailings pore water discharges into the subsurface. Specifically, meteoric water moving through the cell, and the slimes, which have a high water content, are considered a continuing source of contamination. Seepage from tailings impoundments used during milling operations resulted in moisture infiltrating terrace deposits beneath the disposal cell. This section presents a discussion of the current understanding of moisture conditions within and beneath the disposal cell.

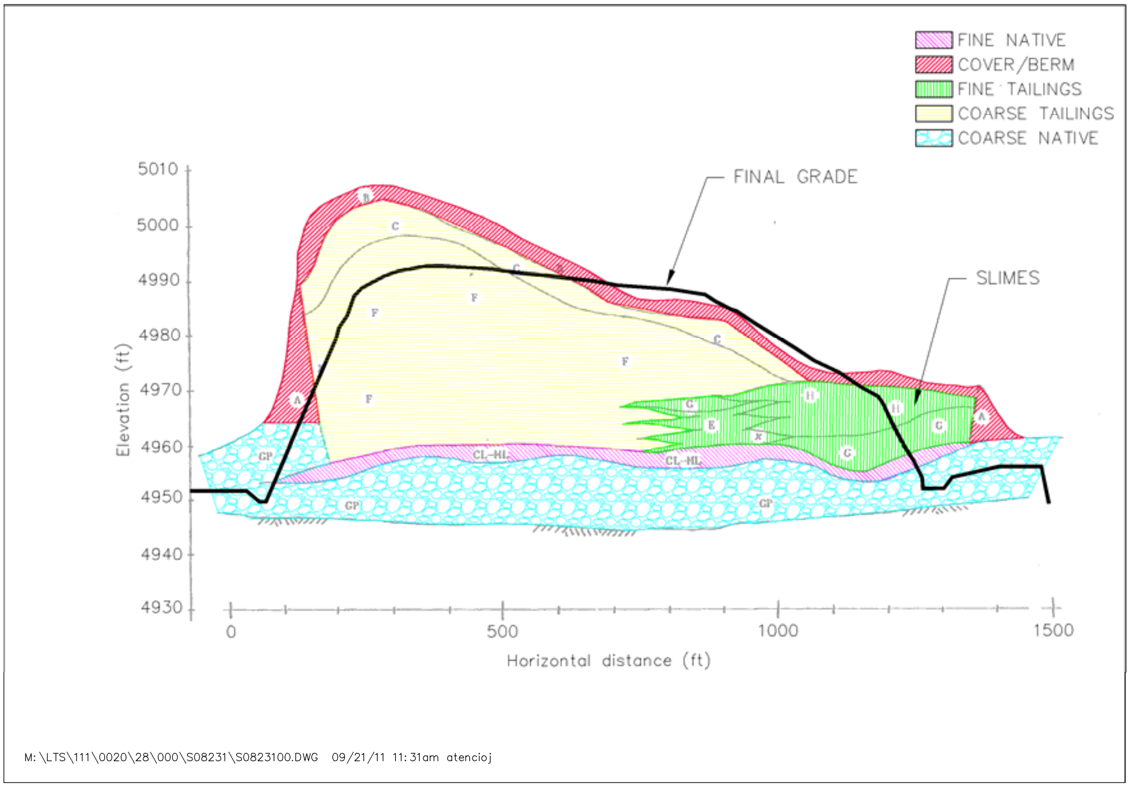
5.1 Subsurface

The water balance computation for the tailings ponds (Appendix A, Computation 3, “Shiprock Tailings and Raffinate Ponds Water Balance”) provides an estimated range of possible volumes of water that could have percolated into the subsurface during the operational life of the mill (1954 to 1968). Percolation volumes were estimated assuming mill production rates ranging between 300 and 500 TPD and a slurry solids concentration of 30 to 40 percent (see Appendix A, Table A–2). After precipitation and evaporation are accounted for (see Appendix A, Computation 1, “Estimated Precipitation and Evaporation at the Shiprock Mill Site”), the volume of fluid that percolated into the subsurface is estimated to be between 50 million and 390 million gallons. As shown in Appendix A, Computation 1, evaporation from free water surfaces off the tailings piles and raffinate ponds limits percolation to the winter months, estimated to be between November and March.



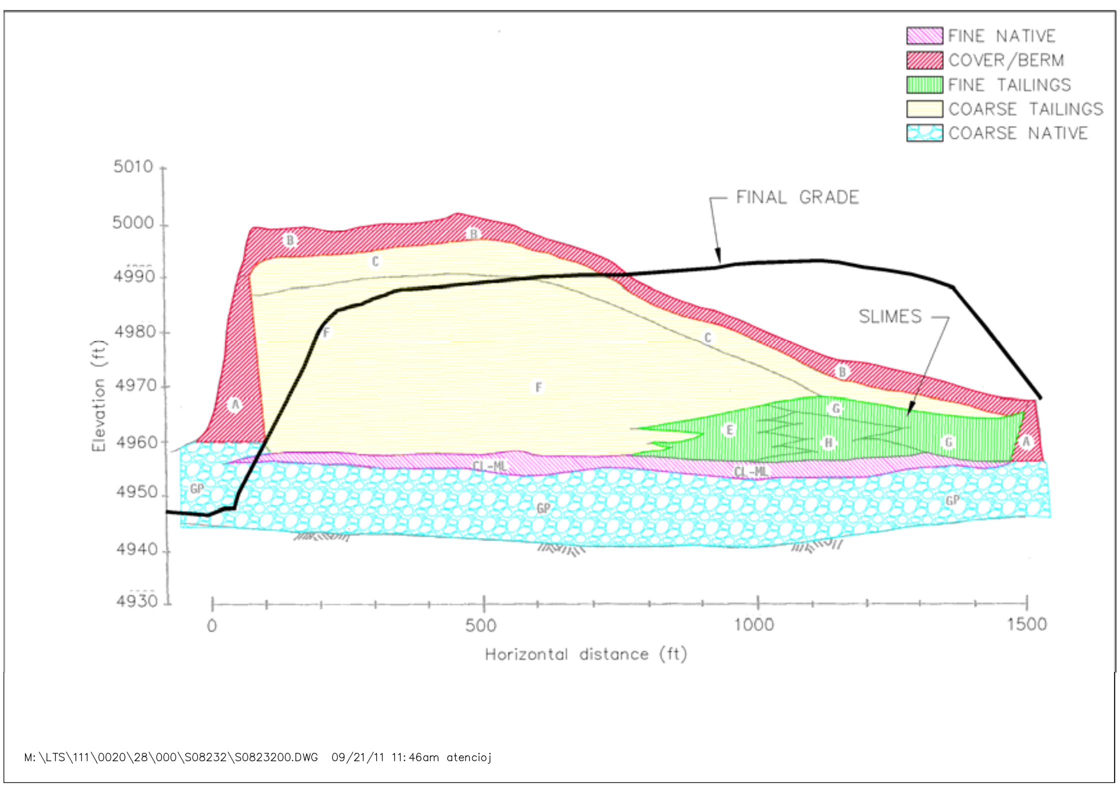
Source: CSU 1985, DOE 2002

Figure 7. Final Disposal Cell Cross Section and Piezocone Locations



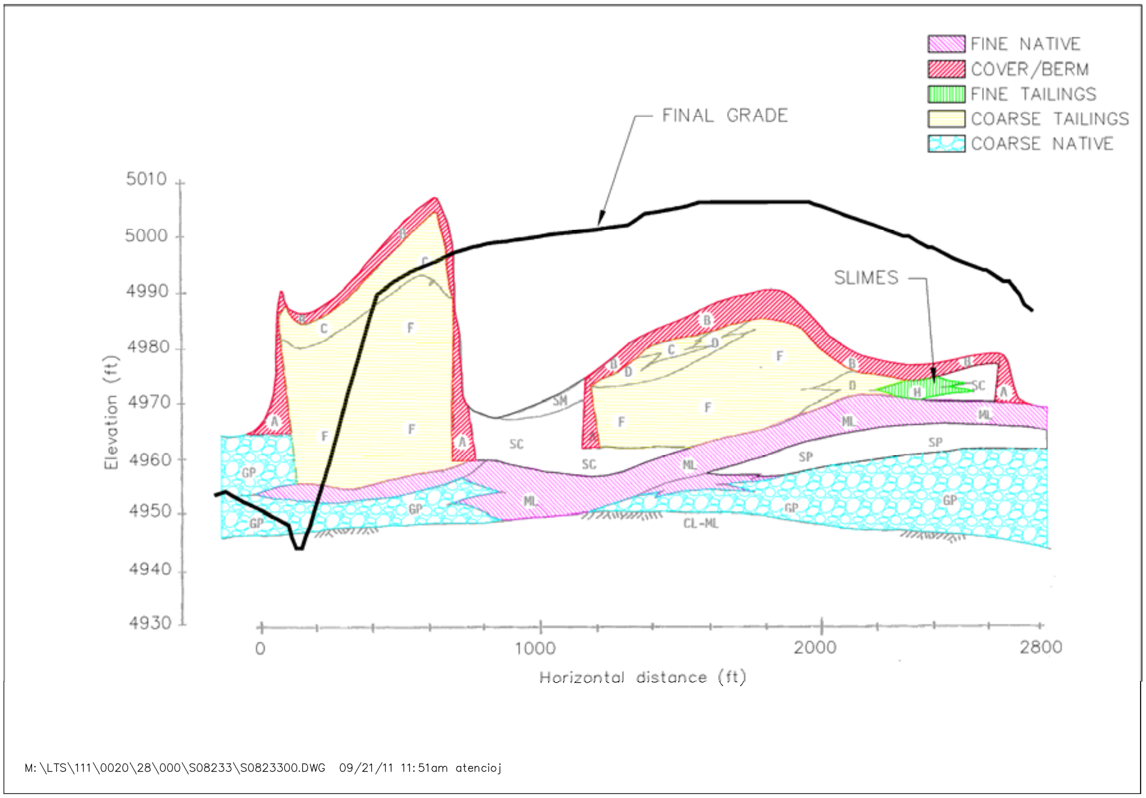
Source: CSU 1985

Figure 8. Final Disposal Cell Cross Section B–B



Source: CSU 1985

Figure 9. Final Disposal Cell Cross Section C–C



Source: CSU 1985

Figure 10. Final Disposal Cell Cross Section D–D

Contaminated fluids from milling operations percolated into terrace gravels and into the weathered upper portion of the Mancos Shale. Contaminants remain in the subsurface and are still available to be remobilized as groundwater passes through these materials.

5.2 Cover Infiltration

UMTRA Project construction reshaped the north and south piles for the final configuration. During construction, sands and slimes were combined, and the tailings were capped with a cover designed to act as a radon barrier and to operate at a lower saturated hydraulic conductivity than the previous interim cover. Laboratory testing of cover soils performed as part of the initial UMTRA design shows a saturated hydraulic conductivity expected to be 2.5×10^{-5} centimeters per second (cm/s) (DOE 1987). The magnitude of hydraulic conductivity is one variable that influences moisture flux through a soil. Because moisture occupies more void space in saturated soil, more flow area is available for moisture movement in saturated soil than in unsaturated soil. Therefore, values for saturated hydraulic conductivity are greater than values for unsaturated hydraulic conductivity for the same soil.

Jacobs Engineering Group (JEG)[1] installed four aluminum neutron probe tubes through the radon barrier into the top of the tailings in September 1988 (2 years after the cell was completed) to monitor in situ moisture contents. Results indicated nearly saturated, but still unsaturated,

[1] JEG was the technical assistance contractor to DOE and was responsible for oversight of disposal cell construction at most UMTRCA Title I sites.

conditions (i.e., most, but not all, voids contain moisture). Because this testing indicated unsaturated conditions, the magnitude of operational hydraulic conductivity will be less than the magnitude determined through laboratory testing. Additional discussion of the study is available in a report prepared by Daniel B. Stephens and Associates for JEG (DBS&A 1988). DOE (1989) also provides additional discussion of moisture content and unsaturated conditions in radon barriers.

In 2001, DOE retested the same neutron tubes installed by JEG in 1988 (DOE 2001). Results of the 2001 test indicated saturation of the radon barrier. Measurements of the operational saturated hydraulic conductivity were also determined during the 2001 study. Paired air-entry permeameter (AEP) tests were used to measure in situ hydraulic conductivity at three locations on the north side slope in the upper 2 to 3 feet of the cover where vegetation had established and at a location adjacent to the first test in an area without vegetation. Saturated hydraulic conductivity from the AEP tests varied by four orders of magnitude, from 4.76×10^{-8} cm/s to 1.19×10^{-4} cm/s, which creates a high degree of uncertainty in predicting a representative value for in situ saturated hydraulic conductivity. DOE (2001) provides additional details of the test.

In 2002, consultants to the Navajo Nation used EPA's Hydrologic Evaluation of Landfill Performance (HELP) computer model to assess cover infiltration at the Shiprock disposal cell. Results from this study indicated that up to 20 percent of annual precipitation could be percolating through the cover (Knight Piėsold and Co. 2002). This rate is facilitated by the rock erosion cover used on the disposal cell. Rock covers have been shown to increase infiltration compared to non-rock-covered areas, including vegetated and bare-slope covers (Waugh et al. 1991; Waugh et al. 1994; Sackshewsky et al. 1995).

5.3 Internal Moisture

Test results of slimes samples collected during the 1981 CSU study indicate nearly saturated conditions. A similar saturation condition of slimes was also noted during the piezocone investigation in 2001, indicating that the draining of moisture from the slimes was slow over the 20 years between investigations. The slow drainage rate under saturated conditions could be the result of moisture being held within the fine-grained slimes. Because the original hydraulic head that was available from a saturated tailings pond is now absent, gravity is the sole driving force for downward movement of moisture. Precipitation recharging the tailings through saturated uniform percolation is unlikely, because piezocone results indicate unsaturated moisture conditions above the slimes. However, moisture is likely recharging tailings in an unsaturated condition, albeit at a very slow (10^{-7} cm/s) rate, similar to that of the unsaturated drainage as discussed in Section 5.4. For the slimes, if the slow recharge from meteoric water exceeds drainage rates from the slimes, then the nearly saturated conditions would remain constant.

5.4 Drainage

Groundwater contamination occurred from mill operations, which took place from 1954 to 1968. To evaluate drainage from the Shiprock disposal cell as a source of continuing groundwater contamination, Knight Piésold Consulting (contractor for Navajo AML/UMTRA) ran the EPA numerical HELP model to understand potential flux from the disposal cell (Knight Piėsold Consulting 2002), resulting in a flux out of the cell of 4.85 gallons per minute over a 70-acre footprint. This converts to a unit flux of 1.1×10^{-7} cm/s, which is controlled by hydraulic conductivities of the tailings materials. This flux is facilitated by the rock erosion cover used on the disposal cell. Knight Piésold also ran the model to determine flux from the cell with a vegetated cover replacing the rock cover. Results of the HELP model with a vegetated cover demonstrated that drainage from the disposal cell would be essentially eliminated.

EPA's HELP model does not account for internal drainage or transient drainage conditions. The HELP model was developed to understand leachate generation from municipal landfills, and it assumes one-dimensional vertical flow under steady-state conditions. Moisture movement is controlled by saturated Darcy flow, taking the influx that is input and forcing the flow through the disposal cell at a rate based on internal saturated hydraulic conductivities and one dimensional Darcy flow. Because of these limitations, what is modeled is a simplified, steady-state, net precipitation flow through the disposal cell.

To understand more details of internal drainage, a one-dimensional variably saturated flow model, HYDRUS-1D, version 4.14, was run on the disposal cell (see Appendix A, Computation 4, "Shiprock Disposal Cell Drainage"). HYDRUS-1D is free software provided by the U.S. Department of Agriculture, U.S. Salinity Laboratory, Agricultural Research Service in Riverside, California.

Because data describing initial moisture conditions in the disposal cell are lacking, it is difficult to predict a definitive value for leachate flux from the cell. However, insight into various drainage conditions is possible by making assumptions based on the northeast portion of the north pile, because material thicknesses and moisture contents are known at a given point in time. It is assumed that moisture conditions existing in 1981 at the time of the CSU characterization can provide a starting point for analysis and provide an estimate of drainage from the slimes tailings from that point in time.

Initial conditions for the tailings depend on depositional history. As discussed in Section 4.1, the north pile has saturated slimes at the base, which are in contact with native fine-grained eolian deposits in the northeastern region of the disposal cell. The eolian deposits are also considered to be saturated because they have been overlain by saturated tailings material since the mid-1950s.

Direct measurements of unsaturated hydraulic properties are not available, so pedotransfer functions are used. Pedotransfer functions are relationships between soil hydraulic properties and soil textural properties. Relationships are obtained using various mathematical and statistical approaches. The U.S. Salinity Laboratory ARS-USDA Rosetta program developed by Marcel G. Schaap predicts soil hydraulic parameters using particle-size distributions and in situ bulk densities (dry unit weight), which for the Shiprock disposal cell are available from the CSU characterization data. Particle-size distribution and dry unit weight data are derived in the computation of slimes drainage (Appendix A, Computation 4, "Shiprock Disposal Cell Drainage"). Using the Rosetta program with particle-size information produces the unsaturated hydraulic parameters shown in Table 2.

Table 2. Unsaturated Tailings Parameters

Material	θ_r	θ_s	α (1/cm)	*n* (unitless)	K_{sat} (cm/s) [a]
Coarse tailings (sand/slimes, sands)	0.127	0.470	0.00035	3.923	2.6×10^{-5} 5.0×10^{-5}
Fine tailings (slimes)	0.223	0.640	0.00085	3.857	5.3×10^{-5} 3.1×10^{-6}

[a] Values of saturated hydraulic conductivity (K_{sat}) produced by Rosetta are counterintuitive in that the coarse tailings have a lower saturated hydraulic conductivity than the fine tailings, so laboratory-tested values are used. The differences may be a result of the dry unit weight values input into Rosetta.

Notes: θ_r and θ_s are residual and saturated water contents (cm^3/cm^3), respectively; α and n are curve-fitting parameters.

Unsaturated drainage of soil is a transient, nonlinear phenomenon dependent on hydraulic boundary conditions. For this problem, only the fine tailings are modeled with HYDRUS-1D because they have the lowest hydraulic conductivity and will control flux out of the disposal cell. For the upper surface of the slimes, three different boundary conditions are considered to help understand potential drainage scenarios: (1) a steady-state boundary flux equivalent to the geometric mean flux of the cover system of 7×10^{-6} cm/s (based on DOE 2001), (2) a steady-state boundary flux equivalent to the mean annual precipitation of 7.05 inches (5.7×10^{-7} cm/s), and (3) near-zero ($\sim 10^{-9}$ cm/s) influx to represent a working vegetation cover.[2] The lower boundary condition is modeled as free drainage, which assumes that the hydraulic conductivity of native materials is at least one order of magnitude greater than that of the slimes tailings.

As reported in Appendix A, Computation 4, "Shiprock Disposal Cell Drainage," steady-state moisture conditions within the slimes material exist for each boundary condition. Thus, a steady-state boundary flux of 7×10^{-6} cm/s corresponds to a steady-state volumetric moisture content of 47 percent; a boundary flux of 5.7×10^{-7} cm/s corresponds to a steady-state volumetric moisture content of 34 percent; restricting the boundary flux to 1.6×10^{-9} cm/s produces a steady-state volumetric content of 24 percent.

Applying the total volume of slimes previously computed (6,110,000 ft^3 [226,000 cubic yards, or 12 percent of the cell volume]) to the difference in the saturated volumetric moisture content (0.64) and the steady-state volumetric moisture content results in an approximation of the volume of moisture available to drain from the slimes (Table 3).

Table 3. Approximate Volume of Drainable Moisture from Slimes

Average Annual Flux (cm/s)	Difference in Steady-State Volumetric Moisture Content [a]	Approximate Drainable Volume (gallons)
7×10^{-6}	17%	138,850
5.7×10^{-7}	30%	245,000
1.6×10^{-9}	40%	326,700

[a] The difference in flux causes a difference in steady-state volumetric moisture content and drainage volume.

[2] Under this scenario, the influx would be similar to that measured at the vegetation cover constructed at the Monticello, Utah, Site, where the annual influx is restricted to 1.6×10^{-9} cm/s (Waugh et al. 2009).

Results of the modeling indicate that when the influx is greater than the saturated hydraulic conductivity of the slimes, moisture mounds above the slimes. When the influx is less than the saturated hydraulic conductivity of the slimes, steady-state drainage from the slimes equal to the influx occurs within 5 years for the modeled conditions. When near-zero influx is specified, the tailings drain to residual moisture contents in approximately 20–30 years, dependent on the saturated hydraulic conductivity of the slimes. Drainage rate from the slimes after 20–30 years is around 10^{-9} cm/s under near-zero influx conditions. Drainage from the non-slime material is expected to be nearly constant at the value determined by the Knight Piésold study of 10^{-7} cm/s.

Uncertainties

Unsaturated moisture characteristics—the unsaturated hydraulic conductivity and moisture storage—depend on the moisture content of the tailings. Influx and seepage from the disposal cell are governed by hydraulic boundary conditions at the surface and base of the disposal cell. Because both moisture content and boundary conditions are continuously changing, values used in the computations were selected to represent the possible range of conditions that may exist.

5.5 Moisture Conditions Summary

- Moisture monitoring of the cover system and upper tailings using neutron tubes and results from a piezocone investigation indicate that nearly saturated to saturated conditions existed at the time of the investigations.
- Some quantity of moisture is percolating through the cover, but actual rates are uncertain.
- Nearly saturated to saturated slimes directly overlie native terrace deposits at the base of the north and east portions of the disposal cell.
- Approximate volume of drainable moisture in the slimes ranges from 138,850 gallons to 326,700 gallons. As discussed in Section 5.4, there is considerable uncertainty regarding the length of time required for this moisture to drain.
- Contaminated tailings fluids percolated into native subsurface materials for approximately 15 years during mill operation when ponded fluids were present over the materials. Contaminated fluids probably remain in isolated pockets, and contamination that has sorbed to subsurface materials will continually, although slowly, flush by recharge.

6.0 Conclusion

Calculations based on historical mill production rates indicate that a minimum of 50 million gallons of milling-related fluids discharged into the subsurface over the operational life of the mill, which resulted in the legacy groundwater contamination present in the subsurface at the site. Additional seepage likely occurred during irrigation of the south pile to suppress dust and from moisture infiltration through temporary covers until the disposal cell was constructed.

The infiltration rate most likely varies considerably over the cover area, given the variation in saturated hydraulic conductivity observed. However, based on cell cover tests, the saturated hydraulic conductivity is likely greater than the value (10^{-7} cm/s) presented in previous discussions (e.g., DOE 1989).

Slimes that directly overlie native terrace deposits have been nearly saturated to saturated during previous investigations. Moisture in the slimes is expected to seep into the subsurface at a steady-state rate equal to the percolation through the cover, decreasing to around 10^{-9} cm/s if percolation through the cover is eliminated. The estimated volume of seepage from the slimes ranges from 138,500 gallons to 326,700 gallons, which is less than 1 percent of the estimated volume of milling-related fluids discharged into the subsurface over the operational life of the mill. Discharge for remaining materials within the disposal cell is dependent on moisture flux through the cover (see discussion under "Observations" in Appendix A, Computation 4).

The amount of contaminated water available to leach into the groundwater system is a function of percolation through the cover system and drainable moisture from tailings within the disposal cell. Tailings fluid is draining from the cell. However, the volume of this fluid is very small compared to the minimum volume of 50 million gallons of milling-related water estimated to have percolated into the subsurface during the operation of the mill. Consequently, contamination will remain in subsurface sediments, and groundwater contamination will persist regardless of any contaminant contribution from the cell.

7.0 References and Annotated Bibliography

Caldwell, Jack. A., 1992. "Engineering Perspectives for Near-Surface Disposal," in *Deserts as Dumps? The Disposal of Hazardous Materials in Arid Ecosystems,* Charles Reith and Bruce Thomson, eds., University of New Mexico Press, Albuquerque, New Mexico.

The reference by J. Caldwell that "A practical hydraulic conductivity is 10^{-7} centimeters per second (cm/s)" has been taken as the saturated field hydraulic conductivity for the radon barrier constructed at the Shiprock disposal cell. This is only a guidance value that can be achieved with proper construction methods, not a tested field value.

CSU (Colorado State University), 1985. *Characterization of Inactive Uranium Mill Tailings Sites: Shiprock, New Mexico*, prepared by the CSU Geochemical Engineering Program, Department of Civil Engineering, Fort Collins, Colorado, for the U.S. Department of Energy, Albuquerque, New Mexico.

Provides the only source of in situ geotechnical data for the tailings. In situ and remolded index properties, strength properties, and consolidation characteristics are given. Fifteen borings were made in 1981, and four interpretive cross-sections were developed. Samples were collected from both undisturbed and disturbed materials. Discusses general background information: site history, location, environment, and climate. Provides a description of the tailings impoundments, present (1982) site description, and a probable tailings depositional sequence. Discusses exploration and laboratory testing of the tailings. Laboratory tests included soil classification, moisture-density relationships, saturated and partially saturated compression testing, undisturbed and remolded saturated hydraulic conductivity testing, triaxial shear strength testing.

DBS&A (Daniel B. Stephens & Associates, Inc.), 1988. *Summary of Neutron Logging at the Shiprock UMTRA Site during September 1988*, prepared for Jacobs Engineering Group Inc., Albuquerque, New Mexico, October.

Documents installation of four aluminum neutron access tubes used to monitor moisture conditions within the radon barrier at the Shiprock site. Unsaturated moisture conditions are measured with a neutron probe calibrated with remolded site soils at known moisture contents. Results indicated that the radon barrier appears to be saturated or nearly saturated throughout, but results need to be verified by actual sampling of the barrier. Report states that saturation results are "undoubtedly an artifact of the methods used to calculate saturation."

DOE (U.S. Department of Energy), 1984. *Processing Site Characterization for the Uranium Mill Tailings Site at Shiprock, New Mexico*, UMTRA Project Office, Albuquerque, New Mexico.

Provides a brief review of the mill history; references mill construction in 1953. Discusses operation of the mill—ore crushing, leaching with sulfuric acid, washing, and extraction with solvent. Tailings from the wash circuit are deposited in tailings ponds; raffinate from the solvent extraction (SX) circuit is disposed of in separate evaporation ponds (raffinate ponds). Windblown contamination is found on a 34-acre area of the floodplain below and northeast of the tailings pile and on a 6-acre area north of the tailings. The south pile is approximately 15 feet high, contains tailings deposited by slurry, contaminated materials, and rubble from the mill area and ore storage areas. NECA placed debris and contaminated soils in the south pile (1968–1974) as part of decommissioning activities. Containment dikes were constructed around the north and south piles, and both piles were covered with a 6-inch-thick layer of site soils. An irrigation system (sprinklers) was used on the south pile to control dust.

DOE (U.S. Department of Energy), 1985. *Remedial Action Plan and Site Conceptual Design for Stabilization of the Inactive Uranium Mill Tailings Site at Shiprock, New Mexico,* Appendix B of Cooperative Agreement No. DE-FC04-83AL16258.

Original final restoration design proposed by Jacobs Engineering Group with stabilization of the north and south piles separately with a swale between them.

DOE (U.S. Department of Energy), 1987. *Shiprock, New Mexico, Uranium Mill Tailings Site Remedial Action Completion Report Volume 1*, prepared by Morrison Knudsen Engineers, Inc., and Health Physics and Radiological Measurements by Chem-Nuclear Systems, Inc. for the UMTRA Project Office, Albuquerque, New Mexico, August.

Material summary data sheet for earthen materials. All laboratory data are for remolded materials. Laboratory test results of remolded K_{sat} correlated to compaction criteria. MK calculations providing material properties for final restoration work. Aerial photographs of final restoration August 1, 1985, to September 30, 1986.

DOE (U.S. Department of Energy), 1989. *Moisture Contents and Unsaturated Conditions in UMTRA Project Radon Barriers*, DOE/UMTRA-400656, DE91 005816, UMTRA Project Office, Albuquerque Operations Office, Albuquerque, New Mexico, January.

Explains that UMTRA Project compliance with proposed EPA groundwater standards (40 CFR 192) involves demonstrating that seepage from a disposal cell will not result in contaminant concentrations that exceed maximum concentration limits at points of compliance. Such a demonstration usually involves computing a seepage rate from the disposal cell and modeling resulting contaminant concentrations. The document states that the typical radon barrier, especially one designed prior to the proposed EPA groundwater protection standards, has a saturated hydraulic conductivity of approximately 1 × 10^{-7} cm/s. Because of this statement, a saturated hydraulic conductivity of 1 × 10^{-7} cm/s is used in computation of cover seepage without any field tests. This leads to considerable misunderstanding of actual performance.

DOE (U.S. Department of Energy), 2001. *Disposal Cell Cover Moisture Content and Hydraulic Conductivity: Long-Term Surveillance and Maintenance Program Shiprock, New Mexico, Site*, GJO-2001-204-TAR, ESL-RPT-2001-04, prepared by the Environmental Sciences Laboratory, Grand Junction, Colorado, May.

Six saturated hydraulic conductivity (K_{sat}) measurements were taken in the radon barrier with an air-entry permeameter in the upper portion of the cover on the north side slope at and adjacent to various plant locations. These are the only observations made to document field K_{sat} of the radon barrier cover at Shiprock. Values range from 1.19 × 10^{-4} cm/s to 4.76 × 10^{-8} cm/s, revealing a high degree of uncertainty. Unsaturated moisture contents were measured in the same neutron probe tubes that Jacobs Engineering Group installed through the radon barrier into the tailings in 1988. Moisture contents showed saturation throughout the radon barrier. Samples of the radon barrier material were collected for particle-size analysis and soil classification following U.S. Department of Agriculture procedures.

DOE (U.S. Department of Energy), 2002. *Results of a Piezocone Investigation, Shiprock, New Mexico*, GJO-2001-276-TAR, MAC-GWSHP 13.3-1, Grand Junction Office, Grand Junction, Colorado, February.

Documents a piezocone investigation conducted on the Shiprock disposal cell in 2001 to determine if free water was present in the cell. Twenty-nine soundings were attempted in a more-or-less equally spaced grid over the cover. Eight soundings were able to penetrate the cover below a meter. Refusal in the 18 other soundings was attributed to a former highly compacted interim cover (three soundings were made in off-pile locations in ditches surrounding the disposal cell). Saturated slimes (indicated by a positive pore pressure during the sounding that did not fully dissipate) were observed in six of the soundings; thicknesses varied from 2.5 ft to 10 ft, median of 5.0 ft

Ford, Bacon and Davis, Utah, 1981. *Engineering Assessment of Inactive Uranium Mill Tailings Sites, Shiprock Site, Shiprock, New Mexico Phase II,* DOE/UMT-0104, FBDU 360-02.

Good history of the mill site and early operations. Topographic maps of the site in early 1980s.

Knight Piẻsold Consulting, 2002. *The Navajo Nation Navajo Uranium Mill Tailings Remedial Action Program Results of HELP Modeling of Shiprock Site Disposal Cell,* prepared for Navajo AML/UMTRA Department, March 20.

Analyzes infiltration through the Shiprock radon barrier using the EPA's HELP computer code. Model results indicate that approximately 20 percent of precipitation falling at the site infiltrates the existing cover, resulting in a flux from the base of the disposal of 4.85 gallons per minute. This flux from the cell occurs over the entire 70-acre base of the modeled cell. According to the model, modifying the existing riprap cover to a vegetation cover will essentially eliminate recharge.

Certain assumptions made to use this model are questionable; for example, the model does not incorporate drainage of tailings materials. Unsaturated conditions or temporal (transient) conditions are also ignored. The report provides a good discussion of expected moisture contents within the disposal cell.

Merritt, Robert C., 1971. *The Extractive Metallurgy of Uranium*, Colorado School of Mines Research Institute, Golden, CO.

Good commentary on the milling process but limited data on tailings deposition. Mill normally operated at 300 tons per day. Ore feed minimum 0.20 percent, average 0.23 percent with uranium recovery at 97 percent. Vanadium ore grade 1.5 percent.

Quinn, J.E., 1957. "Kerr-McGee Oil Industries, Inc. Shiprock Uranium Concentrator," *For Your Engineering Notebook*, Bulletin No. M4-B90, Ion Exchange Solvent Extraction Uranium-Vanadium, Denver Equipment Company.

Covers the specifics of the milling operation—ore crushing and sampling, grinding, leaching, classification and thickening, tailings slurry deposition (pumping requirements, 40 percent solids), uranium recovery by ion exchange (IX), solvent extraction recovery, precipitation (yellowcake production), and vanadium recovery. Includes a history of the mill, indicating that contract negotiations between Kerr-McGee Oil Industries and the U.S. Atomic Energy Commission for a 200 ton per day mill were completed in August 1953, and construction began in December 1953. During construction, the need for additional capacity was recognized, and the capacity was increased to 400 tons per day. The mill began production in November 1954.

Sackshewsky, M.R., C.J. Kemp, S.O. Link, and W.J. Waugh, 1995. "Soil water balance changes in engineered soil surfaces," *Journal of Environmental Quality*, 24:352–359.

Results of this lysimeter study shows that significant percolation occurs in landfill covers consisting of nonvegetated soils covered with clean gravel and rock even under very low annual precipitation (160 millimeters [6 inches] per year). By comparison, no percolation occurred through a vegetated soil-rock cover even under high annual precipitation (450 millimeters [18 inches] per year).

Sullenberger, Robert, 1993. "100 Years of Uranium Activity in the Four Corners Region," Part II Chapter VI, "Navajo Indian Reservation Uranium Mills," *Journal of the Western Slope*, Mesa State College, 8(1): 14–28, Winter.

Covers the history of uranium mining and milling in the Four Corners area, including the beginning of the Shiprock mill. Quotes Perry H. Charlie of Navajo AML, who states that construction of the Navajo Uranium Mill began 1 year earlier than the year given in other accounts.

USDHEW (U.S. Department of Health, Education, and Welfare), 1961. *Stream Surveys in Vicinity of Uranium Mills IV Area of Shiprock, New Mexico—November 1960*, Public Health Services Region VIII, Denver, CO, Colorado River Basin Water Quality Control Project, December.

Reports findings of an 8-day field survey of stream conditions in the San Juan River immediately below the Shiprock mill, conducted November 15–23, 1960. The study was conducted following a breach of the raffinate ponds during August 22–23, 1960. Includes a brief history of the site, followed by a discussion of water use at the mill site and adjacent helium plant. All process wastes at the mill are contained in ponds. At the time of the investigation, all slurry was deposited in the new north tailings pond. Raffinate is directed to the raffinate ponds located immediately south of the south tailings pile. Liquids not evaporated in the ponds or tailings piles percolate into subsurface terrace gravels and flow laterally over the Mancos Shale to the edge of the bluff. Seepage appears in the washes.

USEIA (U.S. Energy Information Administration), undated. Independent Statistics and Analysis: "Shiprock Mill Site,"http://www.eia.gov/cneaf/nuclear/page/umtra/shiprock_title1.html, accessed 6 September 2011.

Historical summary of the mill site construction, including a good history of early mines in the region that led to the need for a mill.

Waugh, W.J., M.E. Thiede, L.L. Cadwell, G.W. Gee, H.D. Freeman, M.R. Sackschewsky, and J.F. Relyea, 1991. "Small Lysimeters for Documenting Arid Site Water Balance," pp 151–159, in R.G. Allen, T.A. Howell, W.O. Pruitt, I.A. Walter, and M.E. Jensen, eds., *Lysimeters for Evapotranspiration and Environmental Measurements,* American Society of Civil Engineers (ASCE), New York, NY.

Waugh, W.J., M.E. Thiede, and D.J. Bates, 1994. "Plant Cover and Water Balance in Gravel Admixtures at an Arid Waste-Burial Site," *Journal of Environmental Quality*, 23: 676−685.

Waugh, W.J., C.H. Benson, and W.H. Albright, 2009."Sustainable Covers for Uranium Mill Tailings, USA: Alternative Design, Performance, and Renovation," Proceedings of the 12th International Conference on Environmental Remediation and Radioactive Waste Management, ICEM2009, October 11–15, 2009, Liverpool, UK.

Appendix A

Computations

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Computation 1: Estimated Precipitation and Evaporation at the Shiprock Mill Site

Problem Statement

Estimate precipitation and evaporation of water from the tailings piles and raffinate ponds at the Shiprock mill site on a monthly basis.

Given

Published precipitation and evaporation values for the site and adjacent areas.

References

Cooley, K.R., 1970. *Evaporation from Open Water Surfaces in Arizona*, U.S. Water Conservation Laboratory, Soil and Water Conservation Research Division, U.S. Department of Agriculture.

Western Regional Climate Center, updated July 28, 2006, http://www.wrcc.dri.edu/cgi-bin/cliGCStP.pl?nmship, accessed 2 September 2011.

NOAA (National Oceanic and Atmospheric Administration), 1982, Technical Report NWS 33, U.S. Department of Commerce, National Weather Service.

Assumptions

Cooley data from northeast Arizona represent the climate at Shiprock (within 30 miles) and will provide monthly data for water balance computations.

Precipitation values obtained from the Desert Research Institute website accurately represent precipitation values at the mill site.

Solution

1. Use Cooley's data to determine evaporation rates by months for northeast Arizona.
2. Determine an adjustment factor to apply Cooley's monthly data to annual published evaporation values for Shiprock. Sum data from Cooley to determine an annual evaporation rate. Obtain the annual rate for Shiprock from NOAA data and determine the adjustment factor as the NOAA annual evaporation rate divided by the annual rate from Cooley's data.
3. Prorate monthly data from NOAA with Cooley's data.
4. Obtain site monthly precipitation data from the Western Regional Climate Center at the Desert Research Institute in Reno, Nevada.

Evaporation Data from Cooley

Month	Normal monthly evaporation (inches)
Jan	2.2
Feb	3.1
Mar	5.0
Apr	6.6
May	9.0
Jun	9.9
Jul	9.9
Aug	9.0
Sep	6.9
Oct	5.3
Nov	3.3
Dec	2.2
Total	**72.4**

Evaporation Data from NOAA

Annual evaporation for Shiprock = 60.0 inches
Adjustment factor = 60.0 ÷ 72.4 = 0.83

Month	Adjusted monthly evaporation (inches)
Jan	1.8
Feb	2.6
Mar	4.1
Apr	5.5
May	7.5
Jun	8.2
Jul	8.2
Aug	7.5
Sep	5.7
Oct	4.4
Nov	2.6
Dec	1.8
Total	**60.0**

Precipitation

See attached printout from Western Regional Climate Center.

Discussion

Use the adjusted monthly evaporation values and precipitation values for water-balance computations.

SHIPROCK, NEW MEXICO

Period of Record General Climate Summary - Precipitation

Station:(298284) SHIPROCK														
From Year 1926 To Year 2006														
	Precipitation											Total Snowfall		
	Mean	High	Year	Low	Year	1 Day Max.		>= 0.01 in.	>= 0.10 in.	>= 0.50 in.	>= 1.00 in.	Mean	High	Year
	in.	in.	-	in.	-	in.	dd/yyyy or yyyymmdd	# Days	# Days	# Days	# Days	in.	in.	-
January	0.46	2.61	1969	0.00	1928	2.00	24/1969	4	2	0	0	1.5	8.8	1973
February	0.47	2.04	2005	0.00	1954	0.78	02/1988	4	2	0	0	0.6	4.2	1990
March	0.54	3.07	1938	0.00	1933	1.19	19/1985	4	2	0	0	0.6	5.0	1964
April	0.41	2.11	1941	0.00	1927	1.19	19/1985	3	1	0	0	0.0	0.3	1966
May	0.53	3.10	1992	0.00	1927	1.34	05/1973	3	2	0	0	0.0	0.0	1948
June	0.29	2.63	1949	0.00	1929	1.60	18/1949	2	1	0	0	0.0	0.0	1948
July	0.68	3.00	1930	0.00	1938	1.31	21/1971	4	2	0	0	0.0	0.0	1948
August	1.01	3.34	1982	0.00	1958	2.90	18/1989	5	3	0	0	0.0	0.0	1948
September	0.80	3.28	1927	0.00	1930	1.27	10/1980	4	2	0	0	0.0	0.0	1948
October	0.77	5.03	1969	0.00	1930	2.77	04/1969	3	2	0	0	0.0	1.0	1972
November	0.53	3.16	1991	0.00	1929	1.08	01/1961	3	2	0	0	0.2	3.2	1988
December	0.57	2.12	1992	0.00	1930	0.82	18/1978	4	2	0	0	1.0	7.4	1987
Annual	7.05	15.85	1941	2.14	1950	2.90	19890818	41	21	3	1	3.9	13.0	1990
Winter	1.50	5.14	1993	0.04	1959	2.00	19690124	11	5	0	0	3.1	15.3	1973
Spring	1.48	5.68	1941	0.00	1933	1.34	19730505	9	5	1	0	0.6	5.0	1964
Summer	1.98	5.55	1929	0.22	1958	2.90	19890818	11	5	1	0	0.0	0.0	1948
Fall	2.10	6.60	1969	0.20	1956	2.77	19691004	10	6	1	0	0.2	3.2	1988

Table updated on Jul 28, 2006

For monthly and annual means, thresholds, and sums:

Months with 5 or more missing days are not considered

Years with 1 or more missing months are not considered

Seasons are climatological not calendar seasons

Winter = Dec., Jan., and Feb. Spring = Mar., Apr., and May

Summer = Jun., Jul., and Aug. Fall = Sep., Oct., and Nov.

Computation 2: Estimated Total Volume of Water Used in Mill Production

Problem Statement

Estimate the total volume of production water used by the Shiprock uranium mill during operations from 1954 to 1968.

Given

1. Mill in operation from November 1954 to May 1968.
2. Mill production rate 300 tons per day (TPD) to 500 TPD (see J.E. Quinn).
3. Specific gravity of solids = 2.70
4. Slurry solids concentration = 30% (typical for industry) to 40% (J.E. Quinn)

References

MKE (Morrison-Knudsen Engineers, Inc.), 1987. *Shiprock N.M. Uranium Mill Tailings Site Remedial Action Completion Report*, Materials Properties Calculation, Summary of Material Properties.

Quinn, J.E., Kerr-McGee Oil Industries, Inc. *Shiprock Uranium Concentrator*, Bulletin No. M4-B90, Denver Equipment Company.

Assumptions

- Air-entrained in slurry mixture is minor and will be neglected.
- Slurry concentration is given in weight terms, i.e. 300 TPD means 300 solid tons of ore are processed per day.

Solution

The slurry phase diagram shown in Figure A–1 is used to derive property relationships needed to determine the volume of water used during operations based on the quantity of solid ore milled.

Property relationships are presented below.

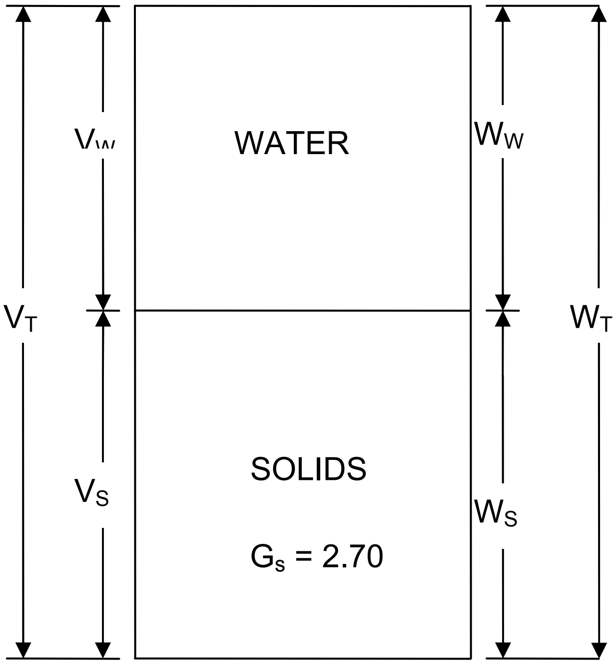

Figure A–1. Phase Diagram—Slurry

Slurry concentration = S.C.
Gravity of solids = G_S

$V_T = V_S + V_W$

$V_S = S.C. \times V_T$

$V_T = (S.C. \times V_T) + V_W$

$V_W = V_T - (S.C. \times V_T)$

$V_W = V_T \times (1.0 - S.C)$

$V_T = V_W \div (1.0 - S.C)$

$V_S = V_T - V_W$

$V_S = V_W \div (1.0 - S.C) - V_W$

$V_S = V_W \times [1.0 \div (1.0 - S.C)] - 1.0$

$V_S = W_S \div G_S \times \gamma_W$

$W_S \div G_S \times \gamma_W = V_W \times [1.0 \div (1.0 - S.C)] - 1.0$

$V_W = (W_S \div G_S \times \gamma_W) \div [1.0 \div (1.0 - S.C)] - 1.0$

Apply given parameters:

$G_S = 2.70$
S.C. = 0.30; 0.40
γ_W = 62.4 pounds per cubic foot (pcf)
W_S = 300 T; 500 T

Production Rate	W_S		S.C.	G_S	V_w (ft^3/day)
	tons	pounds			
300 TPD	300	600,000	0.30	2.70	8,310
	300	600,000	0.40	2.70	5,342
500TPD	500	1,000,000	0.30	2.70	13,849
		1,000,000	0.40	2.70	8,859

Production Rate	S.C.	Water Use			
		Day (ft^3)	Day (gallon)	Month* (ft^3)	Month* (gallon)
300 TPD	0.30	8,310	62,163	253,455	1,895,970
	0.40	5,342	39,960	162,931	1,218,805
500 TPD	0.30	13,849	103,597	422,395	3,159,722
	0.40	8,859	66,270	270,200	2,021,227

* 30.5 days per month

Discussion

Monthly water use will be used as input to water-balance computations.

Computation 3: Shiprock Tailings and Raffinate Ponds Water Balance

Problem Statement

Estimate the range of percolation into subsurface deposits beneath the tailings and raffinate ponds at the Shiprock mill from startup in November 1954 to closure in May 1968. A range of slurry water volumes are used with annual climatic conditions expressed on a monthly basis to provide a range of possible volumes of water that could have percolated into the subsurface during mill operations.

Given

Computation of the volume of water used in mill production.
Computation of the precipitation and evaporation at the Shiprock site.

Reference

USDHEW (U.S. Department of Health, Education, and Welfare), 1961. *Stream Surveys in Vicinity of Uranium Mills IV Area of Shiprock, New Mexico—November 1960*, Public Health Services Region VIII, Denver, CO, Colorado River Basin Water Quality Control Project, December.

Assumptions

- Moisture stored with the tailings is considered percolated subsurface water.
- Water surface areas presented in Table A–1 are representative of actual operating surface areas during mill production (see attached Figure 2 from USDHEW 1961 for water surface area determinations).
- Evaporation and percolation water volumes are modeled to behave abruptly based on monthly times, i.e., there is no ramping-up or down in water surface areas. For example, the surface of the north tailing pond immediately encompassed 475,000 ft^2 of free water from the first month of production and retained that value throughout the entire period of mill production.

Table A–1. Free Water Surfaces

Water Surface	Operational Date	Water Surface Area (ft^2)
Raffinate ponds	November 1954–April 1960	810,000
	May 1960–May 1968	750,000
South tailings pond	November 1954–April 1961	300,000
	May 1961–May 1968	150,000
North tailings pond	November 1954–April 1961	0
	May 1961–May 1968	475,000

Solution

A simple water-balance approach will be applied to estimate the potential amount for mill water available to percolate into the subsurface at the Shiprock mill site during the years of operation. The water-balance equation is given in equation (1) below:

$$S = I - O \quad (1)$$

where: S = storage = volume of water percolated into the subsurface.
I = inflow = volume of precipitation + volume of water in slurry.
O = outflow = volume of water lost to evaporation.

Equation (1) can be rewritten as:

$$\text{Percolation} = (\text{precipitation} + \text{volume of water used in slurry}) - \text{evaporation} \quad (2)$$

The volume of water evaporated is computed as the monthly evaporation in inches, which is converted to feet and multiplied by the surface area in square feet to produce a volume of evaporated water in cubic feet. This is only evaporative losses from the free water surface from the raffinate ponds and free water on tailings ponds. There are no plants to transpire moisture from free water surfaces.

Precipitation in inches is applied to the water surface areas as an additive volume converted to monthly amounts. The volume of water used in slurry transport of tailings is also added to the monthly total.

Equation (2) is solved in monthly time steps for the time of mill operations with spreadsheet computations. A copy of the spreadsheet is provided with this computation; however, a printed output is not provided because of size limitations.

Water-balance values repeat themselves on an annual basis because all inputs remain constant on an annual basis. Values change after the surface area of the raffinate ponds changed following the breach of two northern cells in 1960 and when the north tailings pond was put into use.

Table A–2. Potential Percolation Volumes

Nov 54–Aug 60
Potential Annual Percolation

ft^3	condition	gallons
352,227	300 TPD, 30%	2,634,831
76,638	300 TPD, 40%	573,289
1,205,197	500 TPD, 30%	9,015,475
418,680	500 TPD, 40%	3,131,934

Potential Cumulative Percolation

ft^3	condition	gallons
2,113,360	300 TPD, 30%	15,808,986
459,827	300 TPD, 40%	3,439,734
7,231,181	500 TPD, 30%	54,092,852
2,512,079	500 TPD, 40%	18,791,605

Sep 60–May 68
Potential Annual Percolation

ft^3	condition	gallons
200,504	300 TPD, 30%	1,499,870
15,864	300 TPD, 40%	118,674
886,859	500 TPD, 30%	6,634,148
264,181	500 TPD, 40%	1,976,206

Potential Cumulative Percolation

ft^3	condition	gallons
1,403,528	300 TPD, 30%	10,499,093
111,051	300 TPD, 40%	830,719
6,208,012	500 TPD, 30%	46,439,035
1,849,267	500 TPD, 40%	13,833,442

Potential Total Cumulative Percolation
Nov 54–May 68

ft^3	condition	gallons
3,516,888	300 TPD, 30%	26,308,079
570,878	300 TPD, 40%	4,270,453
13,439,194	500 TPD, 30%	100,531,888
4,361,346	500 TPD, 40%	32,625,047

Discussion

Dates of operational changes are estimated from limited photographic evidence and various narrations of mill site history. Thus, the precision of the water-balance computations is only moderately reliable. However, the results do indicate that large volumes of water percolated into the subsurface deposits over the operational life of the mill.

Table A–3. Shiprock Mill Tailings Ponds Evaporation

Date	No. of Days	Tabular Monthly Evaporation (Inches)	Free Water Surface Areas (ft^2)			Total Evaporation (ft^3)
			Raffinate Pond	South Pond	North Pond	
Nov-54	30	2.6	810,000	300,000	0	249,750
Dec-54	31	1.8	810,000	300,000	0	186,388
Jan-55	31	1.8	810,000	300,000	0	163,448
Feb-55	28	2.6	810,000	300,000	0	233,100
Mar-55	31	4.1	810,000	300,000	0	398,583
Apr-55	30	5.5	810,000	300,000	0	518,925
May-55	31	7.5	810,000	300,000	0	688,200
Jun-55	30	8.2	810,000	300,000	0	735,375
Jul 55	31	8.2	810,000	300,000	0	748,418
Aug-55	31	7.5	810,000	300,000	0	688,200
Sep-55	30	5.7	810,000	300,000	0	543,900
Oct-55	31	4.4	810,000	300,000	0	398,583
Nov-55	30	2.6	810,000	300,000	0	249,750
Dec-55	31	1.8	810,000	300,000	0	186,388
Jan-56	31	1.8	810,000	300,000	0	163,448
Feb-56	29	2.6	810,000	300,000	0	241,425
Mar-56	31	4.1	810,000	300,000	0	398,583
Apr-56	30	5.5	810,000	300,000	0	518,925
May-56	31	7.5	810,000	300,000	0	688,200
Jun-56	30	8.2	810,000	300,000	0	735,375
Jul 56	31	8.2	810,000	300,000	0	748,418
Aug-56	31	7.5	810,000	300,000	0	688,200
Sep-56	30	5.7	810,000	300,000	0	543,900
Oct-56	31	4.4	810,000	300,000	0	398,583
Nov-56	30	2.6	810,000	300,000	0	249,750
Dec-56	31	1.8	810,000	300,000	0	186,388
Jan-57	31	1.8	810,000	300,000	0	163,448
Feb-57	28	2.6	810,000	300,000	0	233,100
Mar-57	31	4.1	810,000	300,000	0	398,583
Apr-57	30	5.5	810,000	300,000	0	518,925
May-57	31	7.5	810,000	300,000	0	688,200
Jun-57	30	8.2	810,000	300,000	0	735,375
Jul-57	31	8.2	810,000	300,000	0	748,418
Aug-57	31	7.5	810,000	300,000	0	688,200
Sep-57	30	5.7	810,000	300,000	0	543,900
Oct-57	31	4.4	810,000	300,000	0	398,583

Table A–4. Monthly Inflow from Precipitation and Mill Production

Inflow		Daily Mill Production (ft^3)				Monthly Mill Production (ft^3)			
Monthly Precipitation (Inches)	Monthly Precipitation (ft^3)	300 TPD		500 TPD		300 TPD		500 TPD	
		30%	40%	30%	40%	30%	40%	30%	40%
0.53	49,025	8309.6	5341.9	13,849.3	8858.8	249,288	160,257	415,479	265,764
0.57	52,725	8309.6	5341.9	13,849.3	8858.8	257,598	165,599	429,328	274,623
0.46	42,550	8309.6	5341.9	13,849.3	8858.8	257,598	165,599	429,328	274,623
0.47	43,475	8309.6	5341.9	13,849.3	8858.8	232,669	149,573	387,780	248,046
0.54	49,950	8309.6	5341.9	13,849.3	8858.8	257,598	165,599	429,328	274,623
0.41	37,925	8309.6	5341.9	13,849.3	8858.8	249,288	160,257	415,479	265,764
0.53	49,025	8309.6	5341.9	13,849.3	8858.8	257,598	165,599	429,328	274,623
0.29	26,825	8309.6	5341.9	13,849.3	8858.8	249,288	160,257	415,479	265,764
0.68	62,900	8309.6	5341.9	13,849.3	8858.8	257,598	165,599	429,328	274,623
1.01	93,425	8309.6	5341.9	13,849.3	8858.8	257,598	165,599	429,328	274,623
0.80	74,000	8309.6	5341.9	13,849.3	8858.8	249,288	160,257	415,479	265,764
0.77	71,225	8309.6	5341.9	13,849.3	8858.8	257,598	165,599	429,328	274,623
0.53	49,025	8309.6	5341.9	13,849.3	8858.8	249,288	160,257	415,479	265,764
0.57	52,725	8309.6	5341.9	13,849.3	8858.8	257,598	165,599	429,328	274,623
0.46	42,550	8309.6	5341.9	13,849.3	8858.8	257,598	165,599	429,328	274,623
0.47	43,475	8309.6	5341.9	13,849.3	8858.8	240,978	154,915	401,630	256,905
0.54	49,950	8309.6	5341.9	13,849.3	8858.8	257,598	165,599	429,328	274,623
0.41	37,925	8309.6	5341.9	13,849.3	8858.8	249,288	160,257	415,479	265,764
0.53	49,025	8309.6	5341.9	13,849.3	8858.8	257,598	165,599	429,328	274,623
0.29	26,825	8309.6	5341.9	13,849.3	8858.8	249,288	160,257	415,479	265,764
0.68	62,900	8309.6	5341.9	13,849.3	8858.8	257,598	165,599	429,328	274,623
1.01	93,425	8309.6	5341.9	13,849.3	8858.8	257,598	165,599	429,328	274,623
0.80	74,000	8309.6	5341.9	13,849.3	8858.8	249,288	160,257	415,479	265,764
0.77	71,225	8309.6	5341.9	13,849.3	8858.8	257,598	165,599	429,328	274,623
0.53	49,025	8309.6	5341.9	13,849.3	8858.8	249,288	160,257	415,479	265,764
0.57	52,725	8309.6	5341.9	13,849.3	8858.8	257,598	165,599	429,328	274,623
0.46	42,550	8309.6	5341.9	13,849.3	8858.8	257,598	165,599	429,328	274,623
0.47	43,475	8309.6	5341.9	13,849.3	8858.8	232,669	149,573	387,780	248,046
0.54	49,950	8309.6	5341.9	13,849.3	8858.8	257,598	165,599	429,328	274,623
0.41	37,925	8309.6	5341.9	13,849.3	8858.8	249,288	160,257	415,479	265,764
0.53	49,025	8309.6	5341.9	13,849.3	8858.8	257,598	165,599	429,328	274,623
0.29	26,825	8309.6	5341.9	13,849.3	8858.8	249,288	160,257	415,479	265,764
0.68	62,900	8309.6	5341.9	13,849.3	8858.8	257,598	165,599	429,328	274,623
1.01	93,425	8309.6	5341.9	13,849.3	8858.8	257,598	165,599	429,328	274,623
0.80	74,000	8309.6	5341.9	13,849.3	8858.8	249,288	160,257	415,479	265,764
0.77	71,225	8309.6	5341.9	13,849.3	8858.8	257,598	165,599	429,328	274,623

Table A–5. Estimated Total Inflow and Percolation

Total Inflow (ft^3)				Percolation (ft^3)			
300 TPD		500 TPD		300 TPD		500 TPD	
30%	40%	30%	40%	30%	40%	30%	40%
298,313	209,282	464,504	314,789	48,563	–40,468	214,754	65,039
310,323	218,324	482,053	327,348	123,935	31,936	295,666	140,960
300,148	208,149	471,878	317,173	136,700	44,701	308,431	153,725
276,144	193,048	431,255	291,521	43,044	–40,052	198,155	58,421
307,548	215,549	479,278	324,573	–91,035	–183,034	80,696	–74,010
287,213	198,182	453,404	303,689	–231,712	–320,743	–65,521	–215,236
306,623	214,624	478,353	323,648	–381,577	–473,576	–209,847	–364,552
276,113	187,082	442,304	292,589	–459,262	–548,293	–293,071	–442,786
320,498	228,499	492,228	337,523	–427,920	–519,919	–256,189	–410,895
351,023	259,024	522,753	368,048	–337,177	–429,176	–165,447	–320,152
323,288	234,257	489,479	339,764	–220,612	–309,643	–54,421	–204,136
328,823	236,824	500,553	345,848	–69,760	–161,759	101,971	–52,735
298,313	209,282	464,504	314,789	48,563	–40,468	214,754	65,039
310,323	218,324	482,053	327,348	123,935	31,936	295,666	140,960
300,148	208,149	471,878	317,173	136,700	44,701	308,431	153,725
284,453	198,390	445,105	300,380	43,028	–43,035	203,680	58,955
307,548	215,549	479,278	324,573	–91,035	–183,034	80,696	–74,010
287,213	198,182	453,404	303,689	–231,712	–320,743	–65,521	–215,236
306,623	214,624	478,353	323,648	–381,577	–473,576	–209,847	–364,552
276,113	187,082	442,304	292,589	–459,262	–548,293	–293,071	–442,786
320,498	228,499	492,228	337,523	–427,920	–519,919	–256,189	–410,895
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323,288	234,257	489,479	339,764	–220,612	–309,643	–54,421	–204,136
328,823	236,824	500,553	345,848	–69,760	–161,759	101,971	–52,735
298,313	209,282	464,504	314,789	48,563	–40,468	214,754	65,039
310,323	218,324	482,053	327,348	123,935	31,936	295,666	140,960
300,148	208,149	471,878	317,173	136,700	44,701	308,431	153,725
276,144	193,048	431,255	291,521	43,044	–40,052	198,155	58,421
307,548	215,549	479,278	324,573	–91,035	–183,034	80,696	–74,010
287,213	198,182	453,404	303,689	–231,712	–320,743	–65,521	–215,236
306,623	214,624	478,353	323,648	–381,577	–473,576	–209,847	–364,552
276,113	187,082	442,304	292,589	–459,262	–548,293	–293,071	–442,786
320,498	228,499	492,228	337,523	–427,920	–519,919	–256,189	–410,895
351,023	259,024	522,753	368,048	–337,177	–429,176	–165,447	–320,152
323,288	234,257	489,479	339,764	–220,612	–309,643	–54,421	–204,136
328,823	236,824	500,553	345,848	–69,760	–161,759	101,971	–52,735

Note: Highlighted cells indicate positive percolation values.

Computation 4: Shiprock Disposal Cell Drainage

Problem Statement

Determine if tailings in the Shiprock disposal cell will drain under various conditions determined by upper and lower boundary conditions. Use the tailings slimes fraction to represent partially saturated drainage from the final disposal cell. Drainage will occur as a partially saturated phenomenon.

Given

Geotechnical characterization data from 1985 CSU report:

- Grain-size distributions
- In situ data from Shelby Tubes

Data Source

CSU (Colorado State University), 1985. *Characterization of Inactive Uranium Mill Tailings Sites: Shiprock, New Mexico*, prepared by the CSU Geotechnical Engineering Program, Ft Collins, Colorado, for the U.S. Department of Energy, Albuquerque, NM.

DOE (U.S. Department of Energy), 2002. *Results of a Piezocone Investigation, Shiprock, New Mexico*, GJO-2001-276-TAR, MAC-GWSHP 13.3-1, Grand Junction Office, Grand Junction, Colorado, February.

References

DOE (U.S. Department of Energy), 2001. *Disposal Cell Cover Moisture Content and Hydraulic Conductivity: Long-Term Surveillance and Maintenance Program Shiprock, New Mexico, Site*, GJO-2001-204-TAR, ESL-RPT-2001-04, prepared by the Environmental Sciences Laboratory, Grand Junction, Colorado, May.

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Assumptions

- Slimes are in a nearly saturated to saturated condition.
- Partially saturated drainage is occurring.
- Slimes are located at the base of the disposal cell and directly overlie fine-grained, native eolian deposits, which lie directly on porous native terrace deposits consisting of coarse-grained cobbles, gravels, and sands. Terrace deposits rest on relatively nonporous, weathered and unweathered Mancos Shale. The native eolian deposits are assumed to be saturated to nearly saturated from the time milling operations began in 1954 (57 years ago).
- Unsaturated moisture conditions that existed in 1981 and 2001 accurately described the moisture conditions of the tailings.
- Pedotransfer functions (grain-size distributions, in situ dry bulk density) adequately describe the soil moisture characteristics (SMC) curve and soil hydraulic properties of the tailings.
- Average saturated hydraulic conductivity of the cover is equal to a flux rate into the tailings.

Method of Solution

1. Determine the SMC using pedotransfer functions modified with actual in situ data when available.
2. Assume possible existing upper and lower boundary conditions on the tailings. Upper boundary condition includes various flux rates at atmospheric conditions. Flux rates are greater under rock covers than under vegetated covers (DOE 2001, Waugh et al. 2009). The lower boundary condition is always free-flowing base.
3. Use unsaturated soil hydraulic relationships provided by US Salinity Laboratory (Rosetta and RETC computer programs) in conjunction with SMC to determine if drainage is possible based on assumed moisture conditions and boundary conditions.
4. When drainage is possible, estimate the drainage rate with HYDRUS-1D.

Solution

1. Use data from the CSU report (attached):
    - Grain-size distribution analysis and percent –200 sieve (to estimate silt-clay split),
    - Dry bulk density (dry unit weight), γ_d, in pounds per cubic foot (pcf),
    - Gravimetric moisture content, w_c (percent).

    Use phase-diagram relationships to determine the following (see attached spreadsheets in Attachment 1 for computations):

    - void ratio, e
    - porosity, f
    - degree of saturation, S (%)

Table A–6. Tailings Properties, Average Values

Tailings Material Type	γ_d (pcf)	w_c (%)	*e*	*f* (or θ_s)	*S* (%)
Sands (<30% –200 sieve)	90.4	11.7	0.90	0.47	34.1
±1 standard error	2.7	2.4	0.06	0.02	5.5
Sand-Slimes (30–70% –200 sieve) (32% silt, 9% clay)	90.0	20.1	0.89	0.47	63.7
±1 standard error	6.1	1.3	0.10	0.03	11.4
Slimes (>70% –200 sieve) (84% silt, 9.5% clay)	63.5	63.0	1.8	0.64	97.7
±1 standard error	3.9	4.9	0.20	0.02	1.1

2. Use tailings property information above and pedotransfer functions available with the Rosetta code to determine SMC and unsaturated hydraulic functions for tailings materials.

   Group sands and sand-slimes together as one material type (coarse tailings) because the dry unit weight, void ratio, and porosity are similar. The hydraulic functions governing moisture movement and storage capacity are the volume of space available for moisture to occupy (given by the dry unit weight), void ratio, and porosity.

   Rosetta requires grain-size distribution data entry; addition of dry bulk density and ⅓ bar moisture content increases precision for hydraulic function estimations. Rosetta output includes partially saturated parameters: residual volumetric moisture content, θ_r; saturated volumetric moisture content or porosity, θ_s; and van Genucthen curve-fitting parameters α and *n* using the Mualem unsaturated conductivity model (the unsaturated hydraulic conductivity is a function of the saturated hydraulic conductivity, where the function is dependent on van Genucthen parameters in Mualem's model).

   Table A–7 lists unsaturated hydraulic parameters determined for the Shiprock tailings. Copies of Rosetta output are provided with the RETC output in Attachment 1 of this computation.

Table A–7*. Unsaturated Tailings Parameters from Rosetta*

Material	θ_r	θ_s	α(1/cm)	*n*	K_{sat} (cm/s)
Coarse tailings (sand/slimes, sands)	0.127	0.470	0.00035	3.923	2.6×10^{-5} 5.0×10^{-5} [a]
Fine tailings (slimes)	0.223	0.640	0.00085	3.857	5.3×10^{-5} 3.1×10^{-6} [a]

K_{sat} = saturated hydraulic conductivity
cm/s = centimeters per second

[a] Values of saturated hydraulic conductivity produced by Rosetta are counterintuitive; the coarse tailings have a lower saturated hydraulic conductivity than the fine tailings, so laboratory-tested values are used. The differences are probably a result of the dry unit weight values input into Rosetta.

3. Movement of moisture through a porous medium, such as mill tailings, is dependent on the volume of voids occupied by moisture. Thus, the unsaturated hydraulic conductivity is dependent on the unsaturated volumetric moisture content. Results from Rosetta are input into the RETC code to determine the relationship between volumetric moisture content θ and unsaturated hydraulic conductivity K. Plots of θ versus K for coarse tailings and slimes tailings are presented in Attachment 1. The relationships between θ and matric potential (suction) are also presented in Attachment 1. Using these figures and in situ data for the tailings provides insight into potential drainage. When the in situ volumetric moisture content is greater than either the field capacity (taken as ⅓ bar matric potential) or the volumetric moisture content predicted for influx values, steady-state drainage will occur.

   Table A–8 lists volumetric moisture content values obtained from θ and field capacity (taken at ⅓ bar matric potential).

Table A–8. *In Situ and Field Capacity Volumetric Moisture Contents*

Material	$\theta_{in\ situ}$	$\theta_{1/3\ bar}$
Coarse tailings (sand/slimes, sands)	0.47	0.47
Fine tailings (slimes)	0.64	0.637

The slimes tailings are used to model the worst-case drainage; that is, the slimes fraction will hold moisture longer and drain slower and for a longer period of time than the coarse tailings.

Various influx values to the tailings are assumed to be equal to various average saturated hydraulic conductivity values of the cover, as listed in Table A–9. Volumetric moisture contents are reported for slimes tailings.

Table A–9. *Influx and Corresponding Volumetric Moisture Contents for Slimes Tailings*

Condition	Average Annual Flux (cm/s)	θ_{influx}
Geometric mean of field tests [a]	7×10^{-6}	0.47
Annual precipitation [b]	5.7×10^{-7}	0.34
Operating vegetated cover [c]	1.6×10^{-9}	0.24

[a] DOE 2001. Geometric mean of field-measured saturated conductivity values.
[b] Climate Summary, Shiprock, New Mexico. http://www.wrcc.dri.edu/cgi-bin/cliGCStP.pl?nmship.
[c] Measured flux through the DOE repository at Monticello, UT, reported in Waugh et al. 2009.

Analysis of values in Tables A–8 and A–9 indicates that if the slimes tailings remained at the moisture content sampled by CSU personnel in 1981 (confirmed by data from the piezocone investigation in 2001), the slimes tailings will drain to reach the steady-state conditions imposed by various covers. If the existing rock cover remains in place, and a constant volume of water equal to the saturated hydraulic conductivity of the radon barrier occurs, approximately 0.17 cm (0.64 – 0.47) of pore water per square centimeter of slimes will drain. If the annual precipitation of 7.05 inches per year occurred at a uniform rate over the entire year, 0.30 cm (0.64 – 0.34) of pore water per square centimeter of slimes will drain. And finally, if the existing cover system is converted to a vegetated cover and operates as successfully as the vegetated cover DOE constructed for the disposal cell in

Monticello, Utah, 0.40 cm (0.64 − 0.24) of pore water per square centimeter of slimes will eventually drain.

Although greater amounts of moisture are predicted to drain from the existing slimes tailings with lower influx values, the total longer-term equilibrium steady-state volume of moisture is less with lower influx values. This is because a lower influx creates a lower flux from the slimes tailings, and less total moisture will drain once steady-state conditions are achieved.

4. The one-dimensional finite element code HYDRUS-1D is used to model drainage from a 13-foot-thick slimes deposit. The HYDRUS program numerically solves the Richards equation for variably saturated water flow modeling Richard's solution to Darcy's equation. This model is run to estimate the time required to reach steady-state conditions for influx values listed in Table A–9.

   The thickness of the slimes deposit is an average of the thickness determined in the piezocone investigation. Soil hydraulic properties listed in Table A–7 are used as initial conditions.

   The lower boundary condition is specified as free-draining, allowing both saturated and unsaturated flow. This boundary condition is reasonable, given that the slimes rest directly on eolian silts and sands that have been saturated for more than 50 years. The slimes deposit is assumed to have a saturated hydraulic conductivity at least one order of magnitude less than that of the eolian silts and sands and can therefore be considered free-draining.

   The upper boundary condition is a flux boundary initially under a slight matric potential (−44 cm) representing the overlying unsaturated slimes/sand deposit. Flux values in Table A–9 are used to represent a range of influx possibilities.

   Results of the runs are listed in Table A–10 and are provided graphically in the HYDRUS output in Attachment 1 of this computation.

Table A–10. Drainage Rate Predictions Based on Influx

Condition	Slimes Tailings Hydraulic Conductivity (cm/s)	Flux (cm/s)	Drainage rate (cm/s)
Geometric mean of field tests	5.3×10^{-5}	7×10^{-6}	7×10^{-6} immediate
Annual precipitation	5.3×10^{-5}	5.4×10^{-7}	5.4×10^{-7} at 2 years
Operating vegetated cover	5.3×10^{-5} 3.1×10^{-6}	1.6×10^{-9} 1.6×10^{-9}	3×10^{-9} at 25 years 9.9×10^{-9} at 30 years

Observations

- Conservative influx values are worst-case scenarios, that is, water is modeled to be always available at magnitudes equal to saturated conductivity values in the geometric mean and annual precipitation conditions, whereas, under realistic conditions the moisture arrives periodically or seasonally.
- Both types of tailings materials were near their field capacity (⅓ bar matric potential) when CSU sampled the tailings in 1981, indicating that the tailings were already in steady-state

moisture conditions. The interim cover used at that time limited influx from annual precipitation to values near 5×10^{-5} cm/s or greater, based on assumed hydraulic conductivities to keep volumetric moisture contents near the field capacity.

- When the influx is greater than the hydraulic conductivity of the tailings, the tailings will stay at their in situ moisture value, and the drainage rate is equal to the tailings hydraulic conductivity.
- If a vegetated cover is used to reduce influx through the cover to minimal values, tailings will dry to their residual moisture content; however; this will take considerable time. Tailings must be open to atmospheric conditions to dry to a steady-state condition. If an impermeable liner is used in the cover system, moisture will remain in the tailings. This condition is analogous to that of holding a finger over the end of a straw that has been placed in a glass of water; when the straw is withdrawn from the glass, the water in the straw does not drain.

Conclusion

Numerical values reported in this computation do not provide precise values of drainage, but they do provide insight into possible drainage scenarios. This analysis suggests that tailings slimes have been saturated since deposition and have remained saturated to nearly saturated. The interim cover placed over the tailings prior to final remediation did not allow the slimes tailings to drain. The fact that the slimes were still saturated during the 2001 piezocone investigation suggests that the magnitude of moisture flux passing through the existing final cover is greater than the saturated hydraulic conductivity of the slimes, which is preventing drainage.

If the goal is to allow the tailings to drain to a steady-state dry condition, a cover system that limits influx to rates below the saturated conductivity of the tailings and is open to the atmosphere should be considered. Once a cover system is in place that achieves this goal, the tailings will drain to residual moisture contents over the next 25 to 30 years at negligible rates.

Attachment 1 of Computation 4

RETC and HYDRUS-1D Output and Geotechnical Information

C4-A.1 HYDRUS-1D Output

C4-A.2 RETC (with Rosetta) Output

C4-A.3 Geotechnical Information

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A.1 Hydrus-1D Output

In Situ Tailings Sand and Slimes (30%–70% –200 sieve)

Sample	% - #200	% silt	% clay	γ_d (pcf)	G_s	w_c (%)	void ratio	porosity	% saturation
SHR 207 @ 20'	49.3	39.3	10.0	77.8	2.70	17.8	1.170	0.54	41.1
SHR 212 @ 30'	35.0	30.0	5.0	96.9	2.73	20.1	0.758	0.43	72.4
SHR 214 @ 10'	49.1	44.1	5.0	95.3	2.72	22.3	0.781	0.44	77.7
SHR 202 @ 15'	30.0	15.0	15.0						
# sample	4.0	4.0	4.0	3.0	3.0	3.0	3.00	3.0	3.0
mean	40.9	32.1	8.8	90.0	2.72	20.1	0.90	0.47	63.7
Std. Dev.	9.9	12.8	4.8	10.6	0.0	2.3	0.23	0.06	19.8
Std. error	4.9	6.4	2.4	6.1	0.0	1.3	0.13	0.03	11.4
+ 95% conf. interval	50.5	44.7	13.4	102.0	2.73	22.6	1.16	0.54	86.1
- 95% conf. interval	31.2	19.5	4.1	78.0	2.70	17.5	0.64	0.40	41.3

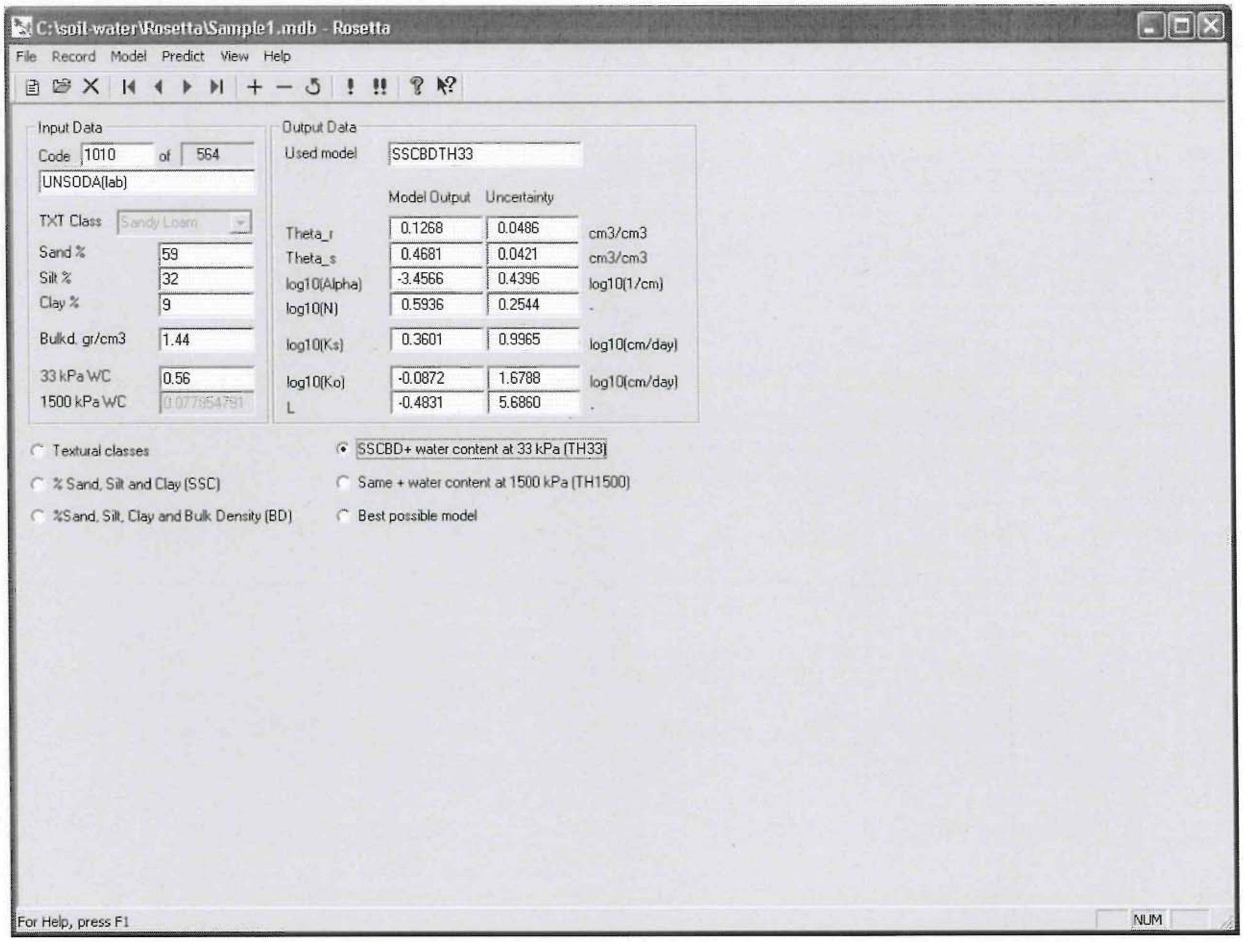
In Situ Tailings Slimes (>70% –200 sieve)

Sample	% - #200	% silt	% clay	γ_d (pcf)	G_s	w_c (%)	void ratio	porosity	% saturation
SHR 205 @ 0'	92.0	77.0	15.0						
SHR 205 @ 6.5'	87.3			68.7	2.87	55.0	1.6	0.6	98.0
SHR 211 @ 7.5'	88.0	78.0	10.0	51.8	2.82	82.0	2.4	0.7	96.8
SHR 204 @ 20'	100.0	90.0	10.0						
SHR 205 @ 15'	100.0	90.0	10.0						
DM-10 @ 18.7' (#9010)				73.0	2.85	48.5	1.4	0.6	96.2
DM-10 @ 19.2' (#9010)				57.0	2.85	71.2	2.1	0.7	95.7
DM-10 @ 19.3' (#9010)				67.0	2.85	59.2	1.7	0.6	102.0
DM-11 @ 24.2' (#9011)						61.9			
# sample	5.0	4.0	4.0	5.0	2.0	6.0	5.0	5.0	5.0
mean	93.5	83.8	11.3	63.5	2.85	63.0	1.8	0.64	97.7
Std. Dev.	6.2	7.2	2.5	8.8	0.0	12.0	0.4	0.05	2.5
Std. error	2.8	3.6	1.3	3.9	0.0	4.9	0.2	0.02	1.1
+ 95% conf. interval	98.9	90.8	13.7	71.2	2.87	72.6	2.2	0.68	100.0
- 95% conf. interval	88.0	76.7	8.8	55.8	2.82	53.4	1.5	0.60	95.5

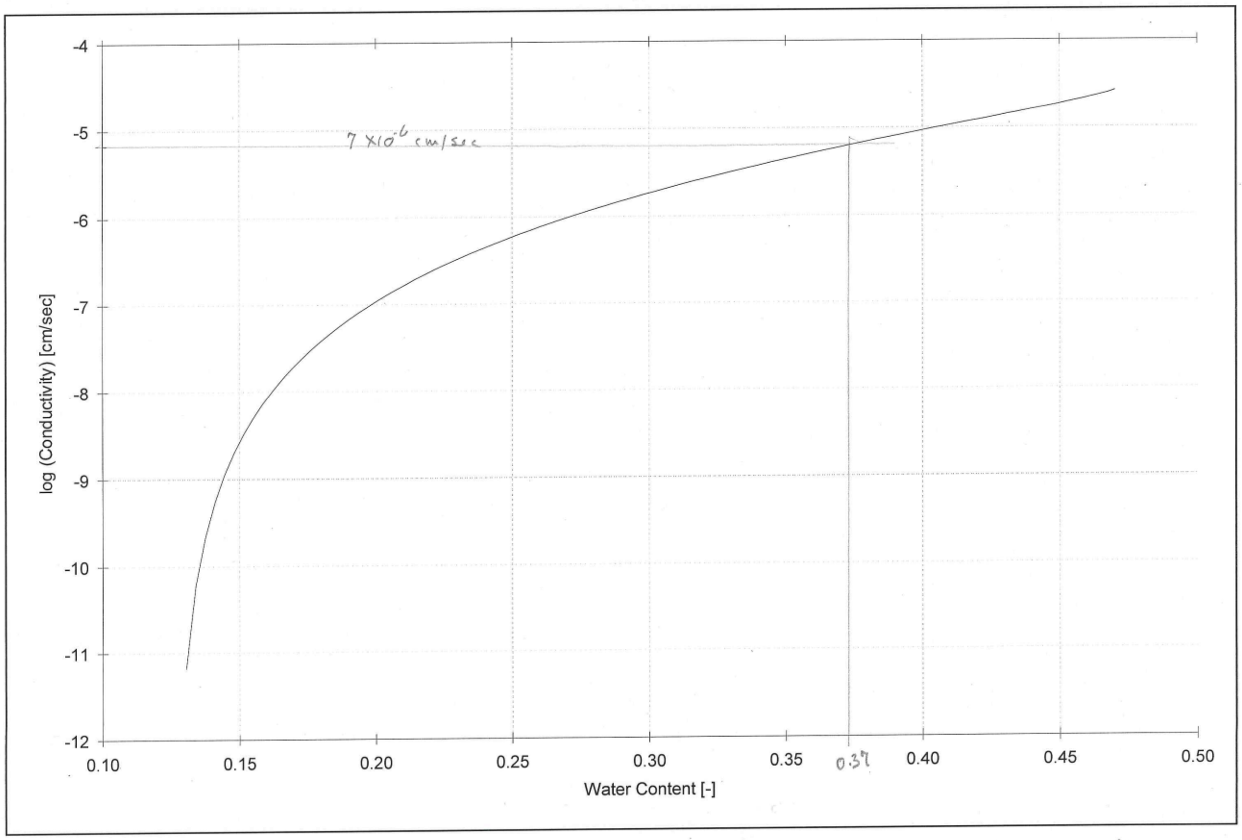
In Situ Tailings Sand (<30% –200 sieve)

Sample	% - #200	γ_d (pcf)	G_s	w_c (%)	void ratio	porosity	% saturation
SHR 201 @ 30'	26.3	94.3	2.78	2.3	0.807	0.45	7.9
SHR 202 @ 40'	18.2	82.7	2.72	9.2	1.060	0.51	23.6
SHR 203 @ 20'	15.0	99.3	2.71	11.5	0.703	0.41	44.3
SHR 207 @ 5'	14.0	86.9	2.72	6.2	0.946	0.49	17.8
SHR 208 @ 15'	19.9	95.9	2.72	11.3	0.770	0.44	39.9
SHR 210 @ 10'	19.3	92.6	2.72	10.6	0.827	0.45	34.9
SHR 210 @ 25'	21.8	90.8	2.71	8.4	0.862	0.46	26.4
DM-10 @ 9.2' (#9010)	-	103.0	2.72	2.9	0.648	0.39	12.2
DM-10 @ 14' (#9010)	-	101.0	2.72	17.5	0.680	0.40	70.0
DM-11 @ 4.2' (#9011)	-	89.0	2.72	4.0	0.907	0.48	12.0
DM-11 @ 9.2' (#9011)	-	94.0	2.72	12.5	0.806	0.45	42.2
DM-11 @ 14.2' (#9011)	-	78.0	2.72	21.8	1.176	0.54	50.4
DM-11 @ 19.2' (#9011)	-	68.0	2.72	34.2	1.496	0.60	62.2
# sample	7.0	13.0	7.0	13.0	13.0	13.0	13.0
mean	19.2	90.4	2.73	11.7	0.899	0.47	34.1
Std. Dev.	4.2	9.8	0.02	8.7	0.233	0.06	19.7
Std. error	1.6	2.7	0.01	2.4	0.065	0.02	5.5
+ 95% conf. interval	22.3	95.7	2.74	16.5	1.026	0.50	44.8
- 95% conf. interval	16.1	85.1	2.71	7.0	0.772	0.44	23.5

A.2 RETC Output

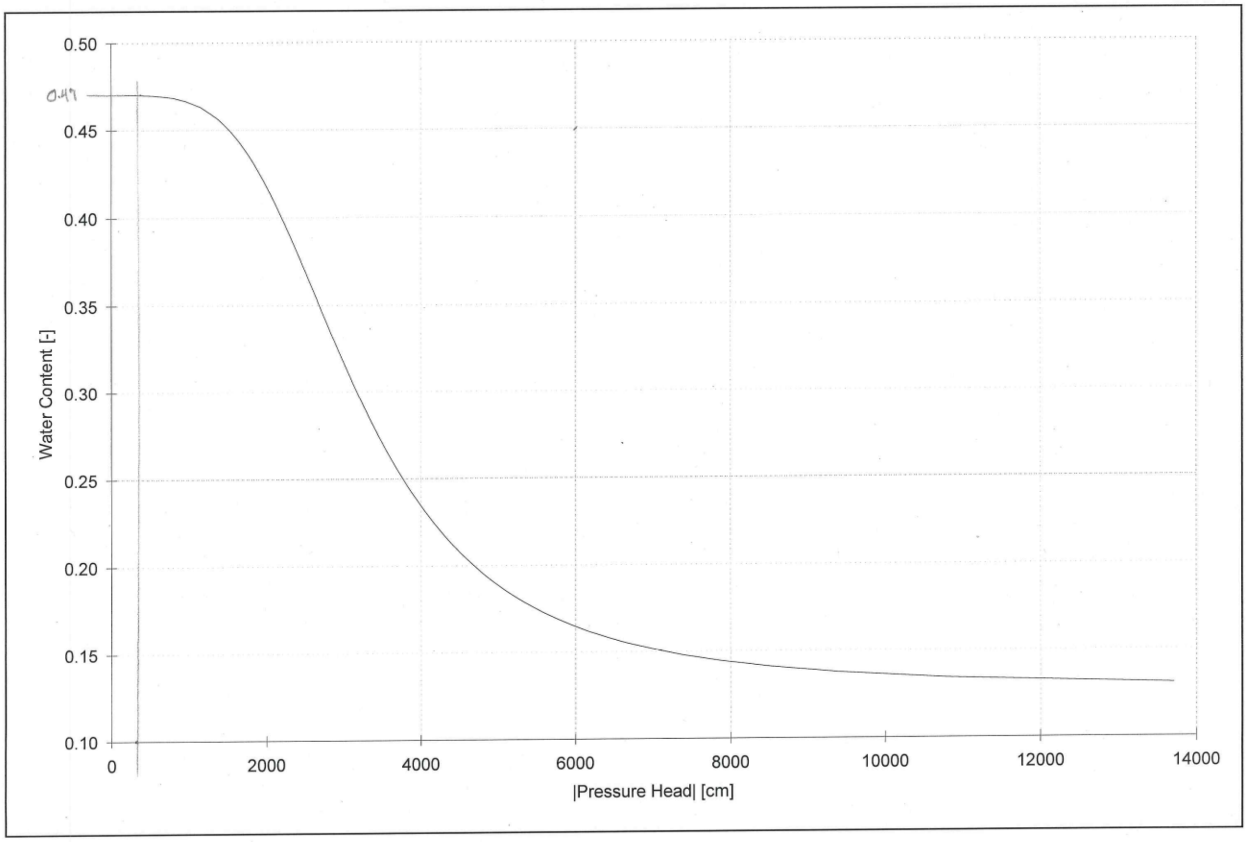


Hydraulic Properties: log K vs. Theta

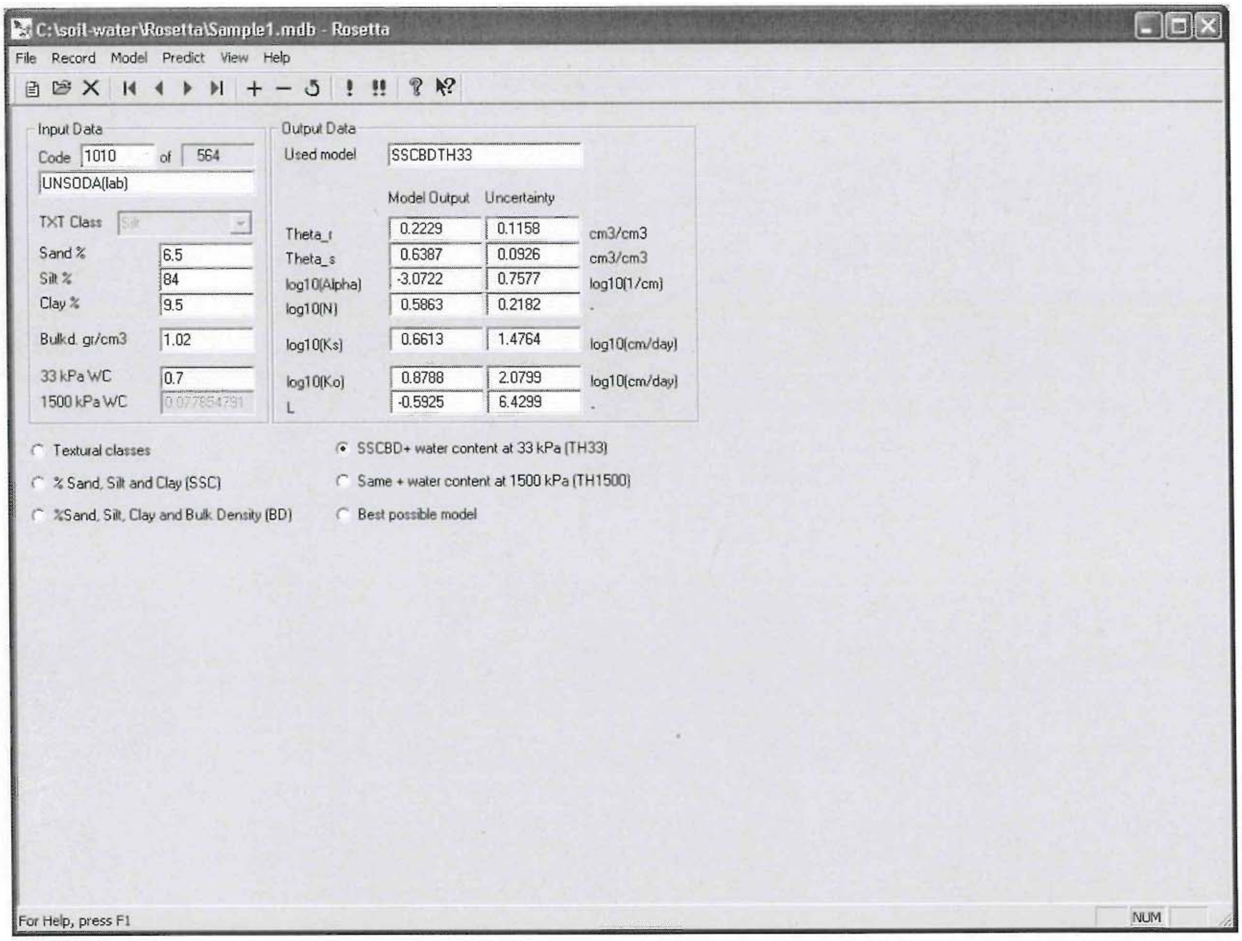


Hydraulic Properties: Theta vs. h

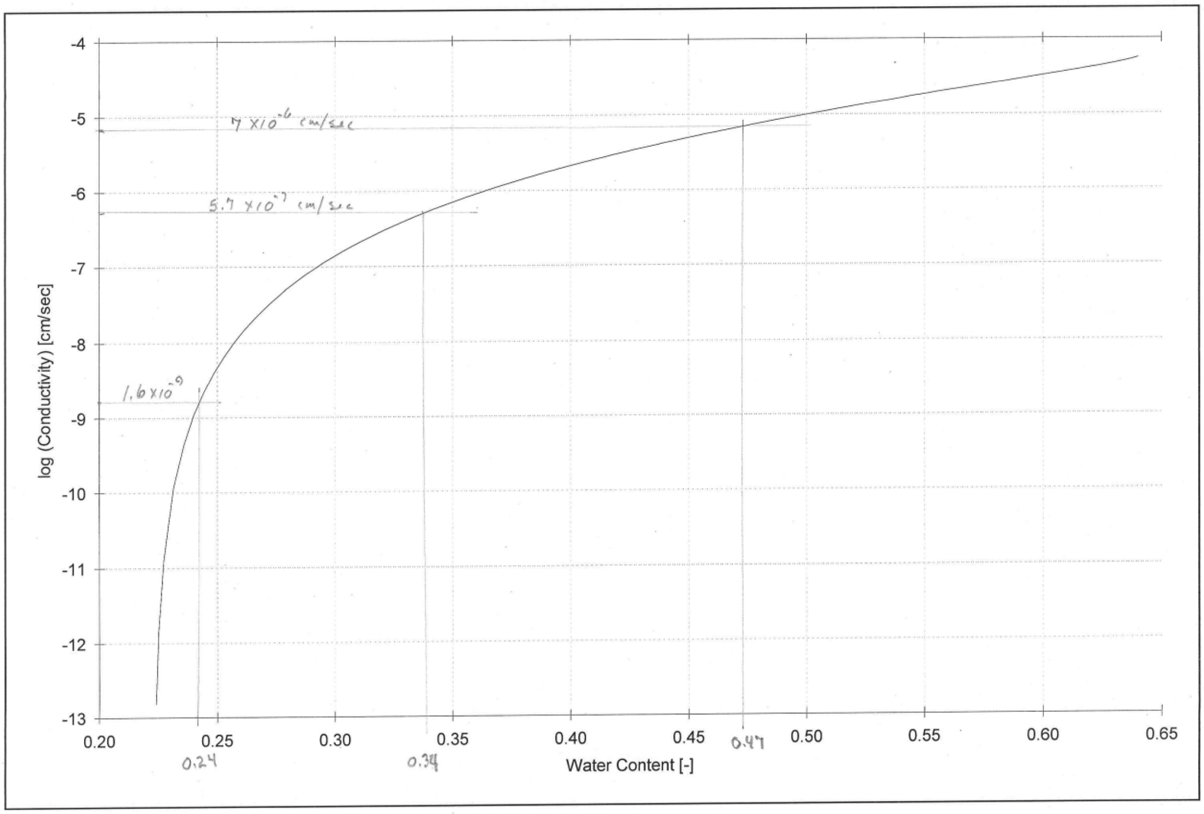
Sand/Slime



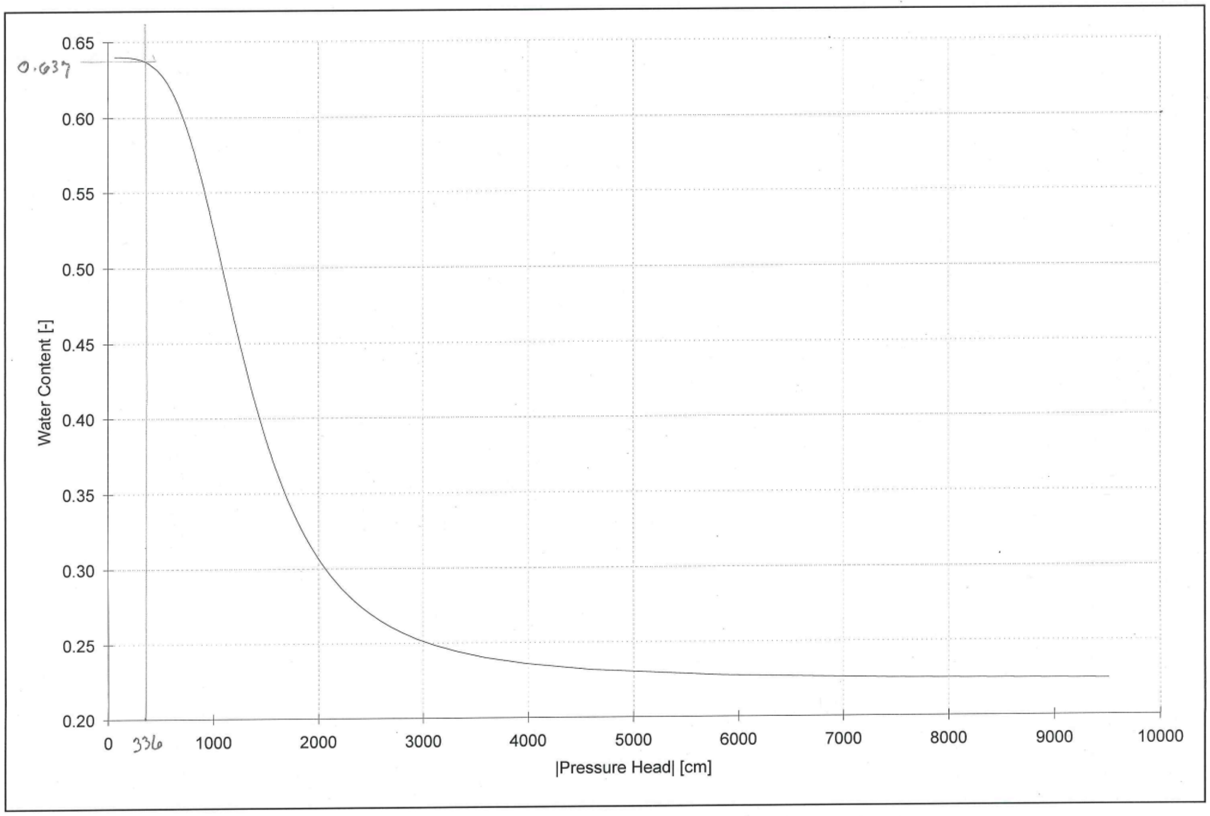
Slimes


C:\soil-water\Rosetta\Sample1.mdb - Rosetta
File Record Model Predict View Help
Input Data
Code 1010 of 564
UNSODA(lab)
TXT Class Silt
Sand % 6.5
Silt % 84
Clay % 9.5
Bulkd. gr/cm3 1.02
33 kPa WC 0.7
1500 kPa WC
Output Data
Used model SSCBDTH33
Model Output Uncertainty
Theta_r 0.2229 0.1158 cm3/cm3
Theta_s 0.6387 0.0926 cm3/cm3
log10(Alpha) -3.0722 0.7577 log10(1/cm)
log10(N) 0.5863 0.2182
log10(Ks) 0.6613 1.4764 log10(cm/day)
log10(Ko) 0.8788 2.0799 log10(cm/day)
L -0.5925 6.4299
Textural classes
% Sand, Silt and Clay (SSC)
%Sand, Silt, Clay and Bulk Density (BD)
SSCBD+ water content at 33 kPa (TH33)
Same + water content at 1500 kPa (TH1500)
Best possible model
For Help, press F1
NUM

Hydraulic Properties: log K vs. Theta



Hydraulic Properties: Theta vs. h Slime



A.3 Geotechnical Information

Table 6.1 Moisture-density test data

Boring Number	Material Description	Sample Depth (feet)	Dry Density (pcf)	Moisture Content (%)	
DM-1	Mancos Shale	13.0	111	16.4	
DM-3	SP (fill)	4.3	96	12.7	
DM-3	ML	8.8	95	27.3	
DM-3	SP	14.5	113	5.8	
DM-4	ML	4.0	92	5.8	
DM-4	Mancos Shale	19.5	104	14.1	
DM-5	Mancos Shale	13.8	100	13.3	
DM-6	SP	10.3	97	6.4	
DM-6	Mancos Shale	36.3	149	1.9[a]	
DM-6	Mancos Shale	53.5	148	4.4	
DM-7	ML	8.3	97	10.2	
DM-7	Mancos Shale	38.3	149	2.1[a]	
DM-7	Mancos Shale	68.0	149	3.7	
DM-8	SP	4.0	109	10.3	
DM-8	CL-ML	9.0	101	10.2	
DM-8	SP	13.5	103	13.0	
DM-10	Tailings (SP)	9.2	103	2.9	sand
DM-10	Tailings (SP)	14.0	101	17.5	sand
DM-10	Tailings (CL)	18.7	73	48.5	slime
DM-10	Tailings (CL)	19.2	57	71.2	slime
DM-10	Tailings (CL)	19.3	67	59.2	slime
DM-10	ML	23.5	92	15.8	
DM-10	ML	28.5	94	14.4	
DM-10	Mancos Shale	45.7	144	1.4[a]	
DM-10	Mancos Shale	47.2	146	1.6[a]	
DM-10	Mancos Shale	69.3	148	1.3[a]	
DM-10	Mancos Shale	73.8	146	3.7	
DM-11	Tailings (SP)	4.2	89	4.0	sand
DM-11	Tailings (SP)	9.2	94	12.5	sand
DM-11	Tailings (SP)	14.2	78	21.8	sand
DM-11	Tailings (SP)	19.2	68	34.2	sand
DM-11	Tailings (CL)	24.2	---	61.9	slime
DM-11	Tailings (SP/CL)	24.3	65	47.7	
DM-11	GP	29.1	109	2.2	

[a]Moisture drier than in-situ.

Ref. Dames and Moore, 1982.

tailings sand, n=6, $\bar{x}$ = 15.5, s = 11.8

51.4 13.7 S.E. = 11.8/√6 = 4.8

TABLE 3.1

Shelby Tube Sample Characteristics

Boring	Depth (ft.)	Description	% Finer No. 200 Sieve	Dry Density γ_D, pcf	Water Content w, %	Gs	Void Ratio e	θs	Saturation S, %	Plasticity Index (%)	Liquid Limit (%)	USCS[(1)]
SHR 201	30	Tan, silty med. sand	26.3	94.3	2.3	2.78	.807	0.45	7.93			SM
SHR 202	40 a	Tan, fine, silty sand	18.2	82.7	9.2	2.72	1.06		23.6	NP		SM
SHR 203	20 b	Tan, silty med.-fine, sand	15.0	99.3	11.5	2.71	.703	0.41	44.3	NP		SM
SHR 205	6.5	Gray, clayey silt slime	87.3	68.7	55.0	2.84	1.61	0.62	98.2			–
SHR 207	5	Tan, silty med.-fine, sand	14.0	86.9	6.2	2.72	.946		17.8			SM
SHR 207	20	Tan, med.-fine, silty sand (slime-sand mixture)	49.3	77.8	17.8	2.76	1.17	0.54	41.1			SM
SHR 208	15	Tan, silty, fine sand	19.9	95.9	11.3	2.72	.77		39.9			SM
SHR 210	10	Fine silty sand	19.3	92.6	10.6	2.72	.827		34.8			SM
SHR 210	25	med.-fine, silty sand	21.8	90.8	8.4	2.71	.862		26.4			SM
SHR 211	7.5	Grey clayey silt slime	88.0	51.8	82.0	2.82	2.39	0.71	96.6			–
SHR 212	30	Grey, fine, sand silt, sand slime	34.9	96.9	20.1	2.73	.758	0.43	72.4	NP		SM
SHR 214	10	Tan, fine, sand grey silt sand slime	49.1	95.3	22.3	2.72	.781	0.44	77.7	3.5	26	SM

(1) Samples classified without Atterburg limits were assumed to be of low plasticity.

TABLE 3.9

Undisturbed Sample Saturated Permeability

Boring	Depth (ft.)	% Minus No. 200 Sieve	Permeability K_T, cm/sec (1)
201	30	26.3	2.1×10^{-3}
202	40	18.2	6.4×10^{-4}
203	20	37.8	4.7×10^{-6}
205	6.5	87.3	3.1×10^{-6}
212	30	34.9	1.3×10^{-5}
214	10	49.1	2.3×10^{-5}

(1) Coefficient of permeability not corrected to standard temperature.

SUMMARY OF MATERIAL PROPERTIES

Material	Specific Gravity (G)	In-Situ Moisture Content (%)	Target Moisture Content (%)	Total Unit Weight (pcf)	Saturation (%)	Initial Void Ratio (e_o)	Undrained Shear Strength (ksf)	Cohesion (ksf)	Internal Friction Angle (Degree)	Atterberg Limits LL/PI (%)	Permeability (cm/sec)	Compression Index (C_c)	Coeff of Consolid cm²/sec	Remarks
• Cover of Radon Barrier														
Sandy Silt / Silty Sand	2.70	5	16	128	82	0.53		0	34		2.5×10^{-5}			95% Comp. ASTM D698
• Rehandle Tailings														
Mixed sands and slimes	2.72	~~8~~ 12	12	110	45	0.73		0	32	18/2	5.0×10^{-5}	0.08		90% Comp. ASTM D698
• In-Situ Tailings														
Gravelly Sandy silt / Silty Sand	2.70	8	8	~~98~~ 102	25	0.85		0	32		5.0×10^{-5}	0.10	2.1×10^{-6}	
Mixed Sands and slimes	2.72	14	14	104	42	0.91		0	25	18/2	to 0.7×10^{-6}	0.15		
Slimes	2.84	58	58	110	100	1.65	1.0	0	17	55/19	3.1×10^{-6}	0.50	1×10^{-3}	
• Foundation														
Sandy silt / clayey silt	2.73	14	14	110	50	0.76	1.7	0.5	29	23/2	1.3×10^{-5}	0.12	3×10^{-2}	
Sand and Gravel	2.70	4	4	115	21	0.51		0	35		1.0×10^{-3}			
Mancos shale														
Highly Weathered (shallow)	2.65	15	15	120	67	0.58		0	40		2.2×10^{-4}			
Slightly Weathered (Deep)	2.65	4	4	155	96	0.11	100							

• Borrow Material

Silty Sand / Sandy silt : Specific Gravity = 2.70, In-Situ Moist Cont = 5%, Compaction (ASTM D698) Opt Moist Cont = 13% Max Dry Density: 116.6 pcf

Mancos shale : Specific Gravity = 2.65, In-Situ Moist Cont = 4%, Compaction (ASTM D698) Opt. Moist Cont = 12.8% Max. Dry Density = 121.3 pcf

INTERNATIONAL ENGINEERING COMPANY, INC.

Project UMTRA/SHP
Feature Embankment Design
Item Material Properties
Contract No. [illegible]
Designed WYL
Checked ABH
Sheet [illegible]
File No.
Date [illegible]
Date [illegible]