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Model Assessment of Alternatives for Reducing Seepage from Buried Uranium Mill Tailings at the Morton Ranch Site in Central Wyoming

Prepared by R.W. Nelson, A.E. Reisenauer, G.W. Gee

Battelle-Pacific Northwest Laboratory

Prepared for
U.S. Nuclear Regulatory Commission

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SUMMARY

A model assessment was made to evaluate contaminant transport to ground water from clay-lined and partially-lined pits containing uranium mill tailings. The assessment involved combined subsurface fluid flow and contaminant transport modeling of four alternatives for controlling seepage from buried tailings. The input hydrologic soil characteristics were measured on materials typical of those found at the Morton Ranch uranium mill site in central Wyoming. The assessment included combined saturated and partially saturated flow and contaminant transport models for two-dimensional vertical, cross sections typical of the tailings burial pits proposed for use at Morton Ranch.

The results obtained from the models were the contaminant flow paths away from the tailings pits, the advancing contaminant flow fronts for various sorbed and non-sorbed constituents of major environmental concern, and the associated quantities of contaminant flow for each of the alternatives. These results enable us to compare the environmental consequences of the four alternatives. It was also possible to gain considerable insight about combining the beneficial alternatives to obtain the best overall method for controlling seepage from the buried pits.

The four alternatives we considered to minimize seepage of contaminants from buried mine tailings included:

1) Placement of saturated tailings in a covered pit with a clay liner in the bottom, but no side liners.
2) Placement of dewatered tailings in a covered pit with clay bottom liner, but no side liners.
3) Placement of saturated tailings in a pit having a clay bottom liner, no side liners, and drains to facilitate pumping of drainage solution from sumps placed above the bottom clay liner.
4) Placement of saturated tailings in a pit with both bottom and side clay liners.

All four alternatives might be interpreted as being based upon a premise or goal of isolating and containing the drainage solution through use of clay liners. Such a goal is never realized, however, because clay, like any other liner material, always has a low rate of seepage which allows losses to occur over extended time periods. Accordingly, complete containment is not a goal that can be realized; rather the goal is to economically minimize the detrimental environmental consequences of seepage.

The first alternative — the one with no side wall liner — is the most economical of the four but it is the least effective for minimizing environmental consequences. The undesirable environmental effects come from excessive seepage out of the pit side walls; however, the study results conclusively show that seepage is not uniform over the entire height of the side wall. In fact, the model results demonstrate that seepage into the upper 70 to 80% of the side wall results in few if any detrimental effects. The greatest seepage occurs at the bottom, i.e., near the intersection of the bottom clay liner with the side wall. At higher and higher levels on the side wall, the contaminant seepage diminishes and becomes insignificant. The negligible effects higher on the side wall are explained by the well-established nonlinear theory for partially saturated flow.

These results have important implications for considering management alternative No. 4, which uses clay liners over the entire side wall height: Little or no actual environmental benefits result from placing clay on the upper 70 to 80% of the pit side wall. Therefore, lining the entire side wall with clay is economically wasteful and should not be done.

Alternatives No. 2 (dewatered tailings) and No. 3 (using drains in the tailings) emphasize reducing the actual volume of fluid available for seepage from the pits coupled with using a bottom clay liner to minimize vertical seepage from the much larger bottom area of the pit. Both of these alternatives significantly reduce the detrimental environmental consequences as compared to alternative No. 1.

A comparison of sulfate peak loss rates for alternates No. 1, 2, and 3 shows the merits of reducing the volume of fluid potentially available for seepage from the pits. Alternative No. 1 (with no attempted fluid reduction) had a peak outflow rate of 383 kilograms per day per lineal meter of pit length. Alternatives No. 2 (dewatered tailings) and No. 3 (installed drains), both of which reduce the fluid volume for potential seepage from the pit, had maximum rates of 3.2 and 2.2 kg/day/m, respectively. These results represent more than a 120-fold reduction in peak sulfate outflow for dewatered tailings. When a drain is placed in the tailings above the bottom clay liner, the reduction is more than a factor of 170. Reductions of this magnitude indicate the significant benefits of reducing the fluid volume in the tailings as a means of controlling contaminant seepage from the burial pits.

The sulfate, which moves with the tailings water, was found to be the most environmentally harmful leachate constituent in the tailings solution. Other chemical and nuclide constituents of lesser concern, viz. ^{120}Pb, ^{238}U, and pH, were considered in the transport analysis. Each of these constituents was evaluated in terms of the distance of movement of the contaminant front away from the pit with time. The acid front represented by a pH value of 2.2 was determined first, since the sorbtion distribution factor (Kd) of the lead and uranium was very strongly dependent upon the pH. Also, the sorbtion distribution coefficients of ^{230}Th at pH 2.2 was so similar to ^{238}U that only the ^{238}U transport analyses were made. In all cases, the front advance for these contaminants simply reconfirmed the results already presented for the control alternatives as shown by the sulfate results.

The best contaminant seepage control would be provided by combining the most desirable features of the four alternatives considered in this study. In addition to the accepted covering procedure already proposed we recommend:

1) Provision of a bottom clay liner placed at least 3.05 m (10 ft) above the regional water table and not less than 0.91 m (3 ft) thick;

2) Provision of stub clay side liners only part way up the pit side wall to form a saucer-shaped bottom and side liner for the pit;

3) Installation of a network of gravity drains and pumping sumps with the drains in the tailings sufficiently above the bottom clay liner to provide very effective drainage of the tailings;

4) Pumping of tailings drainage effluent from the sumps during filling of the pit with tailings and as required for the first 6 to 8 months after the filling is completed.

The tailings placed in the pits could be either dewatered or saturated, providing, of course, that adequate drain and pumping capacity are provided for the wetter saturated tailings. If tailings were slurried into the pit, perhaps separate decant sumps should be used, or extreme care must be exercised to assure that the tailings underdrains would not be clogged by settlement of decant-carried sediment in the sumps.

It is important to realize that there is a trade off between the height to which the side liners must be placed in the pit wall and the effectiveness of the underdrainage system. The effectiveness of the drain alternative found in this study, when no side liner was present to give a saucer effect, hints that only small side liner heights may be required.

Additional studies, however, will be required to determine the exact side liner heights needed to insure acceptable minimum contaminant seepage in the most economical way. Specifically, further study of various soil materials and other pit configurations using the combined approach of lining and reducing tailings water (as proposed above) will be necessary. Companion field observations should be conducted during implementation of the proposed management practices at Morton Ranch in order to check, verify, and improve upon the disposal control practices. In this way, it will be possible to reduce the cost of disposing of contaminant seepage and better assure adequate disposal methods for uranium tailings in burial pits.

CONTENTS

CONTENTS (contd)

FIGURES

1.0 INTRODUCTION

GENERAL

The advantages of returning uranium mill tailings to the pits excavated during surface mining operations are being more widely recognized and utilized to minimize any undesirable environmental effects. Particularly notable among the benefits is the better control of radon gas emission through appropriate mill tailings burial. This advantage alone warrants burial of the tailings. Also, through burial of tailings, the mined-out site is returned to nearly the original topography and vegetative habitat. All of these benefits are being included in the planning of the mining and milling operations at the Morton Ranch Site in Converse County, Wyoming.

As plans are made for the burial of the tailings in pits, (as opposed to using conventional tailings ponds above the ground surface), concern arises about the potential for contaminant seepage from the buried tailings. Disposal in the mined out pits places the tailings nearer ground water and may lead to ground water contamination. However, through appropriate construction operations and placement practices, the possibilities for subsurface contamination may be reduced to acceptable levels.

PURPOSE

The purpose of this study is to examine potential ground water contamination by seepage from buried tailings under four alternatives of clay liners and tailings placement, which have been proposed for possible use at the Morton Ranch Site. To accomplish this comparison of alternatives, laboratory work and numerous measurements were made on materials typical of the Morton Ranch Site. These measurements provide the soil characteristics necessary for input to the hydrologic flow and transport models.

The results obtained from the flow and transport models allow direct comparison of the environmental consequences of the four seepage control alternatives. When the probable environmental consequences are known, the construction, operations and maintenance costs can be considered to enable selection of the best overall alternative for use at the Morton Ranch Site.

ORGANIZATION OF REPORT

Section 2 presents an overview of the geologic setting of the Morton Ranch Mill Site. Also considered are typical burial pits at the site, the construction practices proposed and disposal practices considered by the Morton Ranch Site management as most useful for handling the tailings. Many of these practices are widely accepted as the most desirable way to proceed and need not be considered in more detail. However, other management aspects may involve several alternatives that must be assessed in terms of their environmental consequences.

Section 3 describes the alternatives that will be modeled, including consideration of net or element configuration, relative location of the various materials, appropriate boundary conditions and initial conditions. Laboratory measurements on materials typical of Morton Ranch are also presented.

Section 4 gives an overview of the flow modeling process and summarizes flow results and their use in the subsequent pathline and transport analysis steps. The bulk of the flow data is presented in the Appendix, which includes 1) a description of the methods used to measure soil characteristics, 2) the measured soil charateristics, and 3) the intermediate results of the flow analysis, namely, the moisture content distribution sequences. Although they are important findings that aid in better understanding the four management alternatives, the moisture distribution sequences are only used incidentally in the course of the subsequent transport analysis.

Section 5 describes the study's flow path modeling approach for water coincident contaminants, and elaborates on the FLUX and MILTVL computer codes developed in the course of this research. The way in which the flow path models provided arrival distributions is also described; and the arrival distributions are used to compare worst-case sulfate seepage rates over time for each management alternative.

Section 6 describes the contaminant transport accounting for the delay of specific species due to the pH buffering capacity of the materials and the sorbtion of specific isotopes (^{238}U, ^{230}Th, and ^{210}Pb). Section 6 also shows how the FLUX and MILTVL models were used to obtain data about the movement of the pH and contaminant fronts away from the tailings burial pit.

Section 7 discusses the results obtained for the four management alternatives studied and recommends a seepage control alternative for use at Morton Ranch. Areas of additional study are identified that would facilitate application of these results to sites other than Morton Ranch.

2.0 MORTON RANCH SITE GEOLOGY AND MINE PITS SYSTEM PROPOSED FOR MILL TAILINGS DISPOSAL

GEOLOGIC SETTING

The Morton Ranch Uranium Mine and Mill Site is located in central Wyoming in Converse County. The geology of the area is discussed in detail in the UNC Environmental Report (UNC 1976). Briefly, the site lies in the southernmost part of the Powder River Basin. This basin is a large structural depression bounded on all sides by areas of uplift (Figure 2.1). The area to the east rises to the Black Hills and the area to the west rises into the eastern slopes of the Rocky Mountains. Since pre-Cambrian times, the history of the Powder River Basin has consisted largely of periods of subsidence and sedimentation.

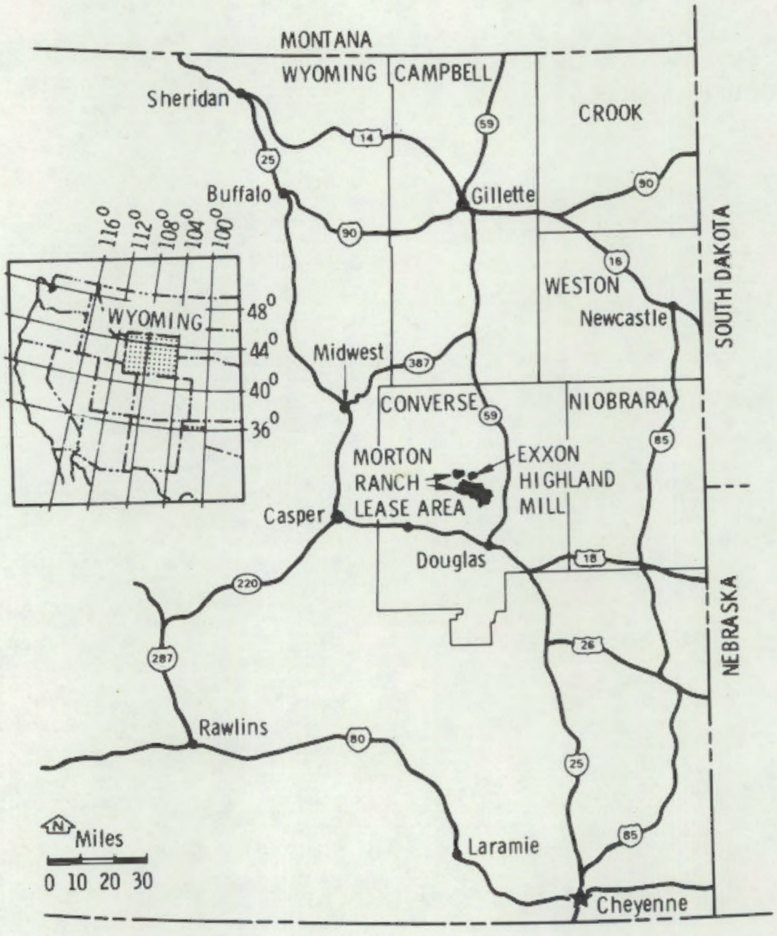


FIGURE 2.1. Regional Location Map of Morton Ranch Uranium Properties

Accumulation of sedimentary rocks has occurred to depths of 4570 m (15,000 ft). The underlying sediments of the basin are primarily carbonates, sands and shales deposited in a marine environment.

The uppermost sediments are freshwater fluvial (river transported) deposits of the Fort Union and Wasatch Formations. The Wasatch Formation is the uppermost bedrock unit exposed throughout the mill site area. In this area, all but the bottom 100 m (+330 ft) has been stripped away by stream erosion. The Wasatch Formation is comprised of fluvial sediments of interbedded silty claystones and sandy siltstones that contain thick lenses of coarse, arkosic (granular) sandstone. The Fort Union Formation underlies the Wasatch Formation and typically consists of poorly consolidated continental deposits about 1000 m thick. At the mill site area, the formation consists of fluvial, interbedded silty claystones, sandy siltstones, relatively clean sandstones and granular sands. The sandstones of the upper Fort Union Formation are the host rocks for the uranium deposits.

MINE PIT SYSTEM PROPOSED FOR TAILINGS DISPOSAL

Extensive drilling at the Morton Ranch Site has delineated those areas where surface mining pits will be excavated to obtain uranium ore. From this excavation plan has come a proposed tailings disposal system which is shown in Figure 2.2. The map indicates the general layout of the mill site, including the placement of disposal pits and an earthen dam designed for water impoundment. Figures 2.3 and 2.4 show pit cross sections BB' and CC', which are typical of most sections.

Some of the construction and management practices that have been proposed to reduce the adverse environmental effects of tailings burial in pits are illustrated in Figure 2.3. The bottoms of the pits are backfilled when necessary with overburden material that is compacted to an elevation of at least 3.05 m (10 ft) above the regional water table. A clay liner is placed over the compacted overburden fill or over the bottom of the pit if the water table is far enough below the bottom that no backfill is needed. The bottom clay liner is at least 0.91 m (3 ft) thick and is compacted at optimal moisture

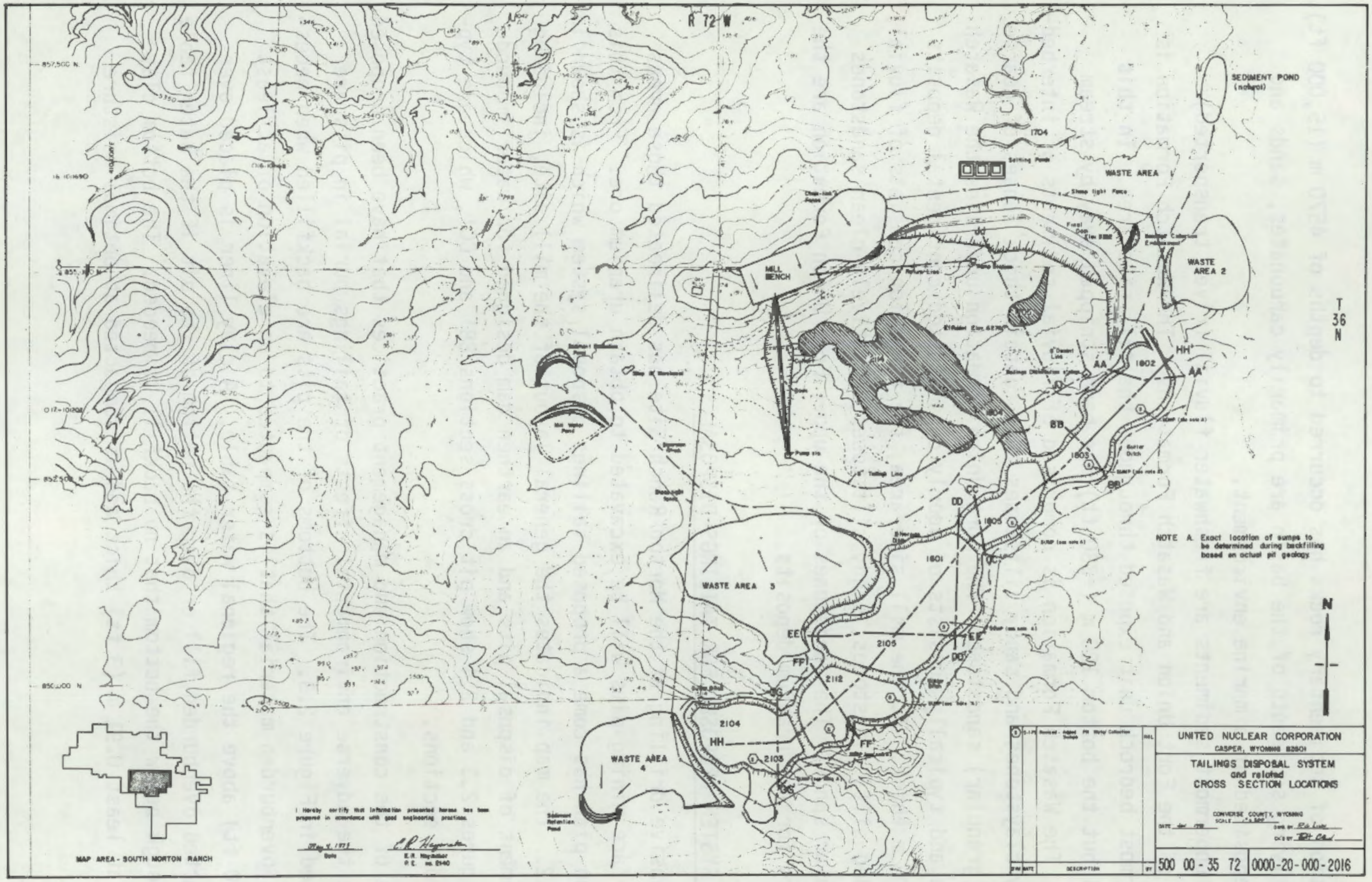
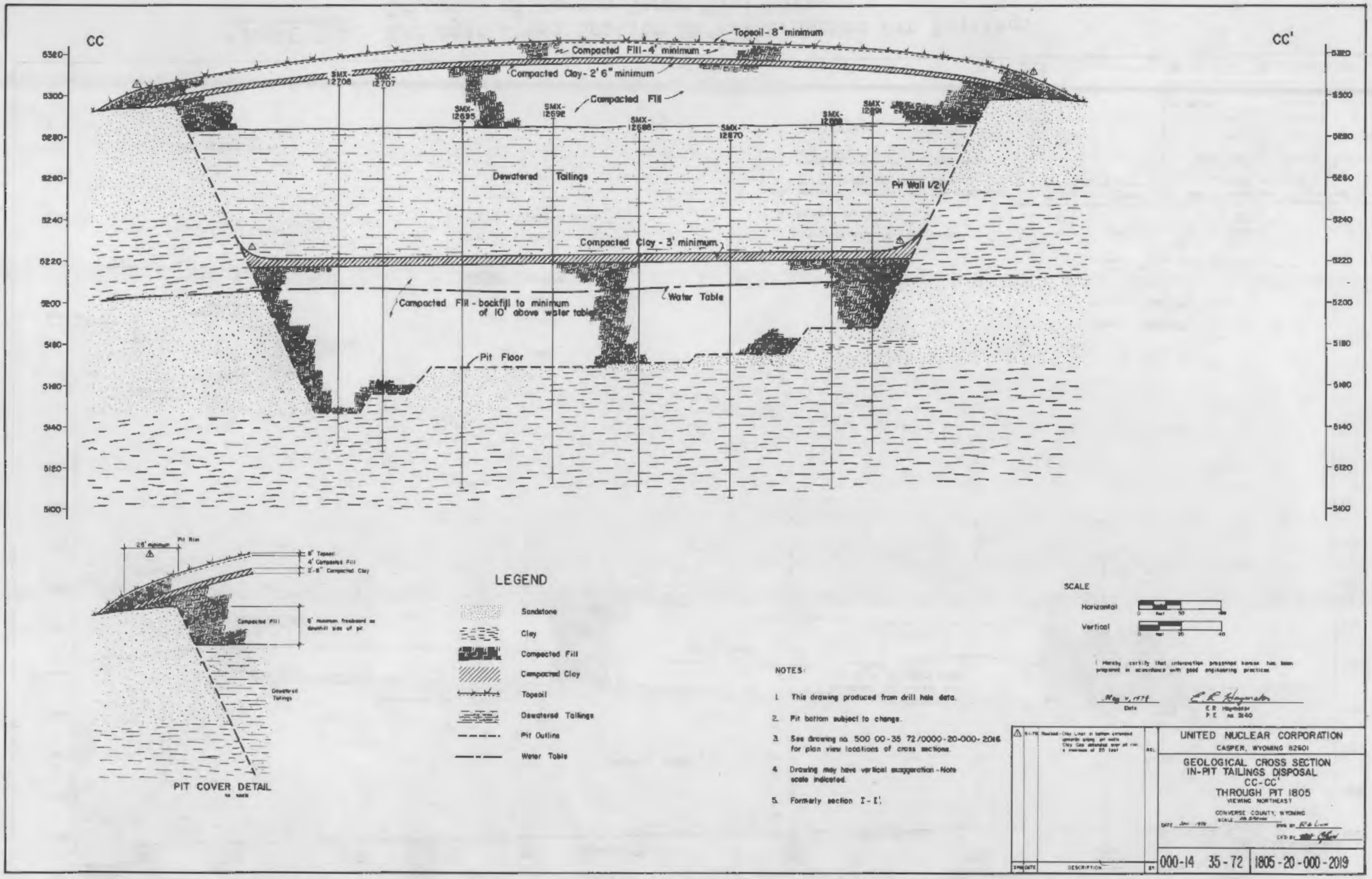


FIGURE 2.2. Tailings Disposal System and Related Cross Section Locations at Morton Ranch Mill Site



NOTES:

1. This drawing produced from drill hole data.
2. Pit bottom subject to change.
3. See drawing no. 500 00-35 72/0000-20-000-2016 for plan view locations of cross sections.
4. Drawing may have vertical exaggeration - Note scale indicated.
5. Formerly section I - I'.

I Hereby certify that information presented hereon has been prepared in accordance with good engineering practices.

May 4, 1979
Date

E R Haymaker
P E No. 3140

SYM	DATE	DESCRIPTION	BY
△	5-1-79	Revised - Clay Liner in bottom extended upwards along pit walls. Clay Cap extended over pit rim a minimum of 25 feet	RCL

UNITED NUCLEAR CORPORATION
CASPER, WYOMING 82601

GEOLOGICAL CROSS SECTION
IN-PIT TAILINGS DISPOSAL
CC-CC'
THROUGH PIT 1805
VIEWING NORTHEAST

CONVERSE COUNTY, WYOMING
SCALE As Shown
DATE Jan 1979
DWN BY R L Lee
CKD BY

000-14 35-72 1805-20-000-2019

FIGURE 2.3. Geologic Cross Section CC' of Proposed Pit Tailings Disposal System at Morton Ranch Mill Site

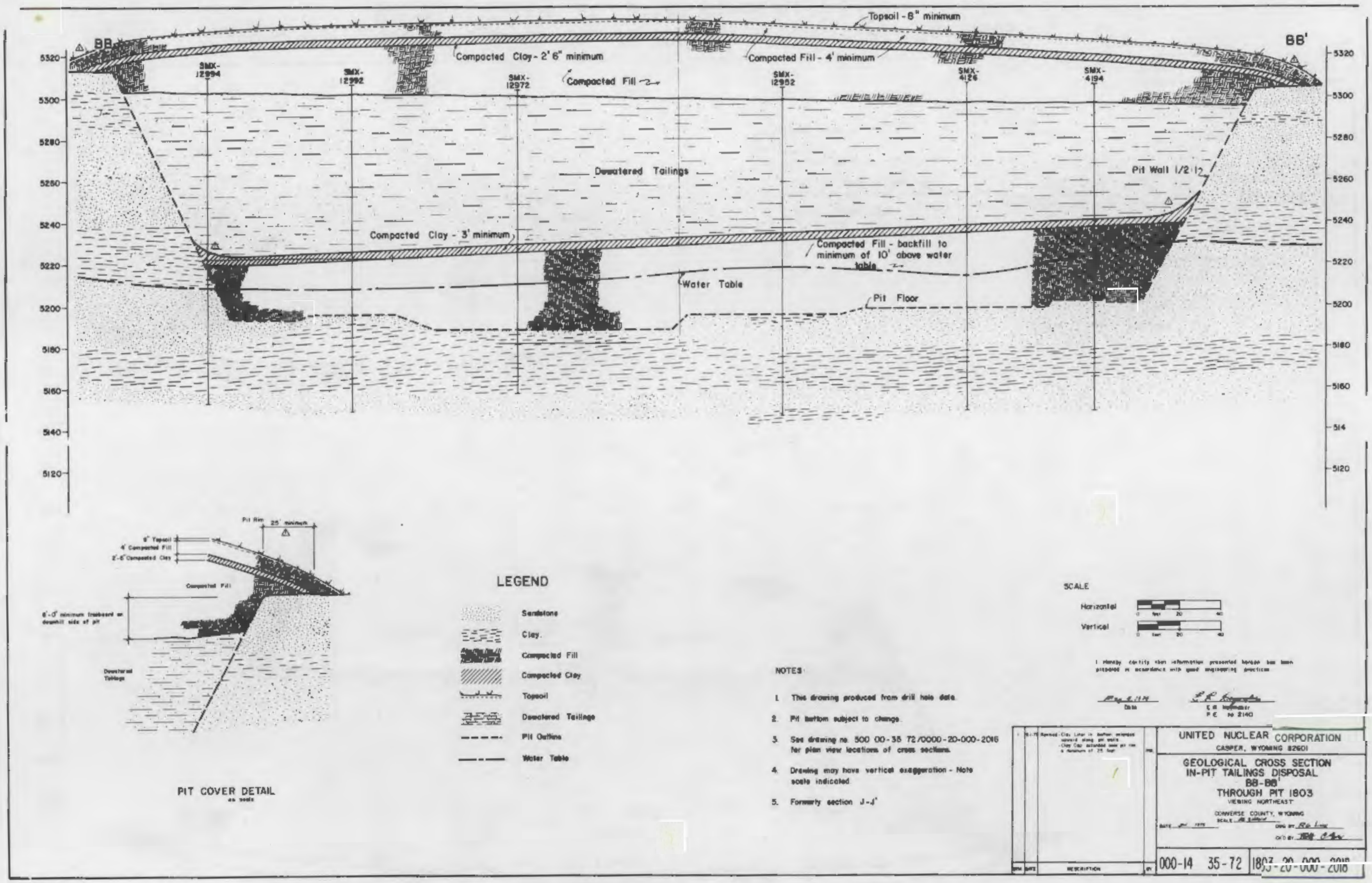


FIGURE 2.4. Geologic Cross Section BB' of Proposed Pit Tailings Disposal at Morton Ranch Mill Site

content. Filling of the pit with tailings would then proceed to within 2.4 to 3 m (8 to 10 ft) of the original ground surface. As shown in Figure 2.3, compacted overburden is placed over the tailings to provide a base for the upper clay cover. The clay cover is 0.76 m (2.5 ft) or more in thickness. Fill is placed above the upper clay liner and finally covered by top soil to enable plant growth for erosion control. Such a sequence in the pit's top cover should adequately control radon gas emissions and at the same time restrict rain or melting snow from infiltrating the soil and reaching the buried tailings. The combination of vegetation growing over the pit, the semi-arid climate at Morton Ranch, and the clay cover over the pit should adequately restrict infiltration.

Additional measures for minimizing seepage from the buried tailings could be useful but may be rather expensive to implement. Among these measures are the use of clay liners along the sides of the pits, the placement of dewatered tailings in the pit, and possible pumping of tailings drainage from the pits. The implementation of each alternative would produce some degree of benefit but considerable expense could be involved in using a particular alternative.

3.0 SOME ALTERNATIVES AND THEIR ASSESSMENT THROUGH MODELS

ALTERNATIVES CONSIDERED FOR REDUCING CONTAMINANT SEEPAGE

The alternatives suggested in the previous section would probably reduce contaminant seepage from the buried mill tailings. Each alternative appears to have individual merit although the extent of the benefit or relative desirability of the alternative is not known in every instance. Associated with the unknown benefit may be significant expenses required to implement the process. It is, therefore, important to determine the relative advantages of adopting the various alternatives.

Four major alternatives for reducing the loss of contaminants from mill tailings are considered in this study. The first alternative includes no additional control and is essentially illustrated in Figure 2.3 where no clay liner is used on the sides of the pits and saturated tailings are placed in the pit. Alternative No. 1 does however utilize a bottom clay liner. Alternative No. 2 is the same as alternative No. 1 except that dewatered tailings instead of saturated tailings are placed in the pit. The third alternative is again similar to the first in that no side wall liners are used, and the tailings are saturated. However, alternative No. 3 includes placing drains in the tailings above the bottom clay liner. The drains empty into sumps from which effluent from the tailings is pumped out of the pit for reuse in the mill. Any excess tailings leachate goes to a surface evaporation pond. The fourth alternative involves completely lining the pit, both bottom and sides, with clay. Specifically then the alternatives are:

No. 1) Placement of saturated tailings in a covered pit that has a clay liner on the bottom but no side liners

No. 2) Placement of dewatered tailings in a covered pit that has a clay bottom liner but no side liners

No. 3) Placement of saturated tailings in a covered pit that has a clay bottom liner, no side liners, and drains to facilitate pumping of drainage solution from sumps placed above the bottom clay liner

No. 4) Placement of saturated tailings in a covered pit that has both bottom and side clay liners.

Each of these four alternatives was modeled considering a combination of partially saturated and saturated flow conditions followed by a 3-step convective transport model analysis.

CONCEPTUAL FORMULATION OF MODELS FOR THE ALTERNATIVES

The disposal pit CC' shown in Figure 2.3 is representative of many pit facilities. Topography and special excavation techniques necessary to remove the uranium ore may alter individual configurations somewhat. A second cross section BB' (shown in Figure 2.4) is wider and deeper and has a regional water-table gradient. Selecting and combining particular features from Sections BB' and CC' (Figures 2.3 and 2.4) would provide a pit configuration rather typical of those at Morton Ranch with which we can model the four pit design alternatives.

Figure 3.1 shows half of a cross-section of a typical burial pit on the Morton Ranch Site. Only half of the typical cross section is shown for use in modeling since the other half would be a mirror image. The typical pit shown has an average width of 132.88 m or 600 ft (300 ft in Figure 3.1) and a depth of buried tailings of 25.91 m (85 ft), with the water table initially at 3.96 m (13 ft) below the top of the clay liner.

Model Grid of Typical Tailings Pit

The typical tailings pit cross section and the immediately surrounding area were discretized into irregular elements for use in the integrated finite difference numerical solution method, which is used in the TRUST code for solving problems involving both partially saturated and saturated flow. The resulting element network is shown in Figure 3.2. It is convenient to think of each element in the figure as having a grid point at approximately the center of the element. In actual practice, a number is assigned to each central grid point or element, and all calculations are performed in terms of that element number. Similarly, the soil characteristics, boundary conditions, and initital conditions are all indexed in terms of the individual node or element number.

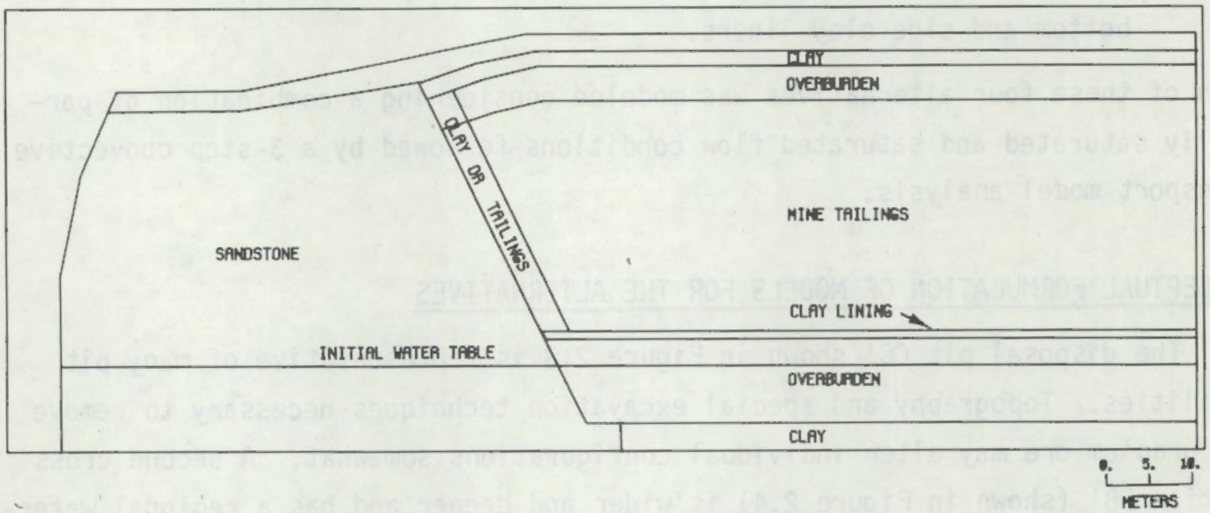


FIGURE 3.1. Schematic Diagram of Half of the Typical Tailings Burial Pit at the Morton Ranch Site

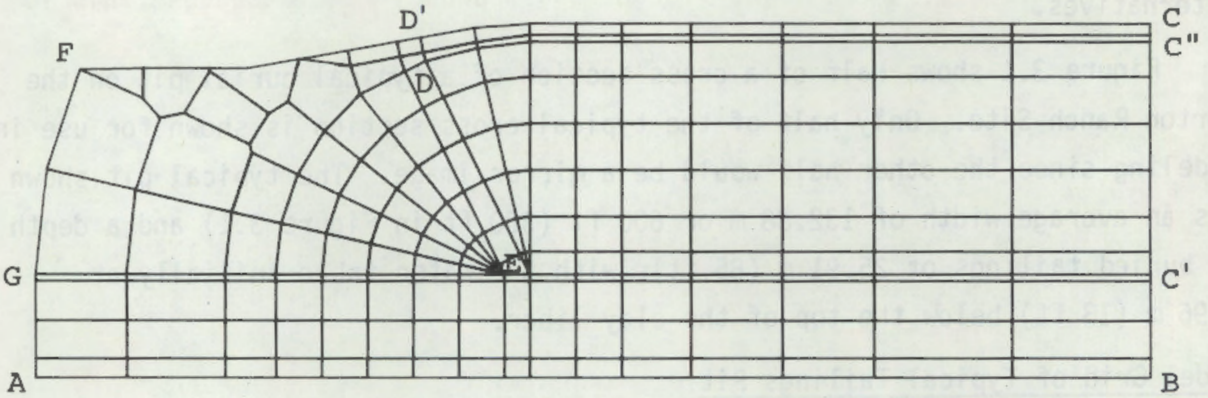


FIGURE 3.2. Model Grid Elements for Half of a Typical Tailings Burial Pit at Morton Ranch Site

The element configuration shown in Figure 3.2 was designed to accommodate data for different soil materials such as those shown in the slim horizontal elements representing the clay liner beneath the tailings and in the clay cover for the tailings. For example, in the slim elements between C' and E in Figure 3.2, compacted clay material data are used; while in the slim elements between E and G, regular sandstone characteristics are used. In elements between D and E, if clay material is used then the side-lined alternative (No. 4) can be analyzed; however, if those same elements are specified as tailings material, then one of the alternatives that does not have side wall liners may be considered. There are also advantages in using the radial elements outward from point E to represent the sloping side wall of the pit. These radial elements provide connections between elements, which generally correspond with the expected flow directions. Such elements should provide the most realistic discretized system for solution.

Fluid Flow Boundary Conditions

The boundary conditions are quite similar for the four control alternatives to be modeled. Specifically, in Figure 3.2, along the lower boundary between A and B, the flow normal to the boundary is zero. In other words, there may be flow parallel to AB, but there is no flow vertically across this boundary. Similarly, there is no flow across boundary BC'C"C because this is a boundary of symmetry with horizontal flow components of zero. No inflow of infiltration across the top boundary CD'F is assumed. The semi-arid climate with limited precipitation and with plant growth over the tailings at Morton Ranch should result in very little, if any, deeper infiltration. Moreover, the top clay cover would further restrict or stop infiltration. The boundary FGA was held as an equipotential boundary at the potential head of 9.75 m (32 ft), which is the initial water table elevation. Such a boundary condition between points A and G in Figure 3.2 results in essentially horizontal outflow toward the left of the system. For practical purposes, the outflow between points G and F is effectively zero for this constant potential condition. The hydraulic conductivity in the very dry, partially saturated region between points G and F is very small.

The boundary conditions just described are applicable for all four of the alternatives being studied. There is one additional boundary condition for alternative No. 3, namely that required to represent the drain placed in the small triangular element immediately to the right of the element labeled E in Figure 3.2. The drain was installed at an elevation of 15.09 m (49.5 ft) or

1.37 m (4.5 ft) above the top of the clay liner and near the end of the liner. Placing the drain some distance above the clay liner makes the drain more effective. Accordingly, the tile drain was placed 1.37 m above the clay liner in the tailings. The potential was maintained in the drain at a head of 15.15 m (49.70 ft) of water for the first 112 days after the pit was filled with saturated tailings. The analysis showed that after 112 days the potential in the tailings around the drain became less than the potential in the drain. From then on, the tailings immediately around the drain were desaturated so that no water would enter the drain.

Fluid Flow Initial Conditions

The initial conditions or starting conditions at zero time for the flow systems for the four alternatives are identical for the region outside of the pit, or for the region in Figure 3.2 enclosed by ABC'EDC"CD'FGA. In this region, the materials are considered to be in equilibrium with the regional water table, which is located 3.96 m (13 ft) below the top of the bottom clay liner. The water table is at a potential head of 9.75 m (32 ft). Accordingly, everywhere in the region — except in the pit and up to the clay layer that covers the pit — the initial potential head is 9.75 m (32 ft). This assumes that only minor water table fluctuations may have occurred recently and that the large mass of natural material around the pit has not been significantly disturbed.

Inside the pit, two different initial conditions are required, depending upon whether the tailings are placed in the pit under saturated conditions or are first dewatered. For those alternatives with saturated tailings, the initial potential head was set at 44.65 m (146.5 ft) i.e. the tailings are all saturated. A more involved initial condition was required for the dewatered tailings case.

Experimental work indicated that the moisture content on a volume basis in the pit would be 0.33 cm^3/cm^3 if the dewatered tailings left the mill at 20% moisture by weight and were placed in the pit at a bulk density of 1.63 gm/cm^3. Setting the initial condition in the pit for the dewatered tailings involved assigning the appropriate potential at each element grid point, such that the initial moisture content would be 0.33. This was done using the measured material characteristics to determine the capillary pressure head associated with the 0.33 moisture content (see the appendix). The required initial potential head could then be obtained using that capillary pressure head and the elevation of the element grid point being considered.

The initial conditions just described assume that the burial pit is completely filled at the initial time (time equals zero) either with saturated or dewatered tailings, depending upon the situation being studied. No seepage or drainage is assumed to have occurred prior to time equals zero. In actual practice, the pit is filled gradually and some seepage occurs during this time; however, any seepage losses during filling correspondingly reduce the saturation in the tailings; i.e., the two phenomena tend to be compensatory. In other words, the initial condition assumes that seepage lost during filling is still in the tailings pit at time equals zero, and that all fluid must drain out later. Such an initial condition tends to represent a worst-case maximum stress to the system, and is a basis for comparing the four alternatives from the standpoint of environmental consequences.

Soil Materials

The materials used for this study represent both the materials that will be mined and processed in the mill operation and the undisturbed sediments adjacent to the mine pits through which the leachate may move. The materials characterized included the following: uranium mill tailings, clayliner, overburden, and sandstone.

Uranium Mill Tailings

These tailings were taken from the Exxon Highland Mill located approximately 9.6 km (6 mi) from the proposed mill site at Morton Ranch. The Highland mill tailings are subjected to a sulfuric acid-leach process similar to that being planned at Morton Ranch. In addition, the ore materials at the two sites are similar due to the close proximity of the existing Highland mill and the proposed mill site at Morton Ranch. These considerations formed the basis for selecting the Highland mill tailings to represent those that will be produced at Morton Ranch.

Clay Liner

This material was taken from the 1704 pit at the Morton Ranch site (see Figure 2.2). The liner material tested was composed primarily of interbedded silty claystone materials of the Wasatch formation.

Overburden

This material was also taken from the 1704 pit at Morton Ranch. The overburden material was a mixture of clay, silts, and sands of the Wasatch formation mixed with overlying alluvial materials. The relative coarse texture of the material reflected a mixture that was predominantly of sandstone origin.

Sandstone

Sandstone was taken from the side wall of the 1704 pit. Care was taken to minimize mixing of the clean sandstone material with adjacent finer materials.

Chemical and physical characteristics of the materials are described in detail in a companion report (Gee et al. 1980). The hydraulic properties of these materials are described below. These properties were used extensively in the modeling effort.

Hydraulic Properties

Selected physical properties, including hydraulic characteristics for materials used in the model, are shown in Table 3.1. These data represent a wide variety of soil characteristics ranging from a very permeable sandstone that drains readily, to a low permeability clay liner that drains only slightly. All materials were tested using standard methods of soil analysis (Black 1965). Water retention curves were run on slurried as well as dewatered, recompacted tailings (Figure 3.3). Although measurable differences in drainage are observed between packing treatments for the tailings, the

TABLE 3.1. Selected Physical Characteristics for Materials Used in Model of Morton Ranch Tailings Pit

Water Retention Characteristics for Test Materials

Head (-cm)	Tailings	Clay Liner	Overburden	Sandstone
0	0.441	0.385	0.296	0.340
10	0.394	0.385	0.295	0.337
20	0.375	0.385	0.295	0.218
30	0.364	0.385	0.294	0.154
40	0.354	0.385	0.293	0.102
50	0.330	0.385	0.291	0.094
60	0.308	0.385	0.289	0.082
100	0.260	0.383	0.279	0.066
300	0.184	0.338	0.208	0.048
1,000	0.156	0.301	0.181	0.043
10,000	0.084	0.264	0.109	0.019
10^6	0.020	0.052	0.031	0.009
Particle Density (g/cm^3)	2.91	2.75	2.70	2.65
Bulk Density (g/cm^3)	1.63	1.69	1.90	1.75
Max. Compaction (g/cm^3)	----	1.84	2.03	----
Void Ratio	0.789	0.626	0.421	0.515
Porosity	0.441	0.385	0.296	0.340
Saturated Conductivity (cm/s)	2.2×10^{-4}	2.5×10^{-8}	1.3×10^{-6}	7.5×10^{-3}

slurried tailings water characteristic-drainage curve was used in all modeling efforts. This allowed for direct comparison of the cases studied and eliminated tailings packing differences. In practice, sand and slime separation and packing differences would alter the shape of the tailings drainage curve and

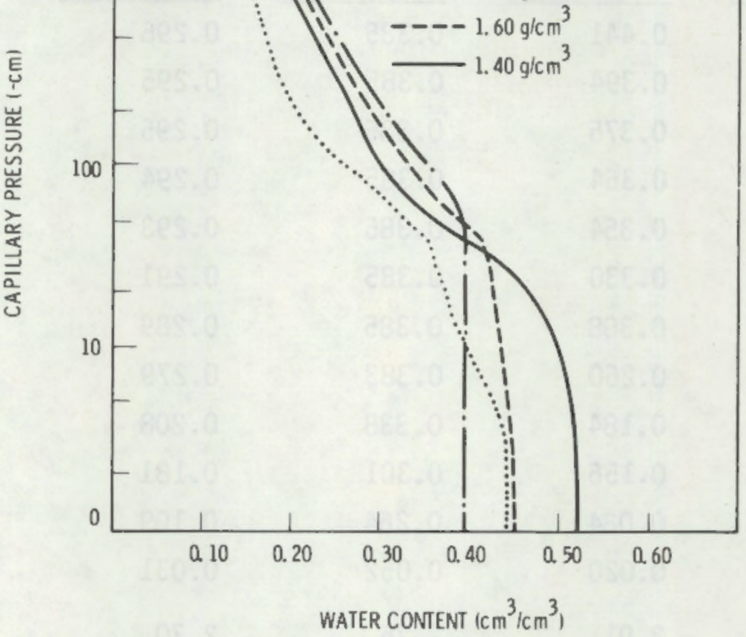


FIGURE 3.3. Effect on Tailings Moisture Characteristics of Dewatering on Recompaction to Different Densities

consequently affect the unsaturated flow characteristics of the tailings. In the model cases run, these segregation problems were not simulated. A preliminary analysis showed that a sand-slime separation would act to delay the drainage. We chose to maximize the drainage by using the curve for uniform slurried tailings materials.

The water retention characteristics of all materials used in the model calculations are shown in the appendix. Also shown is the water conductivity moisture content relationship used in the model calculation. These conductivity values were determined from water retention characteristics and saturated conductivity data using a modified Millington and Quirk method (Reisenauer 1973).

Chemical Properties

The chemical properties used in the models reflect the characteristics of the material to retard radionuclide and contaminant transport. The movement of an acid from through the test material was evaluated by assessing the neutralizing capacity of the materials. The neutralizing capacity was determined by titrating the materials with acid and determining the resulting pH as a function of the amount of acid added.

An estimate of the attenuation of the pH front due to the neutralizing capacity of the material was made by calculating the ratio of neutralized hydrogen in equivalents per gram to the hydrogen ion concentration in solution at pH 2. Values obtained from the titration curves are shown in Table 3.2.

TABLE 3.2. Neutralizing Capacity of Morton Ranch Test Materials

Material	Density (g/ml)	Neutralized Hydrogen (eq/g)	Kd(pH) (ml/g)
Clay liner	1.7	3.31×10^{-5}	3.3
Overburden	1.9	1.79×10^{-5}	1.8
Sandstone	1.8	1.20×10^{-5}	1.2

The computed alkalinity in terms of $CaCO_3$ percentage (APHA 1971) for the three materials was 0.04%, 0.01%, and 0.009% for the clay liner, overburden, and sandstone, respectively (Gee et al. 1980). A distribution type coefficient, Kd, (pH) is used to describe the buffering capacity of acidic solution. We assume that equilibrium conditions are obtained under the relatively low flow rates, which occur during drainage of the tailings solution. We treat the pH (hydrogen ion concentration) changes in the system analogous to those of exchangeable capacity reactions. This is not strictly true since other chemical kinetic reactions (e.g., neutalization) are taking place in addition to ion exchange on the mineral surfaces.

When a distribution capacity coefficient, Kd (pH), is used, it implies that the buffered species is retarded relative to the transport fluid by an amount directly related to the Kd. The pH fronts observed in column studies

(Gee et al. 1980) were observed to be retarded by amounts that reflected the relative buffering capacity of the materials through which tailings solution had passed. The retardation of the pH front through the clay liner was about twice that observed through the overburden material, in qualitative agreement with data shown in Table 3.2 for these two materials. Hydrodynamic dispersion and diffusion are not accounted for in the computation of the Kd (pH), suggesting that the values used may be somewhat conservative.

Kd Values for Radionuclides

In the companion study to this report (Gee et al. 1980), values were determined for the pH dependence of the Kd. The values used in the modeling effort are shown in Table 3.3.

TABLE 3.3. Kd Values of Radionuclides for Morton Ranch Test Materials as a function of pH

pH	Material	U-238	Th-230	Pb-210
2.2	clay liner	1.3	1.2	1,848
	overburden	1.0	1.1	13
	sandstone	1.7	1.9	68
7.7	clay liner	23,700	81,000	10,000
	overburden	20,000	40,000	9,000
	sandstone	15,000	10,000	8,000

These Kd values include the effects of precipitation reactions and reflect the influence that neutralization has on the solution concentration of these isotopes. The pH is the critical factor in determining the transport of these radionuclides.

4.0 FLOW MODEL RESULTS FOR SEEPAGE CONTROL ALTERNATIVES

The conceptual model formulations for the four seepage control alternatives in the previous section provide all of the input conditions and measurement data required for the actual flow models. These data and conditions typical of the Morton Ranch Site were input to the TRUST Computer Code (Narasimhan, 1977, 1978), which provided the combined partially saturated and saturated flow results.

COMPLEXITIES OF PARTIALLY SATURATED FLOW MODEL REQUIRED

Modeling with partially saturated flow conditions as in the TRUST code introduces considerably more complexities than if a more traditional and generally available saturated flow analysis could have been applied. It is also far more realistic to use the two-dimensional TRUST approach rather than to attempt using an approach that couples a one-dimensional partially saturated flow code coupled with a two-dimensional saturated flow code. Any approximation considers only saturated flow cannot be expected to provide anything approaching realistic flow results. For the three cases that use saturated tailings, saturated flow occurs only early in the process, very briefly, and only in the lower part of the pit. It is our task to determine how the partially saturated drainage occurs in the tailings pit, into the clay liners, and into the parent materials outside the clay linings. Thus a realistic modeling of a burial-disposal system for wet tailings requires consideration of partially-saturated flow, which is by nature non-linear and considerably more complicated.

Even those who admit that partially saturated flow must be used in order to achieve a realistic analysis may assert that one-dimensional approximations could nonetheless be used rather than the full two-dimensional approach utilized in this study. Certainly, in some cases (for example, when drainage seeps from a large, moderately shallow, surface pond into a deep underlying water table) a one-dimensional, partially saturated analysis of flow in a vertical column coupled to a two-dimensional saturated model of lateral flow could be very useful. However, regarding the pit leakage problems of concern here, many questions arise. How are the one-dimensional, partially saturated flow cases oriented for realistic analysis? Are they placed perpendicular to the sloping side wall or at some expected flow direction? If the latter is the case, then in what direction? How high on the side wall should the column be placed? Should the column be lower and closer to the bottom clay liner? Surely, vertical one-dimensional partially saturated flow in the pit should be considered to determine how the tailings would drain within the pit and through the clay bottom liner. What fraction of the pit drainage would be assigned to pass through the bottom as compared to through the unlined side wall columns? In short, the drainage of the tailings in the pit and seepage into the surrounding materials for the cases of interest here involved a two-dimensional, if not a three-dimensional situation. To model using flow in less than two-dimensional, vertical cross sections would be unrealistic.

The complexities of the combined partially saturated and saturated flow modeling, in addition to the more involved input soils data, lie in the potential difficulties in numerical solution for this class of non-linear boundary value problems. For the Morton Ranch cases, the numerical solution difficulty could arise either from the sharp wetting fronts (which result as the fluid advances from the tailings into the unlined, relatively dry sandstone side walls), or from the transion zone (which goes from partially saturated flow conditions to saturated conditions immediately above the water table). The TRUST code adequately handled these two potential problems. Small time increments were required at certain points during the solution process, but the automatic time-increment control features in the code controlled any tendency for numerical instabilities. The results reflected excellent outflow mass balance and produced consistent data concern- ing fluid-drainage outflow rates from the tailings.

RESULTS FROM TRANSIENT FLUID FLOW MODELS

The results from the TRUST flow code provide for each flow system element the potential energy, capillary pressure, capillary conductivity, moisture content, and the flux between elements. These large data sets were organized into time sequences, and are provided on magnetic tape for subsequent use. Figures 4.1 and 4.2 show the moisture contents for alternative No. 1 and alternative No. 3 at 6 days after drainage started for the unlined side walls. More detailed results showing the moisture contents for the first three alternatives are shown in the appendix.

The relative overall drainage of the tailings in time for the various alternatives is shown in Figure 4.3. The similar change in tailings water content in time is seen for the unlined cases with and without the drain. Such similarity suggests that installation of a drain only slightly changes the actual fluid drainage pattern inside the pit. The large benefit of the drain is in the amount of tailings solution actually intercepted. The dewatered tailings in Figure 4.3 involves considerably less water in the pit, and the drainage is somewhat slower than for the other cases with no side liners.

It is convenient to consider the outflow from the left hand side of the flow models, in particular across the vertical segment AG in Figure 3.2. This vertical line is some 56.4 m (185 ft) to the left from the end of the bottom clay liner at the pit side wall. In the discussion to follow, unless otherwise stated, an outflow rate of fluid or contamination will refer to the flow rate across this vertical segment of the model.

Figure 4.4 shows the fluid outflow rate as a function of time. The maximum outflow is for alternative No. 1, which has no side wall liner and saturated tailings. Note also the curve immediately inside the curve for alternative No. 1 labeled "Contaminated Water Outflow". Only the outflow under this latter curve, which has a peak value of 12.01 m^3/day, represents outflow of water containing contaminants (such as sulfate and chlorides) from the tailings pit. The fluid outside this curve, but under the larger curve, represents the uncontaminated fluid not originating in the pit, which flows out of the system's boundary. The contaminated fluid outflow rates associated with the alternatives No. 2 and No. 3 are so small that they cannot be plotted in Figure 4.4. Specifically, the peak for the contaminated water outflow rate from

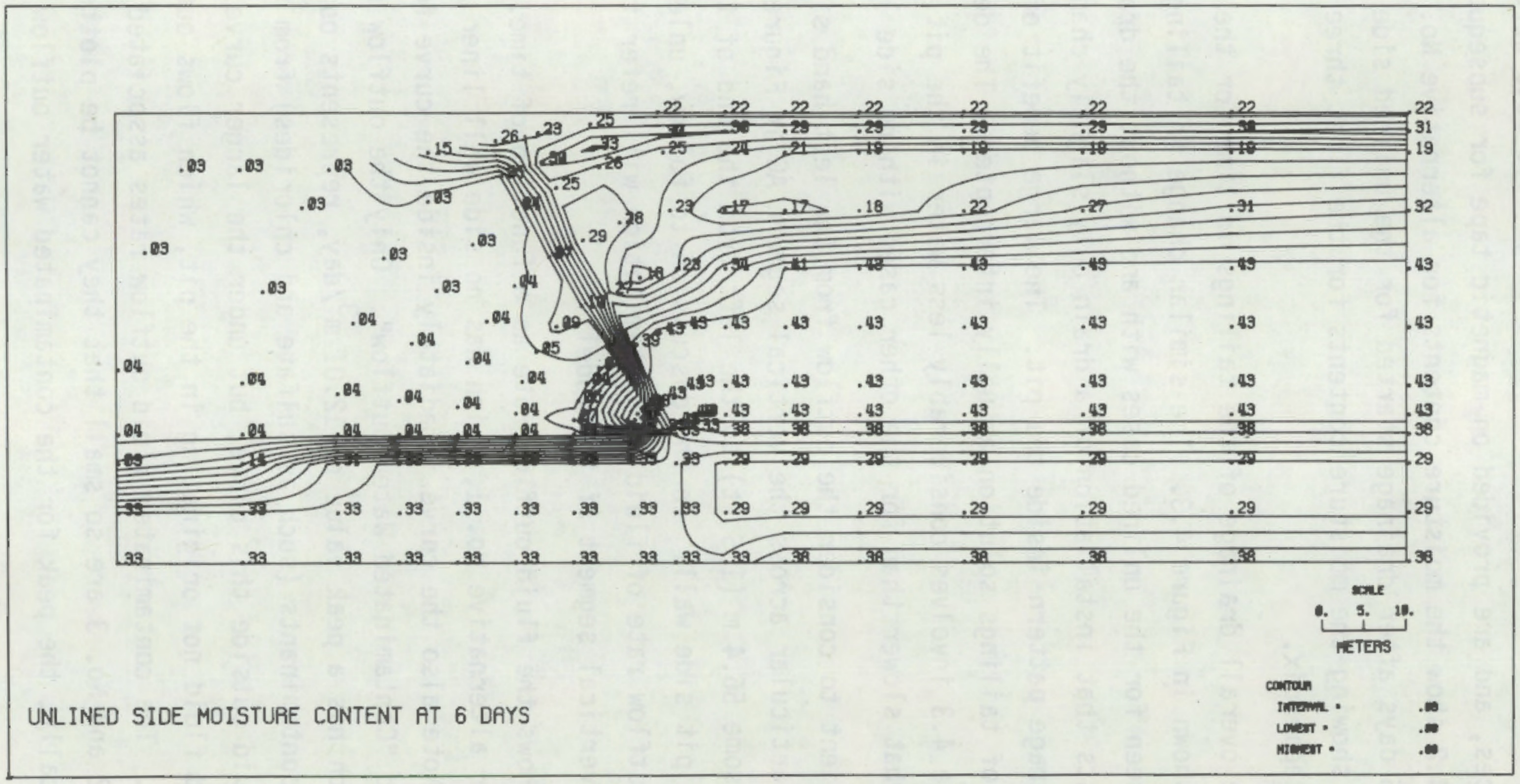


FIGURE 4.1. Moisture Content Distribution at 6 Days for Alternative No. 1 with No Side Wall Liner

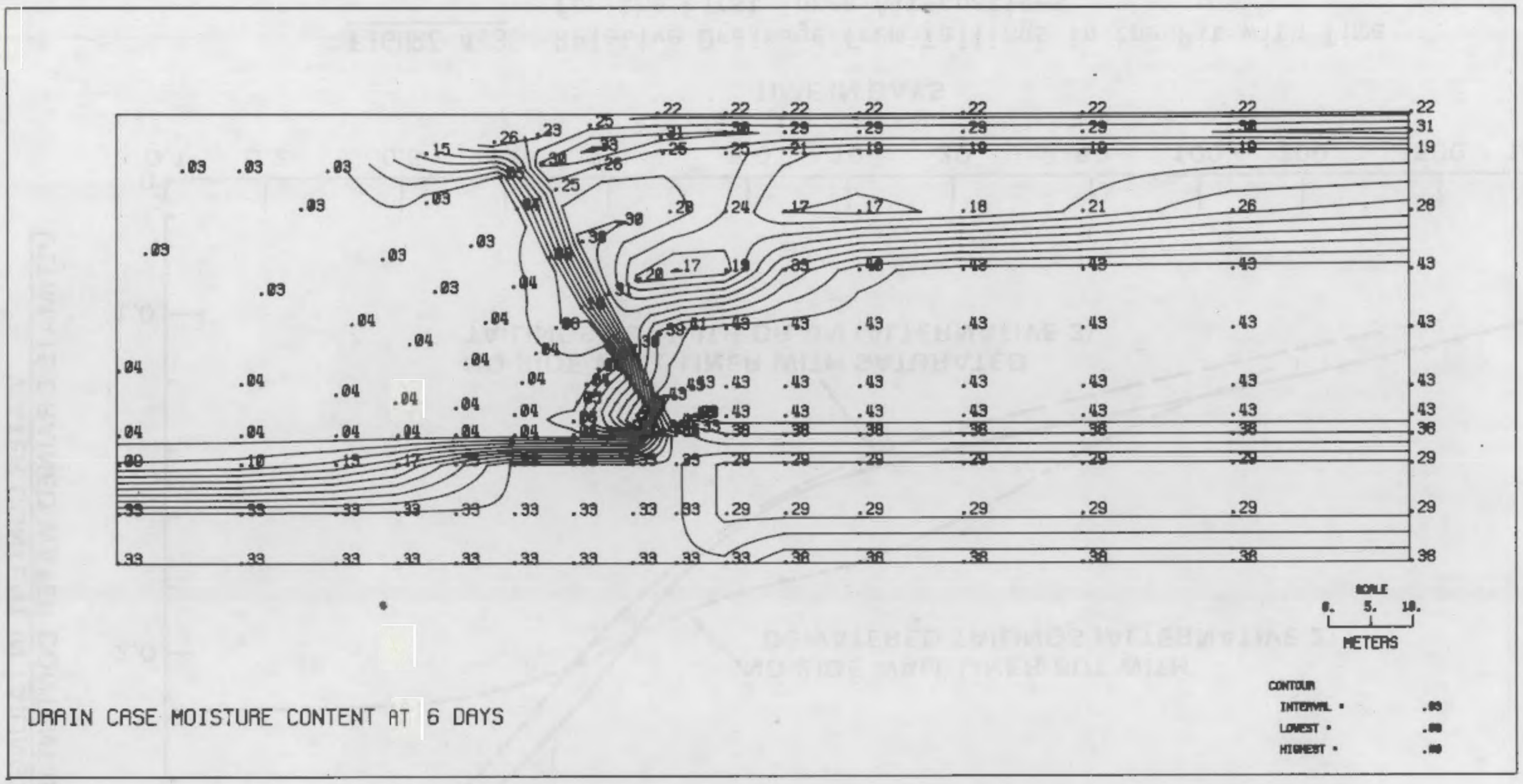


FIGURE 4.2. Moisture Content Distribution at 6 Days for Alternative No. 3 with No Side Wall Liner but with Underdrains

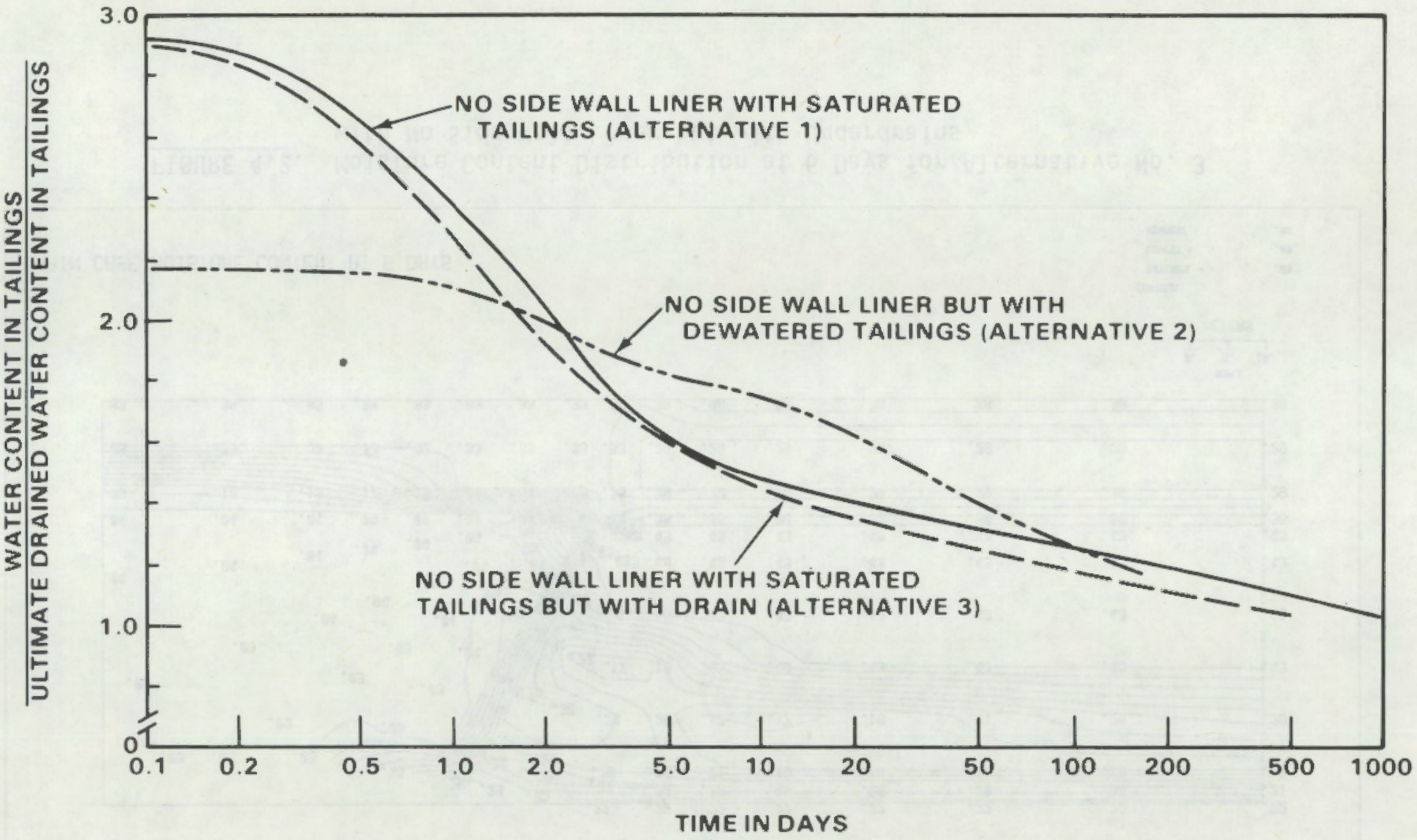


FIGURE 4.3. Relative Drainage from Tailings in the Pit with Time for the First Three Alternatives

alternative No. 2 (dewatered tailings) occurs at 430 days; the rate is 0.0311 m^3/day. The corresponding time and peak outflow rate of contaminant for the third alternative (with drains) is at 300 days and is a value of 0.0214 m^3/day. Figure 4.4 also indicates that after some 100 days, the effective outflow rate is essentially insignificant across the outer boundary.

FLOW RESULTS ENABLE DETERMINING VELOCITY FIELDS FOR ALTERNATIVES

The flow results provided in the previous section are useful in understanding the system from an overall point of view but are secondary to the many results obtained and needed to allow calculating the expected velocity field. In particular, the potential energy, capillary conductivity, and moisture content distributions are all provided by the TRUST computer code. As the results are obtained, the large data sets are stored on magnetic tape for subsequent use in obtaining fluid and contaminant flow paths. The water flow paths and associated water coincident contaminants are described in the next section.

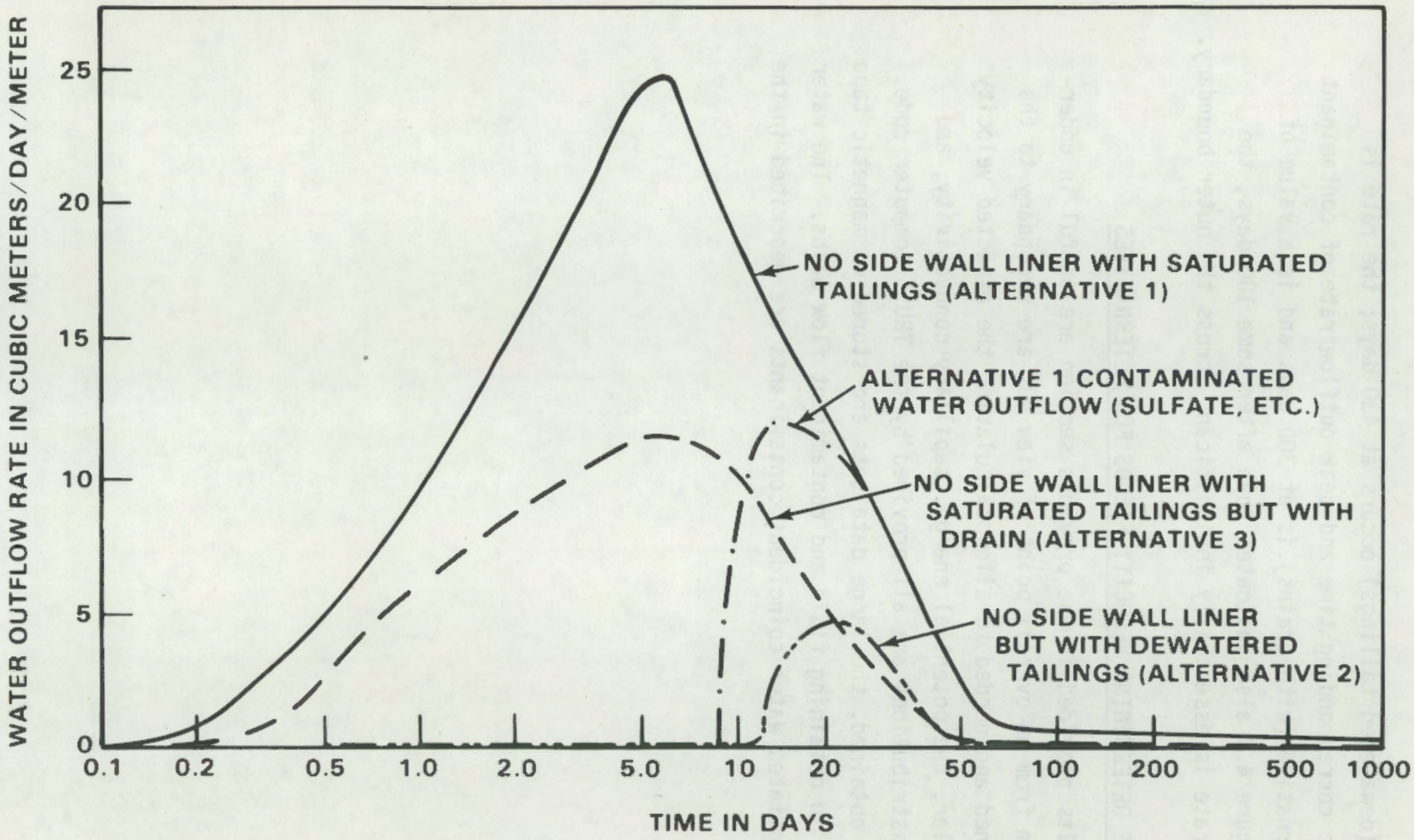


FIGURE 4.4. The Changes in Water Outflow Rates for the First Three Seepage Control Alternatives

5.0 WATER AND WATER COINCIDENT CONTAMINANT FLOW PATHS AND ARRIVAL DISTRIBUTIONS

Once the flow results are available, the time and spatially dependent pore velocity field for the modeled systems can be determined. By the same token, once the velocity field is known for the whole region and throughout all of the times of interest, then the water flow paths and the paths followed by contaminants moving coincident to the water can be obtained. The progress of the contaminant with time along each flow path is also provided.

Hydrologists seem hesitant to determine the paths and travel times from the flow results. Often, instead of being used to determine the flow paths of actual contaminants, the flow system results are used only to make qualitative inferences or to discuss where the water coincident contaminants are transported. Although additional analysis is necessary to identify flow paths, there are no additional field data required beyond that already available for the flow analysis in partially saturated systems. Since no additional data is required, it appears essential that the contaminant flow path and flow time results should be provided. From such results, the contaminant arrival distributions are easily assembled, allowing direct evaluation of the overall environmental consequence.

GENERATION OF PORE VELOCITY FIELDS

An important ancillary part of the work performed during this study was development of several interactive computer modules necessary to provide the contaminant flow paths and the related transport results. Among these were preprocessing subroutines and the code FLUX, which utilizes the flow results from TRUST, the model element data, and the soil data to obtain the pore velocity field. Specifically provided by FLUX are the Cartesian velocity components at each element grid point for the entire time history. The velocity results are then input into a newly developed interactive code, MILTVL, which determines the flow paths and travel times along those flow paths.

CONTAMINANT FLOW PATH RESULTS

The water flow paths beginning from various points along the edge of the tailings pit were generated using the MILTVL code. Those contaminants considered to move with the fluid, i.e., water coincident constituents such as sulfates and chlorides, follow the fluid pathlines. It is convenient to use flow paths, fluid pathlines, and water coincident contaminant flow paths interchangeably in our discussion in this section. Discussion of the paths of fluid or water particles may also be used interchangeably when discussing the gross contaminant ions flow paths for the water coincident contaminants.

Figure 5.1 shows the paths of fluid particles that started at the edge of the tailings for alternative No. 1 (no side wall liner). For those pathlines originating along the bottom of the pit just above the clay liner, the flow is diagonally to the left through the clay and changes vertically to more directly leave the clay. Most of the pathlines passing through the clay bottom liner end. The end point indicates the position of water particles at 9956 days or 27.2 years or when the drainage of the tailings is essentially completed. Some of the pathlines, however, which started on the top of the clay liner nearer the pit side wall, are seen to reach the outflow (left) end of the model, in which case the arrival time at the boundary is obtained. The path-

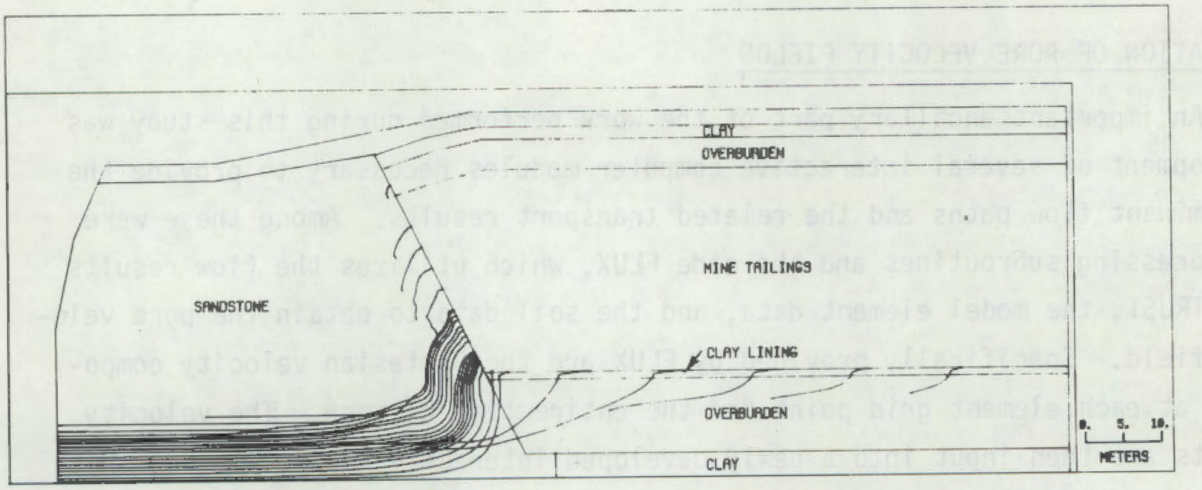


FIGURE 5.1. The Paths of Flow for Water Coincident Contaminants from the Buried Tailings for Alternative No. 1 with No Side Liner

lines that exit low on the pit side wall near the end of the bottom clay lining are those that are predominantly reaching the outflow boundary at the left side of the figure.

After a short distance up the pit side wall, the pathlines again stop or end before reaching the outflow boundary. The end of a pathline indicates the location of the fluid particle at slightly over 27 years. At a height of 4.6 m (15 ft) or higher along the side wall, no fluid particles or water coincident contaminants such as sulfate or chloride reach the outflow boundary. Still higher along the side wall, the distance traversed by water coincident contaminant from the pit over the 27 years becomes less and less. Therefore, the upper 70% to 80% of the unlined side wall contributes little or no contamination over very long periods of time. The primary losses as shown by the pathlines occur in the bottom 4 to 5 m (13 to 16 ft), with the greatest being at the bottom and diminishing higher and higher on the side wall.

It is interesting to compare the relative lengths of the short stubby pathlines along the upper three-quarters of the side wall with those pathlines that pass through the bottom clay liner (see Figure 5.1). All of the pathlines through the clay liner traversed longer distances, hence, they moved considerably faster than did the fluid and contaminants moving out from the upper three-fourths of the side wall. The side wall is sandstone; the MRO soil beneath the bottom clay liner has a saturated hydraulic conductivity three orders of magnitude lower; and the clay liner material is five orders of magnitude lower than the sandstone (Table 3.1).

However, since the sandstone is much drier high on the side wall, it is really the partially saturated hydraulic conductivity that should be compared with the saturated clay conductivity of the bottom liner. The partially saturated hydraulic conductivity of the sandstone higher on the side wall is more than three orders of magnitude smaller than that of the clay liner (see the appendix). This indicates that the very small seepage in the upper part of the pit side is due to partially saturated flow system characteristics.

The pathlines for the first fluid leaving the pit for alternative No. 3 (with drains) are shown in Figure 5.2. In general, the pathline configuration is very similar, with only those paths departing low on the pit wall ever reaching the outflow boundary of the model. The stubby flow paths, which end at a time of 24 years, are again high on the sandstone side wall. Fewer pathlines tend to reach the outflow boundary when drains are used. This observed tendency is indicative of the longer travel times by which the contaminants reach the outflow boundary for the alternative with drains. Pathline patterns for the other two cases were also calculated. Pathlines were obtained for fluid particles departing from the tailings at times other than zero (as was shown in Figures 5.1 and 5.2). These results enable us to obtain the needed arrival distribution.

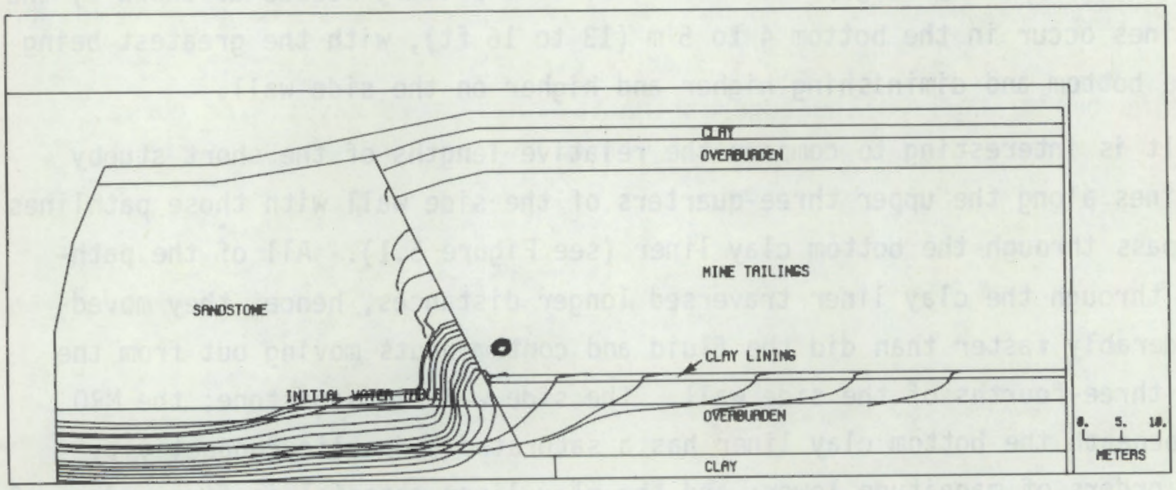


FIGURE 5.2. The Paths of Flow for Water Coincident Contaminant from the Buried Tailings for Alternative No. 3 with No Side Liner but with Underdrains

CONTAMINANT ARRIVAL DISTRIBUTIONS FOR ALTERNATIVES

The pathlines described in the previous section and the travel times along those pathlines are conveniently assembled in the arrival distribution, which summarizes the results and enables a determination of the overall environmental implication of seepage from the pit. Only the location arrival time distribution (Nelson 1978a,b,c,d) is needed here since the flow across the outflow boundary is uniform and essentially horizontal (see Figures 5.1 and 5.2).

The location arrival time distribution for alternative No. 1 (with no side wall liner) is shown in Figure 5.3. The location where the pathline reaches the boundary is denoted by the height above the bottom of the model, S. This height where the pathline leaves the left-hand end of the flow model is plotted against the arrival time, T, which is when the fluid particle arrives at the outflow boundary as in Figure 5.1. The first and highest curve in Figure 5.3 is for the fluid particles, which departed from the tailings pit at zero time, i.e., $t_0 = 0$. The next curve $t_0 = 10$ days represents the arrival of the fluid pathlines particles or water coincident contaminant traversing the appropriate pathlines, which departed the edge of the tailings at 10 days. Similarly, the curve labeled $t_0 = 25$ days is the arrival curve for the particles departing from the edge of the tailings at 25 days. The curve, $t_0 = 0$, indicates that the first arrival of a fluid coincident contamination such as sulfate would occur at S = 4.8 m and arrive at a time, T = 8.85 days. The same curve suggests that at an arrival time of 10 days, the contaminated fluid leaves the model at all points between S = 2 m and S = 6.3 m along the outflow boundary.

Figure 5.4 shows the arrival time curves for alternative No. 2 (with dewatered tailings). The dewatered tailings changed the arrival curves in at least two ways. Much later arrival times of the water coincident contaminants result, i.e., the first arrival is at location S = 5.1 m and at time T = 141.8 days or about 16 times later than with saturated tailings. The arrival curve for $t_0 = 50$ days in the figure also shows that the later departing contaminants arrive over a significantly shorter part of the vertical outflow area.

Figure 5.5 shows the outflow location arrival time distribution for alternative No. 3, in which underdrains are used. Again, longer first arrival times are found with a value of 79.74 days at a location of S = 4.2 m. The diminishing bounding outflow location at longer times to the right side of the graph indicates the stronger reducing effects of the drain on contaminant seepage rates.

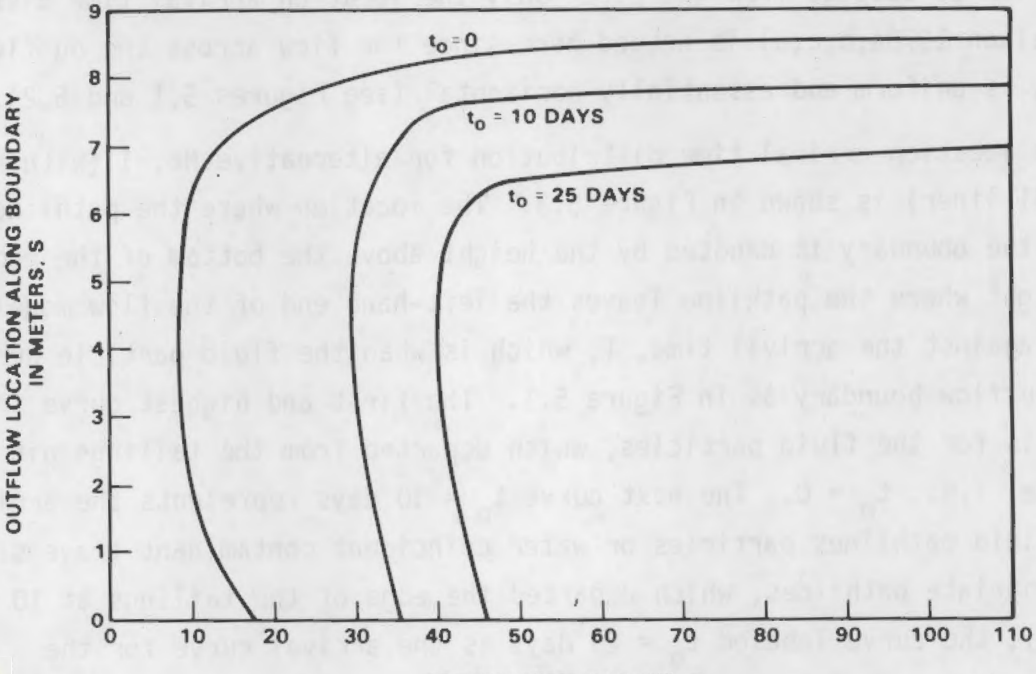


FIGURE 5.3. The Outflow Location - Arrival Time Distribution for Alternative No. 1 with No Pit Side Wall Liner

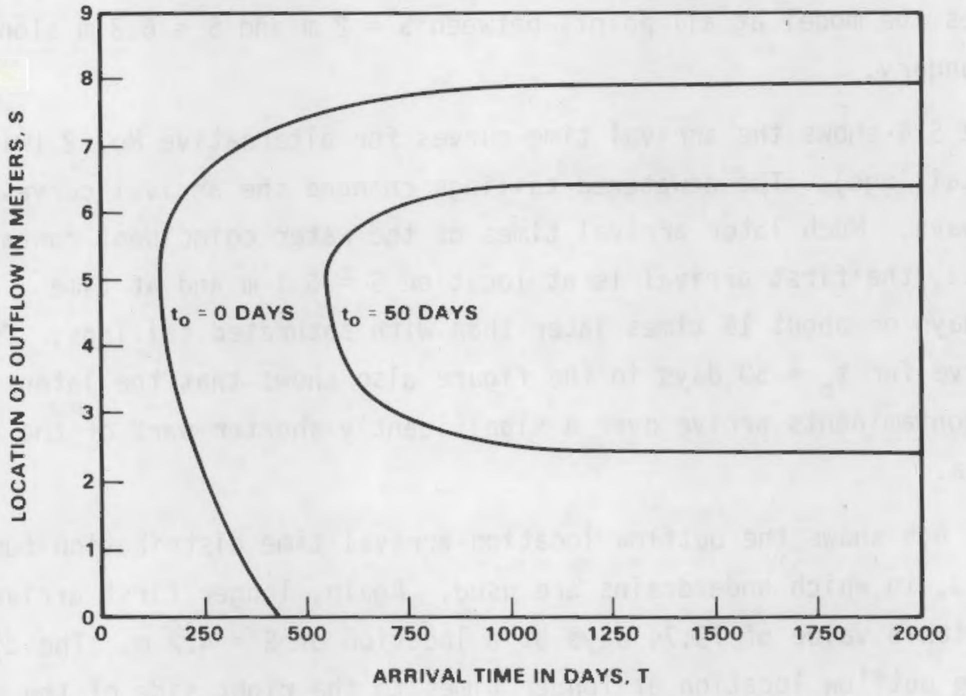


FIGURE 5.4. The Outflow-Arrival Time Distribution of Alternative No. 2 with No Side Wall Liner but with Dewatered Tailings

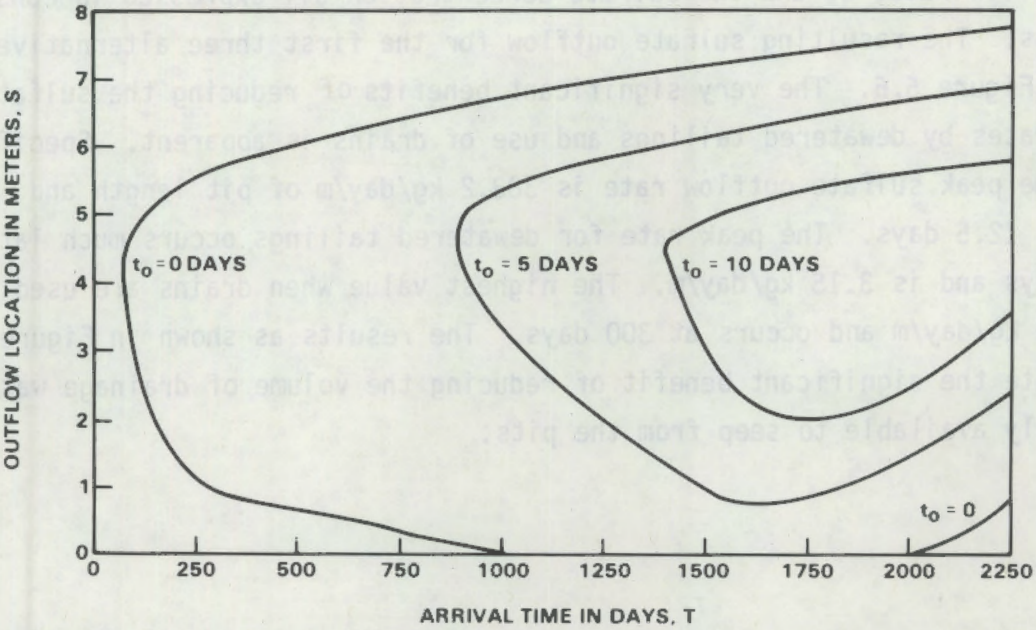


FIGURE 5.5. The Outflow-Arrival Time Distribution of Alternative No. 3 with No Side Wall Liner but with Underdrain

SULFATE OUTFLOW RATES FOR UNLINED SIDE WALL ALTERNATIVES

The most serious contaminant in the tailings drainage that may move directly with the water is sulfate. The sulfate is considered here at a concentration of 15.95 gm/l since it is the most serious, but any other water coincident contaminant is easily incorporated simply by using its concentration instead of the 15.95 gm/l sulfate concentration.

In the companion study (Gee et al. 1980), it was observed that the sulfate concentration in effluent from test columns was always below the maximum concentration of 15.95 g/l. For the model calculations, however, this maximum concentration was used as a worst-case estimate of the contamination potential.

The sulfate outflow rate for the three alternatives is easily obtained using the location arrival time distribution results from the previous section and unit fluid outflow rates obtained from the total fluid outflow rates shown previously in Figure 4.4. These results are given in Table 5.1. The instantaneous sulfate outflow rate is the product of the contaminated outflow distance, i.e., the difference in S's from the arrival distributions, the unit fluid outflow rate, q, and the sulfate concentration all expressed in consistent units. The resulting sulfate outflow for the first three alternatives is shown in Figure 5.6. The very significant benefits of reducing the sulfate outflow rates by dewatered tailings and use of drains is apparent. Specifically, the peak sulfate outflow rate is 383.2 kg/day/m of pit length and occurs at 12.5 days. The peak rate for dewatered tailings occurs much later at 430 days and is 3.15 kg/day/m. The highest value when drains are used is only 2.25 kg/day/m and occurs at 300 days. The results as shown in Figure 5.6 demonstrate the significant benefit of reducing the volume of drainage water potentially available to seep from the pits.

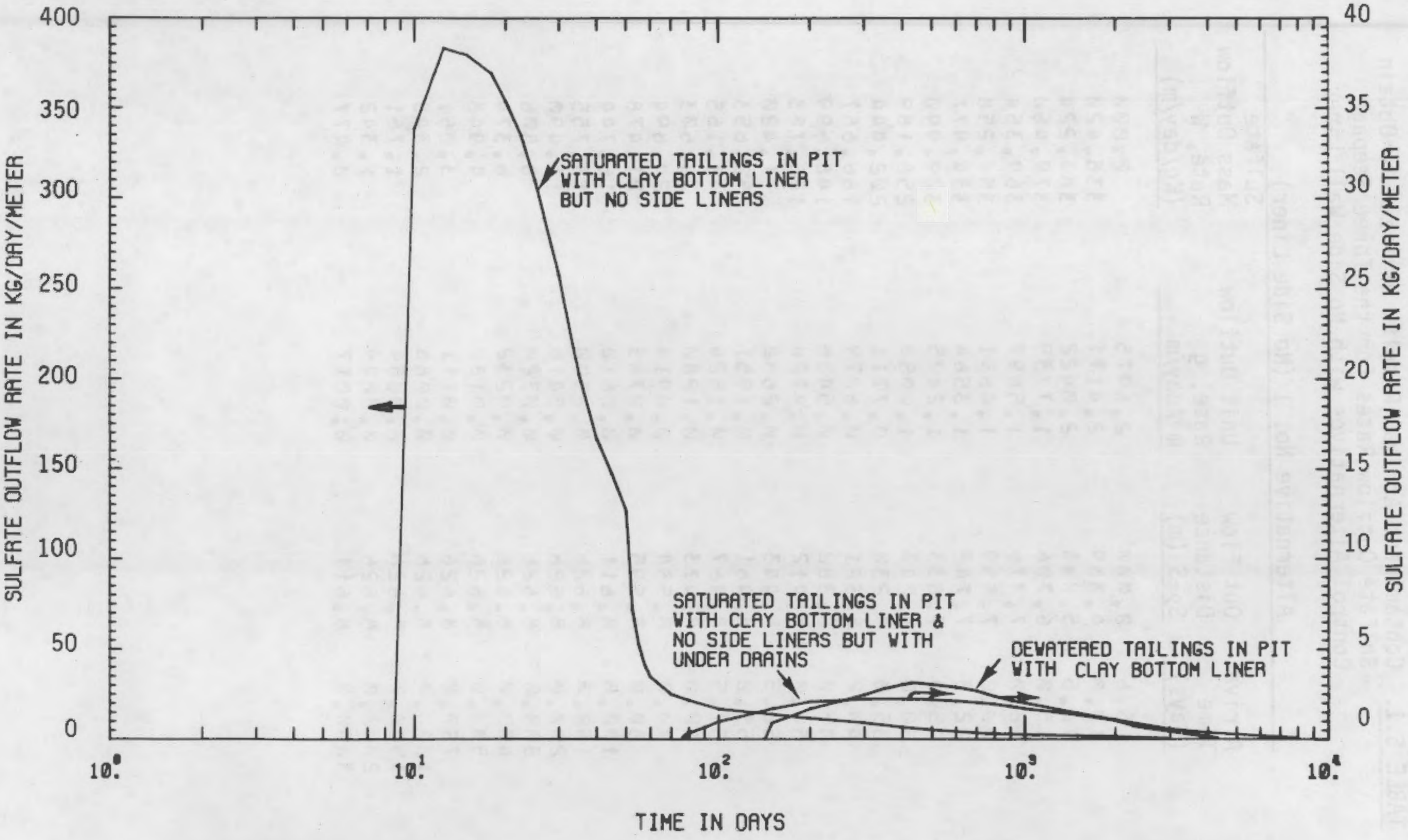


FIGURE 5.6. Sulfate Outflow Rate at Model Boundary for the Three Alternatives with No Side Wall Liner

TABLE 5.1. Contaminant Arrival Results Utilized to Obtain Sulfate Outflow Rates for the Three Seepage Control Alternatives with No Side Wall Liner

Alternative No. 1 (No Side Liner)

Arrival Time (Days)	Out Flow Distance S_2-S (m)	Unit Outflow Rate, g m^3/day/m	Sulfate Mass Outflow Rate, W (Kg/day/m)
8.6	0.000	2.6975	0.000
10.0	4.389	2.4171	338.420
12.5	5.883	2.0422	383.224
15.0	6.706	1.7739	379.460
18.0	7.376	1.5697	369.354
20.0	7.559	1.4691	354.258
22.5	7.742	1.3564	334.977
25.0	7.833	1.2405	309.990
30.0	8.047	1.0058	258.189
35.0	8.230	0.7711	202.444
40.0	8.321	0.6279	166.667
45.0	8.382	0.5486	146.699
50.0	8.412	0.4724	126.783
52.5	8.443	0.2652	71.420
55.0	8.461	0.1951	52.653
57.5	8.467	0.1524	41.165
60.0	8.473	0.1280	34.603
70.0	8.534	0.0914	24.894
80.0	8.595	0.0785	21.478
100.0	8.611	0.0610	16.744
150.0	8.626	0.0500	13.755
200.0	8.626	0.0418	11.490
300.0	8.626	0.0320	8.806
400.0	8.626	0.0232	6.374
500.0	8.626	0.0180	4.948
750.0	8.626	0.0111	3.061
1000.0	8.626	0.0085	2.348
1500.0	8.626	0.0064	1.761
2000.0	8.626	0.0049	1.342
3000.0	8.611	0.0017	0.477

TABLE 5.1. (Continued)

Alternative No. 2 (Dewatered Tailings)			
Arrival Time (Days)	Out Flow Distance S_2-S (m)	Unit Outflow Rate, g m^3/day/m	Sulfate Mass Outflow Rate, W (Kg/day/m)
141.8	0.000	0.0170	0.000
150.0	1.707	0.0168	0.913
200.0	3.292	0.0163	1.709
250.0	4.359	0.0152	2.119
300.0	5.273	0.0147	2.476
350.0	6.248	0.0142	2.831
400.0	6.949	0.0138	3.054
430.0	7.315	0.0135	3.151
500.0	7.437	0.0128	3.037
600.0	7.620	0.0118	2.875
700.0	7.742	0.0106	2.672
800.0	7.803	0.0095	2.367
900.0	7.864	0.0086	2.149
1000.0	7.894	0.0079	1.996
1500.0	7.910	0.0057	1.446
2000.0	7.925	0.0043	1.079
3000.0	7.925	0.0022	0.555

TABLE 5.1. (Continued)

Alternative No. 3 (With Underdrains)

Arrival Time (Days)	Out Flow Distance S_2-S (m)	Unit Outflow Rate, g m^3/day/m	Sulfate Mass Outflow Rate, W (Kg/day/m)
79.7	0.000	0.0185	0.000
80.0	0.610	0.0184	0.359
90.0	1.158	0.0183	0.675
100.0	1.707	0.0181	0.984
150.0	3.200	0.0168	1.711
200.0	3.993	0.0165	2.104
250.0	4.450	0.0152	2.163
300.0	4.785	0.0147	2.243
400.0	5.121	0.0137	2.240
500.0	5.364	0.0127	2.180
600.0	5.639	0.0117	2.111
700.0	5.913	0.0108	2.030
800.0	6.187	0.0098	1.937
900.0	6.462	0.0088	1.809
1000.0	6.706	0.0078	1.676
1250.0	6.980	0.0068	1.507
1500.0	7.224	0.0059	1.349
1750.0	7.376	0.0050	1.176
2000.0	7.620	0.0042	1.022
2100.0	7.498	0.0039	0.940
2200.0	7.193	0.0037	0.839
2300.0	6.828	0.0034	0.744
3000.0	3.048	0.0021	0.208

6.0 TRANSPORT OF INTERACTING CONTAMINANTS

Only contaminants in the tailings drainage that move with the fluid were considered in the previous section. Emphasis was placed on sulfate, which had the highest concentration and posed potentially the greatest environmental concern. In this section, transport of selected contaminants from the drainage solution which interact with the porous material is considered. Those species considered are either typical of others in the tailings solution or are those of the most potential environmental concern. They were selected based upon the extensive laboratory studies of pit lining materials of which this modeling task is a part (see Gee et al. 1980).

The laboratory studies on clay liner properties, buffering capacity, and material stability indicated that the pH change was particularly important. The soils at Morton Ranch have a pH in the range of 7.7 to 8.5, but the mill tailings solutions typically range from pH 2.0 to 2.5. The experimental results also show a very strong dependence upon pH of sorbtion of the tailings contaminants by the natural soils (see Table 3.3). Accordingly, the change of pH is considered here in terms of the advance of the pH front away from the tailings pit with passing time for the seepage control alternatives. The pH then is important both since the low pH may be a direct environmental concern, and perhaps even more important, because the transport of other tailings solution constituents is so strongly pH dependent.

A convective transport analysis was formulated using the experimental results and neutralization approach discussed previously in Section 3.3. The resulting formulation was incorporated into the auxillary routines and into the two main computer codes, FLUX and MILTVL, to enable determining the advance of the pH front away from the pit. The two codes also allow calculating the advance of other sorbed contaminants, such as uranium species, thorium, and lead away from the pits, taking into account the equilibrium sorbtion coefficient's dependence upon pH.

THE pH RESULTS FOR TWO CONTROL ALTERNATIVES

The model fluid flow results were used with the pH buffering capacities in Table 3.2 as additional input to the FLUX code. The FLUX code then generates the potential for pH front movement throughout the flow system, which may be called for brevity "the retarded pH velocity field." Use of this pH velocity field in the MILTVL code provides the advance of the pH front, which is shown for the case with unlined side walls and saturated tailings (alternative No. 1) in Figure 6.1. Figure 6.2 shows the advance of the front for pH = 2.2 for alternative No. 3 (no side wall liners, saturated tailings but with underdrains). Though some inprecision is contained in the computer generated pH fronts in the figures due to straight lines being used to connect the location at a given time on different pH pathlines, the fronts are nontheless effective in bounding the outermost or largest soil mass, where acid conditions are expected to occur. The advantage of drains in reducing the advance of the pH front is very apparent. Also, essentially the same advance is noted in the bottom clay liner as occurs into the unlined walls high on the sides of the pit.

TRANSPORT RESULTS FOR URANIUM-238 AND LEAD-210

The transport analysis for ^{238}U and ^{210}Pb was obtained using the FLUX code, but this time the sorbtion distribution coefficients, Kd's, used are also dependent upon the pH. The Kd's used for the soils were those listed in Table 3.3. All of the interactions are combined in the FLUX code to provide the retarded ^{238}U and ^{210}Pb velocity field, which is utilized by the MILTVL program to provide the advance of the particular interacting contaminant front away from the pit. Figures 6.3 and 6.4 show the advancing fronts for the ^{238}U for the unlined side wall cases without and with underdrains, respectively. The ^{210}Pb is not shown in figures since the movement of the fronts was too small to be seen or plotted. Only a single solid line would be seen along the side wall and along the bottom clay liner. Such very small movement is the direct result of the larger Kd values for the ^{210}Pb (Table 3.3). The ^{320}Th was not considered since the Kd values were so close to the ^{238}U case already shown in Figures 6.3 and 6.4. In fact, the results would be essentially identical to the ^{238}U results.

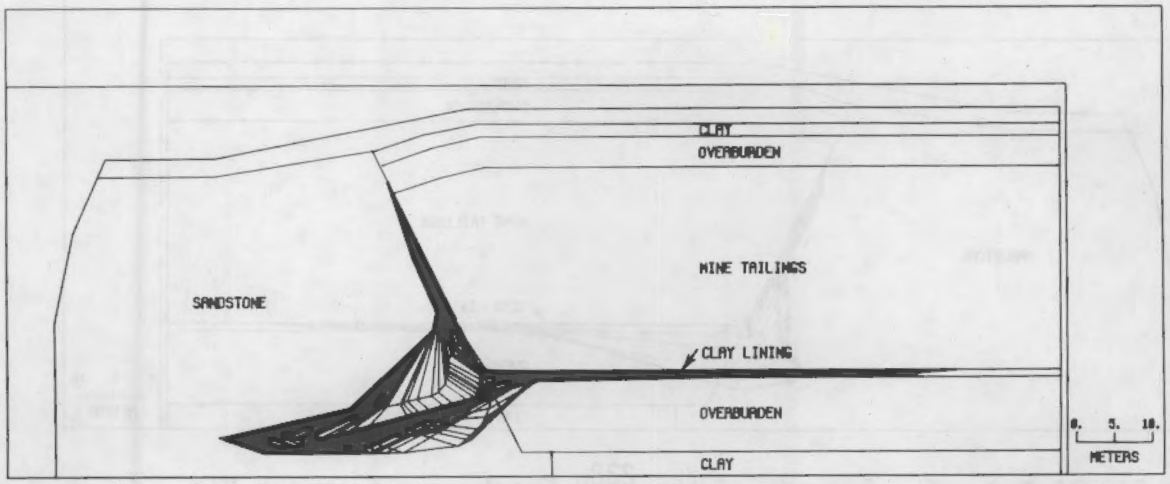


FIGURE 6.1. The Advance of the pH = 2.2 Front in Space and Time for Alternative No. 1 with No Side Wall Liners

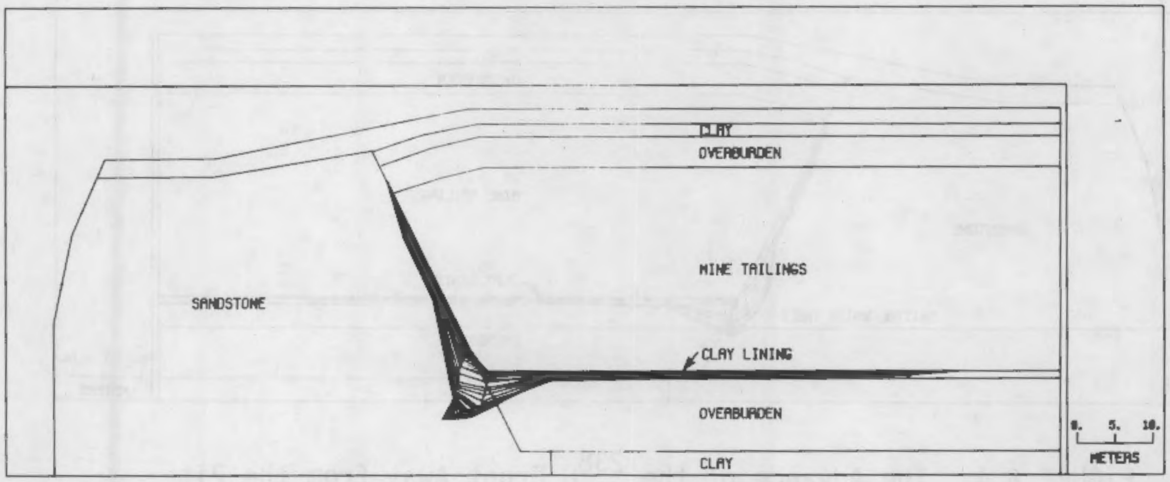


FIGURE 6.2. The Advance of the pH = 2.2 Front in Space and Time for Alternative No. 3 with No Side Wall Liners but with Underdrains

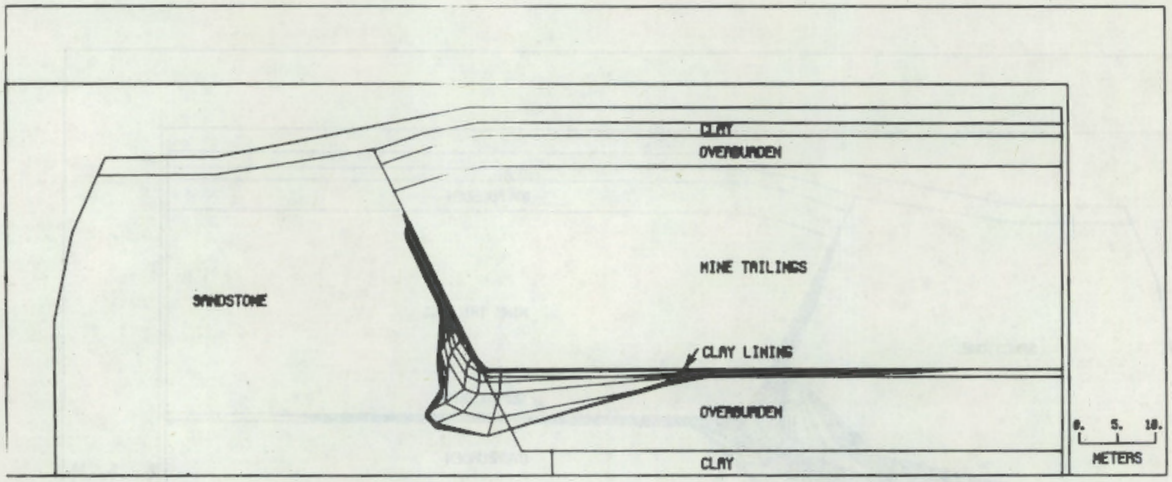


FIGURE 6.3. The Advance of the ^{238}U Front away from the Pit for Alternative No. 1 with No Side Liner

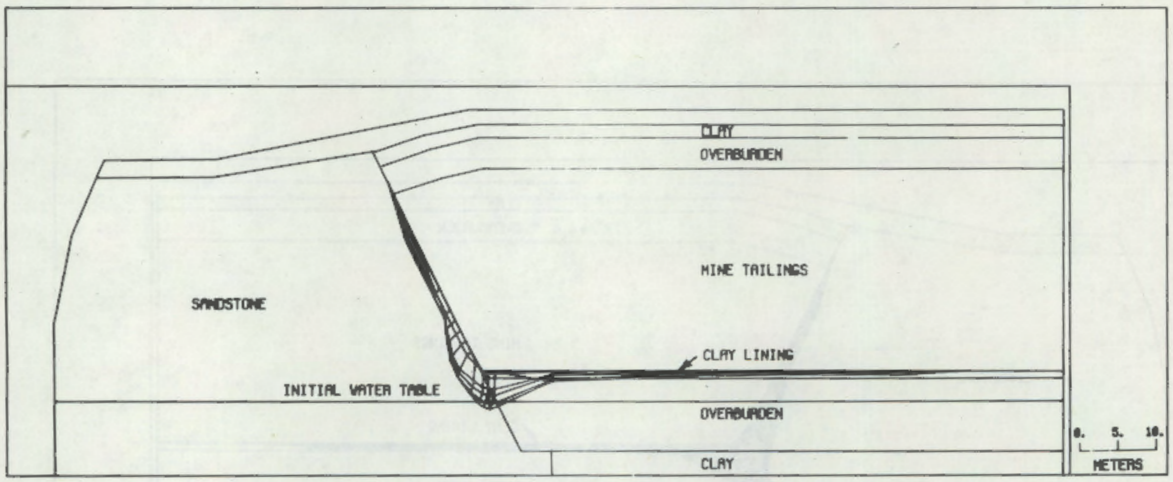


FIGURE 6.4. The Advance of the ^{238}U Front Away from the Pit for Alternative No. 1 with No Side Liners but with Underdrains

7.0 DISCUSSION OF RESULTS AND RECOMMENDATIONS

Although four alternatives were considered in this study, only the first three alternatives, which utilize a bottom clay liner but no side liner, provide important results. All of the results obtained in this study demonstrate a side liner on the upper 70 to 80% of the side wall height is of very little or no benefit in reducing contaminant seepage; hence, high side wall liners are unnecessary and use of such would moreover be economically wasteful.

The study has demonstrated the very real benefits of reducing the volume of fluid available to seep from the tailings. The similarity of contamination consequences for systems that use dewatered tailings or underdrains tends to indicate that the means of reducing the volume available for seepage is less important than the actual volume reduction of water that can be realized.

RECOMMENDATIONS FOR A PROPOSED CONTROL ALTERNATIVE

Based upon what has been learned from this study, it is the authors' considered opinion that the best contaminant seepage control would be provided through combining the desirable features of the four alternatives considered. The recommendations would include the accepted pit covering procedure already planned for the Morton Ranch Site: specifically, the additional proposed control alternative is:

1) to provide a well constructed bottom clay liner placed at least 3.05 m (10 ft) above the regional water table and not less than 0.91 m (3 ft) thick;
2) to provide stub clay side liners continuing part way up the pit side wall to form a continuous saucer-shaped bottom and side liner for the pit;
3) to install a network of gravity drains and pumping sumps with the drains in the tailings sufficiently above the bottom clay liner to provide very effective drainage of the tailings;
4) to pump the tailings drainage effluent from the sumps while the pit is filled with tailings and as required for the first 6 to 8 months after the filling is completed.

The above proposed control features are shown conceptually in Figure 7.1, which contains a 5 m (16.4 ft) high stub sidewall clay liner and underdrains located above the clay liner. Though such a control alternative has not been evaluated through models, it is the proposed alternative that would, in the authors' considered opinions, be among the more conservative cases to be considered if additional model studies had been or were to be made. In other words, actual model results would probably sanction even lower stub side wall liners. However, such lower heights should not be allowed without testing their effectiveness in further studies.

Additional studies, however, will be required to determine the applicability of these side liner recommendations at other sites and to assure acceptable minimum contaminant seepage under other conditions. Specifically, further study is needed for various soil materials and other pit configurations using the combined approach of lining and reducing tailings water. Such studies should also be followed by companion field observation as the recommended management practices are put into use at Morton Ranch or elsewhere to check, verify, and improve upon the recommended disposal control practices. In this way, it will be possible to economically further reduce contaminant seepage and better assure the adequate disposal of uranium tailings in burial pits.

RECOMMENDATIONS CONCERNING MODEL CAPABILITIES DEVELOPED DURING THIS STUDY

Significant model code developments were accomplished during the study that provide essential information about coincident fluid, pH buffering, and sorbed transport analysis capabilities. The developed supporting computer modules, the FLUX program and MILTVL programs, have not been documented, nor have more detailed testing comparisons with analytical or other generally available results been made. The documentation and additional testing work should be done in the near future if the modeling capacity achieved in this study is to be realistically retained. Significant economies could be realized in later use of the modeling sequence if automated grid generation and input calculation capabilities were developed to complement the present capability. Very careful consideration on a first priority basis should be given to retaining the capability demonstrated on the problematic situation at Morton Ranch.

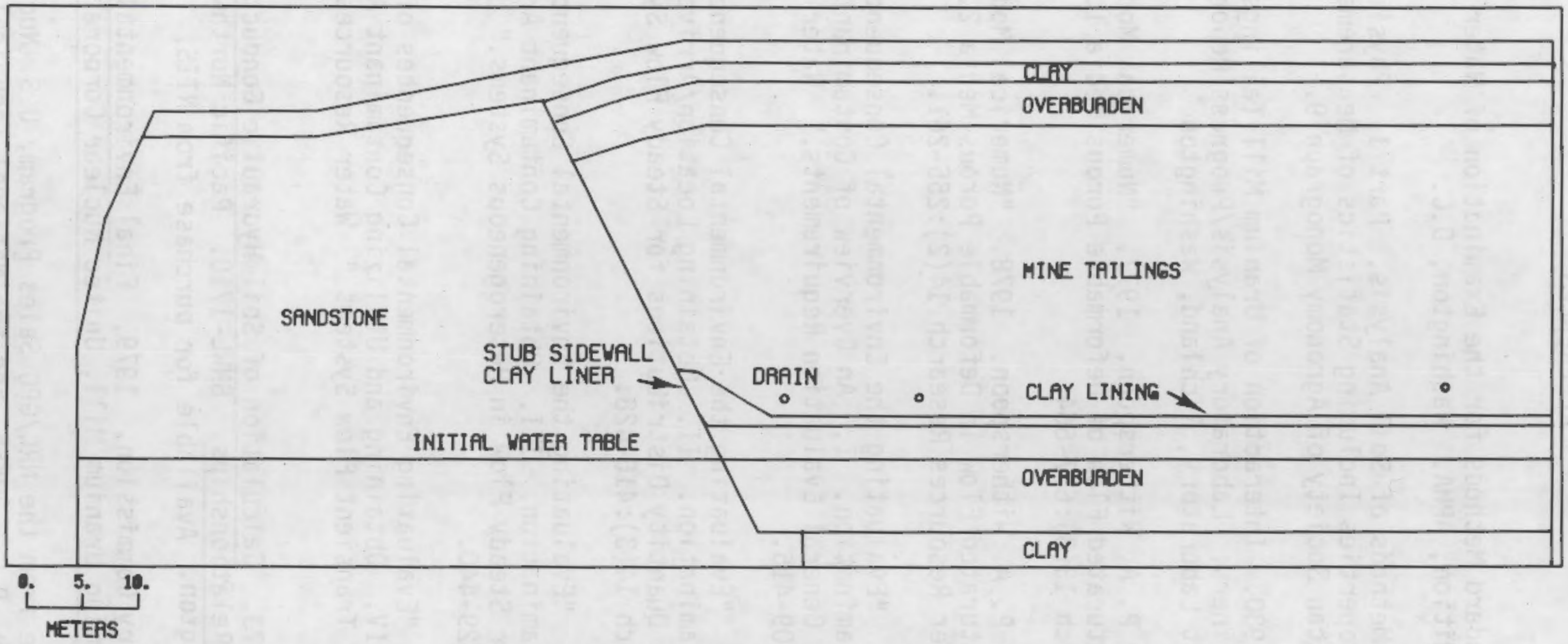


FIGURE 7.1. Proposed Control Alternative Utilizing Stub Clay Side Wall Liners and Underdrains to Minimize Contaminant Seepage from Buried Tailings

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APPENDIX

COMBINED PARTIALLY SATURATED AND SATURATED FLOW MODEL RESULTS AND SOIL CHARACTERISTICS FOR THE MORTON RANCH MILL SITE

APPENDIX

COMBINED PARTIALLY SATURATED AND SATURATED FLOW MODEL RESULTS AND SOIL CHARACTERISTICS FOR THE MORTON RANCH MILL SITE

The classical nonlinear partially saturated flow equations are the theoretical basis for the model utilized to determine the fluid flow results for the typical tailings pit with various alternatives. Combining the conservative of mass and Darcy's Law for partially saturated flow gives

$$\text{div}\,\rho(-K\text{ grad }\Phi) = \frac{\partial\theta}{\partial t} \qquad (1)$$

where

$K = K[x,z,\ p_c(x,z,t)]$ is the partially saturated hydraulic conductivity and is dependent on p_c

$\Phi = p + \rho gz$ is the potential energy per unit volume

$\theta = f\ (p_c)$ is the moisture content on a volume basis and f is a function of p_c

p is the fluid pressure

$p_c = -p$ and is the capillary pressure

ρ is the fluid mass density

g is the gravitational scaler

x is the horizontal independent coordinate variable

z is the vertical coordinate variable parallel with the earths gravitational field and

t is time.

The detailed Boundary Condition and Initial Condition were described in the body of the report.

The above nonlinear system was solved utilizing the TRUST Model which is described in detail by Narasimham (1977, 1978). The model solves the more general case than Equation (1) above where the porous material is assumed deformable. Soils data were not available to use this more complete deformable analysis capability.

The specific soil characteristics for partially saturated flow are summarized in Table 3.1 in the body of the report.

The following Figures, A.1 to A.8, show the water retention and water conductivity relationships determined for the test materials at the Morton Ranch site. These relationships were used as input characteristics for the model TRUST to analyze partially saturated and saturated flow from the pits for specific test cases. Because this was a drainage study, with no evaporation, no hysteresis was considered in the water retention characteristics. Input of a hysteretic function for the overburden and sandstone would have produced results showing slightly lower drainage, hence this flow analysis was considered conservative.

Extensive results from the flow model, TRUST were used in the subsequent contaminant flow path and transport models. These results included the potential, capillary pressure, capillary conductivity, fluxes, and moisture content for each of the discrete elements in the flow system. These very large data sets for the time sequence for each of the four alternatives were stored on magnetic tape and utilized in the subsequent pathways and transport analysis. Out of these large data sets the most informative results are the moisture content changes with time during drainage of the tailings. Figures A.9 through A.15 show the moisture content distribution at various times for management alternative No. 1. Figure A.16 is the calculated moisture distribution to which the three alternatives with no side liners will ultimately drain. The distribution was obtained by setting up the final completely drained boundary value problem and solving that special problem using TRUST.

Figures A.17 through A.24 show the moisture content on a volume basis for alternative No. 2 (dewatered tailings). Comparison of these results with Figures A.9 through A.15 indicates some differences in the drainage pattern. This is indicative of the differences shown in summary form in Figure 4.3 in the body of the report.

Figures A.25 through A.32 show the moisture distribution on a volume basis at various times during tailings drainage for alternative No. 3 (with underdrain). The drainage pattern in time for alternative No. 3 is very similar to No. 1.

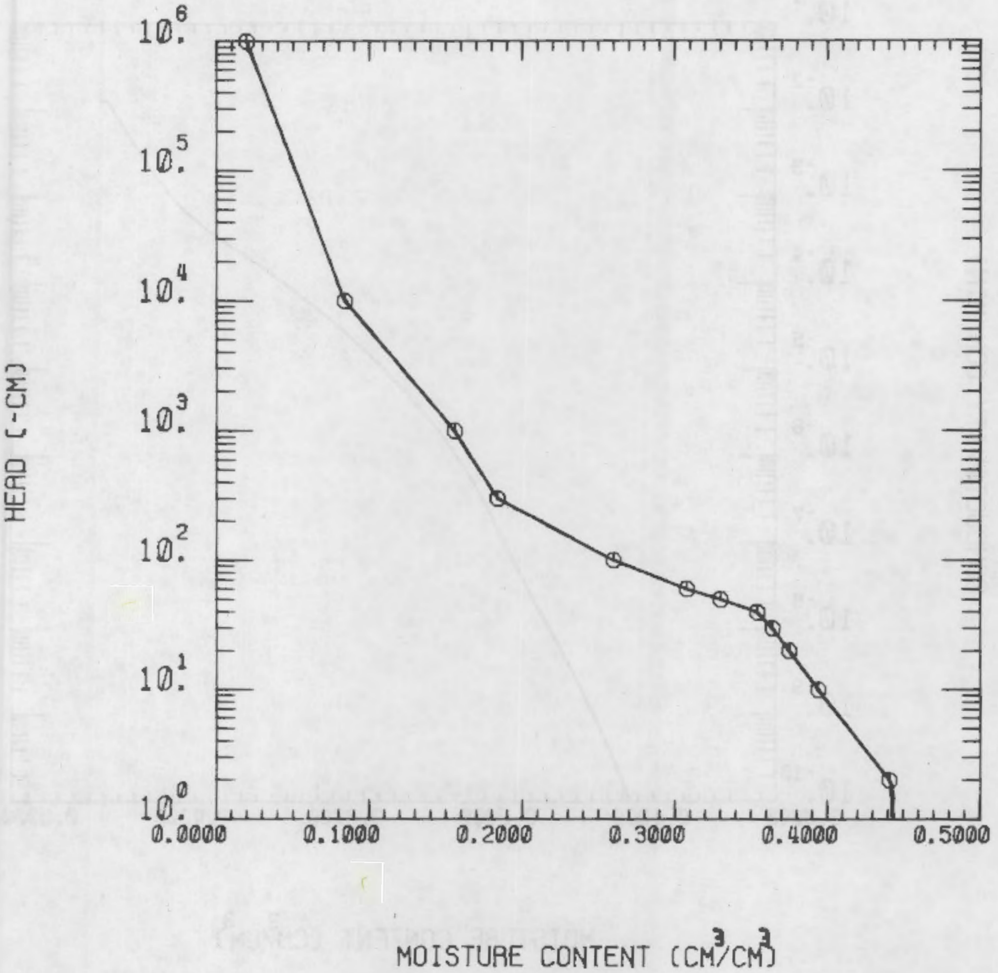

FIGURE A.1. Water Retention Curve Showing the Relationship Between Capillary Pressure Head and Moisture Content for Slurried Mill Tailings

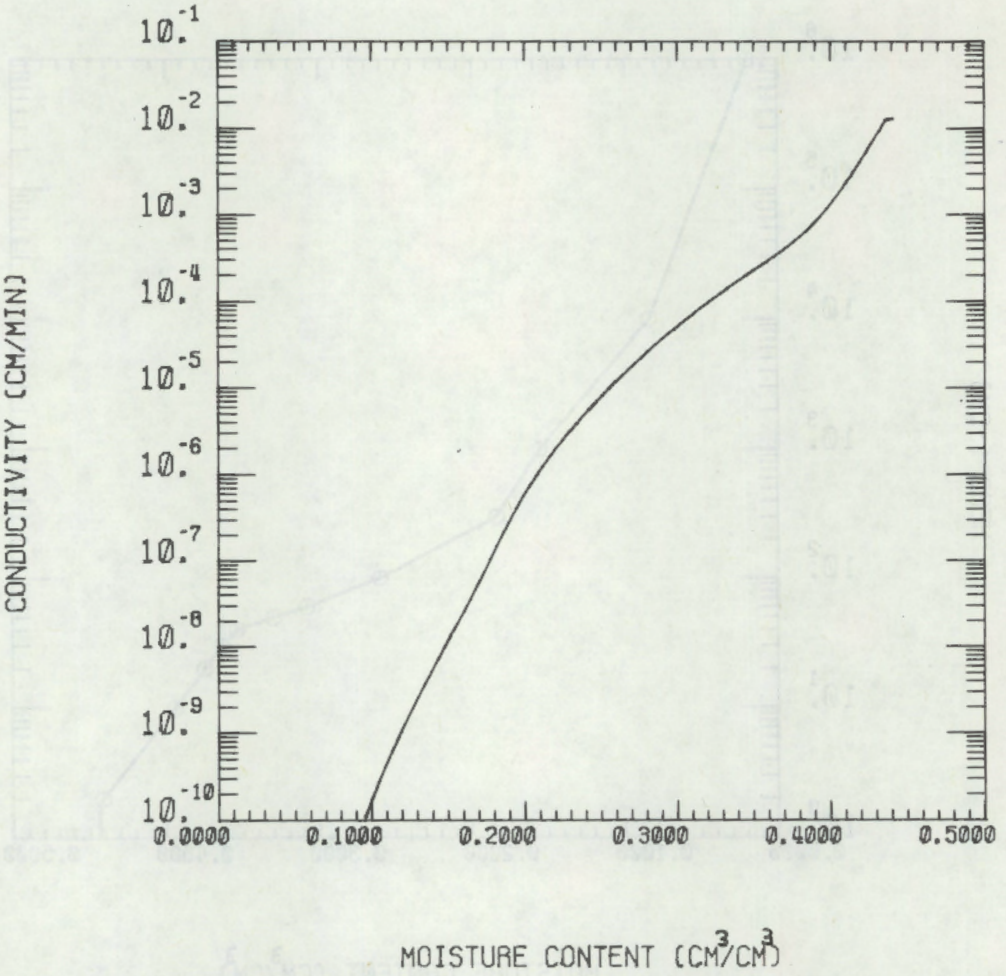

FIGURE A.2. Water Conductivity as a Function of Moisture Content for Slurried Uranium Mill Tailings

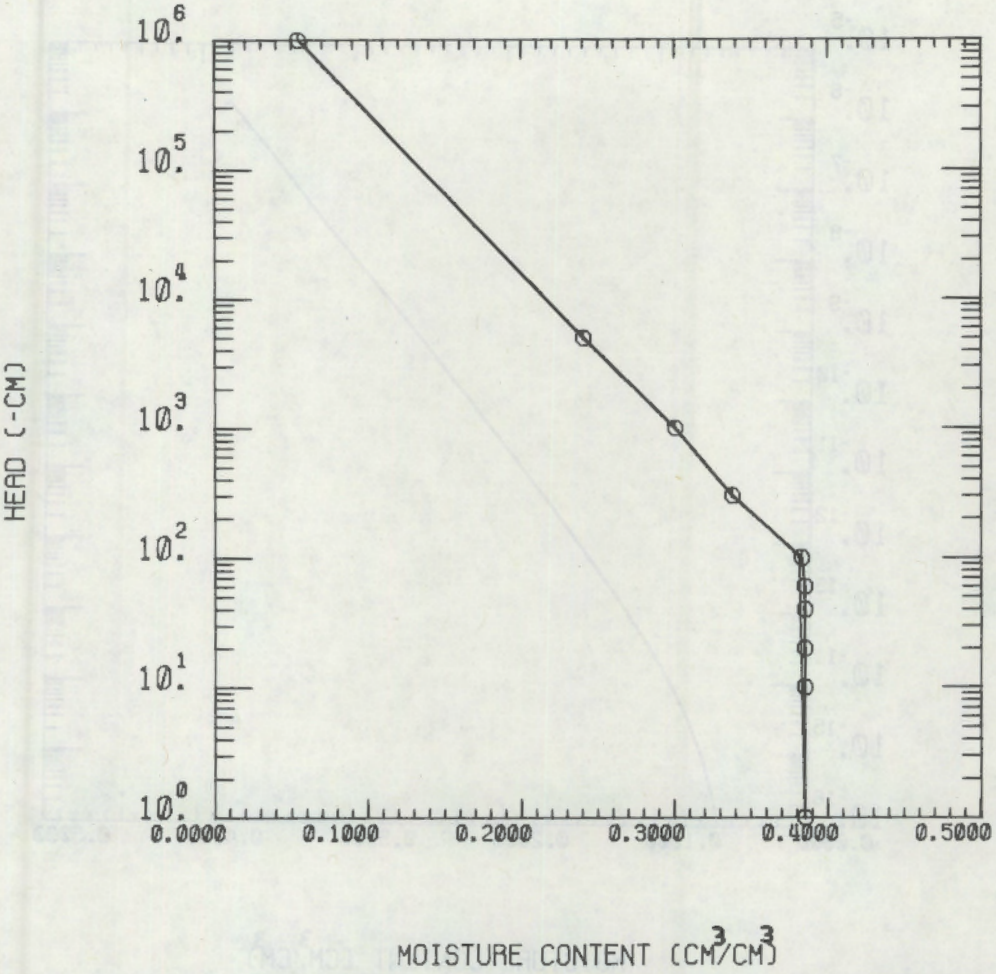

FIGURE A.3. Water Retention Curve Showing the Relationship Between Capillary Pressure Head and Moisture Content for Morton Ranch Clay Liner Material

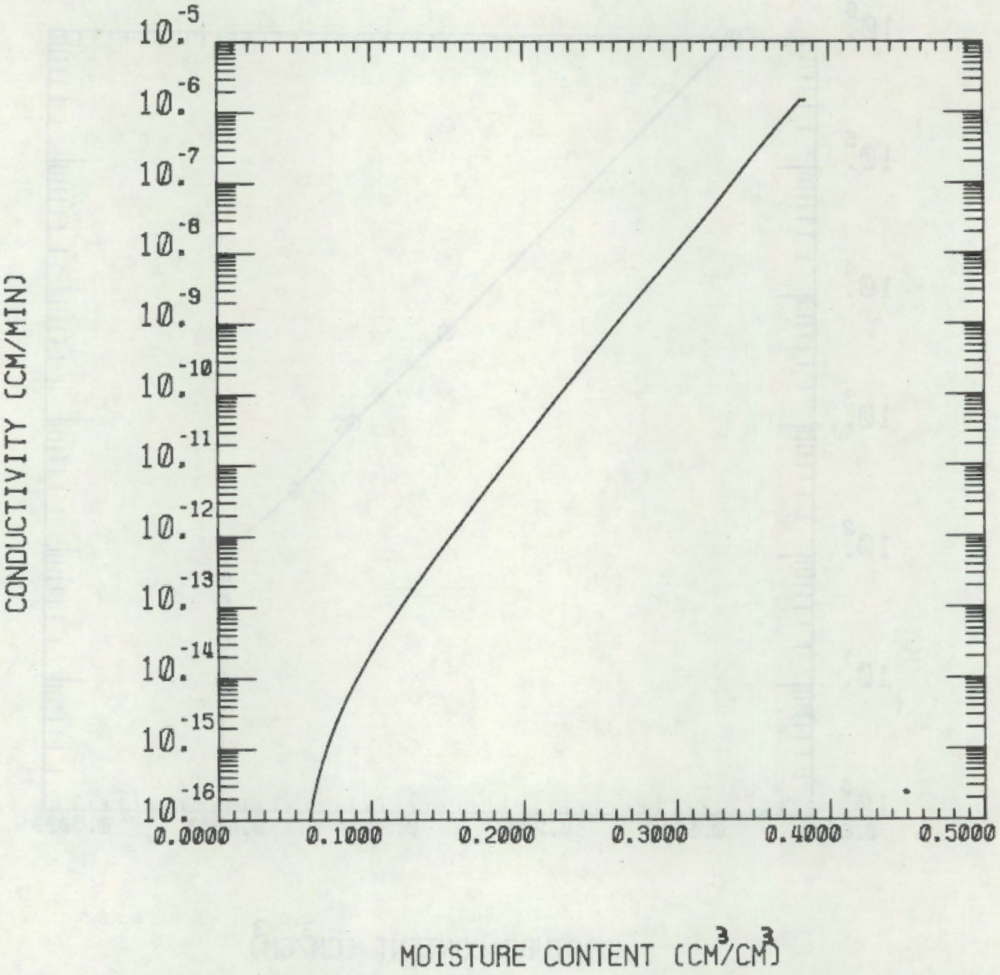

FIGURE A.4. Water Conductivity as a Function of Moisture Content for Morton Ranch Clay Liner Material

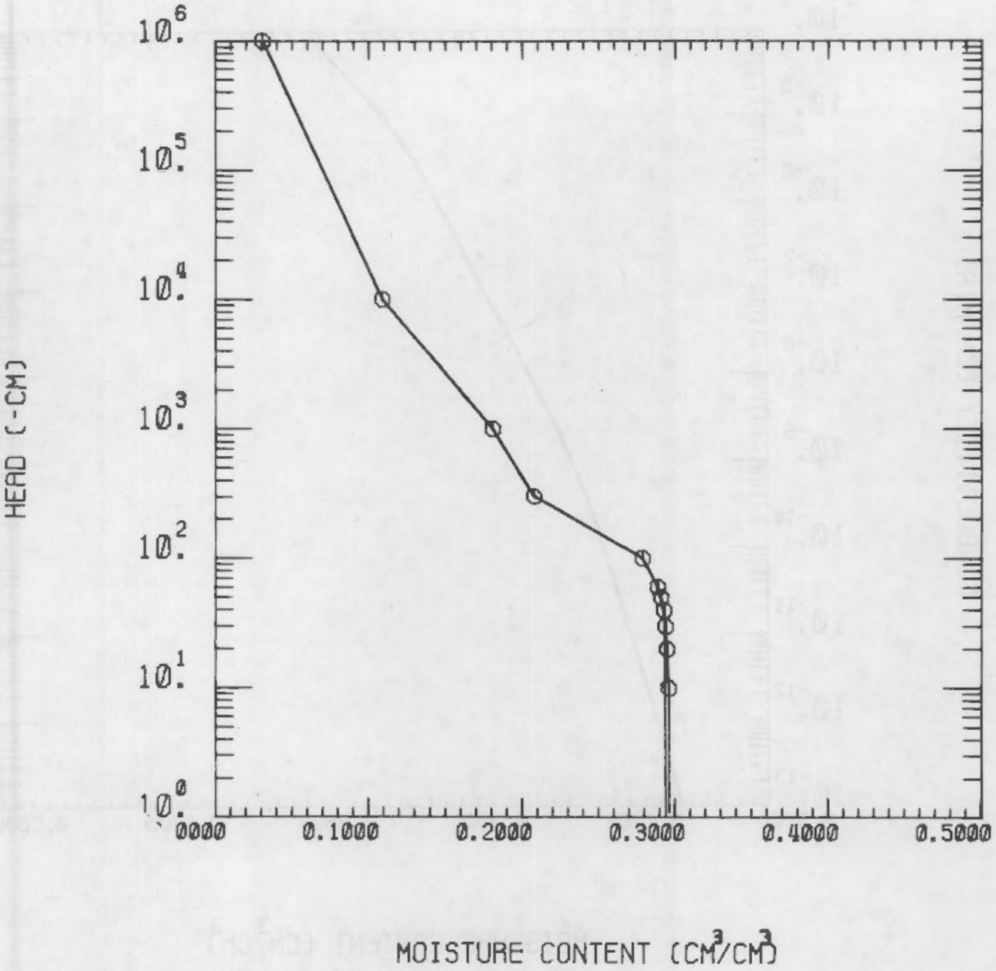

FIGURE A.5. Water Retention Curve Showing the Relationship Between Capillary Pressure Head and Moisture Content for Morton Ranch Overburden Material

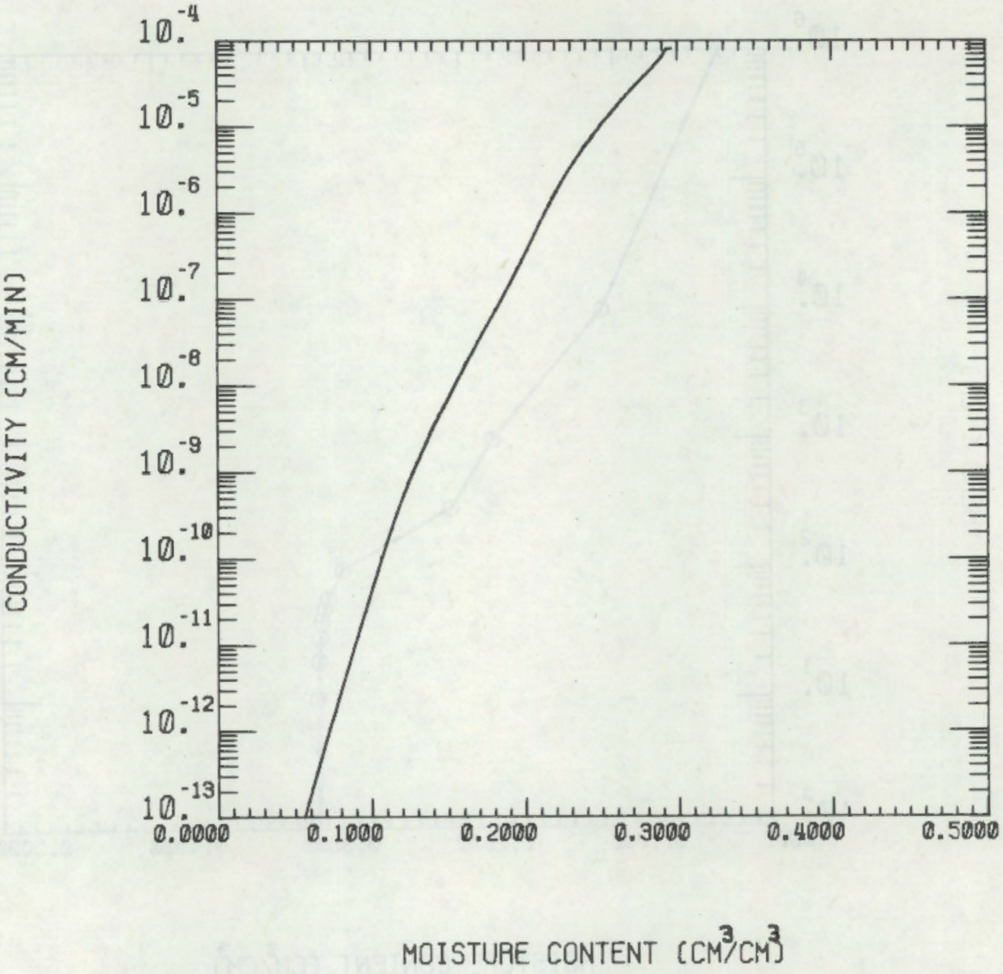

FIGURE A.6. Water Conductivity as Function of Moisture Content for Morton Ranch Overburden Material

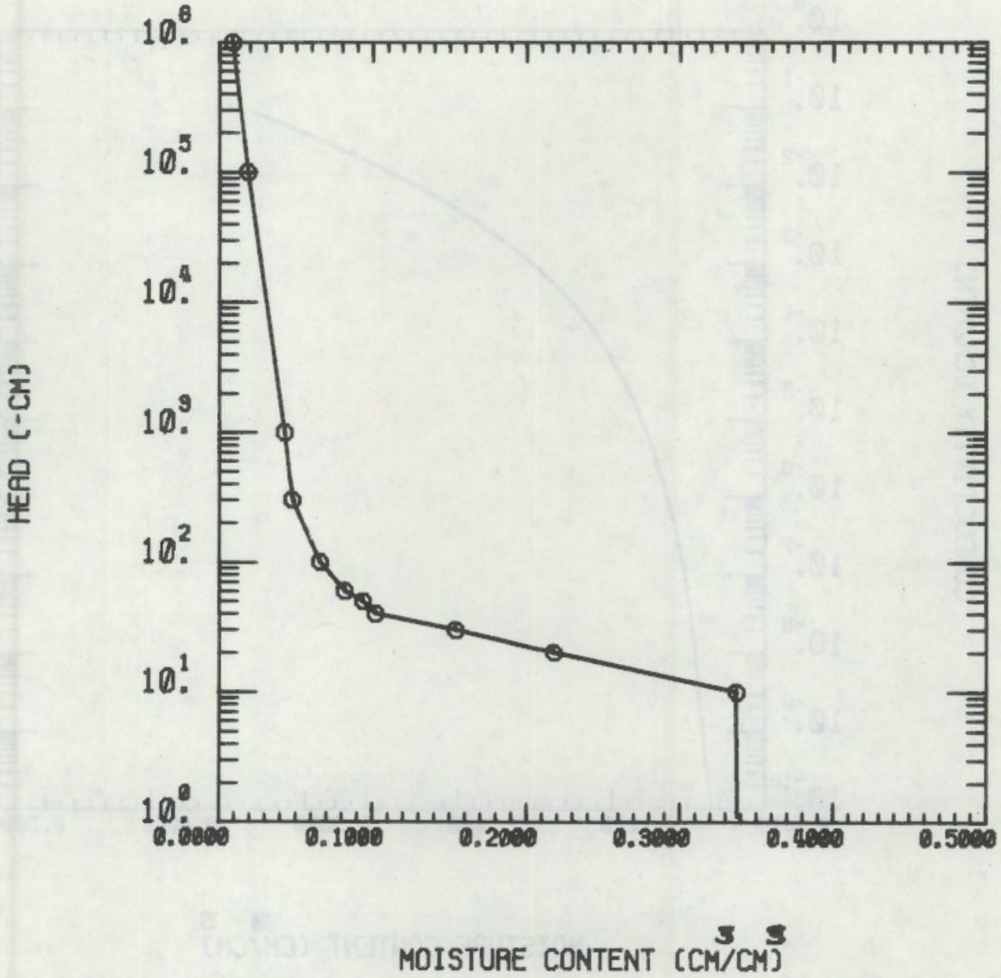

FIGURE A.7. Water Retention Curve Showing the Relationship Between Capillary Pressure Head and Moisture Content for Morton Ranch Sandstone Material

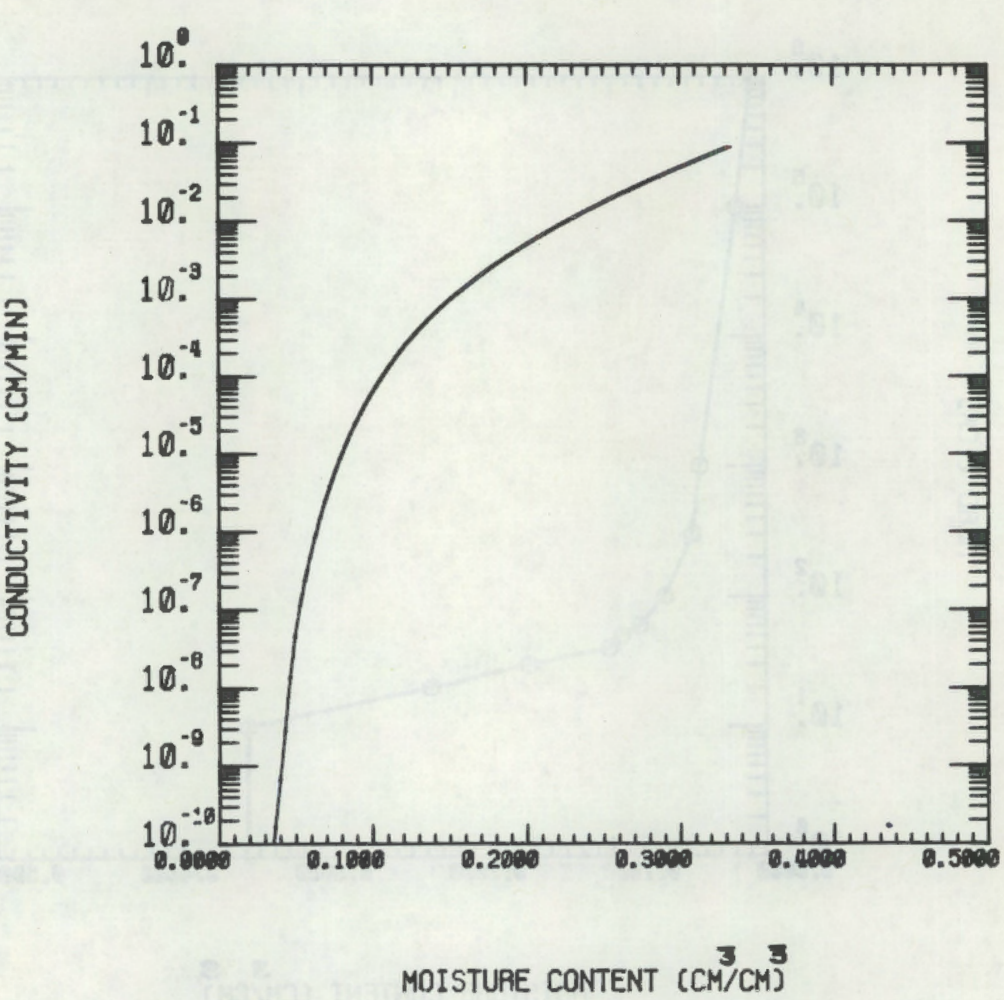

FIGURE A.8. Water Conductivity as a Function of Moisture Content for Morton Ranch Sandstone Material

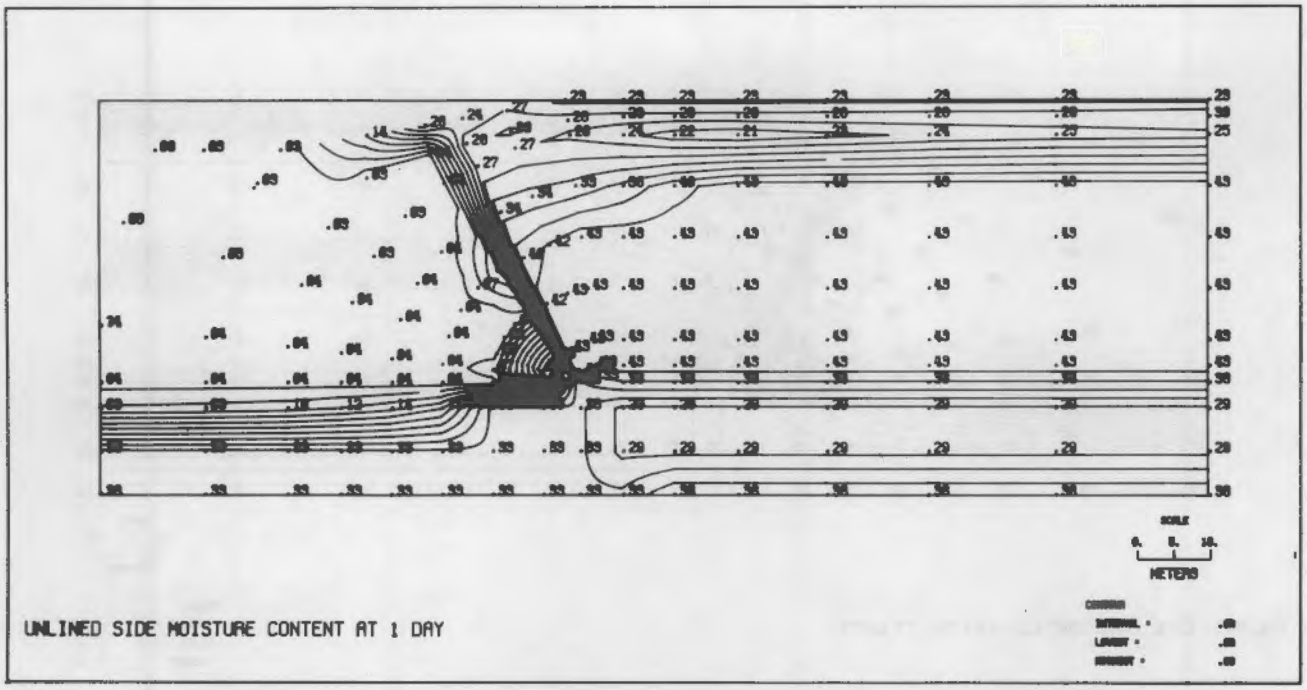

FIGURE A.9. Moisture Distribution for Alternative No. 1 (No Side Liners) at 1 Day

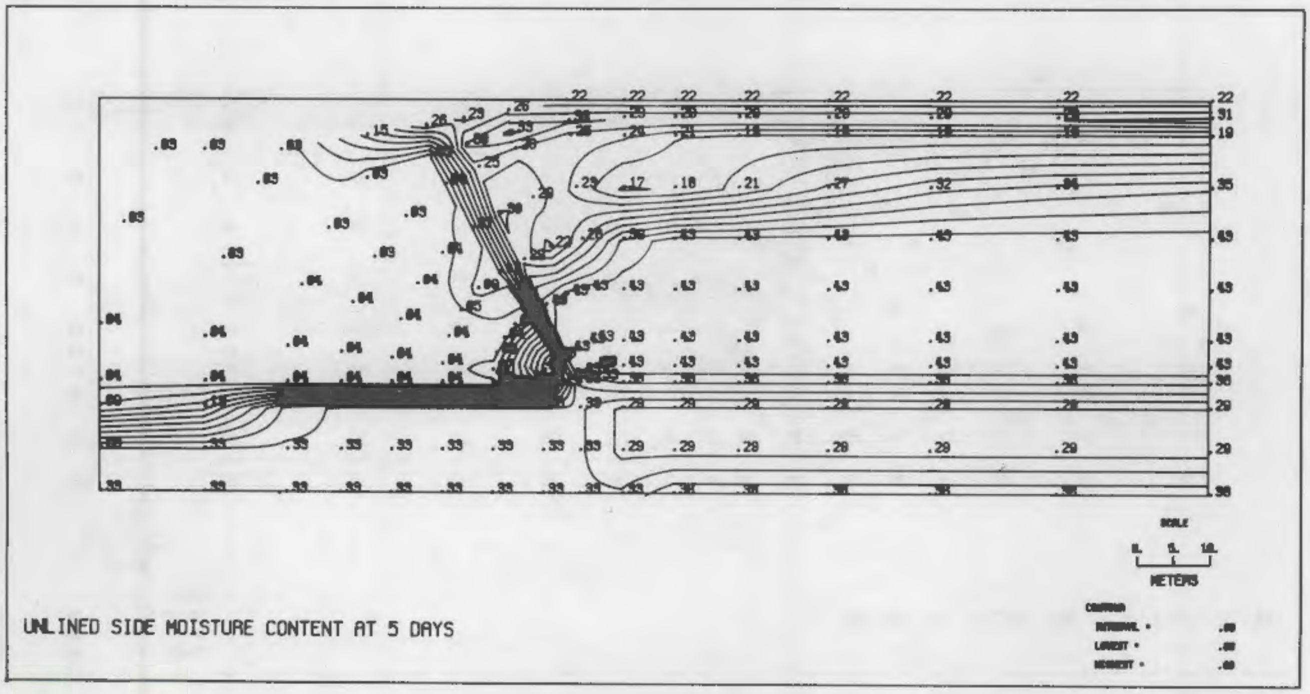

FIGURE A.10. Moisture Distribution for Alternative No. 1 (No Side Liner) at 5 Days

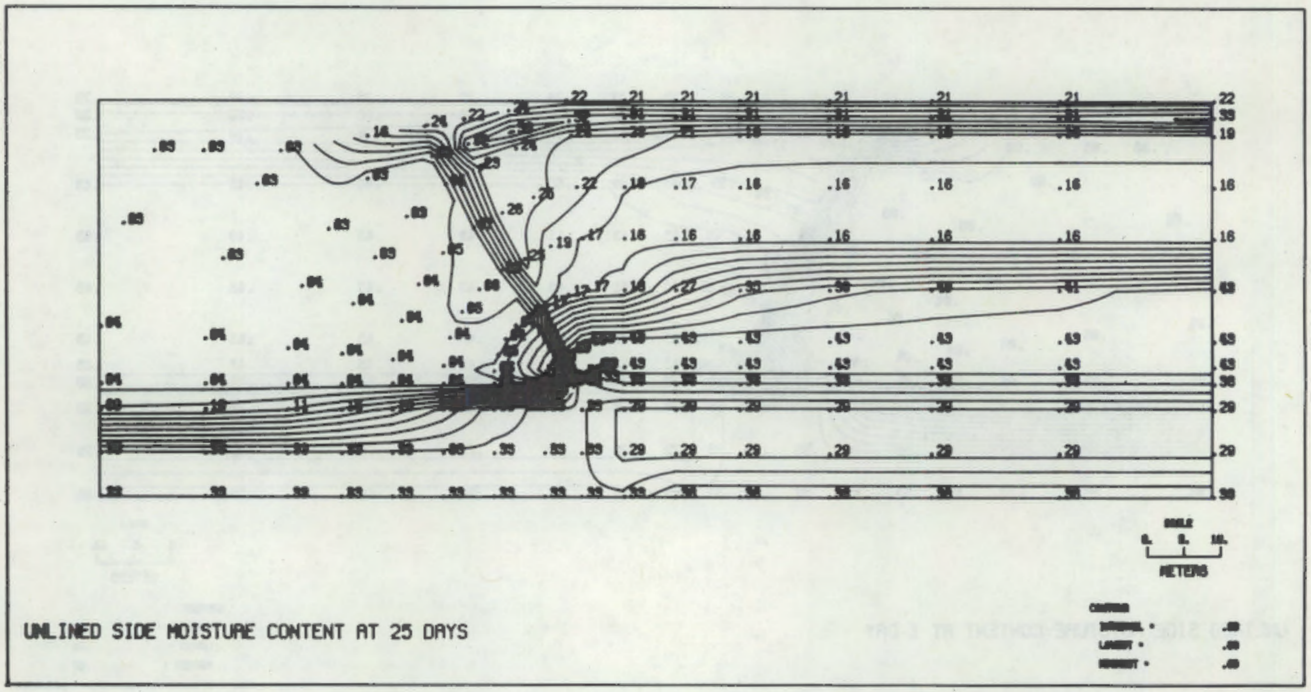

FIGURE A.11. Moisture Content Distribution for Alternative No. 1 (No Side Liner) at 25 Days

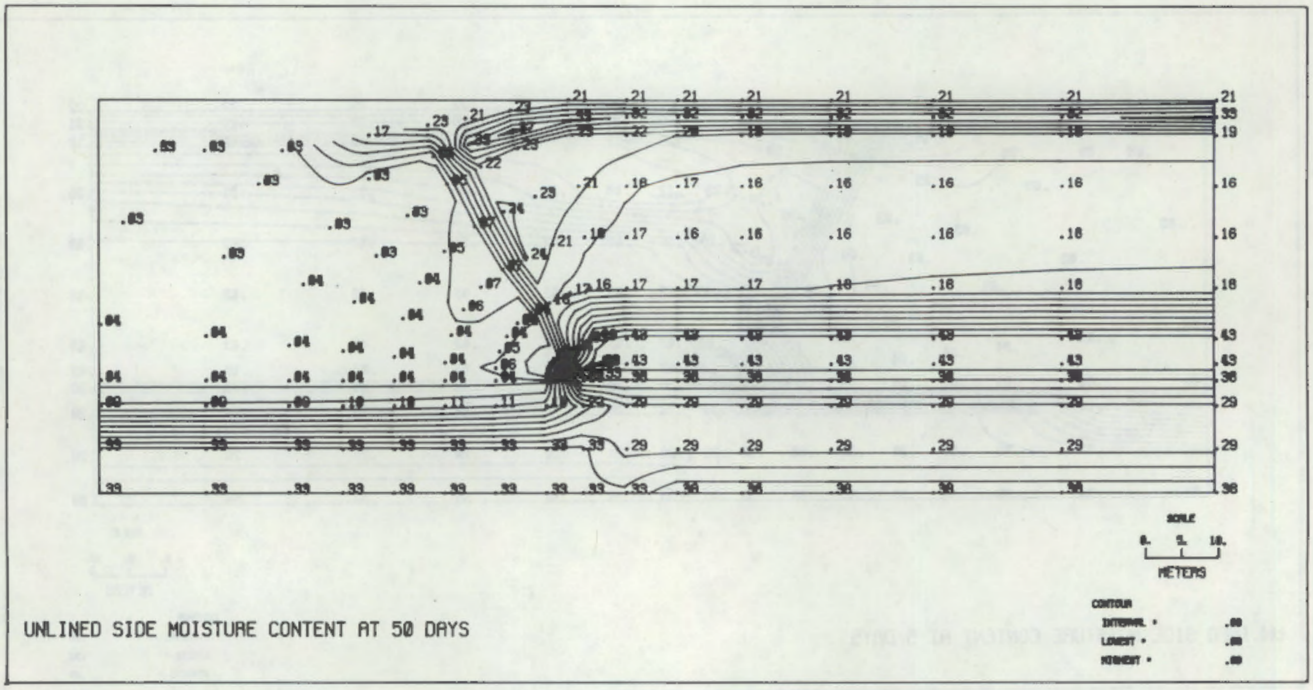

FIGURE A.12. Moisture Distriubtion for Alternative No. 1 (No Side Liner) at 50 Days

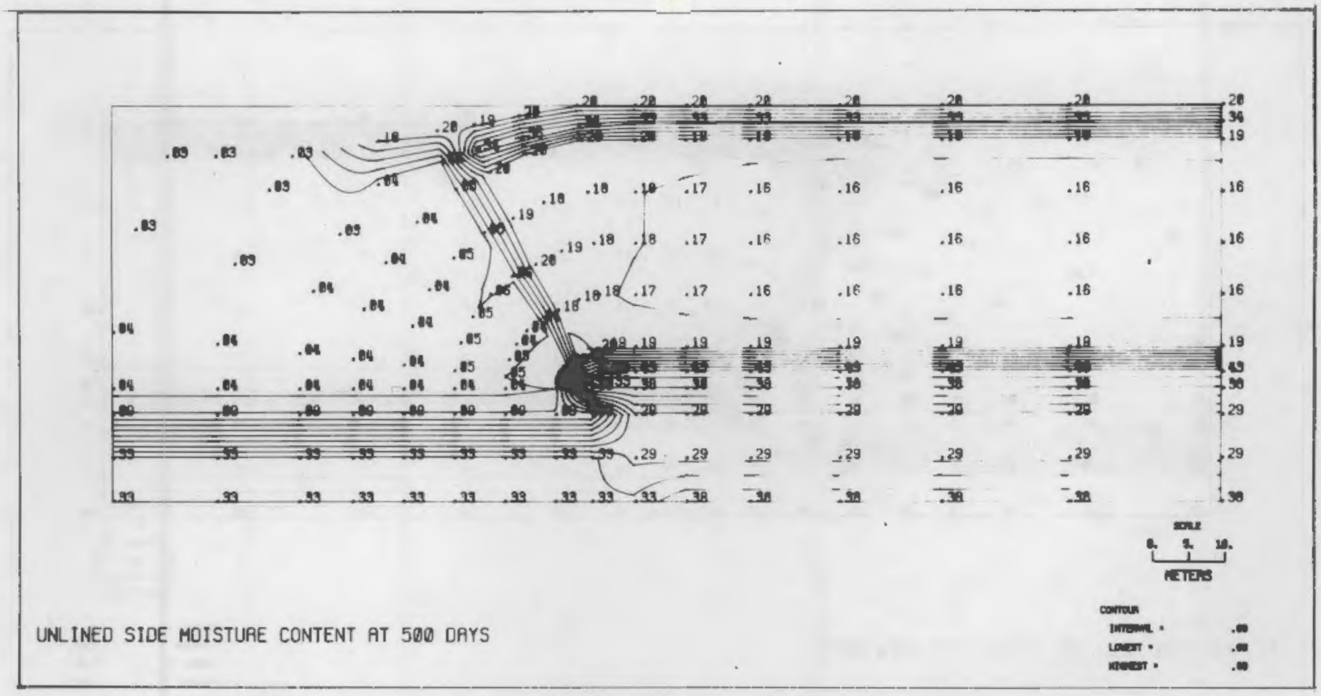

FIGURE A.13. Moisture Distribution for Alternative No. 1 (No Side Liner) at 500 Days

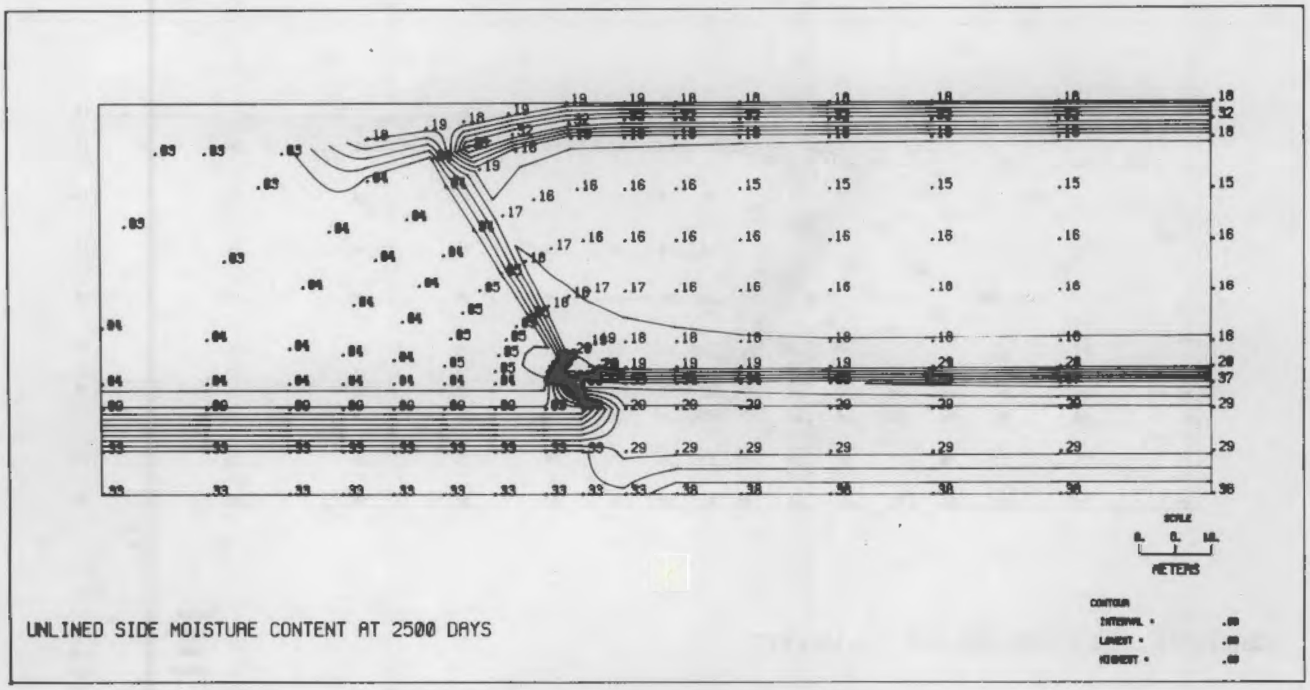

FIGURE A.14. Moisture Distribution for Alternative No. 1 (No Side Liner) at 2500 Days

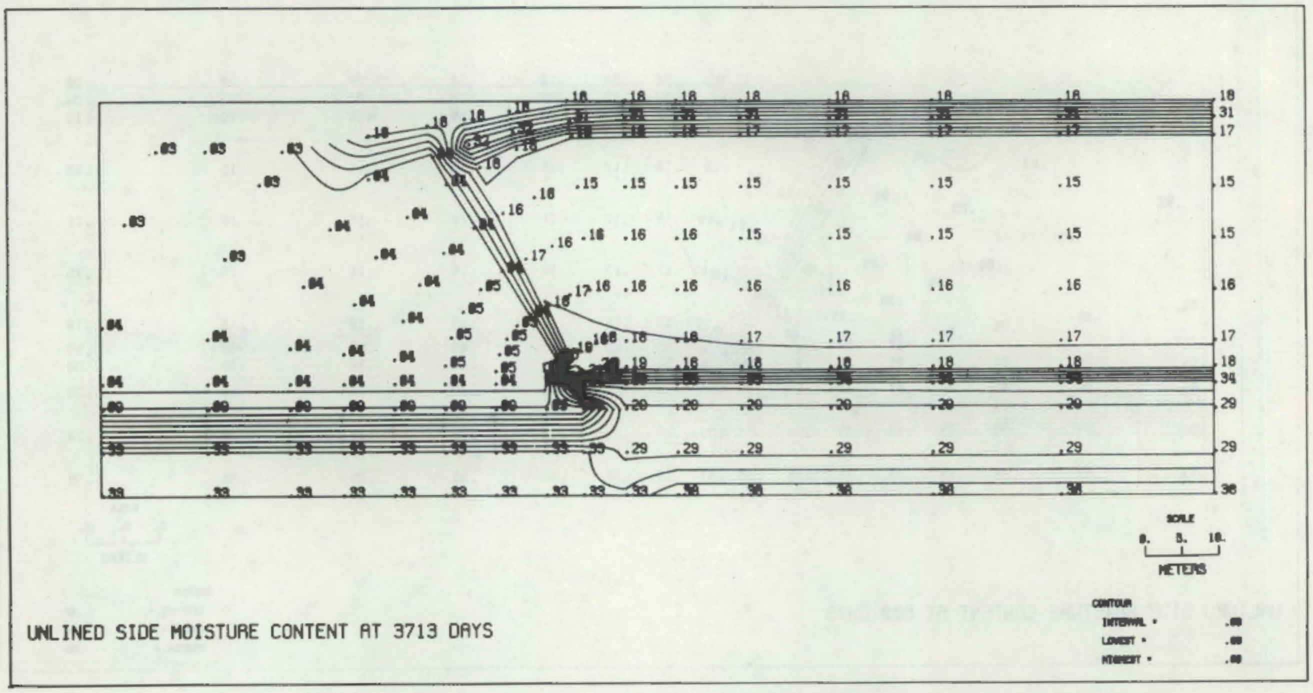

FIGURE A.15. Moisture Distribution for Alternative No. 1 (No Side Liner) at 3713 Days

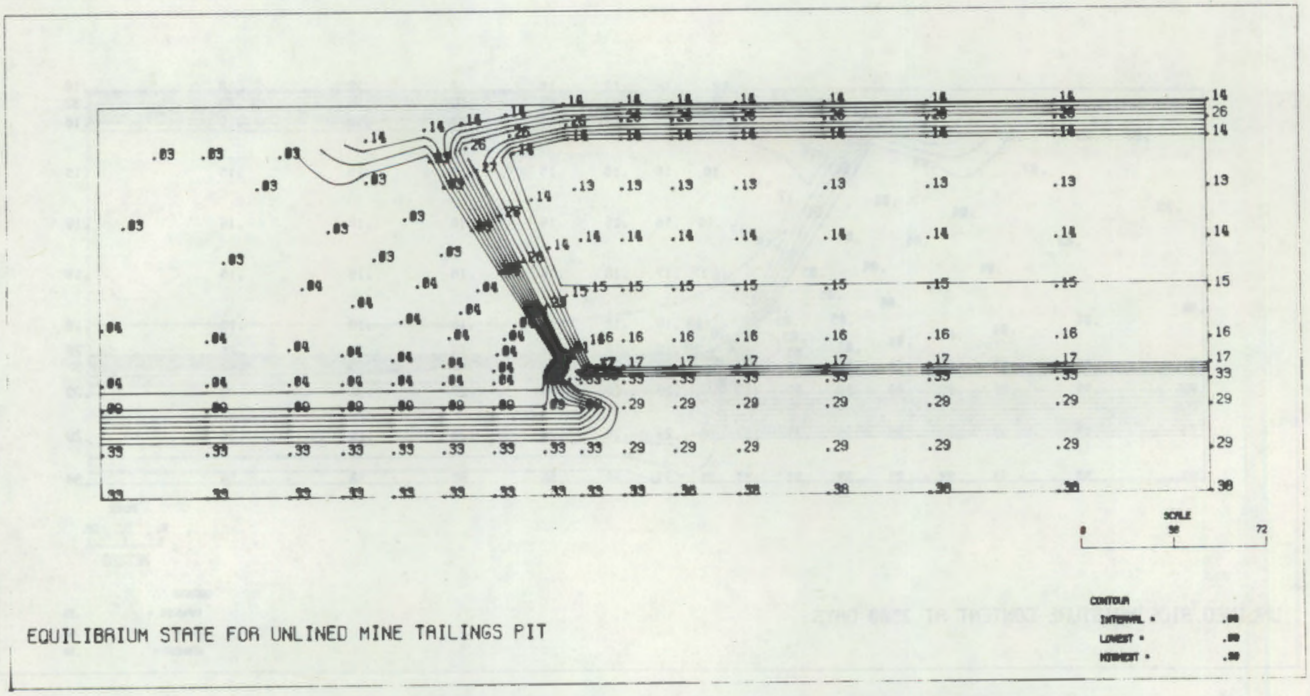

FIGURE A.16. Final Moisture Distribution to Which the Alternatives with No Side Liners Will Ultimately Drain

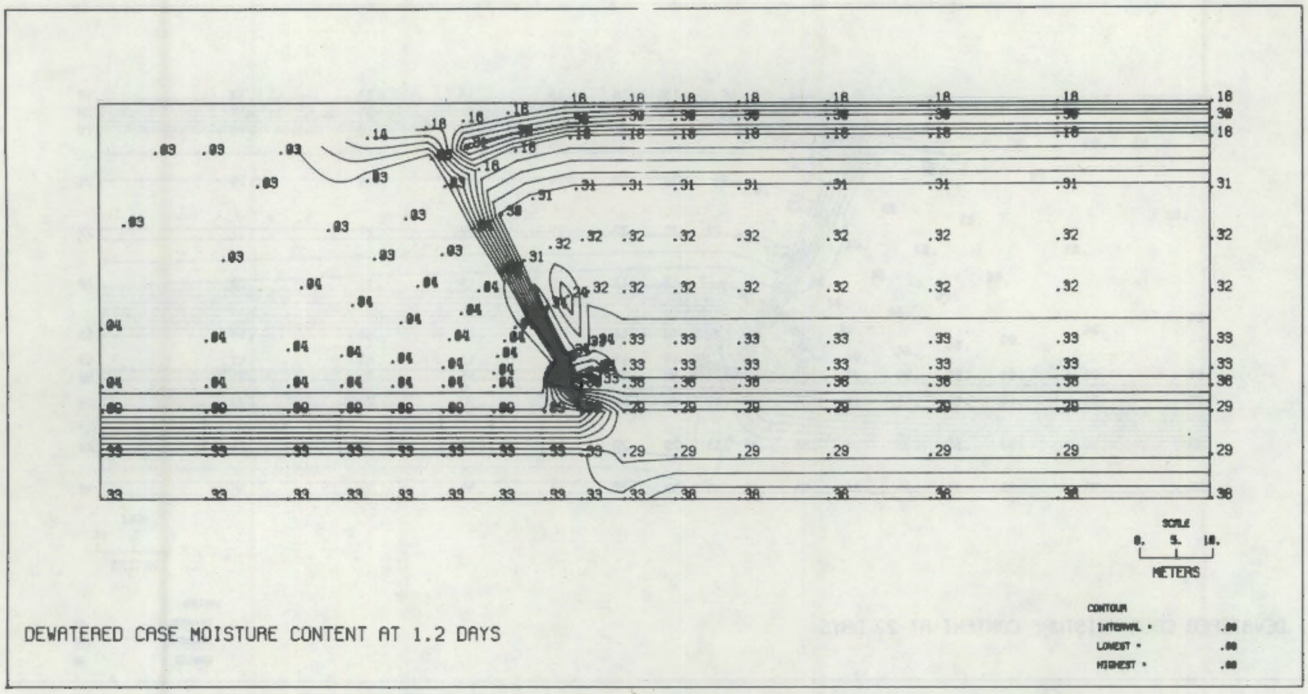

FIGURE A.17. Moisture Distribution for Alternative No. 2 (Dewatered Tailings) at 1.2 Days

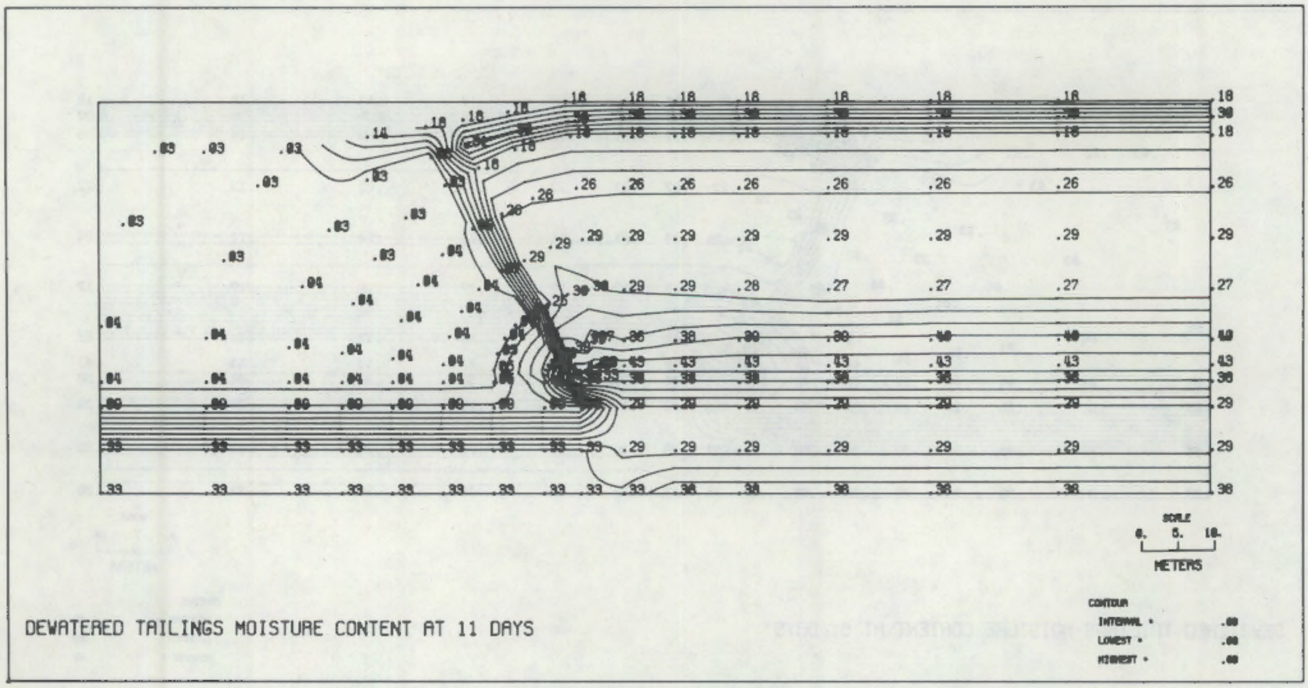

FIGURE A.18. Moisture Distribution for Alternative No. 2 (Dewatered Tailings) at 11 Days

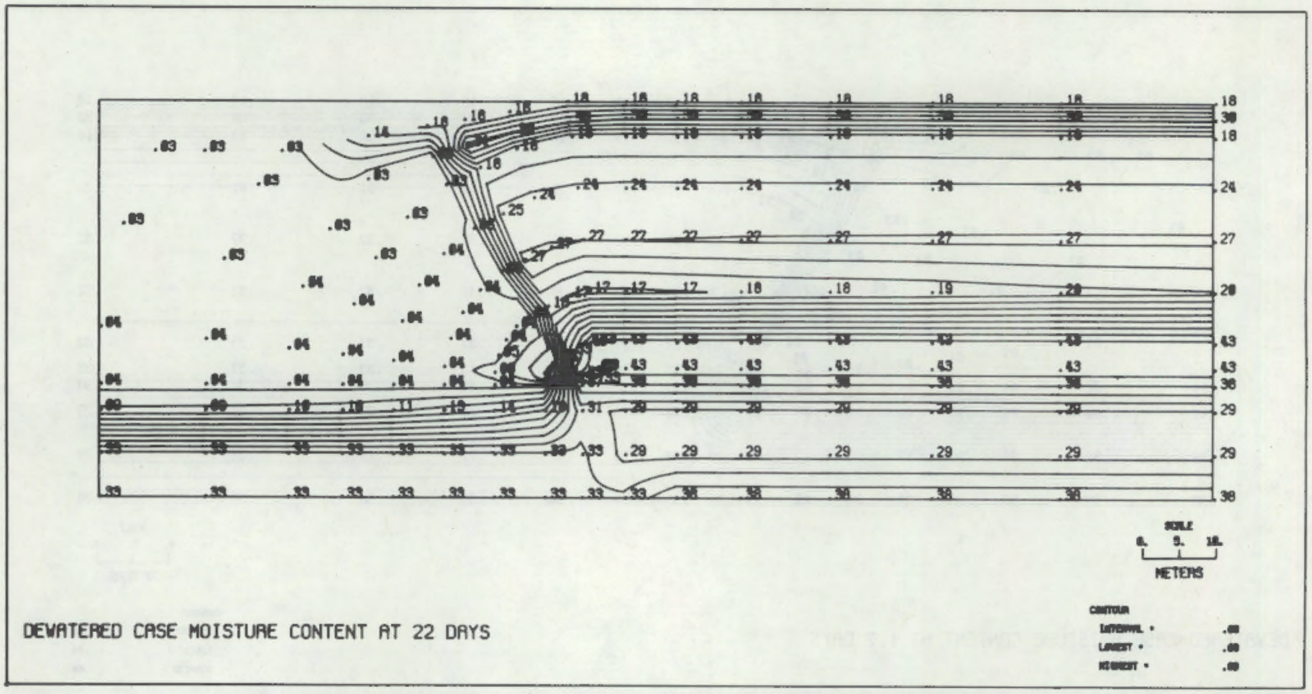

FIGURE A.19. Moisture Distribution for Alternative No. 2 (Dewatered Tailings) at 22 Days

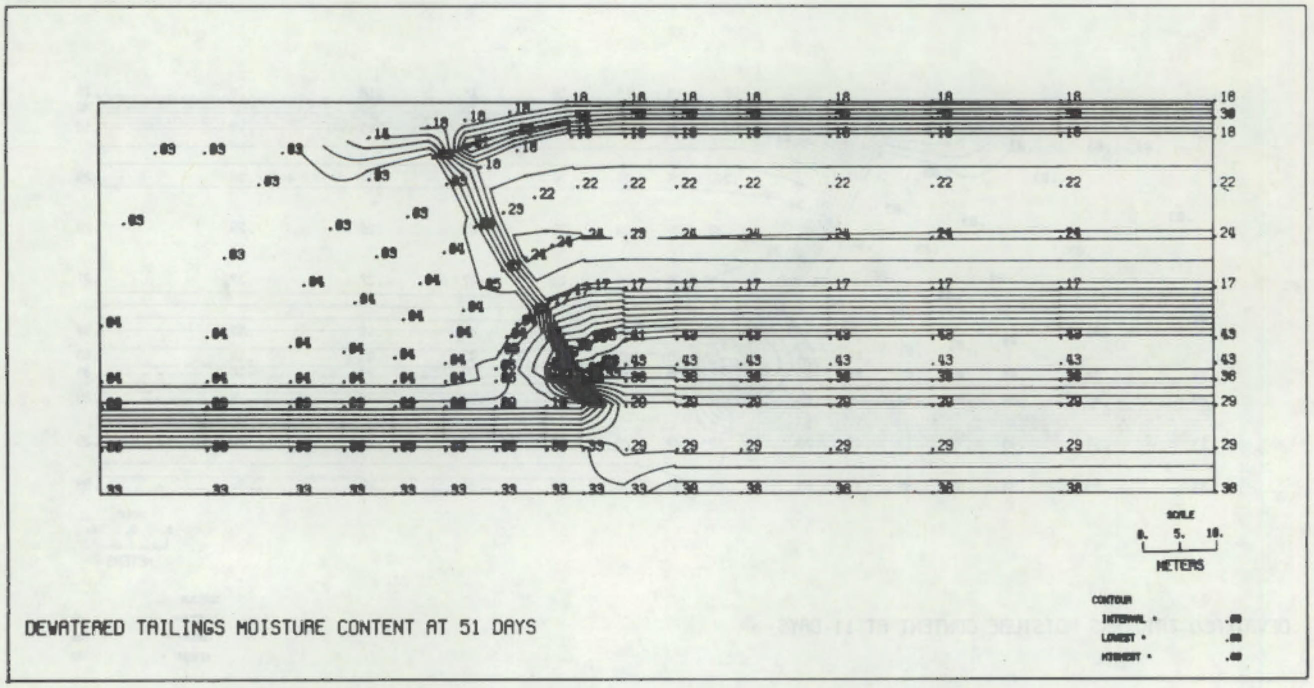

FIGURE A.20. Moisture Distribution for Alternative No. 2 (Dewatered Tailings) at 51 Days

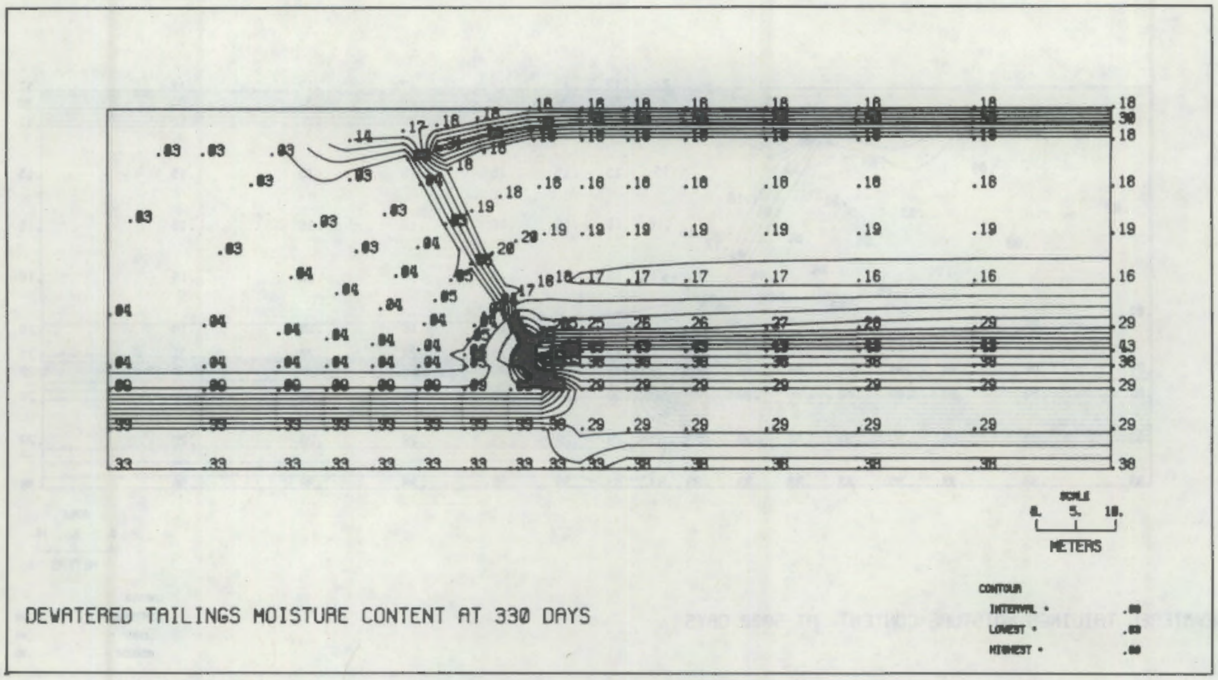

FIGURE A.21. Moisture Distribution for Alternative No. 2 (Dewatered Tailings) at 330 Days

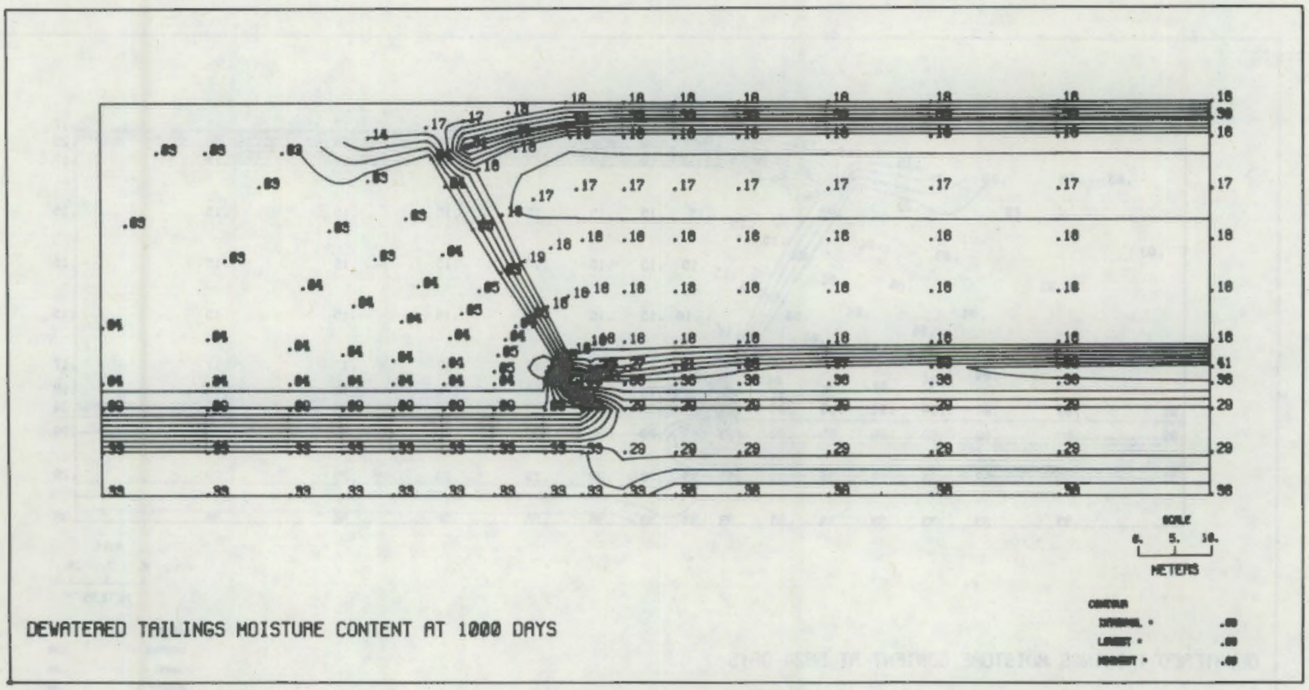

FIGURE A.22. Moisture Distribution for Alternative No. 2 (Dewatered Tailings) at 1000 Days

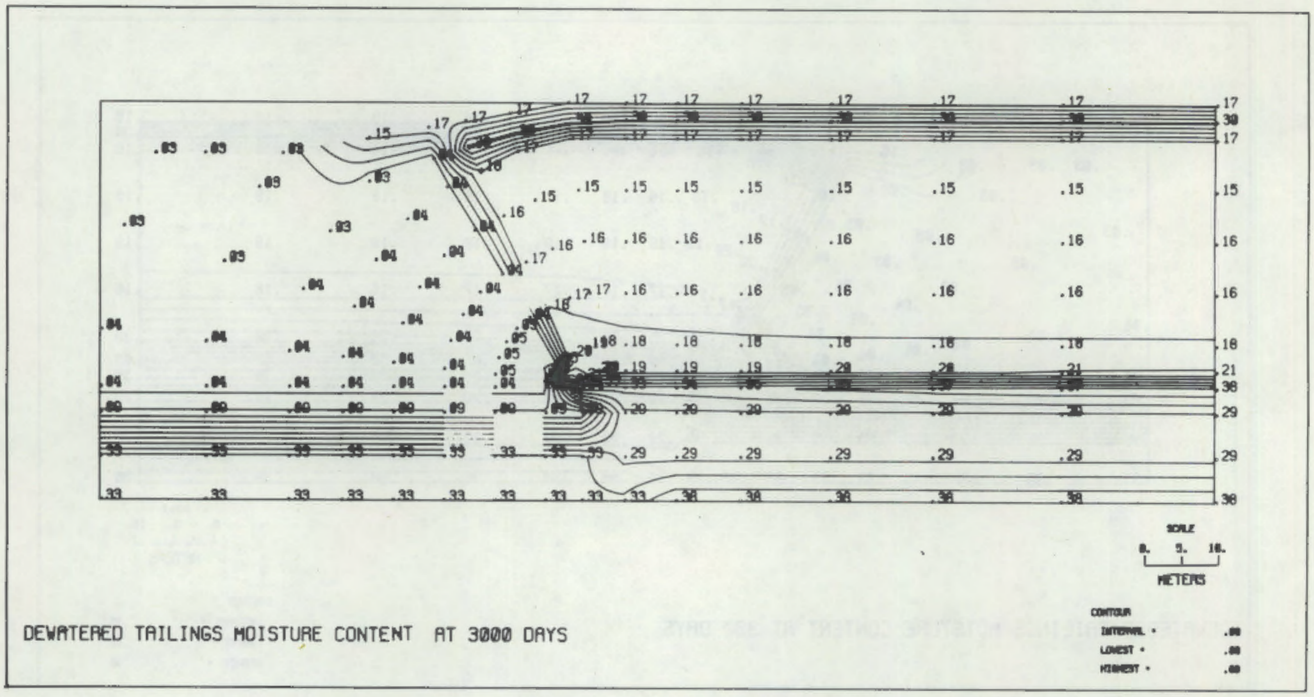

FIGURE A.23. Moisture Distribution for Alternative No. 2 (Dewatered Tailings) at 3000 Days

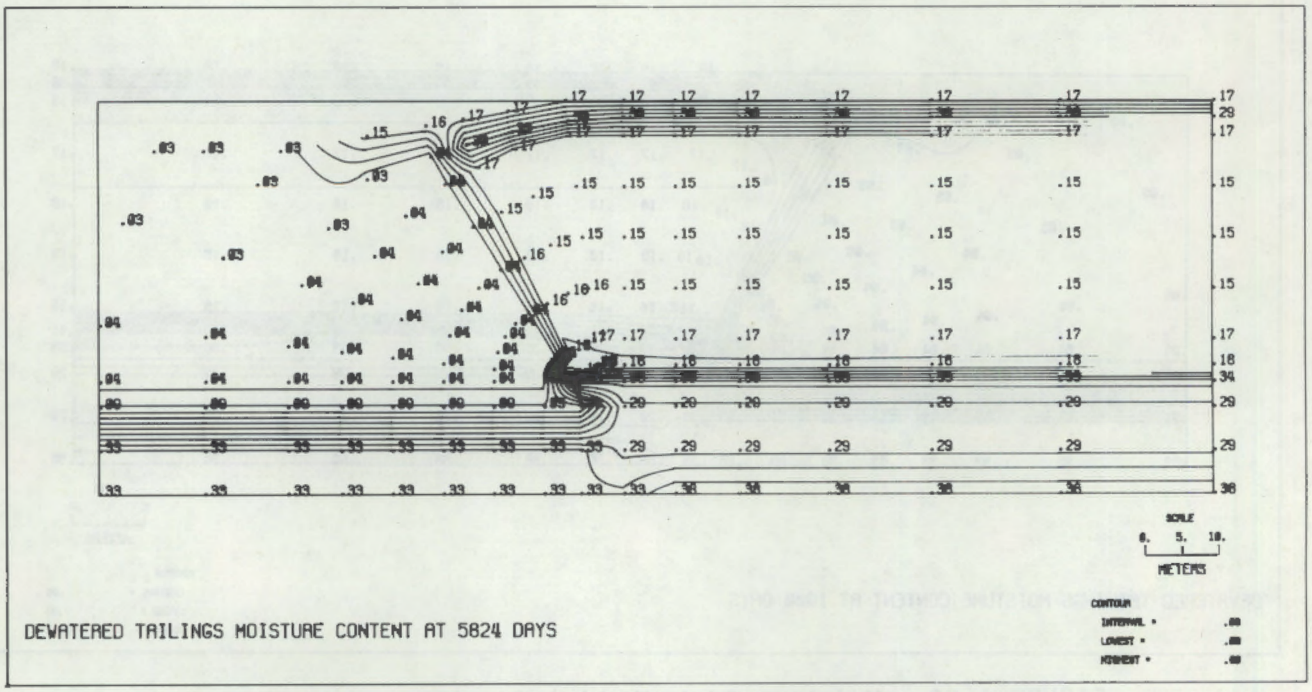

FIGURE A.24. Moisture Distribution for Alternative No. 2 (Dewatered Tailings) at 5824 Days

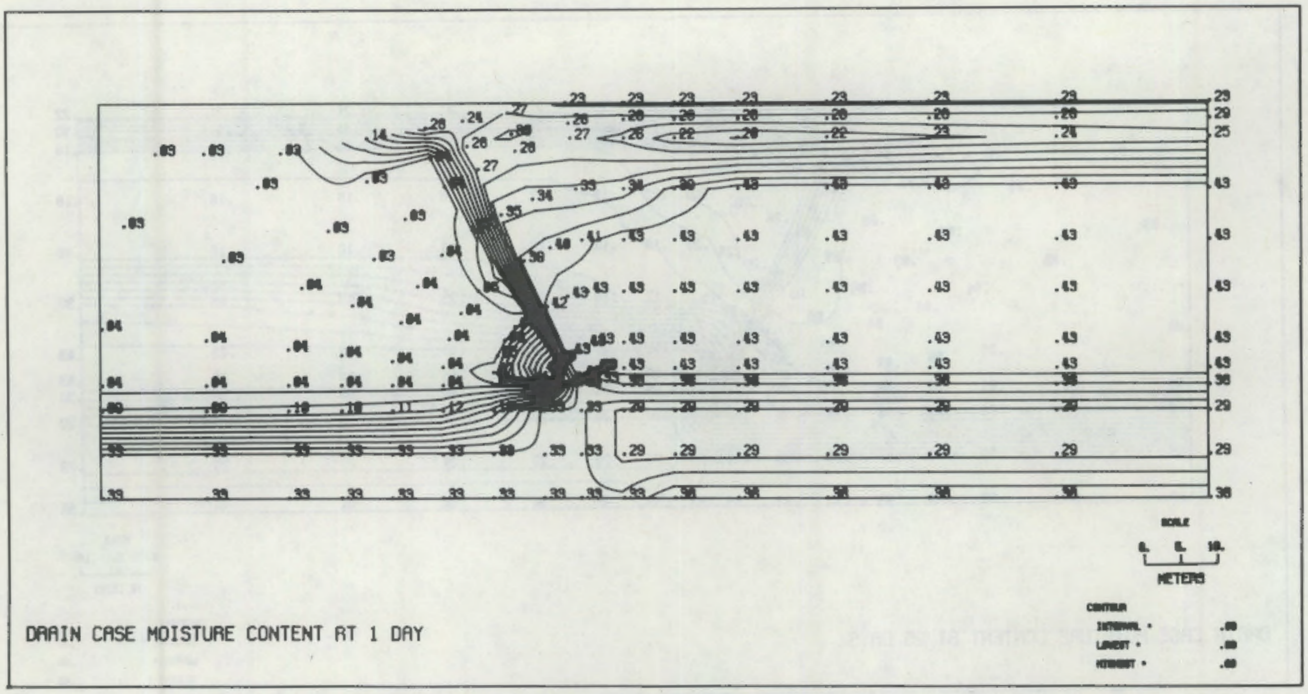

FIGURE A.25. Moisture Distribution for Alternative No. 3 (With Underdrain) at 1 Days

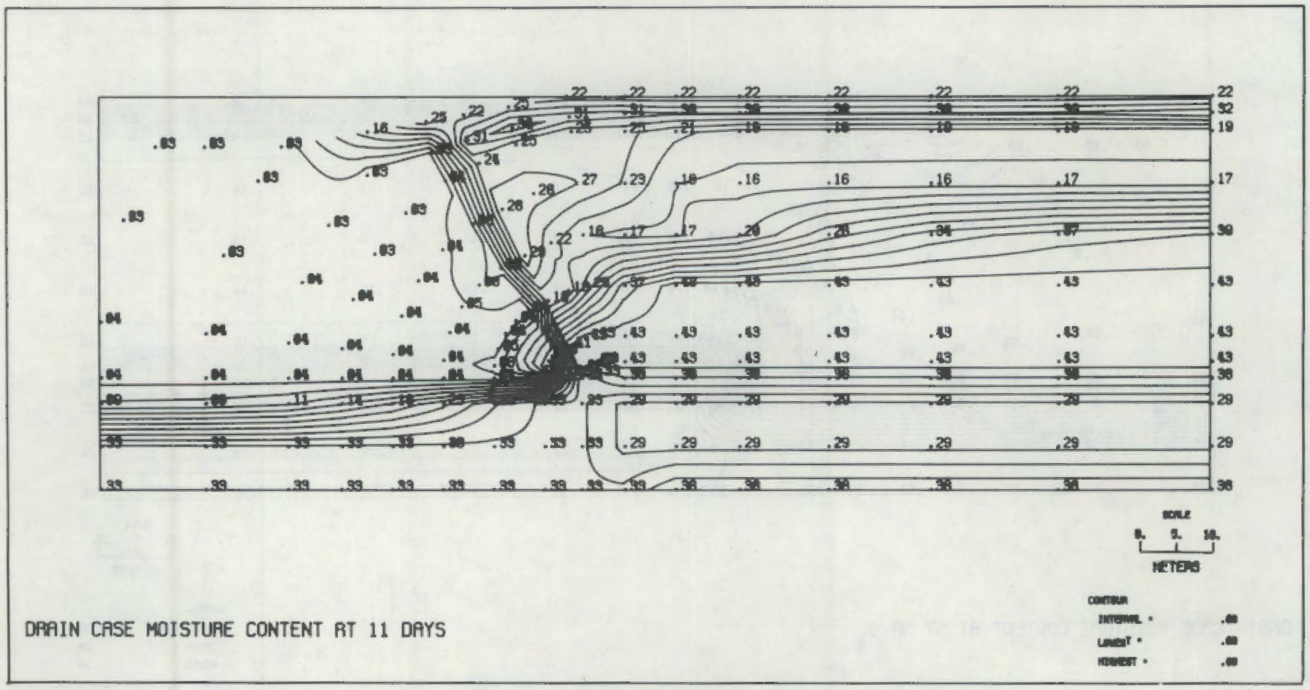

FIGURE A.26. Moisture Distribution for Alternative No. 3 (With Underdrain) at 11 Days

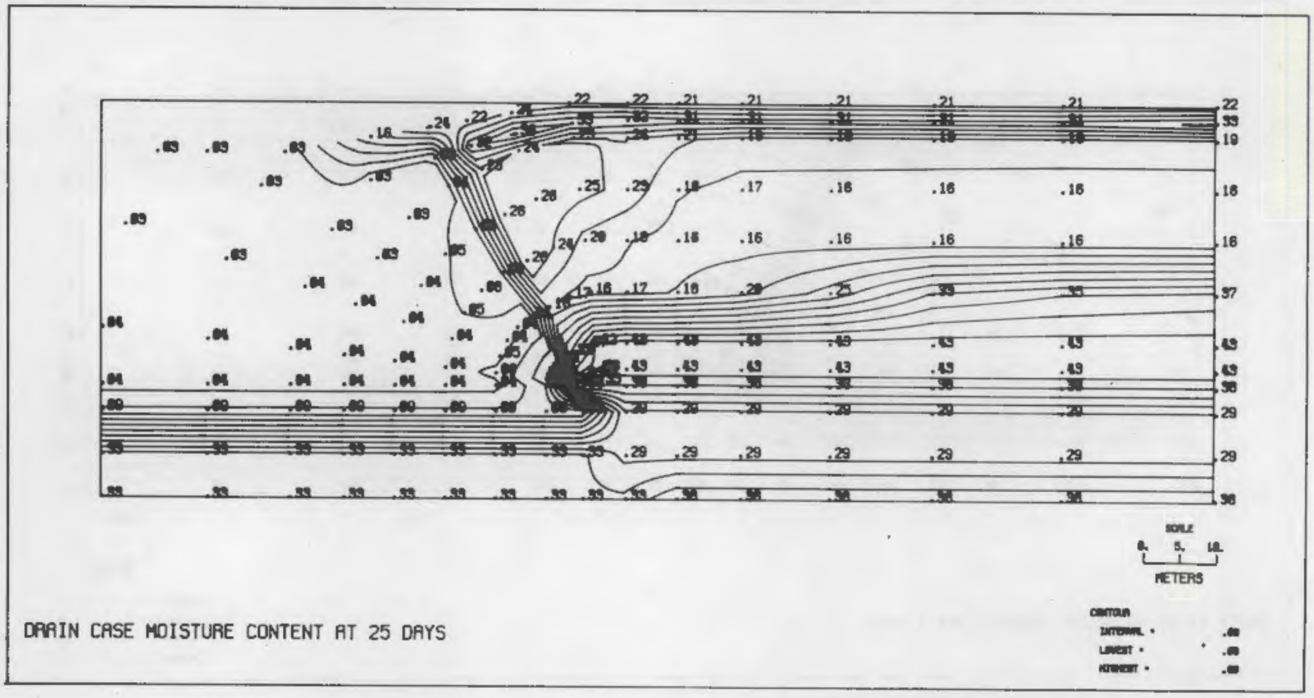

FIGURE A.27. Moisture Distribution for Alternative No. 3 (With Underdrain) at 25 Days

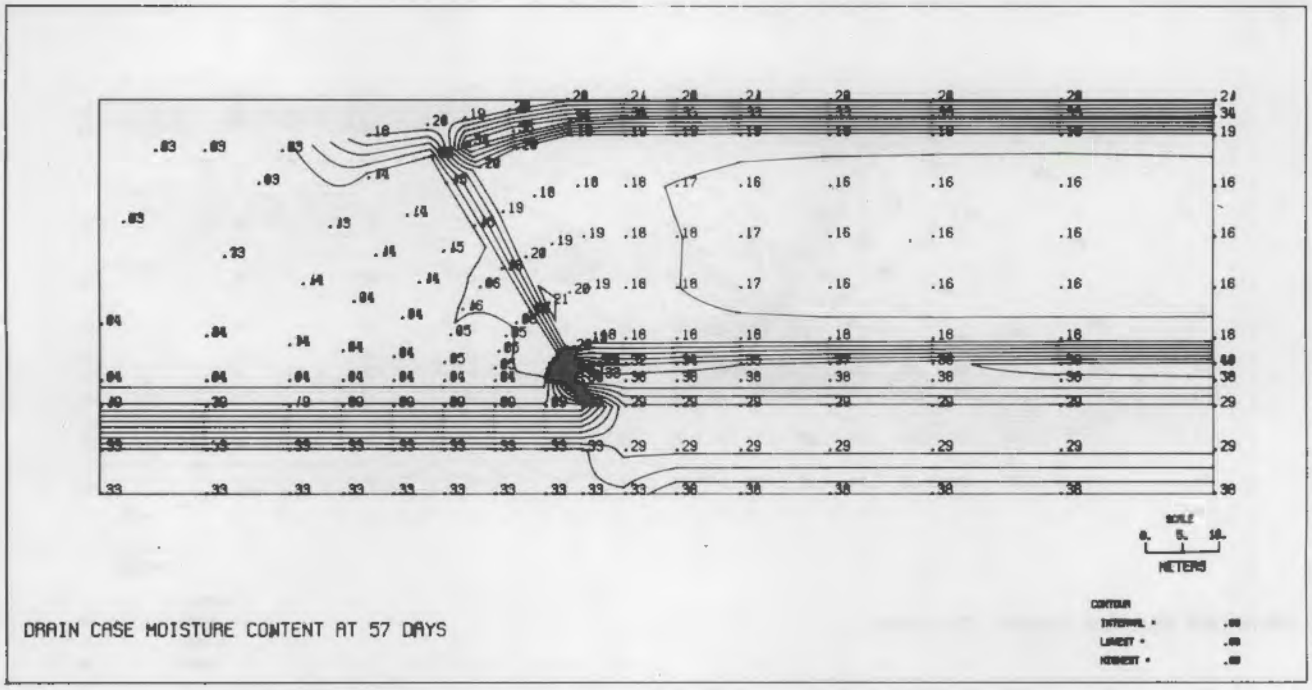

FIGURE A.28. Moisture Distribution for Alternative No. 3 (With Underdrain) at 57 Days

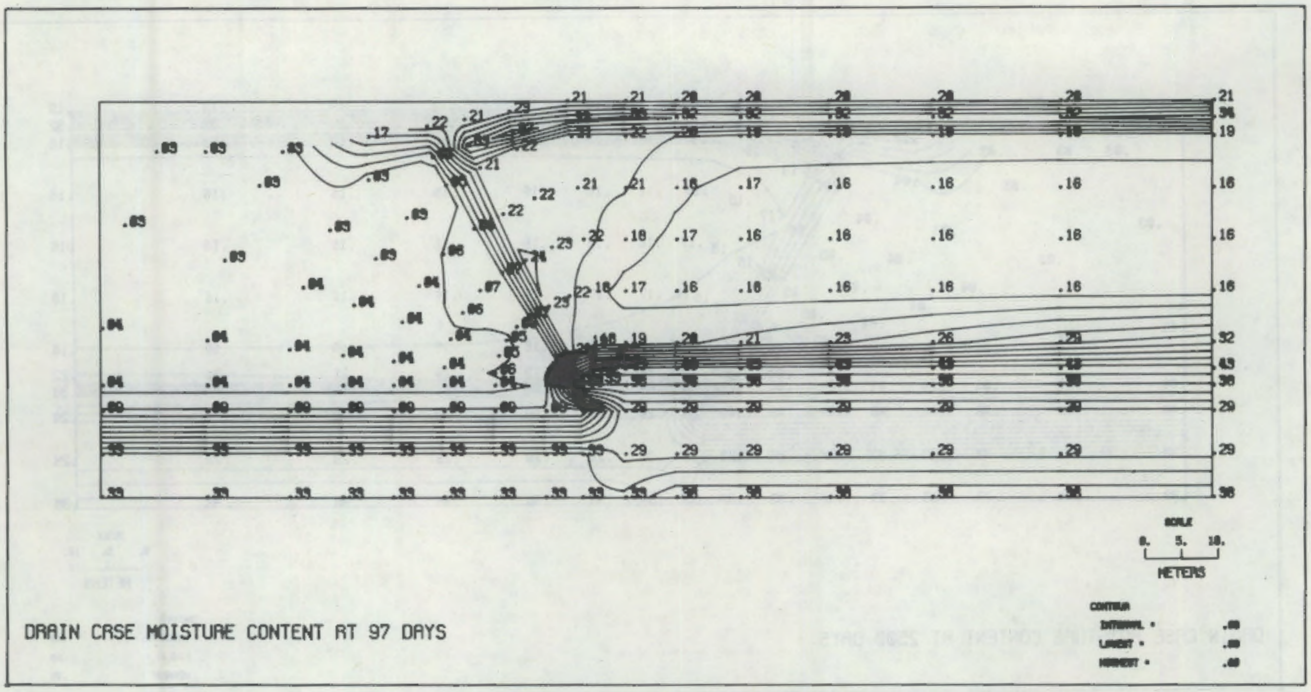

FIGURE A.29. Moisture Distribution for Alternative No. 3 (With Underdrain) at 97 Days

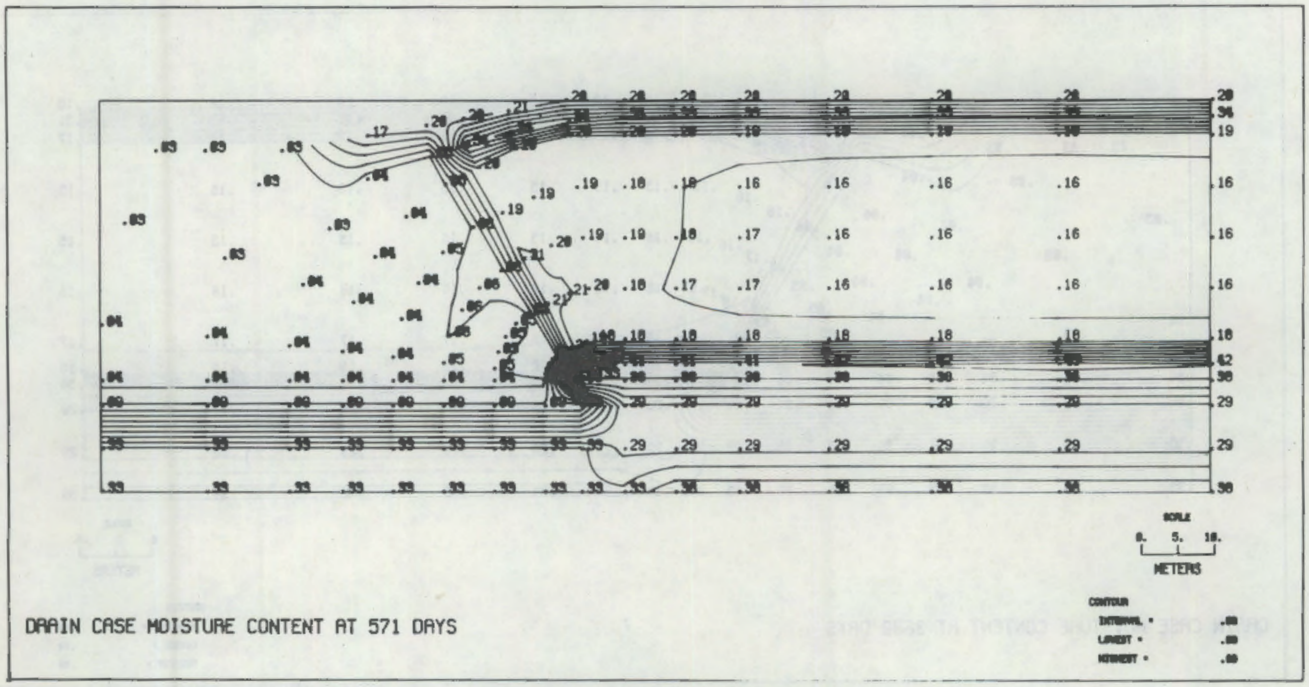

FIGURE A.30. Moisture Distribution for Alternative No. 3 (With Underdrain) at 571 Days

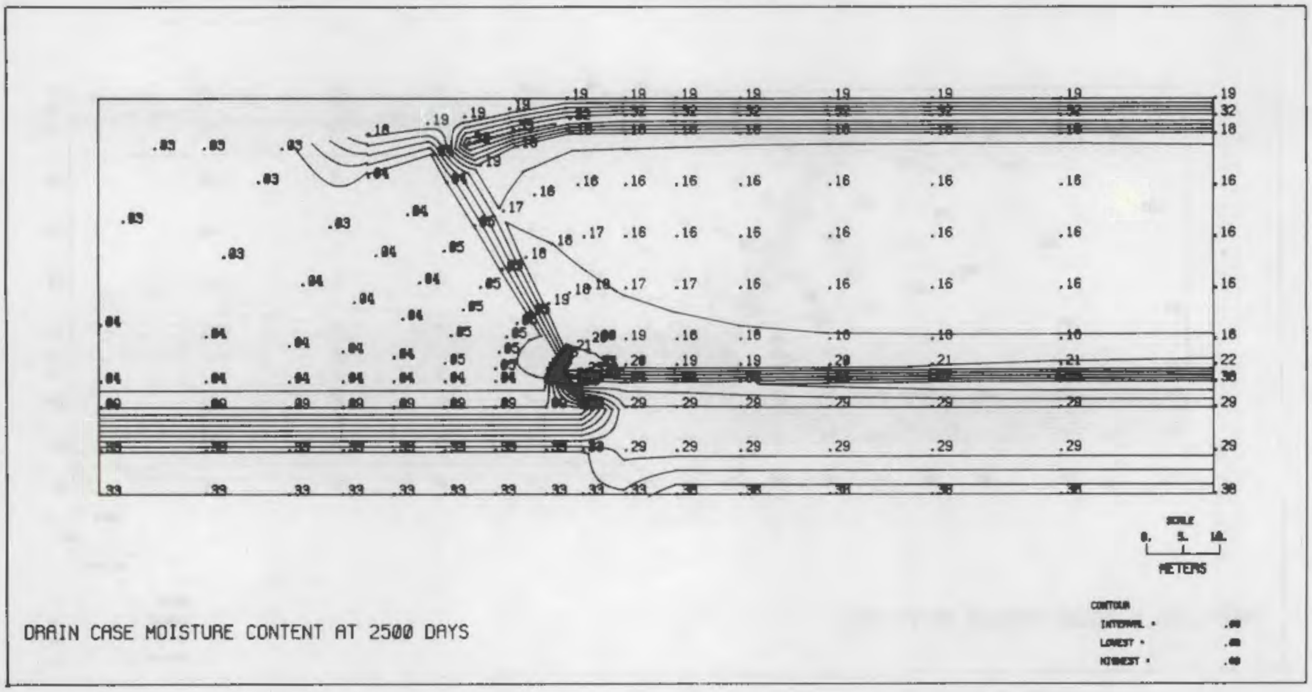

FIGURE A.31. Moisture Distribution for Alternative No. 3 (With Underdrain) at 2500 Days

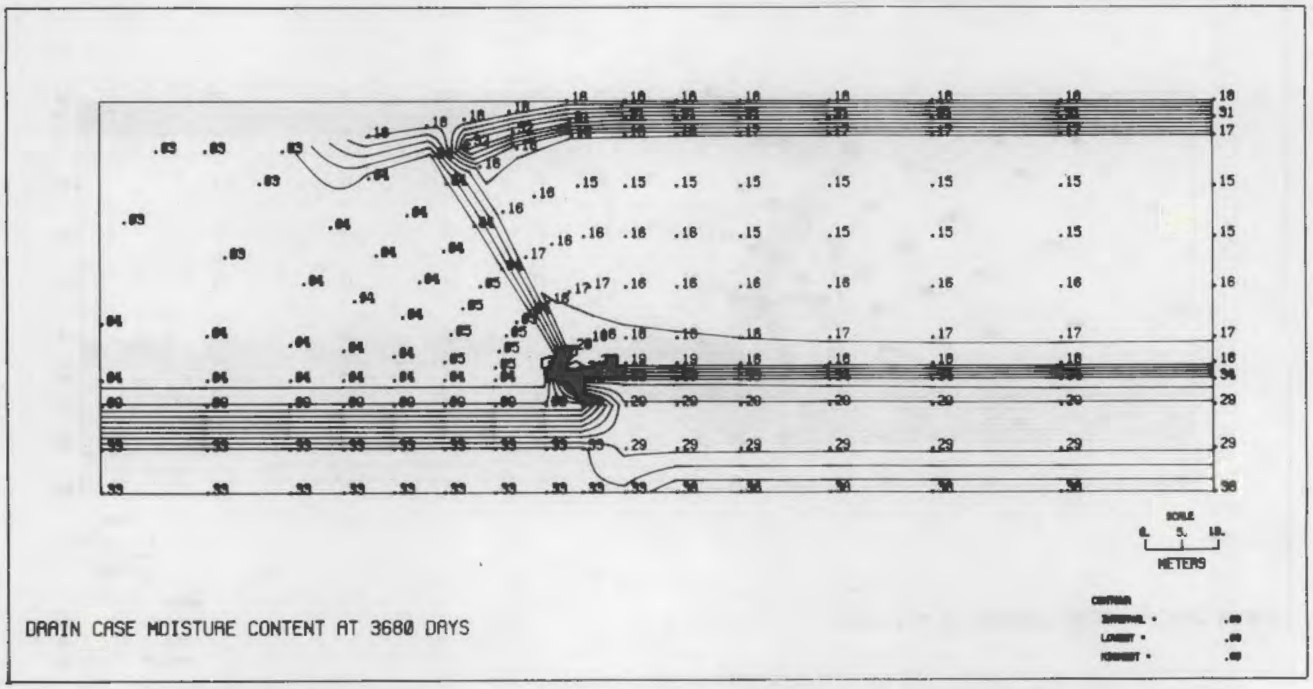

FIGURE A.32. Moisture Distribution for Alternative No. 3 (With Underdrain) at 3680 Days

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16. ABSTRACT *(200 words or less)*

A model assessment was made to evaluate contaminant transport to groundwater from clay lined and partially lined pits containing uranium mill tailings. The assessment involved combined subsurface fluid flow and contaminant transport modeling for four alternatives for controlling seepage from buried tailings. The input hydrologic soil characteristics were measured on materials typical of those found at the Morton Ranch, uranium mill site in central Wyoming. The assessment included combined saturated and partially saturated flow and contaminant transport models for two dimensional vertical cross sections typical of the tailings burial pits proposed for use at Morton Ranch.

The results obtained from the models were contaminant flow paths away from the tailings pits, the advancing contaminant flow fronts for various sorbed and non-sorbed constituents of major environmental concern and the associated quantities of contaminant flow for each of the alternatives. These results enable comparison of the environmental consequences of the four alternatives. It was also possible to gain considerable insight as to the overall desirability of combining the beneficial alternatives to obtain the best overall method for economical control for seepage from the buried pits.

17. KEY WORDS AND DOCUMENT ANALYSIS — 17a. DESCRIPTORS

contaminant transport, seepage control
clay liner, dewatered tailings

17b. IDENTIFIERS/OPEN-ENDED TERMS

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