Hydrology of a waste rock repository capping system at the Zortman Mine
by Elizabeth Anne Warnemuende

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Land Rehabilitation
Montana State University
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Abstract:
Waste rock produced by the mining industry may contain sulfide minerals, which often oxidize to produce acid in the presence of water. This acid production may lead to acid rock drainage. Therefore, it is important to dispose of sulfide - rich waste rock in a way that will minimize exposure to water and the consequent release of acid rock drainage into the environment.

The 300 - foot thick Mill Gulch waste rock repository at the Zortman Mine was capped with a series of oxidized and clayey materials in 1992. The cap was designed to minimize infiltration of water into the repository and thus minimize the probability of acid rock drainage. The purpose of this investigation was to evaluate the hydrology of the Mill Gulch waste rock repository in order to determine whether the capping system adequately precludes infiltration of precipitation into the repository so as to prevent gravitational drainage of water from the repository.

Repository water content was measured monthly over a 12 month monitoring period using a neutron probe. Neutron probe data were collected from eight neutron probe access tubes located on three different terraces on the Mill Gulch waste rock repbsitoiy. Neutron tubes varied in depth from 70 to 310 feet.

A laboratory method for neutron probe calibration in unconsolidated waste rock was developed. A fifty gallon sample of waste rock was oven dried and loaded into a monitoring barrel, which was equipped with time domain reflectometry probes and a neutron probe access tube for the entire profile. The response of time domain reflectometry and neutron probe measurements to calculated volumetric water additions was monitored following additions of 0.5 % volumetric water increments.

A neutron probe calibration for the waste rock material was successfully generated. The relationship between the neutron count ratio and volumetric water content was found to be linear with r = 0.96. The results of the hydrologic study indicated that much of the Mill Gulch waste rock was at or above field capacity; thus water will drain downward in response to gravity. Average drainage from the repository was estimated to be less than the 14.3 inches of precipitation received during the monitoring period. The capping system is thought to be effective at storing infiltration and promoting runoff from the repository. In addition to precipitation, the repository received run - on from a large unreclaimed topsoil stockpile located up gradient from the top bench of the repository. Run - on contributed to infiltration at the repository top.

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This thesis has been read by each member of the thesis committee and has been found to be satisfactory regarding content, English usage, format, citations, bibliographic style, and consistency, and is ready for submission to the College of Graduate Studies.

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Date 12-4-97

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ABSTRACT

Waste rock produced by the mining industry may contain sulfide minerals, which often oxidize to produce acid in the presence of water. This acid production may lead to acid rock drainage. Therefore, it is important to dispose of sulfide - rich waste rock in a way that will minimize exposure to water and the consequent release of acid rock drainage into the environment.

The 300 - foot thick Mill Gulch waste rock repository at the Zortman Mine was capped with a series of oxidized and clayey materials in 1992. The cap was designed to minimize infiltration of water into the repository and thus minimize the probability of acid rock drainage. The purpose of this investigation was to evaluate the hydrology of the Mill Gulch waste rock repository in order to determine whether the capping system adequately precludes infiltration of precipitation into the repository so as to prevent gravitational drainage of water from the repository.

Repository water content was measured monthly over a 12 month monitoring period using a neutron probe. Neutron probe data were collected from eight neutron probe access tubes located on three different terraces on the Mill Gulch waste rock repository. Neutron tubes varied in depth from 70 to 310 feet.

A laboratory method for neutron probe calibration in unconsolidated waste rock was developed. A fifty gallon sample of waste rock was oven dried and loaded into a monitoring barrel, which was equipped with time domain reflectometry probes and a neutron probe access tube for the entire profile. The response of time domain reflectometry and neutron probe measurements to calculated volumetric water additions was monitored following additions of 0.5 % volumetric water increments.

A neutron probe calibration for the waste rock material was successfully generated. The relationship between the neutron count ratio and volumetric water content was found to be linear with r = 0.96. The results of the hydrologic study indicated that much of the Mill Gulch waste rock was at or above field capacity; thus water will drain downward in response to gravity. Average drainage from the repository was estimated to be less than the 14.3 inches of precipitation received during the monitoring period. The capping system is thought to be effective at storing infiltration and promoting runoff from the repository. In addition to precipitation, the repository received run – on from a large unreclaimed topsoil stockpile located up gradient from the top bench of the repository. Run – on contributed to infiltration at the repository top.

INTRODUCTION

The Zortman mine is located approximately 150 miles north of Billings, Montana in the Little Rockies mountain range. The Mill Gulch waste rock repository at the Zortman mine contains sulfide - rich minerals which, if left exposed to water and oxygen, could produce acid rock drainage. The repository consists largely of a cyanite porphyry, which has pyrite mineralogy. The repository was capped with 18 to 36 inches of Emerson shale, 24 to 36 inches of oxidized waste rock, and 12 inches of coversoil in order to minimize infiltration of precipitation into the repository and subsequent downward drainage of water from the repository. The repository top and benches have an additional polyvinyl chloride (PVC) geomembrane liner overlying the Emmerson shale layer. Exclusion of precipitation from the repository may slow the rate of acid production, which results from the oxidation and hydrolysis of pyrite by the chemical reaction:

$$FeS_2 + 15/4\ O_2 + 7/2\ H_2O \Rightarrow Fe(OH)_3 + 4H^+ + 2SO_4^{-2}$$

This study was conducted to evaluate the hydrology of the Mill Gulch waste rock repository in order to determine whether drainage of water through the repository is likely to occur.

Objectives

1) Develop a neutron probe calibration to estimate the volumetric water content of Mill Gulch waste rock.

- Using time domain reflectometry, develop a laboratory neutron probe calibration for Mill Gulch waste rock with which to interpret neutron probe data.
- Evaluate laboratory water retention and drainage data in order to assess the desorption characteristics of Mill Gulch waste rock.

2) Determine whether the Mill Gulch waste rock repository capping system minimizes infiltration of precipitation into the repository and subsequent downward drainage of water.

3) Estimate the quantity of drainage from the Mill Gulch waste rock repository over a 12 month monitoring period.

BACKGROUND

Climatic Conditions

The Zortman mine is located in a semiarid region of north-central Montana. The top of the Mill Gulch repository is at an elevation of 5025 feet. During the study period analyzed (May 1996 - May1997), the Mill Gulch repository received 14.72 inches of precipitation. Precipitation during January, February, and March was typically snowfall. The average annual precipitation during 1995 and 1996 was 20.34 inches. The 14.72 inches of precipitation received during the period of analysis was unusually low in comparison to the 30 year average annual precipitation (1941 - 1970) for the area, which has been reported by the United States Soil Conservation Service (1980) to be greater than 20 but less than 22 inches.

Site Description

The Mill Gulch waste rock repository was constructed as a head - of - valley fill and has a maximum thickness of approximately 300 feet at the outer edge of the repository top and thins towards the toe of the fill. The entire repository was capped using a sequence of materials (Figure 1). An 18 to 36 inch clayey barrier which consists of

Emmerson shale immediately overlies the waste rock. A two to three foot thick layer of low sulfur oxidized waste rock was placed on top of the shale, followed by twelve inches of coversoil. The repository was constructed with four terraces, in order to minimize erosion and the development of rills and gullies from runoff (Figure 2). Benches are back sloped into the repository and sloped down gradient in order to facilitate removal of runoff from the repository. A PVC geomembrane was added to the capping regime on the repository top and terraces, where water is otherwise less likely to run off than on slopes. This geomembrane immediately overlies the Emmerson shale.

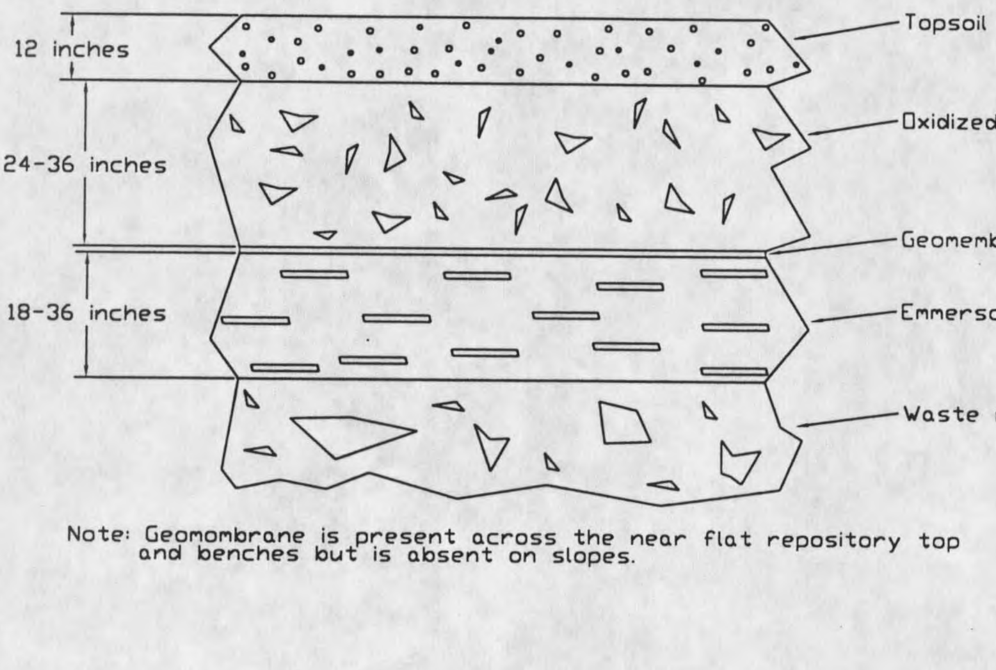

Figure 1. The capping sequence used at the Mill Gulch waste rock repository.

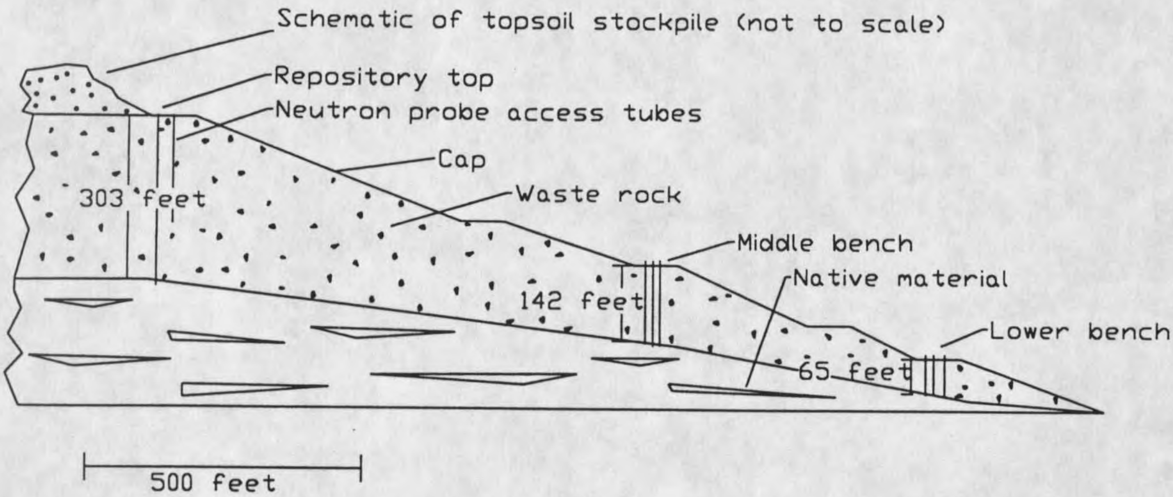

Figure 2. A cross section of the Mill Gulch waste rock repository.

LITERATURE REVIEW

Cap Hydrology

Research has demonstrated that clay caps may not provide a significantly more effective infiltration barrier for tailings impoundments located in areas of low precipitation than capping systems comprised of non - acid producing fill material and coversoil (Dollhopf et al., 1995). These investigators conducted a study at the Golden Sunlight Mine near Whitehall, Montana in order to evaluate the hydrology of several capping systems for a tailings impoundment and to characterize the quantity of recharge into the impoundment under three different capping systems and one uncapped control. The impoundment was designed to minimize infiltration into the tailings and the subsequent oxidation of the tailings materials, which results in acid production.

The capping systems evaluated by Dollhopf, et al. included: 1) a cover consisting of a 55 inch layer of oxidized waste rock followed by a 28 inch layer of coversoil, 2) a cover consisting of a 32 inch layer of waste rock followed by a 28 inch layer of clay and a 30 inch layer of coversoil, and 3) a 50 inch layer of borrow material followed by a 20 inch layer of coversoil. A control plot without any cap was also evaluated. It was found that a cap was necessary to preclude precipitation from the impoundment, but that the clay barrier did not significantly enhance the effectiveness of the cap (Dollhopf et al., 1995).

Capping systems in arid and semiarid regions are often less elaborate then their higher precipitation counterparts. In drier regions, where annual potential evapotranspiration often exceeds precipitation, elaborate capping systems are often deemed unnecessary. However, studies have shown that infiltration through a cap or other porous media is influenced by many factors other than mean annual potential evapotranspiration and precipitation. These factors include: seasonality of precipitation, piston flow, vegetation, and preferential flow (Stephens, 1994).

In areas where mean annual potential evapotranspiration exceeds mean annual precipitation, the season during which precipitation is received plays an important role. If precipitation is most intense during low temperature months, when evapotranspiration is low, potential infiltration will be higher than that of regions with similar water budget, but receiving primarily warm season precipitation. Nichols (1987) found deep percolation occurring on a site receiving less annual precipitation than potential evapotranspiration. The site received proportionally high March precipitation, which exceeded seasonal potential evaporation. Similarly, deep percolation can occur in arid to semiarid regions of proportionally high snowfall because snow melt contributes to high soil moisture during the early spring months when temperature and evapotranspiration are low (Hakonson, et al., 1992).

Soil water often moves through a profile as piston flow. By this process, water added to the soil surface moves downward through the profile by displacing antecedent soil moisture. Soil water content may not change as a function of added water. Stephens

(1985) showed that piston flow may allow infiltrated water to move downward through a soil profile which is less wet than the field capacity water content.

Vegetation plays a crucial role in determining the quantity of infiltration through a soil profile (Stephens, 1994). Studies have shown that deep rooted plants are more effective at preventing deep percolation than shallow rooted grasses. Gee et al. (1989) found that deep percolation through coarse soils with sparse grassy cover accounted for most of the water received by the site, while deep rooted shrubs were more effective at intercepting percolation.

Macropores formed on a cap by plant roots, small animals, or fissures resulting from freeze thaw cycles can facilitate preferential flow, effectively raising the rate of infiltration through the cap. Studies have shown preferential flow can account for 50 to 99 percent of deep percolation through a soil profile (Sharma, et al., 1987).

Neutron Probe

The neutron probe is one of the most accurate tools for measuring volumetric water content through a soil profile commonly used (Carrijo and Cuenca, 1992). The neutron probe can be lowered to any depth in a soil profile through an access tube to obtain volumetric water content data for that depth. The neutron probe consists of a radioactive source, which emits fast neutrons, and a detector tube, which counts slow neutrons. Fast neutrons thermalize to become slow neutrons when they collide with hydrogen nuclei. Because the vast majority of hydrogen atoms in a soil profile are contained in water molecules of the soil water, volumetric water content can be calculated as a function of the ratio of slow neutron count to a background count obtained with the probe in its shield. However, because a soil may contain other sources of hydrogen and non - hydrogen substances capable of thermalizing fast neutrons, a soil specific neutron calibration is required for every soil monitored. Neutron probe calibration is the dominating source of error in volumetric water content measurements obtained by the neutron probe technique (Haverkamp et al., 1984).

A hydrologic study of a waste rock repository was conducted by Schafer and Associates at the Golden Sunlight mine in Whitehall, Montana. Neutron probe access tubes were installed at seven sites on the repository located on both reclaimed and unreclaimed portions of the repository, and monitored for one year. Results indicated reduced infiltration on the regraded, capped, and revegetated portions of the repository as compared to the unreclaimed portions of the repository (Schafer and Associates, 1995). A field neutron probe calibration was developed for this study. The investigators were able to obtain 13 field calibration data points, most of which were between 3.5 and 8.5 percent volumetric water content. Although particle size in the repository was highly heterogeneous, a single neutron probe calibration was used for the entire repository. The field calibration is given in Equation 1, where θ_v equals volumetric water content and NCR equals neutron count ratio. This calibration had a correlation coefficient of 0.77.

$$\theta_v = 19.7 \times NCR + 2.3 \qquad [1]$$

Time Domain Reflectometry

Time domain reflectometry (TDR) is a technique for measuring volumetric water content in soils. The propagation velocity of an electromagnetic pulse along a burried transmission line is measured and used to calculate the dielectric constant of the soil. The dielectric constant is then used to calculate volumetric water content using an empirical calibration equation.

Because the soil bulk dielectric constant is dominated by the dielectric constant of soil water, the dielectric constant of any soil is mainly a function of the volumetric water content. Topp et al. (1980) developed an empirical relationship between the volumetric water content and bulk dielectric constant of the soil. This relationship is given by the third order polynomial relationship in Equation 2, where θ_v equals the volumetric water content of the soil, and ε_b equals the soil bulk dielectric constant.

$$\theta_{vTDR} = -5.3 \times 10^{-2} + 2.92 \times 10^{-2}\, \varepsilon_b - 5.5 \times 10^{-4}\, \varepsilon_b^{\,2} + 4.3 \times 10^{-6}\, \varepsilon_b^{\,3} \qquad [2]$$

Because the dielectric constant of a soil is primarily a function of soil water (Topp and Davis, 1985), which has a dielectric constant about 20 times greater than mineral materials, dielectric constant does not vary greatly with mineral makeup. Topp and Davis (1985) also discovered that the dielectric constant of a soil does not vary significantly with temperature, soil type, or density. Minor changes in soil bulk dielectric constant due to temperature were detected by Pepin et al. (1995). The temperature effect was found to increase with soil water content. Research has shown that dielectric constant does not vary significantly among soil textures ranging from clays to sandy gravels. Drungil et al. (1989) found that the empirical TDR calibration expressed in Equation 1 was applicable to gravelly soils containing coarse fragments.

A physically based TDR calibration was developed by Roth et al., (1990) which accounted for the porosity of the material and the geometric orientation of the probe in relation to the natural layering of the material. According to this model, the volumetric water content of the material is a function of the bulk dielectric constants of all three physical phases within the system, the porosity of the material, and the geometric orientation of the probe. This model produced a calibration curve which is very similar to Topp's calibration for volumetric water contents less than 50 percent (Or and Wraith, 1996).

In time domain reflectometry, electromagnetic pulses are generated by a coaxial cable testing unit (TDR instrument) and transmitted through a coaxial cable to a probe which is inserted in the soil. Both two - rod and three - rod probes have been found to yield accurate time domain reflectometry data. (Kirkschether, 1960), (Zegelin et al., 1989). Reflection waveforms from the electromagnetic pulses are by the instrument and interpreted to estimate pulse propagation velocity. Waveforms are sometimes difficult to interpret. Reflections from the cable to probe interface, soil to air surface and other discontinuities, including large voids that may exist in waste rock, can complicate waveforms to an extent which poses a risk for misinterpretation and false readings.

One method for minimizing risks of misinterpreting TDR waveforms is to create a short circuit at the cable to probe interface in order to determine the point on the waveform that represents the beginning of the probe (Hook et al., 1992). Similarly, short circuiting the end of the probe can be used to identify the point on the waveform representing the end of the probe. A differential technique, such as waveform subtraction enhances the accuracy of waveform interpretation (Hook et al., 1992). In this method, the waveform of the shorted reflection is subtracted from the waveform of the unshorted reflection in order to locate the point on the waveform representing the location of the short circuit. This allows distinguishing of reflections off the cable to probe interface and probe end from extraneous reflections within the measurement zone. A study by Hook et al. (1992) employed shorting techniques coupled with differential techniques to simplify waveforms and identify correct reflections. They found that these techniques "allow easy and reliable waveform interpretation by unskilled operators or by automated system software".

MATERIALS AND METHODS

Neutron Probe Calibration

To calibrate the neutron probe in Mill Gulch waste rock, we evaluated the response of neutron probe and time domain reflectometry measurements to additions of measured volumes of water to oven dried Mill Gulch waste rock. Neutron probe count ratios were collected for the calibration material at known volumetric moisture contents ranging from the oven dried condition to saturation, yielding a complete calibration relationship. In order to identify the volumetric moisture content at which downward drainage through Mill Gulch waste rock occurs in response to gravity, a drainage system in the calibration apparatus allowed drainage to be observed and measured. Drainage recorded during the laboratory calibration indicated that field capacity for the Mill Gulch waste rock sample studied was five percent volumetric water content. Using this value as an estimate of in situ waste rock field capacity made it possible to identify zones within the repository having volumetric water contents at or above field capacity. Homogeneity of waste rock materials throughout the entire repository was assumed in order to extrapolate the field capacity value and neutron probe calibration to the entire repository.

The primary function of the time domain reflectometry (TDR) measurements was to confirm the critical volumetric water content at which downward drainage occurred in response to gravity by tracking the wetting front through the waste rock. Since TDR has a much faster response time than the drainage system and has adequate spatial resolution to quantify depth profiles of water content, the critical moisture content could be determined more accurately using TDR. Barrel outflow confirmed interpretations of TDR data.

Calibration Material

Fifty gallons of Mill Gulch waste rock having particle sizes ranging from less than 1/16 inch to 6.5 inches in diameter, were used as calibration material. The material was oven dried at 40 degrees Celsius for six weeks. A subsample of the dried material, having a representative range of particle sizes, was oven dried for 48 hours at 105 degrees Celsius, and found to have an initial gravimetric water content of 0.016%. The material was loaded into the 55 gallon barrel in 70 pound increments. Each increment was tamped in order to simulate in situ bulk density. Each waste rock increment had a similar particle size distribution, so as to minimize gradation within the barrel profile. Bulk density analysis of Mill Gulch waste rock revealed that the material had an in situ dry bulk density of 15.40 pounds per gallon (1.85 g/cm^3) before removal from the repository and a repacked dry bulk density of 13.19 pounds per gallon (1.58 g/cm^3) in the calibration barrel.

Instrumentation

Time domain reflectometry probes, a neutron probe access pipe, and a drainage system were installed in a fifty-five gallon PVC drum (Figures 3 and 4).

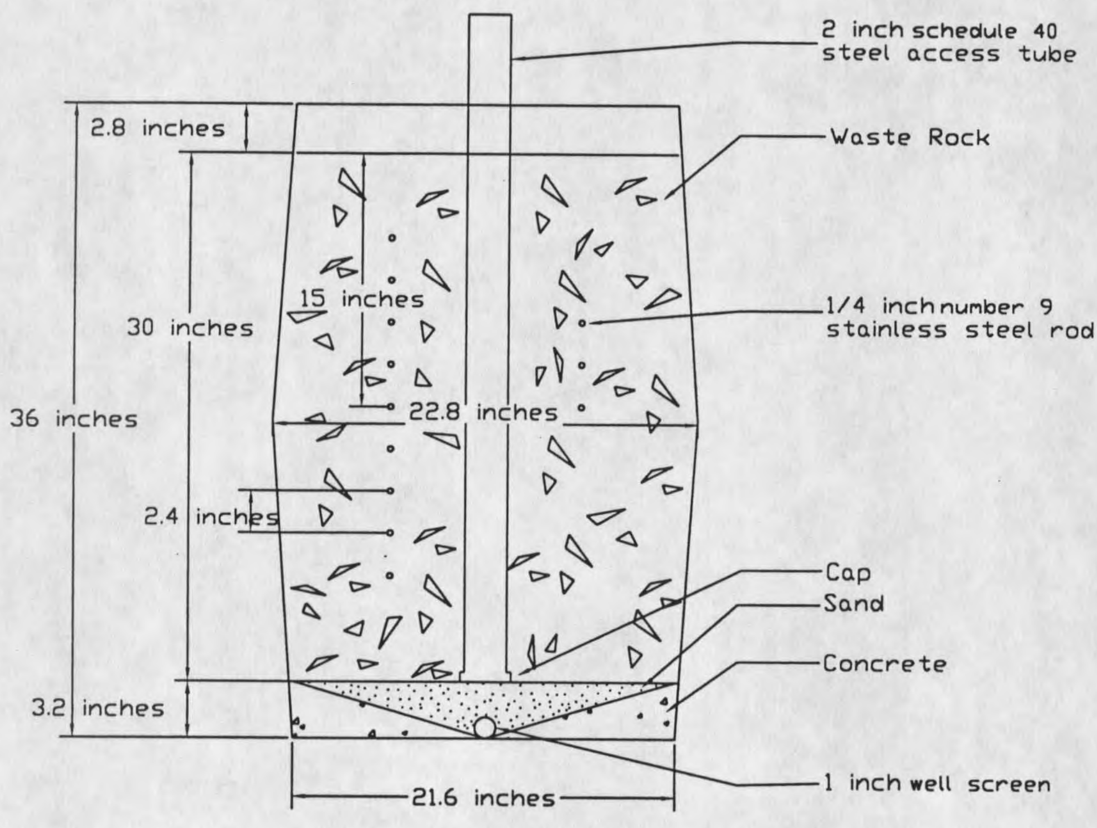

Figure 3. Front view cross section of the calibration apparatus.

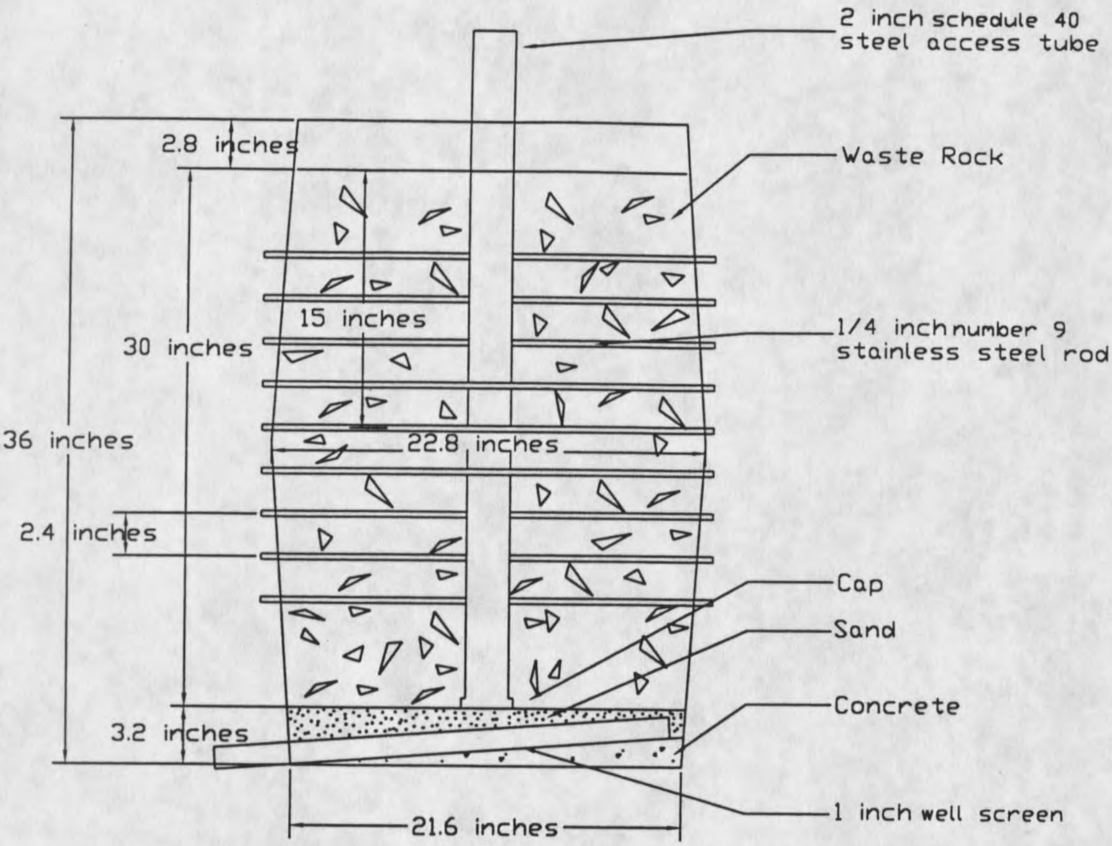

Figure 4. Side view cross section of the calibration apparatus.

Twelve 25 inch lengths of ¼ inch number nine stainless steel rods constituted the time domain reflectometry probes. The rods were installed parallel to one another and at 2.4 inch vertical spacings. They penetrated the barrel horizontally so that water content could be estimated for eight depths. Both ends of the rods penetrated the barrel so that one end of each rod was accessible for making the electrical connection to the TDR instrument, and the other end was accessible for creating a short circuit between rods to enhance the ease of wave form interpretation (Hook et al., 1992). Alligator clips were used to connect the rods to the cable from the TDR. A conductive metal rod was used to short circuit the TDR rods. The twelve rods were installed horizontally such that the distance between the middle of each rod and the horizontal center of the barrel was six inches. Nine of the rods were installed to one side of center, and the other three were installed parallel and to the other side. Each TDR reading requires two rods, thus allowing readings at eight different depths on one side, representing the profile from the 6.6 inch depth to the 23.4 inch depth, and two readings at different depths on the other side, providing duplicate measurements for the profile from 13.8 to 16.2 inches. Rods were spaced such that the duplicate measurements were centered on the point of measurement for the neutron probe.

A drainage system for the barrel was constructed so that field capacity volumetric water content could be confirmed by observation of outflow from the bottom of the barrel. The drainage system design was intended to minimize the response time between downward rock drainage into the bottom of the barrel and observable outflow, and to minimize clogging with fine particles from the calibration material. The drainage system at the bottom of the barrel consisted of schedule 80, one inch PVC, 20 slot well screen, which sloped downward from the back of the barrel to the front, penetrated the front of the barrel, and terminated four inches outside the barrel. Well screen was used to avoid clogging by fine particles. The well screen was threaded for a plug at the front end, so that drainage could be controlled. Concrete was used to build up the bottom of the barrel at the outer edges, creating a slope of 6:1 towards the drainage pipe. A layer of 20 - 30 mesh silica sand was placed over the drainage system, so that the contacting surface with the waste rock was flat and uniform. The thickest portion of the sand layer, covering the drainage pipe at the front of the barrel, was 2.2 inches thick.

The neutron probe access tube used for the calibration was 2 inch schedule 40 steel pipe, the same type and diameter as the tubes used to collect field neutron probe data at the Zortman Mine. The tube was installed vertically down the center of the barrel, after the drainage system was in place.

Barrel Preparation

A plastic 55 gallon drum was opened by removing the entire lid with a saw. Vertical lines, along which the TDR probes will be installed, were marked. In order to properly position these lines, a straight edge was placed across the top of the barrel so that it passed through the horizontal center of the barrel. A second straight edge was positioned parallel to the first, so that its center was equidistant from the center of the first and the side of the barrel. Vertical lines were marked down the side of the barrel from each of two points where the second straight edge intersected the edge of the barrel. These lines were labeled “A”. The second straight edge was then repositioned such that it was to the other side of and parallel to the first, with its center equidistant from the center of the first and the side of the barrel. Vertical lines were again marked down the side of the barrel from each of two points where the second straight edge intersected the edge of the barrel. These lines were labeled “B”.

A drill hole was marked at the center of the effective column along each of the four TDR lines. The center of the effective column was determined to be the plane which was equidistant from the top of the sand layer and the projected top of the column of calibration material. A three inch empty buffer zone was left at the top of the barrel to avoid water loss due to overflow in case water should unexpectedly pond on the surface.

Nine drill hole markings, centered on the vertical center of the effective column and at 2½ inch vertical spacings, were marked along each of the two “A” lines. Three remaining drill holes were marked along the “B” lines, centered on the vertical center of the effective column and at a vertical spacing of 2½ inches. Holes were drilled at each of the markings using a ¼ inch bit.

Drainage System Installation

A hole for the drainage pipe was created by using a 1 3/8 inch hole saw, to drill a hole in the side of the barrel, such that the center of the hole is two inches from the bottom of the drum, and equidistant from line “A” and the corresponding line “B”.

The drainage pipe was installed by running a 2.5 foot length of one inch schedule 80 PVC well screen through the hole into the barrel so that the screen ran the entire diameter of the barrel, at a slope of 4:1 towards the outlet. The exposed end of the screen was threaded to accommodate a plug, and the inside end of the screen was capped. Silicone was applied liberally around the well screen on both sides of the barrel, to prevent water loss through leakage and evaporation.

A concrete drainage channel was created in the bottom of the barrel Side slopes of the channel were 6:1 toward the drainage pipe, so that the bottom of the well screen was completely covered and there was no gap between the well screen and the concrete floor. A sand layer was created by pouring a level layer of sand over the entire floor of the barrel, covering the pipe to a maximum 2.2 inch depth.

Installation of Equipment and Calibration Material

A two inch schedule 40 steel pipe neutron probe access tube was installed vertically at the center of the barrel. The bottom end of the tube was plugged and sealed to prevent the entrance of water into the tube.

The effective column of the barrel was filled with calibration material. Waste rock was added to the barrel in seventy pound increments. All increments were tamped with a sledgehammer, in order to compact the rock to most closely simulate field conditions without causing breakage of the rock. All increments were comprised of material having similar particle size distribution.

Time Domain Reflectometry probes were installed, beginning with the lower probes. As the waste rock level rose to just below each set of ¼ inch holes, the rods were installed through those holes. Each rod was installed horizontally through the barrel. The rods were centered in the barrel such that an equal length of each rod stuck through the front and back of the barrel. Silicone was applied liberally around the each rod to prevent water loss through leakage and evaporation.

The point of measurement of the neutron probe was centered on the vertical center of the effective column and the neutron probe cable was marked so that the neutron probe could be easily and accurately returned to this depth. In this case, the point of measurement was determined to be equidistant from the center of the detector tube and the center of the source. This point was located 4.6 inches from the bottom of the probe. Because of this, the point of measurement was 4.6 inches above the bottom of the neutron probe access tube when the probe was lowered until it hit the bottom of the tube. The measuring point was then located by lowering the probe to the bottom of the neutron probe access tube, and then raising it 10.2 inches to the vertical center of the effective column.

Calibration Protocol

After the calibration barrel was prepared and back filled with calibration material, TDR measurements were collected from all ten probes. Five neutron probe shield counts were then obtained with the neutron probe over the calibration neutron probe access tube, and the radioactive source in its shield. The shield counts were averaged to obtain the mean shield count. Five neutron probe counts were then obtained at the depth of 15 in, the center of the effective profile, and averaged to produce the mean at depth count. A single neutron count ratio for the oven dry condition was calculated using these data.

The mean volumetric water content of the waste rock was then raised by 0.5% by adding 0.25 gallons of water to the barrel. After the addition of water, the barrel was sealed across the top using six mil plastic sheeting taped liberally to the barrel in order to prevent water loss by evaporation. The added water was allowed to percolate for 24 hours before obtaining TDR readings and neutron count ratio for a mean barrel volumetric water content of 0.5% using the procedure described for oven dry TDR readings and neutron count ratios.

It was found that the TDR readings changed over the first seven hours after the addition of water, but did not change over the period of time from seven hours to 24 hours after the addition of water. Twenty four hours was used as the standard delay between time of addition of water and time of measurement taking in order to ensure that the profile water content was steady at the time of measurement.

Water additions and measurements were continued until drainage from the barrel was observed. The drainage pipe was then capped so that the waste rock could be saturated to obtain a final calibration point. Water was added to the barrel until it permanently ponded on the surface of the waste rock. The saturated TDR readings and neutron count ratio were then obtained.

Calibration Calculations

The volume of the column of calibration material in the barrel was calculated to be 50.17 gallons and equals the volume of the drainage system, instrumentation, and the empty portion of the barrel subtracted from the total volume of the barrel, as given by Equation 3, where v = the effective volume of calibration material, v_{tot} = the total barrel volume, v_0 = the volume of the empty portion of the barrel, and v_d = the volume of the drainage system, and v_i = the volume of the neutron probe access tube and TDR probes.

$$v = v_{tot} - (v_0 + v_i + v_d) \quad [3]$$
$$v = 60.32 - (4.44 + 0.53 + 5.16) = 50.19 \text{ gallons}$$

The percent volumetric water added to the barrel was calculated by dividing the total volume of water added by the effective volume of the calibration material, using Equation 4, where θ_v = the calculated mean percent volumetric water content of the calibration material, v = the volume of the calibration material, and v_1 = the cumulative volume of water added to the barrel.

$$\theta_v = \frac{v_1}{v} \times 100 \quad [4]$$

Time domain reflectometry volumetric water contents were calculated by using the apparent length of transmission line, which varies with propagation velocity, to solve for the soil bulk dielectric constant according to Equation 5, where ε_b = the soil bulk dielectric constant, L_a = apparent transmission line length, and L = actual probe length.

$$\varepsilon_b = \left(\frac{L_a}{L}\right)^2 \qquad [5]$$

The soil bulk dielectric constant was then used to calculate volumetric water content according to Equation 2.

During the interval between 5.5 percent and 11.4 percent volumetric water added to calibration material, TDR and neutron count readings did not respond to volumetric water additions. These data are identified in Figure 5, which illustrates the response of time domain reflectometry and neutron count ratios to increases in percent volumetric water added to the calibration material. Additions of water from 5.89 to 12 percent by volume did not result in responses in TDR or neutron count ratio, which were constant until visible outflow from the barrel occurred. Therefore, it is assumed that water added during this interval was progressively displacing water held by the calibration material at the measurement depths, until the entire profile and sand layer of the drainage system reached field capacity, at which time outflow from the barrel was observed. The close correlation between TDR and neutron probe data support this interpretation.

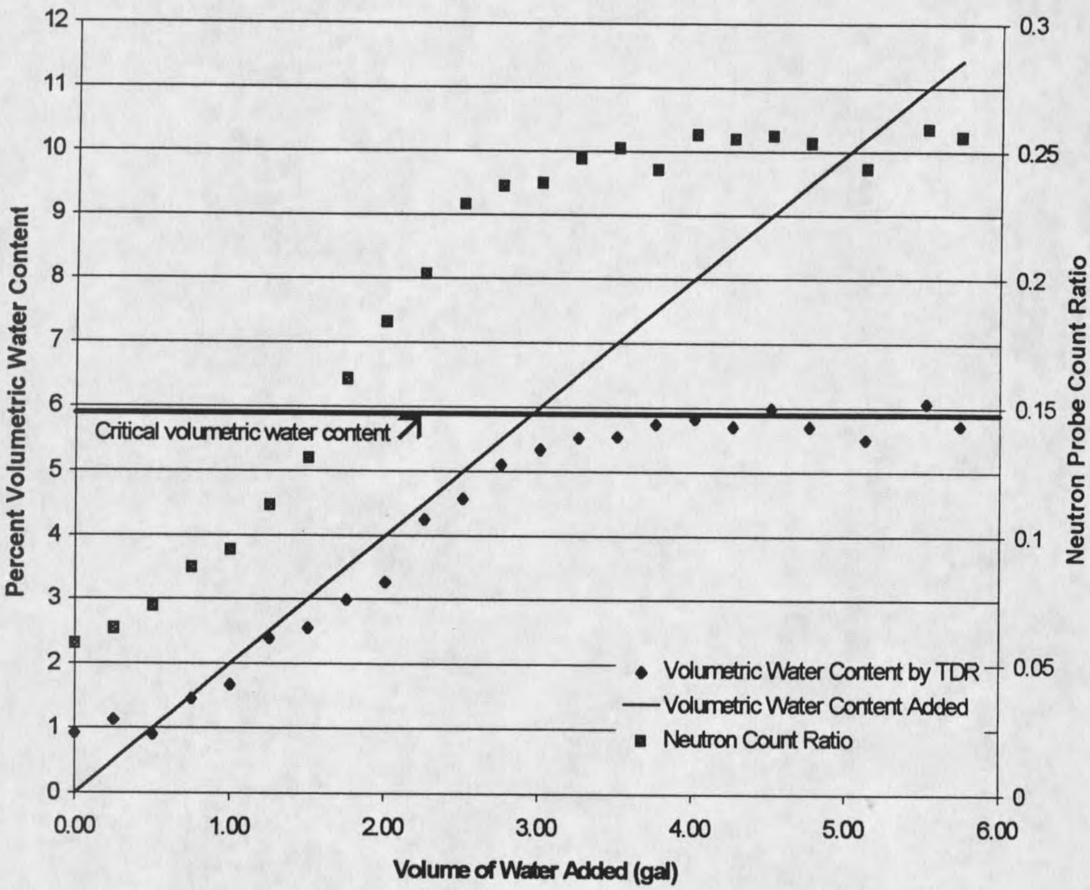

Figure 5. The response of TDR measurements and neutron count ratios to additions of water.

The neutron count ratio at which increases in percent volumetric water added to calibration material did not result in an increase neutron count ratio obtained from the calibration material was identified as the critical neutron count ratio at which water will drain from Mill Gulch waste rock in response to gravity. This value was found to equal 0.25. Neutron probe calibration data are found in Appendix A.

The volumetric water content at which TDR readings failed to respond to additions of water to the calibration material was calculated by averaging the TDR readings for the neutron probe measurement zone at mean barrel volumetric water contents between 5.5 percent and 11.4 percent, and equaled 5.89 percent.

The laboratory calibration equation was obtained by performing a linear regression of volumetric water content of the calibration material against neutron probe count ratio, and is presented along with the factory calibration in Figure 6. The correlation coefficients for the calibration equations are 0.98 for count ratios less than 0.25, which represents the neutron count at which field capacity was reached. Data which were obtained while the calibration material was progressively reaching field capacity and actively draining into the drainage system was not included in the linear regression.

Linear regression yielded the calibration relationship described by Equation 6. By applying the final calibration equation (Equation 6) to the critical neutron count ratio, the critical volumetric water content at which water will drain from Mill Gulch waste rock in response to gravity was found to equal 5.89 percent.

$$\theta_v = 27.479 \times NCR - 0.976 \qquad [6]$$

In neutron probe calibration equations, θ_v equals the percent volumetric water content and NCR equals the neutron count ratio for a given depth increment.

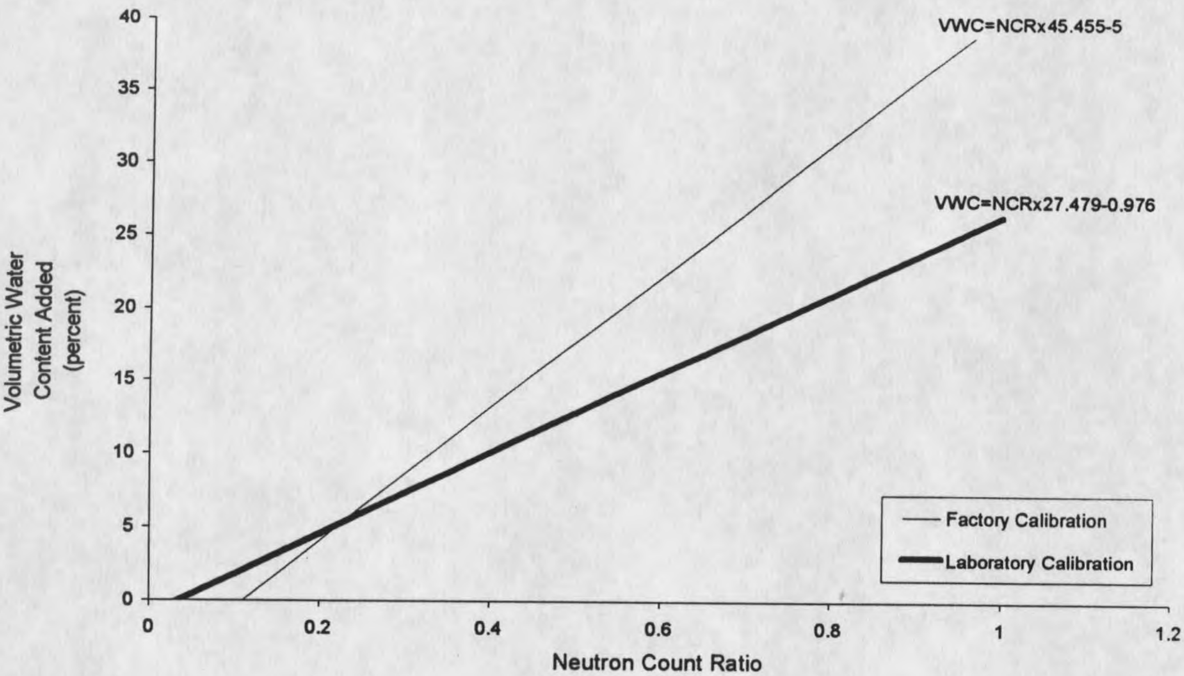

Figure 6. Neutron probe calibration.

Field Data Collection

Neutron count measurements were collected from the Mill Gulch repository on a monthly basis for one year. Neutron count data are presented in Appendix B.

Eight neutron access tubes located on three different benches on the repository were monitored monthly from May of 1996 through April of 1997. Three access tubes located on a lower bench of the repository penetrate to a depth of 70 feet and terminate five feet into the native undisturbed geologic material (Figure 2). Three access tubes on an intermediate bench penetrate to a depth of 150 - 160 feet and terminate ten feet into the undisturbed geologic material. One access tube located on the top of the repository penetrates to a depth of 201 feet and terminates approximately 105 feet above the undisturbed geologic material, and a second access tube on the repository top penetrates to a depth of 318 feet and terminates 15 feet into the undisturbed geologic material.

Neutron probe readings were taken with a Troxler 100 millicurie neutron probe with a Americium-Beryllium source. Readings were taken in increments which allowed water content to be measured in each layer of the capping sequence. Readings were taken every six inches in the capping materials from a depth of 6 inches to a depth of 6 feet. From 6 feet to 10 feet, readings were taken every one foot. For the repository profile below 10 feet, readings were taken every 5 feet. For the deepest tube, readings were taken every 2 feet below the 300 foot depth, in order to obtain more precise water content data for the transition from waste rock to undisturbed geologic material directly underlying the repository.

For each tube, a background neutron count was obtained by calculating the mean of five readings taken with the neutron probe positioned over the tube and in its shield. Background count data are presented in Appendix B.

Precipitation data were collected for the one year period from a weather station located approximately ¼ mile north of the neutron tubes at the top of the repository. The Belfort Instrument Company weighing precipitation gage was equipped with an Alter style wind screen.

Calculations

A neutron count ratio was calculated for each at depth reading by dividing the at depth neutron count by the mean background count according to Equation 7.

$$NCR = \frac{NC}{BC} \qquad [7]$$

In this equation, NCR equals the neutron count ratio for the depth increment, NC equals the neutron count reading for the depth increment, and BC equals the mean background count for the tube. Count ratios for each depth increment on each date are presented in Appendix C.

Volumetric water content was calculated by applying the neutron probe calibration presented above to neutron count ratio data. All Mill Gulch waste rock was assumed to be similar to the calibration material. The standard factory calibration was applied to the capping materials, because the capping sequence is comprised of relatively thin layers of different types of materials and therefore could not be adequately characterized by a field calibration. The standard factory calibration was assumed to be more applicable to the capping materials than the laboratory calibration. A laboratory calibration was produced for the repository waste rock material because wet conditions at accessible repository depths and the unconsolidated condition of the waste rock impeded field calibration efforts.

The standard factory calibration used for the capping material neutron probe data established the relationship between volumetric water content and neutron count ratio according to Equation 8.

$$\theta_v = 45.455 \times NCR - 5 \qquad [8]$$

The laboratory calibration used in processing neutron probe data for Mill Gulch waste rock is represented by Equation 9.

$$\theta_v = 27.479 \times CR - 0.9755 \qquad [9]$$

Changes in water storage within the capping materials and the repository contents were calculated on a month to month basis. Water storage for each tube at each depth increment was determined by multiplying the length of the depth increment by the percent volumetric water content according to Equation 10.

$$W = I \times \theta_v \qquad [10]$$

In Equation 10, W equals the water storage in inches within a given depth increment, I equals the length of the depth increment in inches, and θ_v equals the percent volumetric water content for the depth increment. Drainage from each tube was estimated by summing the negative changes in storage for each month, and infiltration into the repository was determined by summing the positive changes in water content for each month. Water storage and precipitation data are presented in Appendix D. Evapotranspiration was assumed negligible below the PVC geomembrane, but may have contributed to some of the water loss from the topsoil and oxidized waste rock layers of the cap. Because there was minimal vegetation at the site during the period of evaluation, evapotranspiration was not accounted for in drainage calculations.

RESULTS

Drainage Analysis

The Mill Gulch waste rock repository received a total of 14.26 inches of precipitation during the 12 month period of analysis. Drainage from the repository and repository cap ranged from 5.31 inches from the area monitored by the Lower bench - east tube to 23.70 inches from the area monitored by the Top bench - west tube (Table 1). Monthly cap and repository drainage did not appear to respond immediately or consistently to precipitation.

A large unreclaimed topsoil stockpile located up gradient from the top bench of the repository may have contributed run - on to the repository top. Run - on has been observed ponding on the top bench. No PVC liner is present directly under or within an approximate 50 foot distance from the topsoil stockpile. Therefore, ponded run – on could have infiltrated into the repository. Infiltration is assumed to be primarily vertical, with minimal lateral movement. Therefore, run - on from the topsoil stockpile could have greatly influenced water content of the material directly underlying the repository top, and may account for some of the increased drainage reported from the top bench tubes. Because much of this run - on is slowed by infiltration through the topsoil stockpile, with eventual release at the stockpile toe, it is not likely that run - on was consistently concurrent with precipitation event. Lag time between precipitation and run - on probably diminished correlation between precipitation events and drainage.

Table 1. Monthly precipitation and drainage totals from the Mill Gulch waste rock repository and cap.

Lower Bench

		Drainage (inches)								
		West Tube			Center Tube			East Tube		
Month	Precipitation	Cap	Repository	Total	Cap	Repository	Total	Cap	Repository	Total
June	3.29	0.00	0.77	0.77	0.00	0.00	0.00	0.00	0.00	0.00
July	1.04	1.08	0.00	1.08	0.00	0.13	0.13	0.56	0.00	0.56
August	0.32	0.41	0.71	1.11	0.26	0.00	0.26	0.00	0.00	0.00
September	3.13	0.00	1.57	1.57	0.11	2.06	2.17	0.35	1.40	1.75
October	0.95	0.00	0.00	0.00	0.11	0.05	0.16	0.00	0.00	0.00
December	1.96	0.00	0.00	0.00	0.00	1.06	1.06	0.00	0.03	0.03
January	1.35	0.00	2.91	2.91	1.34	0.00	1.34	0.00	2.97	2.97
March	0.83	0.01	0.00	0.01	0.13	0.76	0.89	0.00	0.00	0.00
April	1.39	0.02	0.00	0.02	1.17	0.00	1.17	0.00	0.00	0.00
Total	14.26	1.52	5.96	7.48	3.12	4.06	7.17	0.91	4.40	5.31

Middle Bench

		Drainage (inches)								
		West Tube			Center Tube			East Tube		
Month	Precipitation	Cap	Repository	Total	Cap	Repository	Total	Cap	Repository	Total
June	3.29	0.00	1.78	1.78	0.00	0.22	0.22	0.01	0.00	0.01
July	1.04	1.58	0.66	2.24	1.17	0.00	1.17	1.03	0.00	1.03
August	0.32	0.39	0.00	0.39	0.35	0.00	0.35	0.53	2.65	3.18
September	3.13	0.00	1.32	1.32	0.00	1.77	1.77	0.00	1.74	1.74
October	0.95	0.29	0.00	0.29	0.59	0.00	0.59	0.00	1.39	1.39
December	1.96	0.00	1.29	1.29	0.00	0.00	0.00	0.26	0.00	0.26
January	1.35	0.00	4.99	4.99	0.00	4.18	4.18	0.00	4.35	4.35
March	0.83	0.12	0.00	0.12	no data available					
April	1.39	0.00	0.85	0.85	0.00	0.00	0.00	0.00	0.00	0.00
Total	14.26	2.38	10.88	13.26	2.11	6.17	8.28	1.83	10.13	11.96

Top Bench

		Drainage (inches)					
		West Tube			East Tube		
Month	Precipitation	Cap	Repository	Total	Cap	Repository	Total
June	3.29	0.00	0.30	0.30	1.93	4.86	6.78
July	1.04	0.96	0.00	0.96	0.00	0.03	0.03
August	0.32	0.00	0.00	0.00	0.02	0.00	0.02
September	3.13	0.00	6.97	6.97	0.22	6.46	6.68
October	0.95	0.26	0.00	0.26	0.30	3.30	3.60
December	1.96	0.43	2.90	3.33	0.26	0.00	0.26
January	1.35	0.00	7.48	7.48	0.00	6.33	6.33
March	0.83	no data available					
April	1.39	0.46	0.00	0.46	0.00	0.00	0.00
Total	14.26	2.12	17.65	19.76	2.72	20.97	23.70

It should be noted that during the months of high drainage, water contents were slightly lower than the previous month throughout the entire repository profile. Unless water recharge was from a source other than precipitation, it is highly unlikely that an entire 300 foot profile would lose a consistent amount of water storage in one month and then return to the previous water content the following month. For this reason, it is possible that reported decreases are the result of an equipment malfunction. Because the tubes on the top bench intercept a much longer repository profile than the other tubes, the effect of this type of error would be amplified. An equipment malfunction was discovered at the end of the monitoring period which caused neutron probe readings to be falsely low. The malfunction caused neutron counts to be up to 600 counts low due to a display malfunction in the hundreds place. Because field neutron counts typically ranged from 3,000 to 23,000, this error could have caused up to 20 percent error. It is not known whether this malfunction occurred during field data collection.

In principle, water added to a profile which is more wet than field capacity will displace water downward without causing an increase in volumetric water content. Thus, water may have moved through the repository profile undetected by the neutron probe. For this reason, drainage may have been greater than calculated. This piston displacement phenomenon was observed during the laboratory calibration of the neutron probe for Mill Gulch waste rock. After the volumetric water content of the calibration material had been raised above 5 percent, further additions of water did not result in significant changes in neutron count ratio or TDR volumetric water content, but did result in drainage. The neutron count ratio and TDR volumetric water content responded only when the drainage was capped to prevent further drainage and the calibration material was wetted to saturation. For this reason, drainage calculations for the Mill Gulch repository represent a minimum value, discounting the previously mentioned equipment malfunction.

Volumetric water content data for each depth suggest zones of relatively dry waste rock material interspersed within zones of waste rock which are at or above field capacity. It is likely that the more wet zones have a more fine texture and higher water holding capacity than the calibration material. Therefore, these zones of higher water content may not drain at the calculated field capacity volumetric water content of approximately six percent. It is estimated that approximately 58 percent of the volume of the Mill Gulch repository has a higher water holding capacity than the calibration material.

The heterogeneity of the material in the Mill Gulch waste rock repository creates a condition where lenses of material having a variety of average particle size are likely to exist. The materials used in the calibration exercise consisted of a well graded mixture of particles ranging in size from less than 1/16 inch in diameter to 6.5 inches in diameter. Well graded mixtures have a uniform distribution of a range of particle sizes. It is probable that lenses of poorly graded material having an average particle size of greater than or less than the average particle size of the calibration material exist. Such lenses would have respective water holding capacities of less than and greater than the calibration materials. For this reason, zones of material which consistently have a lower water content than the material directly above do not necessarily represent drainage barriers. It is more likely that these zones represent layers of coarse material which have a high percentage of void space and lower water holding capacity than the calibration material. Such layers would drain quickly into underlying materials. Similarly, zones of material which consistently have water contents exceeding that of the saturated calibration material represent lenses of fine material.

During repository construction, larger particles (boulders) tend to form a rubble zone in the lower areas of each lift, creating a lens of very coarse material, while finer particles tend to remain in the upper zones of each lift, where they are compacted by equipment and haul traffic, forming a lens of fine textured material with higher water holding capacity. These lenses are likely to form at depth intervals which approximate the thickness of each lift.

For instance, at the depth increment from 52.5 feet to 57.5 feet for the Lower bench - east tube, the volumetric water content is consistently less than the calibrated field capacity volumetric water content value of 5.89 percent (Table 2). The volumetric water content of the material directly above this increment is estimated at well above field capacity, indicating that this zone of decreased moisture is probably a rubble zone containing void space. Another zone of slightly decreased water content can be observed in this tube at the 27.5 - 37.5 foot depth increment. The interval between these two zones of decreased moisture content is 30 feet, which is a likely lift thickness for repository construction.

Table 2. Volumetric water contents for the Lower bench – east tube.

Capping Materials

Depth Increment (ft)	Lithology	5-21-96	6-24-96	7-22-96	8-15-96	9-24-96	10-29-96	12-10-96	1-21-97	3-5-97	4-9-97
		Volumetric Water Content (%)									
0.25 - 0.75	This zone is under construction.										
0.75 - 1.25	topsoil							17.64	15.20	16.05	14.03
1.25 - 1.75	topsoil		12.42	7.53	5.40	12.25	9.73	15.39	22.14	24.04	17.67
1.75 - 2.25	oxidized waste rock	9.77	14.73	12.44	11.68	13.68	12.92	12.88	22.50	24.10	24.36
2.25 - 2.75	oxidized waste rock	14.09	16.00	14.18	14.01	14.34	13.86	13.90	20.91	22.13	23.45
2.75 - 3.25	oxidized waste rock	15.35	16.82	15.09	14.69	15.18	14.45	14.79	14.86	15.71	16.15
325 - 3.75	oxidized waste rock	17.30	19.39	16.50	16.73	17.09	16.09	16.53	15.73	18.34	17.56
3.75 - 4.25	Emmerson shale	33.16	33.82	30.10	32.00	30.43	31.62	31.06	29.14	30.91	31.05
4.25 - 4.75	Emmerson shale	37.41	37.96	38.60	39.34	38.44	38.79	38.64	37.89	37.92	37.60
4.75 - 5.25	Emmerson shale	36.71	36.82	36.95	37.38	35.92	36.42	36.26	34.73	37.12	36.25
5.25 - 5.75	Emmerson shale	34.28	35.18	34.86	35.57	34.74	35.27	34.85	32.62	35.05	34.95
5.75 - 6.50	Emmerson shale	32.77	33.87	34.88	34.99	33.65	34.01	34.82	32.02	34.41	34.68
6.50 - 7.50	Emmerson shale	30.16	31.84	32.40	33.51	32.42	32.36	32.50	30.68	32.91	33.45

Waste Rock

Depth Increment (ft)	Lithology	5-21-96	6-24-96	7-22-96	8-15-96	9-24-96	10-29-96	12-10-96	1-21-97	3-5-97	4-9-97
7.5 - 8.5	waste rock	17.45	19.08	19.92	20.83	20.74	20.83	21.16	20.14	21.41	21.60
8.5 - 9.5	waste rock	17.61	18.42	19.56	20.69	20.37	21.42	22.05	20.99	22.63	22.65
9.5 - 10.5	waste rock	17.10	17.73	18.97	19.50	20.05	20.32	20.88	19.73	21.16	21.30
10.5 - 17.5	waste rock	9.11	9.26	9.29	9.53	9.34	9.22	9.07	8.56	8.85	9.10
17.5 - 22.5	waste rock	9.37	9.28	9.61	9.60	9.50	9.29	9.39	8.60	9.37	9.22
22.5 - 27.5	waste rock	6.34	6.37	6.58	6.46	6.32	6.44	6.26	6.52	6.28	6.31
27.5 - 32.5	waste rock	5.84	5.75	6.01	6.08	5.76	5.93	5.77	5.47	5.84	5.90
32.5 - 37.5	waste rock	5.81	5.83	5.78	6.03	5.89	5.90	5.87	5.53	5.60	5.61
37.5 - 42.5	waste rock	8.39	8.62	8.67	8.88	8.32	8.68	8.52	7.99	8.38	8.35
42.5 - 47.5	waste rock	7.42	7.58	7.41	7.70	7.42	7.58	7.53	6.97	7.33	7.36
47.5 - 52.5	waste rock	8.22	8.16	8.49	8.73	8.57	8.38	8.46	7.93	8.28	8.48
52.5 - 57.5	waste rock	6.03	6.06	6.09	6.34	6.16	6.05	6.15	5.69	6.04	5.78
57.5 - 62.5	waste rock	4.69	4.83	4.94	4.95	4.75	4.63	4.80	4.44	4.76	4.65
62.5 - 67.5	native material	6.94	7.01	6.96	7.14	6.65	6.92	6.98	6.40	6.70	6.82
67.5 - 72.5	native material	7.32	7.38	7.07	7.09	6.88	7.12	6.98	6.56	6.86	6.98

Shaded cells indicate volumetric water content is above the critical value at which downward drainage will occur in response to gravity.

The Lower bench - west tube reveals a zone of decreased water content from the 37.5 foot depth to the 62.5 foot depth, not including the interval from 52.5 feet to 57.5 feet (Table 3). This may indicate the presence of the rubble zones from the bottom two lifts of the repository. The more wet depth increment from 6.5 to 17.5 feet probably represents a compacted layer of fine material that formed at the top of the final lift of waste rock.

Table 3. Volumetric water contents for the Lower bench – west tube

Capping Materials

Depth Increment (ft)	Lithology	5-21-96	6-24-96	7-22-96	8-15-96	9-24-96	10-29-96	12-10-96	1-21-97	3-5-97	4-9-97
		Volumetric Water Content (%)									
0.25 - 0.75	topsoil							8.77	4.62	1.06	6.85
0.75 - 1.25	topsoil		9.94	3.37	1.44	10.56	7.95	15.71	19.04	19.87	16.46
1.25 - 1.75	oxidized waste rock		13.63	9.34	8.33	13.02	11.80	14.82	25.95	25.50	20.66
1.75 - 2.25	oxidized waste rock	12.33	17.69	14.12	13.40	15.02	14.58	14.92	25.38	25.74	25.07
2.25 - 2.75	oxidized waste rock	16.40	19.45	16.12	15.86	15.72	15.93	15.79	18.55	18.65	19.06
2.75 - 3.25	oxidized waste rock	17.30	19.59	16.15	16.21	16.75	16.84	16.27	16.65	18.66	17.15
325 - 3.75	oxidized waste rock	16.00	20.14	15.81	15.67	15.92	15.82	15.61	15.29	15.98	15.96
3.75 - 4.25	oxidized waste rock	31.53	31.37	26.75	28.47	27.60	27.24	29.07	27.95	27.32	27.42
4.25 - 4.75	Emmerson shale	36.48	36.68	37.26	37.47	36.26	37.15	36.79	36.39	36.33	36.44
4.75 - 5.25	Emmerson shale	34.31	34.14	34.35	34.05	33.20	33.89	34.27	33.80	33.20	33.64
5.25 - 5.75	Emmerson shale	33.53	33.95	34.04	32.84	32.71	33.79	34.91	34.45	33.75	33.51
5.75 - 6.50	Emmerson shale	31.18	32.54	32.85	28.73	31.74	32.92	34.01	33.68	32.78	33.43

Waste Rock

Depth Increment (ft)	Lithology	5-21-96	6-24-96	7-22-96	8-15-96	9-24-96	10-29-96	12-10-96	1-21-97	3-5-97	4-9-97
6.50 - 7.50	waste rock	18.72	18.90	19.80	19.97	19.36	19.19	23.36	19.92	20.10	20.59
7.50 - 8.50	waste rock	14.41	14.84	15.90	15.97	15.69	16.48	16.98	16.93	16.58	16.84
8.50 - 9.50	waste rock	15.88	16.34	17.22	17.48	17.32	18.31	18.98	18.96	18.74	18.97
9.50 - 10.50	waste rock	17.58	17.60	18.63	18.79	19.00	19.51	20.01	19.86	19.56	20.19
10.50 - 17.50	waste rock	10.64	10.64	11.14	10.78	10.66	10.92	10.79	10.35	10.33	10.74
17.50 - 22.50	waste rock	8.93	8.98	9.20	9.05	8.80	8.82	9.02	8.39	8.67	8.59
22.50 - 27.50	waste rock	8.73	8.64	8.88	8.56	8.14	8.38	8.72	8.29	8.36	8.10
27.50 - 32.50	waste rock	7.28	7.25	7.46	7.22	6.92	8.61	7.32	6.91	6.97	7.18
32.50 - 37.50	waste rock	8.79	8.45	8.68	8.59	8.61	7.16	8.78	8.15	8.08	8.56
37.50 - 42.50	waste rock	3.98	3.87	3.83	4.03	3.84	3.58	3.96	3.61	3.83	3.96
42.50 - 47.50	waste rock	4.31	4.09	4.29	4.33	3.97	3.82	4.36	4.15	4.12	4.24
47.50 - 52.50	waste rock	4.67	4.49	4.56	4.41	4.59	4.34	4.64	4.32	4.24	4.42
52.50 - 57.50	waste rock	7.29	7.11	7.36	7.23	7.04	7.24	7.08	6.79	6.88	7.10
57.50 - 62.50	waste rock	3.15	2.88	3.10	3.24	2.85	3.16	3.01	2.82	2.85	3.00
62.50 - 67.50	waste rock	6.97	6.83	7.01	6.90	6.54	6.98	6.74	6.69	6.48	6.63
67.50 - 72.50	native material	9.31	9.15	9.16	9.30	8.96	9.54	9.18	8.73	8.86	8.70

Shaded cells indicate volumetric water content is above the critical value at which downward drainage will occur in response to gravity.

The Lower bench - center tube shows a zone of decreased water content over the depth increment from 32.5 feet to 37.5 feet, and from 52.5 feet to 62.5 feet (Table 4). These data confirm the presence of a layer containing very coarse fragments between the Lower bench - east tube and Lower bench - west tubes at the depth between 32.5 feet and 62.5 feet.

Table 4. Volumetric water contents for the Lower bench – center tube

Capping Materials

	Date	5-21-96	6-24-96	7-22-96	8-15-96	9-24-96	10-29-96	12-10-96	1-21-97	3-5-97	4-9-97
Depth Increment (ft)	Lithology				Volumetric Water Content (%)						
0.25 - 0.75	This zone is under construction.										7.19297
0.75 - 1.25	topsoil					9.41	8.53	15.29	21.52	19.7154	16.6995
1.25 - 1.75	topsoil		4.52	9.61	8.57	15.99	15.31	15.55	25.35	25.2048	22.3343
1.75 - 2.25	oxidized waste rock	13.56	15.70	16.06	15.07	16.12	15.92	15.18	19.17	19.30	23.83
2.25 - 2.75	oxidized waste rock	15.13	17.36	15.96	15.30	16.18	15.70	15.18	16.21	17.19	20.55
2.75 - 3.25	oxidized waste rock	16.01	17.11	15.82	15.15	15.69	15.66	14.92	14.61	14.37	17.61
325 - 3.75	oxidized waste rock	15.89	17.57	16.16	15.35	16.17	15.51	24.10	15.57	16.15	17.07
3.75 - 4.25	oxidized waste rock	26.02	24.64	23.57	23.38	24.11	22.14	38.06	23.05	23.46	22.89
4.25 - 4.75	Emmerson shale	38.14	37.81	37.66	38.88	38.03	38.07	35.46	37.77	36.72	37.12
4.75 - 5.25	Emmerson shale	35.19	35.30	36.84	36.34	35.68	35.54	34.44	36.07	35.18	35.47
5.25 - 5.75	Emmerson shale	34.36	35.04	35.55	35.08	34.34	34.48	35.69	34.52	34.24	34.47
5.75 - 6.50	Emmerson shale	35.47	35.66	36.09	35.98	35.47	35.54	34.22	35.33	34.45	35.60
6.50 - 7.50	Emmerson shale	34.12	34.39	35.64	35.12	33.70	34.42	38.24	34.26	34.03	34.40

Waste Rock

7.50 - 8.50	waste rock	24.60	24.72	25.18	25.60	25.14	24.72	23.93	25.23	24.35	24.92
8.50 - 9.50	waste rock	23.58	24.04	23.84	24.19	23.77	24.31	23.06	23.88	24.19	24.25
9.50 - 10.50	waste rock	21.18	21.91	22.01	22.85	22.78	22.76	22.23	22.97	22.64	22.72
10.50 - 17.50	waste rock	10.01	10.16	10.43	10.61	10.02	10.28	9.00	9.73	9.96	10.29
17.50 - 22.50	waste rock	9.20	9.09	9.11	9.29	9.05	9.19	9.08	8.92	8.90	9.02
22.50 - 27.50	waste rock	9.43	9.29	9.03	9.57	9.18	8.98	9.39	9.22	8.82	9.10
27.50 - 32.50	waste rock	5.88	5.98	5.96	6.19	5.88	6.03	6.12	5.83	5.63	5.76
32.50 - 37.50	waste rock	4.13	4.30	4.03	4.08	4.08	3.95	3.92	3.88	3.82	3.90
37.50 - 42.50	waste rock	6.43	6.53	6.54	6.53	6.46	6.40	6.16	6.24	6.36	6.34
42.50 - 47.50	waste rock	7.54	7.38	7.40	7.48	7.33	7.15	7.54	7.34	7.31	7.41
47.50 - 52.50	waste rock	8.26	8.52	8.38	8.86	8.24	8.31	8.50	8.39	8.29	8.45
52.50 - 57.50	waste rock	5.02	5.05	4.99	5.15	5.00	4.91	4.93	5.03	4.77	4.96
57.50 - 62.50	waste rock	4.51	4.53	4.53	4.76	4.61	4.43	4.41	4.42	4.24	4.29
62.50 - 67.50	waste rock	7.44	7.46	7.51	7.67	7.36	7.36	7.20	7.36	7.09	7.13
67.50 - 72.50	native material	7.36	7.64	7.38	7.64	7.23	7.27	7.30	7.18	7.14	7.29

Shaded cells indicate volumetric water content is above the critical value at which downward drainage will occur in response to gravity.

Observations from the deeper portions of the middle tubes and Top bench - east tube show a zone of decreased water content immediately overlying the native material (Tables 5 - 8). Because the water content in these zones is moderately variable, these data probably represent a zone of coarser material containing void spaces which may drain quickly and fluctuate in water content from slightly below the actual field capacity of this coarser material to field capacity.

Apparent rubble zones identified where volumetric water contents are consistently much less than 5.89 percent are visible at the 22.5 - 27.5, 82.5 - 87.5, 102.5 - 107.5, 122.5 - 127.5, 152.5 - 177.5 foot, and bottom depth increments of the Top bench - east tube (Table 9). These zones occur at increments which are likely to represent the lift thickness of the repository construction. Rubble zones are also visible in the volumetric water content data collected from the Top bench - west tube.

Drainage from the Lower Bench

A comparison of monthly precipitation to cap and repository drainage totals for the Lower bench is given in Figure 7.

On the Lower bench, the West tube had 0.77 inches of repository drainage and no cap drainage in June, a month during which 3.29 inches of precipitation fell on Mill Gulch, while the center and east tubes had no measurable drainage. Large water storage increases were observed in the capping materials at all three tubes. Water loss from the Lower bench - west tube emanated largely from that portion of the repository 22.50 feet and deeper. Small water changes in the Center and East tubes occurred throughout the entire profile.

Table 5. Volumetric water contents for the Middle bench - west tube.

Capping Materials

	Date	5-21-96	6-24-96	7-22-96	8-15-96	9-24-96	10-29-96	12-10-96	1-21-97	3-5-97	4-9-97
Depth Increment (ft)	Lithology				Volumetric Water Content (%)						
0.25 - 0.75	This zone is under construction.										
0.75 - 1.25	topsoil										
1.25 - 1.75	topsoil	9.58	9.57	3.97	2.32	7.33	5.90	11.78	18.30	18.74	14.08
1.75 - 2.25	oxidized waste rock	16.19	17.32	13.31	12.50	14.48	13.94	14.11	22.36	22.69	24.34
2.25 - 2.75	oxidized waste rock	16.78	17.98	15.53	14.45	15.96	15.37	14.83	17.81	19.05	25.81
2.75 - 3.25	oxidized waste rock	16.78	17.74	15.74	15.36	16.37	15.59	15.54	15.71	14.95	22.65
325 - 3.75	oxidized waste rock	16.48	17.56	15.39	14.84	16.04	15.56	15.24	15.04	16.96	20.87
3.75 - 4.25	oxidized waste rock	16.62	17.62	16.06	15.59	15.89	15.65	15.38	14.03	12.90	14.95
4.25 - 4.75	oxidized waste rock	15.59	17.24	14.84	14.78	15.81	15.19	14.82	14.04	13.25	13.55
4.75 - 5.25	Emmerson shale	22.64	26.03	19.50	18.38	19.63	18.39	18.02	16.42	14.89	16.10
5.25 - 5.75	Emmerson shale	39.61	39.56	38.85	39.80	39.00	39.04	40.16	37.06	37.61	37.36
5.75 - 6.5	Emmerson shale	35.14	36.92	37.63	36.74	37.68	38.42	37.99	37.20	35.72	37.79

Waste Rock

6.5 - 7.5	waste rock	13.14	13.62	13.86	13.90	13.84	13.98	14.06	13.35	13.27	13.51
7.5 - 8.5	waste rock	11.20	11.05	10.96	11.21	10.94	11.38	11.02	10.77	10.96	10.65
8.5 - 9.5	waste rock	10.69	10.51	10.77	10.90	10.34	10.65	10.45	10.14	10.15	10.33
9.5 - 10.5	waste rock	10.81	10.39	10.62	10.78	10.73	10.63	10.65	10.31	10.18	10.40
10.5 - 17.5	waste rock	10.43	10.26	10.19	10.44	10.35	10.62	10.20	9.78	10.07	9.92
17.5 - 22.5	waste rock	10.73	10.60	10.74	10.95	10.47	10.98	10.32	10.17	10.20	10.26
22.5 - 27.5	waste rock	9.55	9.38	9.35	9.65	9.34	9.92	9.60	9.31	9.16	9.39
27.5 - 32.5	waste rock	8.59	8.29	8.55	8.80	8.80	8.88	8.52	8.40	8.75	8.46
32.5 - 37.5	waste rock	9.43	9.36	9.37	9.53	9.45	9.71	9.81	9.01	9.05	9.16
37.5 - 42.5	waste rock	10.54	10.47	10.38	10.63	10.38	10.45	10.40	10.07	10.03	10.09
42.5 - 47.5	waste rock	10.52	10.37	10.16	10.23	10.07	10.48	10.30	9.76	9.78	9.89
47.5 - 52.5	waste rock	9.32	9.20	9.17	9.54	9.31	9.55	9.28	8.80	8.73	9.03
52.5 - 57.5	waste rock	8.60	8.35	8.24	8.36	8.31	8.41	8.29	7.96	7.81	7.95
57.5 - 62.5	waste rock	9.52	9.43	9.50	9.48	9.64	9.91	9.80	9.31	9.15	9.31
62.5 - 67.5	waste rock	9.50	9.49	9.68	9.50	9.67	9.75	9.64	9.22	8.76	9.33
67.5 - 72.5	waste rock	10.36	10.39	10.19	9.96	10.10	10.77	10.24	9.74	10.09	9.81
72.5 - 77.5	waste rock	11.39	10.95	11.17	11.21	10.95	11.12	11.16	10.56	11.10	10.62
77.5 - 82.5	waste rock	6.28	6.51	6.58	6.85	6.64	7.09	6.89	6.56	6.73	6.55
82.5 - 87.5	waste rock	7.52	7.74	7.70	7.62	7.62	7.72	7.80	7.58	7.69	7.45
87.5 - 92.5	waste rock	3.62	3.47	3.33	3.51	3.44	3.55	3.45	3.36	3.24	3.50
92.5 - 97.5	waste rock	10.45	10.14	10.04	10.33	10.33	10.53	10.25	9.85	10.14	9.62
97.5 - 102.5	waste rock	3.66	3.66	3.99	3.71	3.79	3.93	3.80	3.53	4.09	3.81
102.5 - 107.5	waste rock	3,06	2.94	2.85	3.05	3.07	1.86	3.20	2.88	3.34	2.96
107.5 - 112.5	waste rock	3.21	3.04	3.07	3.13	3.19	2.05	3.16	2.99	2.99	3.05
112.5 - 117.5	waste rock	3.66	3.59	3.45	3.51	3.59	3.59	3.58	3.39	3.42	3.36
117.5 - 122.5	waste rock	4.09	3.86	3.73	3.82	3.64	3.88	3.78	3.64	4.07	3.62
122.5 - 127.5	waste rock	4.02	3.60	2.55	2.58	2.53	2.63	2.47	2.33	2.32	2.45
127.5 - 132.5	waste rock	2.98	3.18	3.16	3.13	2.99	3.09	2.96	2.81	3.32	2.84
132.5 - 137.5	waste rock	2.69	2.65	2.55	2.58	2.49	2.69	2.40	2.45	2.23	2.37
137.5 - 142.5	native material	10.58	10.12	9.97	10.18	9.96	10.35	9.52	9.10	8.78	11.56
142.5 - 147.5	native material	12.12	12.14	12.12	12.27	12.17	12.34	11.96	10.89	11.26	18.86

Shaded cells indicate volumetric water content is above the critical value at which downward drainage will occur in response to gravity.

Table 6. Volumetric water contents for the Middle bench - center tube.

Count Ratios of Capping Materials

	Date	5-21-96	6-24-96	7-22-96	8-15-96	9-24-96	10-29-96	12-10-96	1-21-97	4-9-97
Depth Increment (ft)	**Lithology**				**Volumetric Water Content (%)**					
0.25 - 0.75	This zone is under construction.									
0.75 - 1.25	This zone is under construction.									
1.25 - 1.75	topsoil	17.56	15.21	9.86	8.44	13.15	11.47	12.17	20.60	22.81
1.75 - 2.25	oxidized waste rock	22.00	23.39	23.02	19.82	24.45	23.29	22.74	25.49	26.56
2.25 - 2.75	oxidized waste rock	17.46	19.04	16.12	15.42	17.04	15.82	15.56	16.12	16.61
2.75 - 3.25	oxidized waste rock	19.05	23.09	17.76	17.34	18.64	17.04	16.47	17.78	19.09
325 - 3.75	oxidized waste rock	21.99	23.97	19.88	19.08	22.32	19.12	18.31	19.14	20.49
3.75 - 4.25	oxidized waste rock	33.03	31.85	30.55	29.06	29.84	27.99	29.97	27.35	25.61
4.25 - 4.75	Emmerson shale	35.73	36.85	36.61	36.98	36.29	36.58	36.85	35.87	35.26
4.75 - 5.25	Emmerson shale	37.74	38.40	39.13	39.41	38.98	38.86	39.27	38.91	37.84
5.25 - 5.75	Emmerson shale	34.02	35.25	35.30	36.00	36.37	36.79	36.09	35.90	35.54
5.75 - 6.5	Emmerson shale	33.65	34.18	33.56	34.36	34.08	34.38	34.73	33.98	33.80

Volumetric Water Content of Waste Rock

6.5 - 7.5	waste rock	13.29	14.38	15.30	15.53	16.28	16.15	15.58	15.84	15.65
7.5 - 8.5	waste rock	10.42	10.75	10.87	10.83	10.68	10.90	10.82	10.57	10.30
8.5 - 9.5	waste rock	9.84	9.97	9.91	9.84	9.78	9.93	9.69	9.60	9.74
9.5 - 10.5	waste rock	9.54	9.70	9.52	9.74	9.61	9.46	9.40	9.28	9.29
10.5 - 17.5	waste rock	9.32	9.44	9.60	9.54	9.44	9.52	9.51	9.24	9.16
17.5 - 22.5	waste rock	10.12	10.17	10.09	9.99	10.05	10.16	10.03	9.65	9.73
22.5 - 27.5	waste rock	10.50	10.41	10.22	10.46	10.07	10.26	10.23	9.92	9.99
27.5 - 32.5	waste rock	11.85	11.96	11.84	11.95	11.73	12.06	11.91	11.37	11.55
32.5 - 37.5	waste rock	11.46	10.92	11.09	11.10	10.78	10.78	10.79	10.65	10.48
37.5 - 42.5	waste rock	11.12	11.28	11.21	11.28	11.16	11.36	11.27	11.22	10.93
42.5 - 47.5	waste rock	11.84	11.76	11.90	12.22	11.90	11.70	11.84	11.66	11.45
47.5 - 52.5	waste rock	10.49	10.64	10.98	10.82	10.57	10.95	10.28	10.36	10.50
52.5 - 57.5	waste rock	4.37	4.43	4.25	4.23	4.25	3.98	4.27	4.18	3.89
57.5 - 62.5	waste rock	6.21	5.94	5.92	5.95	6.01	5.80	6.82	5.76	5.51
62.5 - 67.5	waste rock	7.73	7.80	7.78	7.98	7.89	7.59	8.16	7.32	7.42
67.5 - 72.5	waste rock	9.04	9.14	9.13	9.07	9.48	9.07	9.10	8.86	9.04
72.5 - 77.5	waste rock	11.71	11.64	11.95	11.79	11.49	11.77	11.77	11.43	11.49
77.5 - 82.5	waste rock	3.59	3.43	3.71	3.62	3.50	3.64	3.84	3.54	3.71
82.5 - 87.5	waste rock	4.51	4.36	4.25	4.28	4.14	4.37	4.45	4.31	4.48
87.5 - 92.5	waste rock	2.50	2.54	2.41	2.39	2.39	2.32	2.44	2.29	2.28
92.5 - 97.5	waste rock	4.72	4.75	4.45	4.49	4.37	4.39	4.62	4.12	4.49
97.5 - 102.5	waste rock	5.28	5.54	5.58	5.58	5.64	5.72	5.45	5.43	5.31
102.5 - 107.5	waste rock	3.50	3.74	3.69	3.88	3.76	3.90	3.67	3.62	3.69
107.5 - 112.5	waste rock	2.75	2.70	2.79	2.97	2.78	2.81	2.75	2.61	2.64
112.5 - 117.5	waste rock	3.53	3.53	3.49	3.61	3.57	3.57	3.43	3.44	3.33
117.5 - 122.5	waste rock	3.62	3.42	3.46	3.41	3.41	3.34	3.29	3.31	3.29
122.5 - 127.5	waste rock	4.06	3.90	3.74	3.95	3.84	3.83	3.77	3.55	3.82
127.5 - 132.5	waste rock	5.69	5.48	5.41	5.18	4.65	4.66	4.67	4.77	4.52
132.5 - 137.5	waste rock	3.10	3.04	3.08	3.18	3.02	2.99	2.94	2.84	2.82
137.5 - 142.5	waste rock	3.14	3.11	3.24	3.15	3.12	3.06	2.95	1.75	2.86
142.5 - 147.5	native material	11.87	11.75	11.76	12.02	11.58	11.58	11.38	11.13	10.91
147.5 - 152.5	native material	10.01	10.18	9.90		9.95				

Shaded cells indicate volumetric water content is above the critical value at which downward drainage will occur in response to gravity.

Table 7. Volumetric water contents for the Middle bench - east tube.

Capping Materials

Depth Increment (ft)	Date / Lithology	5-21-96	6-24-96	7-22-96	8-15-96	9-24-96	10-29-96	12-10-96	1-21-97	4-9-97
					Volumetric Water Content (%)					
0.25 - 0.75	This zone is under construction.									
0.75 - 1.25	This zone is under construction.									
1.25 - 1.75	topsoil	11.38	12.86	5.15	2.90	9.22	6.58	11.20	17.84	16.26
1.75 - 2.25	oxidized waste rock	18.92	20.35	15.97	14.20	16.82	16.22	16.52	27.71	26.44
2.25 - 2.75	oxidized waste rock	19.23	20.61	17.74	16.16	18.50	16.98	17.44	20.56	20.91
2.75 - 3.25	oxidized waste rock	18.16	19.13	17.34	16.34	17.71	17.02	16.51	15.42	15.92
325 - 3.75	oxidized waste rock	19.29	19.95	18.35	17.83	18.07	17.63	17.07	16.79	17.35
3.75 - 4.25	Emmerson shale	20.49	21.56	19.99	19.52	19.92	19.28	18.79	18.50	20.30
4.25 - 4.75	Emmerson shale	30.93	28.45	27.66	26.93	26.79	32.59	26.74	21.65	21.81
4.75 - 5.25	Emmerson shale	35.27	35.53	36.04	36.05	36.03	35.78	36.46	34.98	34.81
5.25 - 5.75	Emmerson shale	35.14	35.79	35.69	35.83	35.36	35.63	35.52	34.96	34.50
5.75 - 6.5	Emmerson shale	33.58	34.29	34.41	34.90	34.55	35.07	34.62	33.93	34.17
6.5 - 7.5	Emmerson shale	26.79	23.47	24.95	24.28	24.65	25.30	24.19	24.82	25.49

Waste Rock

Depth Increment (ft)	Lithology	5-21-96	6-24-96	7-22-96	8-15-96	9-24-96	10-29-96	12-10-96	1-21-97	4-9-97
7.5 - 8.5	waste rock	11.16	11.28	11.32	11.40	11.47	11.29	11.38	11.14	11.25
8.5 - 9.5	waste rock	10.46	10.51	10.80	10.68	10.51	10.59	10.55	10.33	10.44
9.5 - 10.5	waste rock	9.93	10.16	10.17	10.19	10.07	10.01	10.13	9.94	9.85
10.5 - 17.5	waste rock	10.06	10.16	10.39	10.35	10.21	10.13	10.34	9.41	9.74
17.5 - 22.5	waste rock	10.43	10.42	10.68	10.84	10.64	10.57	10.52	10.20	10.14
22.5 - 27.5	waste rock	10.29	10.31	10.87	10.49	10.23	10.39	10.58	10.21	10.26
27.5 - 32.5	waste rock	12.04	12.15	11.92	12.06	11.90	11.66	11.76	11.62	11.90
32.5 - 37.5	waste rock	11.08	11.45	11.53	11.63	11.16	11.25	11.25	11.15	11.66
37.5 - 42.5	waste rock	10.10	10.69	10.71	10.60	10.60	10.35	10.64	10.06	11.09
42.5 - 47.5	waste rock	9.28	9.19	9.16	9.13	8.95	8.92	8.86	8.38	9.48
47.5 - 52.5	waste rock	7.96	8.00	7.99	8.12	7.88	7.77	7.88	7.42	8.06
52.5 - 57.5	waste rock	5.51	5.72	5.55	5.37	5.52	5.45	5.47	5.09	5.61
57.5 - 62.5	waste rock	6.62	6.95	6.93	6.88	6.85	6.73	6.64	6.78	6.42
62.5 - 67.5	waste rock	5.73	6.53	7.07	7.08	7.10	7.22	7.36	7.01	6.94
67.5 - 72.5	waste rock	4.85	5.24	5.35	5.24	5.48	5.49	5.33	5.25	5.32
72.5 - 77.5	waste rock	3.50	3.51	3.70	3.70	3.56	3.57	3.50	3.45	3.37
77.5 - 82.5	waste rock	3.17	3.28	3.31	3.31	3.41	3.19	3.21	2.96	2.96
82.5 - 87.5	waste rock	4.13	4.02	4.28	4.16	4.23	4.15	4.13	4.00	4.04
87.5 - 92.5	waste rock	3.54	3.51	3.56	3.50	3.49	3.51	3.39	3.40	3.59
92.5 - 97.5	waste rock	2.35	2.50	2.65	2.72	2.55	2.50	2.66	2.57	2.66
97.5 - 102.5	waste rock	2.48	2.40	2.45	2.55	2.51	2.48	2.46	2.42	2.36
102.5 - 107.5	waste rock	10.69	10.52	10.94	10.82	10.66	10.65	10.78	10.36	10.22
107.5 - 112.5	waste rock	4.35	4.32	4.53	4.60	4.44	4.44	4.57	4.30	4.44
112.5 - 117.5	waste rock	2.86	3.05	3.04	3.04	3.00	2.78	2.87	2.73	2.80
117.5 - 122.5	waste rock	7.76	7.51	7.52	3.84	3.55	3.49	3.51	3.30	3.31
122.5 - 127.5	waste rock	4.28	4.08	4.11	4.02	3.85	3.66	3.53	3.54	3.52
127.5 - 132.5	waste rock	4.48	4.49	4.23	4.03	3.62	3.46	3.68	3.38	3.50
132.5 - 137.5	waste rock	3.63	3.64	3.83	3.90	3.70	3.46	3.25	3.00	3.08
137.5 - 142.5	waste rock	3.29	3.61	3.73	3.80	3.75	3.62	3.50	3.18	2.76
142.5 - 147.5	waste rock	1.87	1.93	2.04	2.02	1.93	1.80	2.03	1.92	1.85
147.5 - 152.5	waste rock	1.81	2.13	2.35	2.21	2.40	2.24	2.28	2.12	2.12
152.5 - 157.5	native material	4.98	5.54	5.55	5.63	5.79		5.48	5.48	5.03
157.5 - 162.5	native material	10.05		13.91	8.90	8.72		8.66	8.48	8.40

Shaded cells indicate volumetric water content is above the critical value at which downwa drainage will occur in response to gravity.