Parametric seepage rate estimates: Crandon Project waste disposal system: project report 3.1. v. 3.1 1982

Atlanta, Georgia: Golder Associates, Inc., 1982

PARAMETRIC SEEPAGE RATE ESTIMATES
CRANDON PROJECT WASTE DISPOSAL SYSTEM
PROJECT REPORT 3.1

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Golder Associates
CONSULTING GEOTECHNICAL AND MINING ENGINEERS

Report on

PARAMETRIC SEEPAGE RATE ESTIMATES
CRANDON PROJECT WASTE DISPOSAL SYSTEM
PROJECT REPORT 3.1

.tted to:

Exxon Minerals Company
P. O. Box 813
Rhinelander, Wisconsin 54501

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CONSULTING GEOTECHNICAL AND MINING ENGINEERS

March 25, 1982

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Exxon Minerals Company
P. O. Box 813
Rhinelander, Wisconsin 54501

Attn: Mr. C. E. Fowler

RE: EXXON CRANDON PROJECT
WASTE DISPOSAL SYSTEM
CRANDON, WISCONSIN

Gentlemen:

We are pleased to present the final draft of our report "Parametric Seepage Rate Estimates, Crandon Project Waste Disposal System, Project Report 3.1". This report provides a framework for considering seepage rates from ponds with a variety of liner conditions and with underdrains. It also provides estimates of desaturation times based on liner/underdrain conditions and infiltration after reclamation.

We appreciate the continuing opportunity to provide services to Exxon Minerals Company for the Crandon Project and extend our thanks to you and the Exxon staff for their excellent cooperation.

Very truly yours,

GOLDER ASSOCIATES

Gary H. Collison

Gary H. Collison, P.E.
Associate

GHC:dap

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1.0 INTRODUCTION

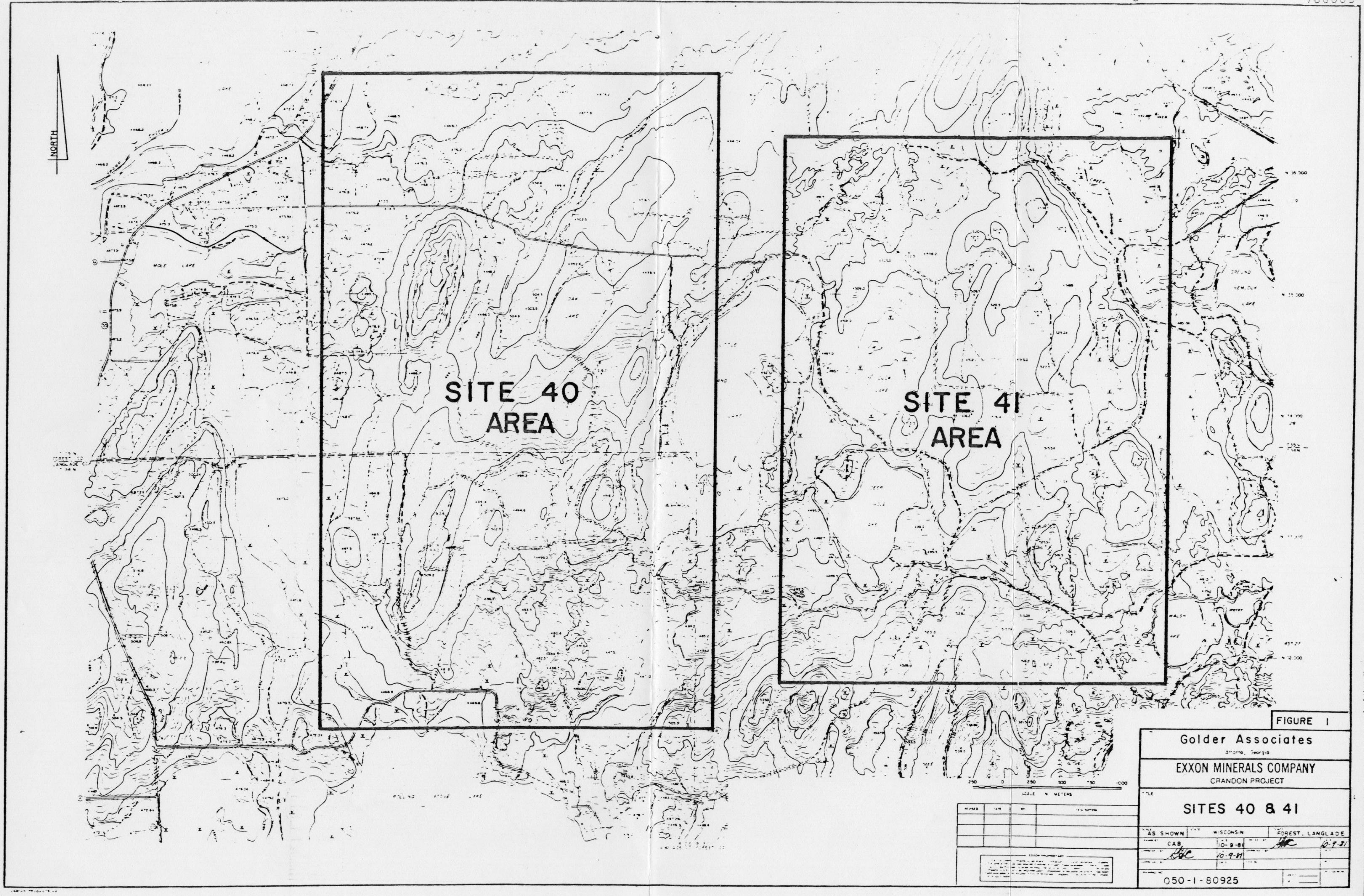
Exxon Minerals plans to mine a copper-lead-zinc ore body near Crandon, Wisconsin using underground mining techniques. During the 30 years of anticipated mining activity, an estimated 36.4 million dry tons (33.1 million dry metric tons) of tailings will be produced. Golder Associates was retained by Exxon to develop designs for tailings disposal facilities.

The purpose of this report is to present the analytical methods and results for estimating seepage rates for slurried tailings disposal facilities of the approximate size required for the Crandon Project. Seepage rate estimates are presented for the disposal facilities both during operation and after they have been reclaimed (after closure). Analyses include unlined tailings ponds, tailings ponds with varying liner conditions, and tailings ponds with an underdrain above a liner. Variations in the seepage rate with time (hereafter referred to as seepage histories) are presented for a single 100 acre (40 ha) pond and for an example disposal system. This size pond is approximately the size anticipated for the final design.

The theoretical principles used in this report to estimate seepage rates are applicable to any waste disposal facility. In applying these principles to disposal facilities at the Crandon site, certain simplifying assumptions have been made. These assumptions always considered the inherent variations in geologic conditions and material properties, and the parameters expected to have a substantial effect on the seepage rate. However it should be recognized that virtually no empirical evidence is available to guide judgments of this kind. Golder Associates considers the seepage rate estimates presented in this report to be consistent with the state-of-the-art in making such estimates.

Seepage rate estimates for a waste disposal system are partially dependent on site specific geologic and hydrologic conditions. For the purposes of this report, the tailings disposal facilities are assumed to be located within the proposed Site 41 waste disposal area and the calculated seepage rates and conclusions apply to waste facilities at this site. However, because of the geologic and hydrologic similarities between proposed waste disposal Sites 40 and 41 (Reference 1), these seepage rate estimates apply to similar facilities at Site 40. The locations of these two sites are shown on Figure 1. The boundaries shown are approximate and intended to show the general location of each site for reference purposes.

The seepage rate estimates presented in this report are not based on a specific waste disposal system of tailings ponds with precisely defined sizes and depths. To make these estimates more useful as the design of the disposal system evolves, a nominal 100 acre (40 ha) pond was selected as the size for a single tailings pond and the system is assumed to include four tailings ponds. This is anticipated to be the type of facility which will be developed based on the present estimate of 36.4 million dry tons (33.1 million dry metric tons) of tailings production. Seepage rate estimates for other pond sizes can be approximated by simple area ratio.


NORTH
SITE 40
AREA
SITE 41
AREA
MOLE LAKE
250 0 250 500 750 1000
SCALE IN METERS
FIGURE 1
Golder Associates
Atlanta, Georgia
EXXON MINERALS COMPANY
CRANDON PROJECT
SITES 40 & 41
AS SHOWN
WISCONSIN
FOREST, LANGLADE
CAB
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2.0 SUBSURFACE CONDITIONS

2.1 Geology

A detailed discussion of the geology and physical characteristics of the overburden soils at Site 40 and Site 41 is presented in Reference 1. A brief description of the geology of these sites is provided herein for general information purposes.

The Crandon Project site is in a glaciated region. Glacial drift materials are present to a depth of approximately 300 feet (90 m) and consist primarily of very dense sands and gravels. A generalized geologic profile at Site 41 is presented in Figure 2. It shows that the glacial overburden can be placed in two primary categories: till and coarse grained stratified drift. The grain-size distribution of the glacial till varies over a wide range. The till consists predominantly of soils which classify as SM, GM, or SP-SM (Unified Soil Classification System) and most samples tested contained between 10 and 30 percent fines. The stratified drift is typically more coarse-grained and more uniformly graded, consisting of soils which usually classify as SP, and SP-SM. The stratified drift typically contains less than 10 percent fines and often contains less than 5 percent fines.

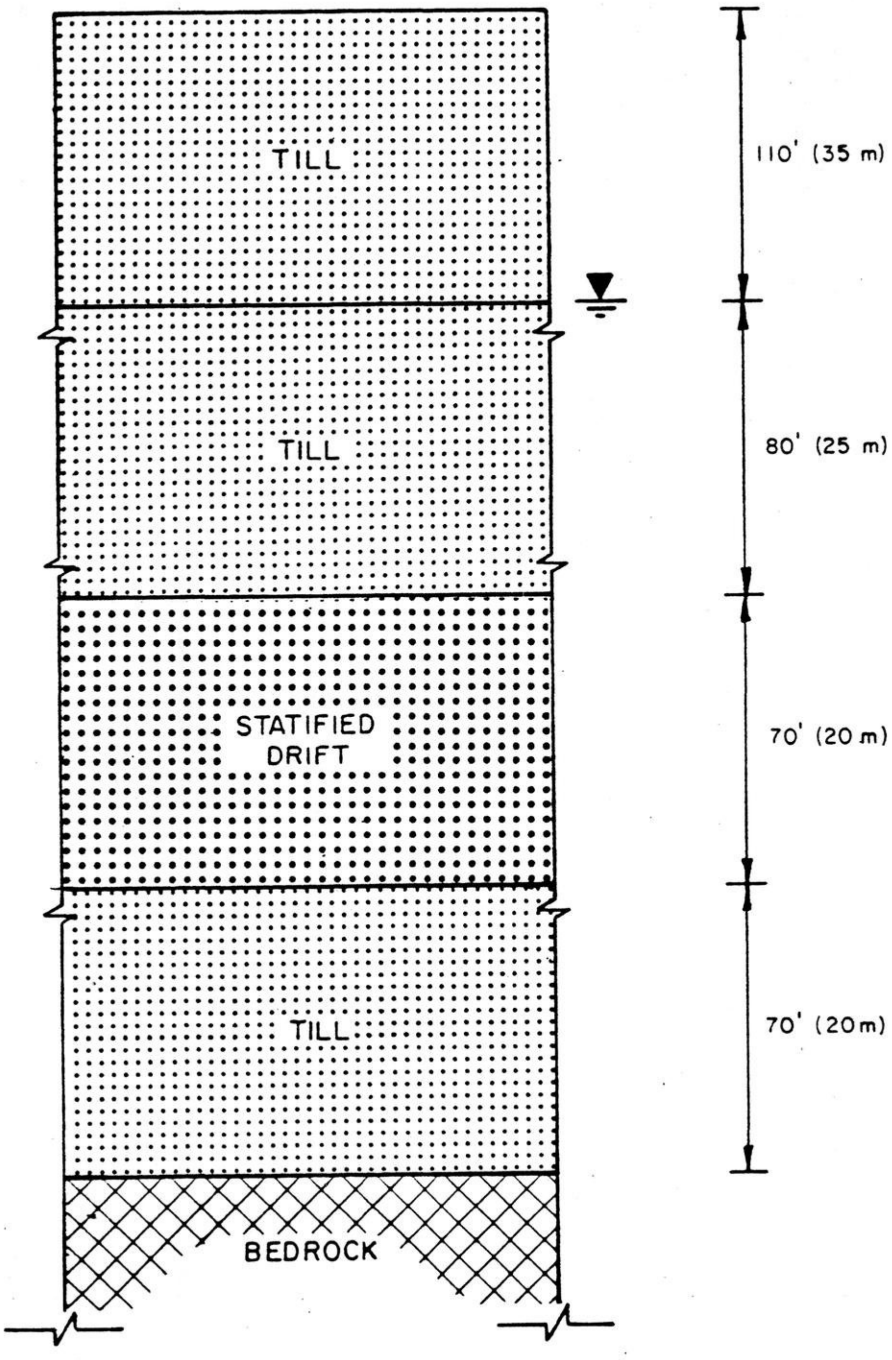
The bedrock which underlies the glacial soils is a partially metamorphosed volcanic rock. The upper part of the rock has been weathered to a clayey soil in some areas.

2.2 Groundwater

Groundwater levels over the Crandon Project site have been primarily determined by measurements in observation wells installed at various times and depths over the past

GENERALIZED GEOLOGIC PROFILE

FIGURE 2



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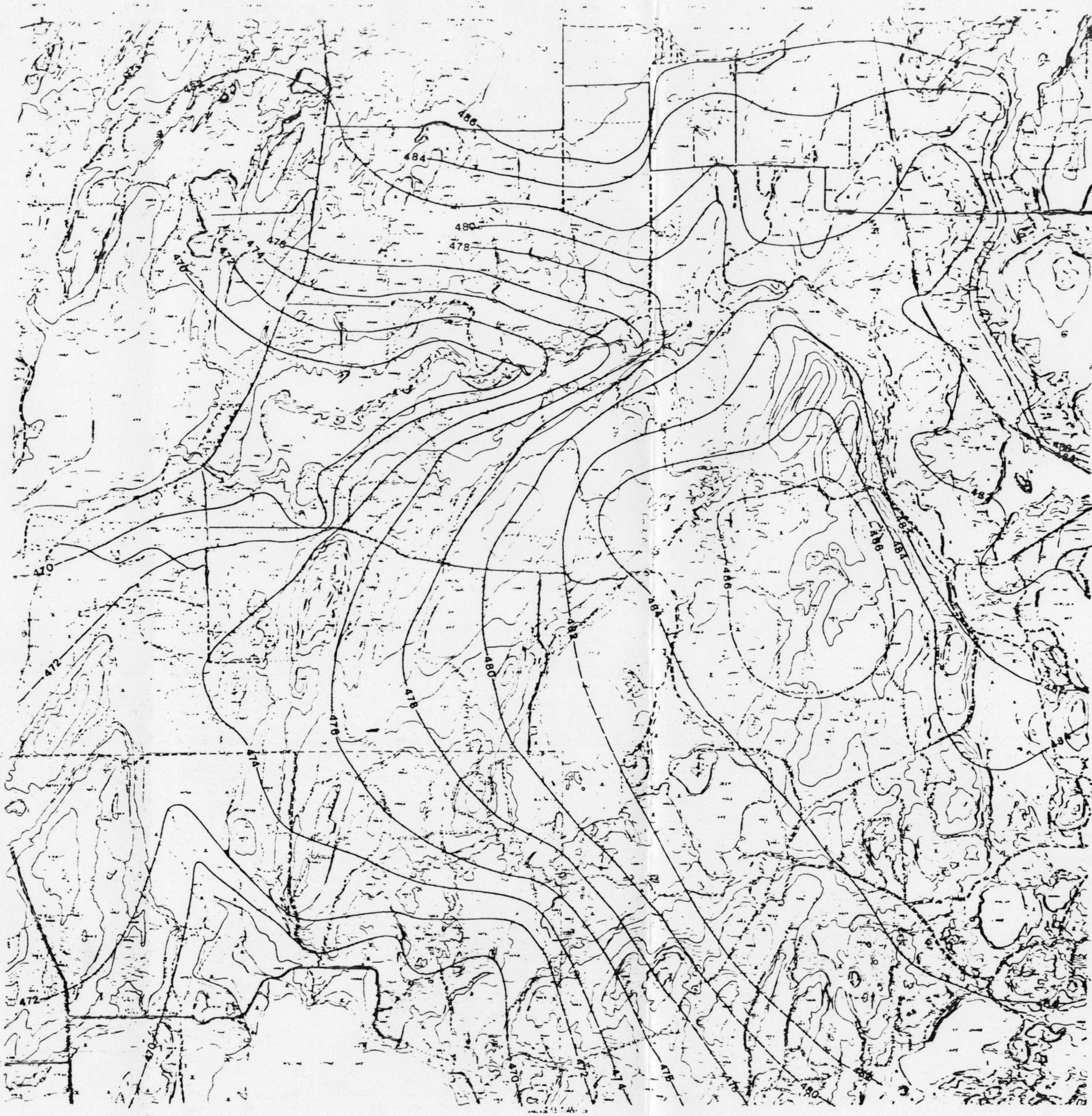
three years. A detailed evaluation of the potentiometric conditions in the glacial overburden has been made to define the groundwater conditions. The resulting potentiometric contour map in the Site 40 and Site 41 waste disposal areas is shown on Figure 3. A complete description of the methods and data used to derive these contours is presented in Reference 2. As can be seen from Figure 3, the regional groundwater level is well below the ground surface over most of Site 40 and Site 41. It is presently planned that the bottoms of proposed waste disposal ponds be well above these groundwater levels.

2.3 Glacial Soil Permeabilities and Porosities

2.3.1 Glacial Till

The permeability of the till has been measured in laboratory tests, borehole permeability tests, and a pump test. Some of the laboratory tests and borehole tests were performed on materials above the water table. The pump test measured the permeability of the till below the water table. Studies to date have shown no systematic difference in either grain size or density between the till above the water table and the till below the water table. Therefore, the permeability measurements on the till below the water table, in particular those from the pump test, are considered applicable to the till above the water table.

Permeability measurements were made in the glacial till using laboratory tests and borehole permeability tests. The results of these tests are reported in Reference 1. Permeabilities measured in laboratory tests on samples of till (SM) taken at shallow depths ranged from 3×10^{-7} to 6×10^{-7} ft./sec. (1×10^{-7} to 2×10^{-7} m/s) for tests run in a triaxial cell and from 6×10^{-9} to 1×10^{-7} ft./sec. (2×10^{-9} to 4×10^{-8} m/s) for tests run in a Proctor mold.



LEGEND

GROUNDWATER ISOPLETHS (contours) IN METERS ABOVE MSL

GROUNDWATER ISOPLETHS IN METERS ABOVE MSL INTERPRETED FROM LIMITED DATA

GROUNDWATER ISOPLETH 486 METERS ABOVE MSL AS ESTIMATED EXCLUDING EFFECTS OF JUNE-JULY 1980 PUMP TEST

NOTE

GROUNDWATER CONTOURS INTERPRETED BY GOLDER ASSOCIATES AND DAMES & MOORE BASED ON THE FOLLOWING DATA:

a GOLDER ASSOCIATES AND DAMES & MOORE OBSERVATION WELL MEASUREMENTS ON SEPT 10 AND 11, 1980
b WATER CHEMISTRY DATA FROM D&M AND DNR
c SURFACE TOPOGRAPHY
d USGS WELL DATA AND GOLDER WELL DATA FROM DIFFERENT TIME PERIODS

BASE MAP PROVIDED BY EXXON MINERALS COMPANY

FIGURE 3

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EXXON MINERALS COMPANY
CRANDON PROJECT

GROUNDWATER POTENTIOMETRIC CONTOURS

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Permeabilities ranging from $2x10^{-7}$ to $1x10^{-5}$ ft./sec. ($6x10^{-8}$ to $4x10^{-6}$ m/s) were computed from borehole permeability tests in the unsaturated till.

The mass vertical permeability of the glacial till was measured in a pump test and ranged from $8.8x10^{-7}$ to $9.9x10^{-6}$ ft./sec. ($2.7x10^{-7}$ to $3.0x10^{-6}$ m/s). The geometric mean was reported to be $3x10^{-6}$ ft./sec. ($9x10^{-7}$ m/s). Details of the pump test are presented in Reference 3.

The permeability of the till measured in the pump test is higher than the values measured in the laboratory and is in the upper range of the values measured in the borehole tests. The lab and borehole tests were run on relatively small samples which may have been representative of the predominant materials in the till, but the mass permeability of the till is not necessarily controlled by the permeability of the predominant material. If zones exist in the till that consist of materials much more permeable than the predominant material, these more permeable zones would control the mass permeability. It is likely that zones of more permeable material exist in the till and that because of them the laboratory and borehole permeabilities do not agree with the permeability measured in the pump test.

The proposed waste disposal system is large enough that the permeability controlling seepage through the till will be the mass permeability, i.e. the permeability measured in the pump test. Therefore, for the purposes of this study, Golder Associates concludes that the vertical permeability of the glacial till, ranges from $8.8x10^{-7}$ to $9.9x10^{-6}$ ft./sec. ($2.7x10^{-7}$ to $3.0x10^{-6}$ m/s) and the mean value is $3x10^{-6}$ ft./sec. ($9x10^{-7}$ m/s) (Ref. 3).

It is necessary to know the storage volume available in the void space of that portion of the glacial till above the groundwater level to estimate the rate of mounding of the groundwater level from pond seepage. The ratio of the volume of available storage to the total volume of the mass (n_s) is equal to the difference in the porosity and the initial volumetric water content. Data on natural moisture content and density are reported in Reference 4. From these data, a representative value for initial volumetric moisture content is 19% and for porosity is 26%. This results in a representative value for n_s of 0.07. Experience suggests a reasonable range of n_s to be 0.03 to 0.3 for similar granular soils.

It is also necessary to estimate the initial head in the unsaturated till immediately below the pond. The head may range from zero to a negative value equal to the height of capillary rise in the soil. The grain size distribution of the till suggests that the height of capillary rise will not exceed a few feet (Reference 12). Therefore, for this study the initial head below the pond has been assumed to be zero.

2.3.2 Coarse Grained Stratified Drift

The hydraulic characteristics of the coarse grained stratified drift are well defined by the results of the pump test (Reference 3). The horizontal permeability of the stratified drift ranges from 2.5×10^{-4} to 7.6×10^{-4} ft./sec. (7.6×10^{-5} to 2.3×10^{-4} m/s) and the mean value is 4.3×10^{-4} ft./sec. (1.3×10^{-4} m/s) (Ref. 3).

Field exploration in the project area indicates that below the coarse grained stratified drift there are layers of till, fine grained stratified drift, and/or weathered rock. The permeability of the coarse grained stratified drift is orders of magnitude greater than the estimated permeabilities of any of these materials. Thus, for purposes of this analysis the materials beneath the coarse grained stratified drift can be considered to form a low permeability base to the coarse grained stratified drift and flow within the coarse grained drift can be taken as being essentially horizontal.

3.0 WASTE PRODUCTS

3.1 Tailings

The waste materials produced by the Crandon mine/mill operation will be separated (split) by size into sand and tailings. The split is presently planned at 30 microns (0.03 mm). The sand fraction (that coarser than 30 microns) will be used as mine backfill and will not be permanently stored in the waste disposal area.

Laboratory test programs and test results for tailings materials are described in Reference 5. From those tests, a tailing permeability of 1.6×10^{-7} ft./sec. (5×10^{-8} m/s) was recommended for use in design. While it is recognized that the actual tailings permeability could vary somewhat from this value, this single value rather than a range of values is used in this report to simplify the presentation.

Another parameter which is important in estimating seepage rates after a pond is reclaimed is the drainable porosity of the tailings. Drainable porosity is defined to be the fraction of the volume of a porous material occupied by the ultimate volume of water released from or added to storage per unit (horizontal) area and per unit decline or rise of a piezometric surface open to the atmosphere. A reasonable estimate of the drainable porosity can be made by taking the difference between the porosity of the tailings (calculated from the estimated in-place void ratio of 1.1 for the tailings recommended in Reference 5) and values of the residual volumetric water content of similar materials reported in the engineering literature (Reference 6). The estimated void ratio of 1.1 for the tailings corresponds to a porosity of 0.52. Laboratory data presented in

Reference 6 suggest that the residual volumetric water content of a predominantly silt-size material, such as the tailings, is likely to be about 0.2. These data suggest that a reasonable estimate for the drainable porosity of the tailings is 0.3.

3.2 Pond Water

Although the amount of free water over the tailings will be maintained at a minimal depth for comparison purposes our estimates include seepage rates for ponds with various depths of free water.

Water will be decanted from the tailings ponds to a reclaim water pond. This pond is different from the tailings ponds since it will contain only water. Also, present closure plans call for this pond to be emptied and the embankments removed so that it will no longer hold water. Thus, there will be no seepage after reclamation.

4.0 SEEPAGE CONTROL FEATURES

4.1 Liners

A detailed report (Reference 7) on the liner types being considered for this project has been prepared by Golder Associates. For this discussion, the liner types being considered are of two general types: (1) soil-bentonite, and (2) polymeric or synthetic.

Soil-bentonite liners for this project would be constructed by mixing bentonite with the glacial till soil at the site. The permeability and compaction characteristics of various till-bentonite mixtures have been evaluated in laboratory tests, and the results are discussed in detail in Reference 5. Golder Associates recommended, in Reference 5, that for design a permeability of 1.6×10^{-9} ft./sec. (5.0×10^{-10} m/s) should be used for soil-bentonite liners.

Polymeric or synthetic liners are discussed in considerable detail in References 7 and 8. The property of synthetic liners that is most important for this report is permeability. With the exception of two specific types of synthetic liners, all the liners considered in References 7 and 8 were reported to have a permeability of 3.3×10^{-14} ft./sec. (1.0×10^{-14} m/s). The thicknesses of the synthetic liners considered ranged from 30 to 80 mils (0.76 to 2.0 mm). Variations in liner thickness in this range will not significantly affect the flow resistance of the liner.

Based on the discussion of soil-bentonite and synthetic liners in References 7 and 8, the following liner thicknesses and permeabilities have been chosen for evaluation in this report.

Liner Type	Thickness		Permeability	
	(ft.)	(m)	(ft./sec.)	(m/s)
Soil-bentonite	0.5	0.15	1.6×10^{-9}	5.0×10^{-10}
Soil-bentonite	1.0	0.30	1.6×10^{-9}	5.0×10^{-10}
Soil-bentonite	2.0	0.61	1.6×10^{-9}	5.0×10^{-10}
Synthetic	0.003	0.001	3.3×10^{-14}	1.0×10^{-14}

4.2 Underdrains

In general, an underdrain for a tailings pond consists of an interconnecting system of granular soil and perforated pipes. In this report the underdrain is always assumed to be underlain by a liner. The primary purpose of an underdrain is to provide a means for capturing most of the water seeping from the tailings and reducing the pressure head on the liner, thereby reducing the seepage through the liner. A secondary purpose of an underdrain is to provide a means for draining the tailings as rapidly as possible after the reclamation cap is in-place.

Underdrains were discussed in detail in Reference 9. In that report several types of underdrains were examined and one type was recommended. The recommended underdrain consists of two layers of granular soil. The upper layer would act as a filter between the tailings and the more coarse-grained lower layer. The recommended thickness of each layer was 1.0 foot (0.3 m). The underdrain would generally be graded from the center of the pond to a perimeter pipe collection system. The seepage into the underdrain would be removed by pumping.

The permeability of the drain material was estimated in Reference 9 using a correlation based on the grain-size distribution of the material (Hazen's Formula). The estimated permeability was 1.6×10^{-2} ft./sec. (5.0×10^{-3} m/s).

5.0 METHODS OF COMPUTING POND SEEPAGE

5.1 Pond Seepage During Operation

The model for computing the seepage rate during operation from a tailings pond with a liner and no underdrain system is shown in Figure 4. The equation in Figure 4 is a version of Darcy's law modified for water flow through two layers of different permeability. The factor in the numerator ($D_w + D_t + D_L - h_f$) represents the differential piezometric head causing seepage. The denominator in the equation represents the combined resistance to water flow of the tailings and the liner. The equation in Figure 4 may also be applied to unlined ponds by taking the liner thickness (D_L) to be zero.

Seepage rates during operation from tailings ponds with liners and underdrain systems can be computed using Darcy's law:

$$Q = k\ i\ A \tag{5.1}$$

where

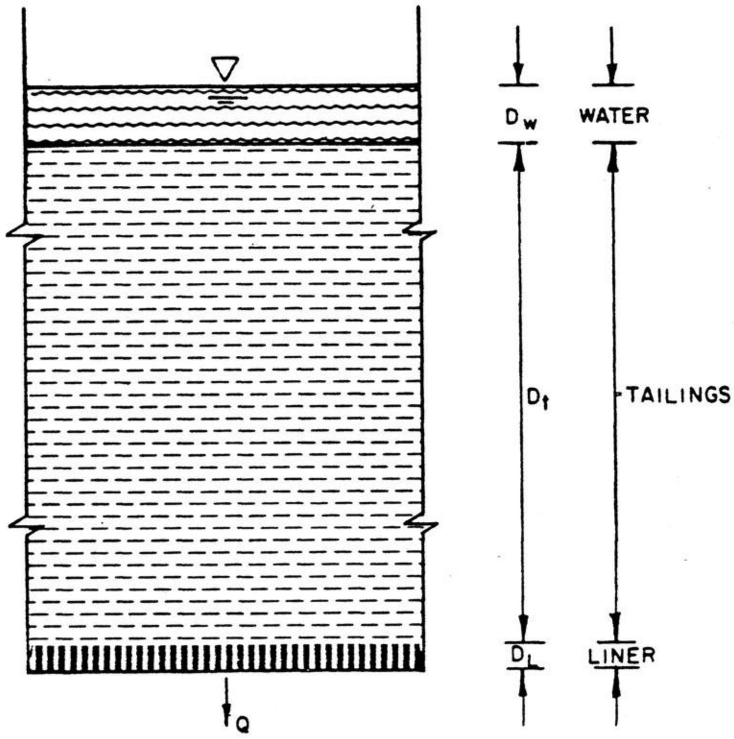
Q = the seepage rate through the liner
k = the permeability of the liner
i = the hydraulic gradient across the liner
A = the area of the pond

In calculating the hydraulic gradient across the liner, it was assumed that the piezometric head in the underdrain (h_D) is uniform over the pond area and is equal to the hydraulic thickness of the underdrain. The method for determining the hydraulic thickness of the underdrain was explained in Reference 9. The hydraulic gradient across the liner (i) in ponds with underdrains is calculated in this report as follows:

$$i = \frac{h_D + D_L - hf}{D_L} \tag{5.2}$$

MODEL FOR COMPUTING SEEPAGE RATE DURING OPERATION

FIGURE 4



$$Q = \frac{(D_w + D_t + D_L - h_f)\ A}{\frac{D_t}{k_t} + \frac{D_L}{k_L}}$$

where

h_f = piezometric head in foundation immediately below pond

k_t = permeability of tailings

k_L = permeability of liner

A = area of pond

Q = seepage rate from pond

D_w = Depth of water

D_t = Depth of tailings

D_L = Thickness of liner

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where h_D is the head in the underdrain and the other terms are defined in Figure 4.

5.2 Pond Seepage After Reclamation

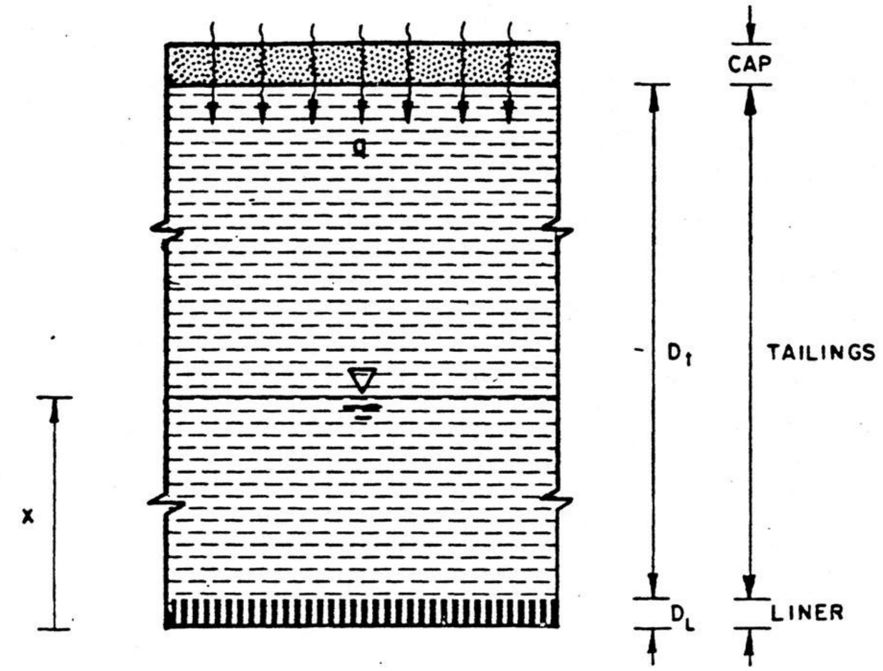
5.2.1 Lined Ponds Without Underdrains

The drainage of water from the pore space in a tailings pond with a bottom liner and no underdrain may be controlled by one of two factors: (1) the combined resistance to water flow of the tailings and liner or (2) by the rate at which water will drain from the pores of the tailings. The first factor controls if the combined resistance to flow of the tailings and liner retard the drainage sufficiently that complete drainage of water from the pores can occur as the piezometric level drops. If the combined resistance of the tailings and liner would allow the piezometric level to drop faster than water will drain from the pores of the tailings, the second factor controls.

The model presented in Figure 5 is for computing seepage rates for the case where the drainage of water is controlled by the combined resistance to flow of the tailings and liner. The derivation of these equations is given in Appendix B. In deriving the equations, some assumptions were made. The piezometric level was assumed to be initially at the surface of the tailings. The rate of infiltration of precipitation into the reclamation cap and the drainable porosity of the tailings were assumed to be constant. Also, seepage caused by consolidation of the tailings during drainage was assumed to be negligible. Throughout the drainage of the tailings, the piezometric head at the base of the liner (h_f) was assumed to be zero. It will be shown in subsequent sections that this assumption is reasonable for the seepage rates expected from lined ponds.

MODEL FOR COMPUTING SEEPAGE RATES AFTER RECLAMATION, FOR LINED PONDS

FIGURE 5



$$Q = \frac{xA}{\frac{D_L}{k_L} + \frac{x - D_L}{k_t}} \quad (1)$$

$$t = n_D\left[\frac{D_L\, k_t (k_t - k_L)}{k_L\, b^2} \ln\left(\frac{k_L\, b\, (D_t + D_L) - C}{k_L\, b\, x - C}\right) + \frac{D_t + D_L - x}{b}\right] \quad (2)$$

$$x_{ss} = \frac{C}{k_L\, b} \quad (3)$$

where

x = PIEZOMETRIC HEAD

q = INFILTRATION RATE

Q = SEEPAGE RATE FROM POND

A = POND AREA

t = TIME REQUIRED FOR WATER LEVEL IN POND TO DROP TO x

k_L = PERMEABILITY OF LINER

k_t = PERMEABILITY OF TAILINGS

n_D = DRAINABLE POROSITY OF TAILINGS

b = $k_t - q$

C = $D_L\, q\, (k_t - k_L)$

x_{ss} = x AT STEADY STATE SEEPAGE CONDITIONS

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For the case where the drainage is controlled by the rate at which water will drain from the pores of the tailings, it will be shown in a subsequent chapter of this report that, for the liners and ponds considered, the rate water will drain from the pores of the tailings does not control the drainage of the tailings.

5.2.2 Lined Ponds With Underdrains

The method of estimating seepage rates through the liner for ponds with underdrains is the same after reclamation as during operation, as long as the piezometric head in the underdrain (h_D) is known. The piezometric head on the liner is dependent on the seepage into the underdrain from the tailings and on the operation of pumps in the underdrain to remove seepage. The seepage rate from the tailings into the underdrain is expected to gradually decrease after the reclamation cap is in place. Eventually the seepage rate into the underdrain will be equal to the infiltration rate into the reclamation cap over the pond surface.

While the pumps in the underdrain are operated the seepage through the liner will essentially be constant or could decrease slightly depending on how the pumping system is operated. If the pumping is stopped after substantial drainage of the tailings has occurred and the rate of seepage from the tailings is equal to the infiltration rate, then the seepage rate through the liner will be equal to the infiltration rate. This rate could be greater or less than the seepage rate through the liner during the time when the pumps are operated, depending on the characteristics of the reclamation cap. On the other hand if the pumps in the underdrain are shut off at a time when substantial drainage of the tailings must still occur, the seepage rate through the liner is expected to increase substantially from the rate during operation of the pond, to a maximum value equal to that if no drain were present. This rate would gradually decrease until it equals the infiltration rate allowed by the reclamation cap.

An important factor in estimating seepage rates after reclamation, from a pond with an underdrain, is the time required for the seepage from the tailings into the underdrain to effectively reach the steady-state rate equal to the infiltration rate. This corresponds to the time when virtually all gravity drainage of the tailings is complete. The method used to estimate the time required to effectively reach steady-state conditions and the corresponding decrease in seepage from the tailings is described in Appendix C and its application discussed in Section 9.3 in this report.

6.0 EFFECTS OF SUBSURFACE CONDITIONS ON POND SEEPAGE

6.1 General

It was shown in Section 5.1 that the piezometric head immediately below the liner (h_f) of a tailings pond affects the seepage from the pond. The piezometric head below the liner at the Crandon site is initially expected to be zero or slightly negative, due to negative capillary pressures in the pores of the till. However, this initial value may be altered by seepage from the tailings pond. The purpose of this section of the report is to determine the conditions under which the piezometric head in the till immediately below the liner (h_f) is likely to increase substantially from its initial value and to determine if there is a potential for such head changes to affect the seepage from the pond.

Considering the glacial soils and location of the groundwater level at the site, there are two conditions that could cause the piezometric head in the till immediately below the liner to increase substantially from its initial value of zero or slightly negative. The two conditions are: (1) the development of a saturated zone immediately below the pond bottom that is not connected to the regional groundwater system, i.e. a saturated zone above the wetting front, and (2) the development of a mound in the groundwater system that rises to the pond bottom. The seepage rates necessary to cause the development of these two conditions are evaluated in Section 6.2 and 6.3, respectively. Also in Section 6.3, an estimate is made of the time required for a mound in the groundwater system to rise to the pond bottom.

6.2 Development of a Saturated Zone Below the Pond Bottom

As a pond is filled, seepage from the pond will enter the unsaturated zone beneath the pond and begin to move downward toward the groundwater. The leading edge of the downward-moving seepage is commonly called a wetting front. If the zone above the wetting front is saturated, h_f will increase from a small negative value to some positive value as the wetting front moves downward. As h_f increases the seepage rate through the zone beneath the pond and from the pond decreases. Therefore, if the zone above the wetting front is saturated, the seepage rate from the pond will decrease with time as the wetting front progresses downward. On the other hand, if the zone above the wetting front is not saturated, h_f will remain at or near its original value, and the seepage rate from the pond will be unaffected by the progression of the wetting front.

The seepage rate at which the zone above the wetting front will be saturated as it moves downward toward the water table can be estimated for the Crandon site using the principles described above. It can be shown (Reference 10) that the zone above the wetting front will not become saturated unless the seepage rate per unit area is greater than or equal to the vertical permeability of the foundation soils. The foundation soils for the ponds will be the glacial till described previously. The vertical permeability of the till was previously discussed and ranges from 8.8×10^{-7} to 9.9×10^{-6} ft./sec. (0.27×10^{-6} to 3.0×10^{-6} m/s). Our best estimate of the vertical permeability of the till is 3.1×10^{-6} ft./sec. (9.4×10^{-7} m/s). Using these permeability values and the principles discussed above, the seepage rate necessary to saturate the zone above the wetting front is expected to be in the range of 1800 to 19,000 gallons per minute per 100 acres (0.11 to 1.2 m^3/s per 40 hectares), with 6000 gallons per minute per 100 acres (0.4 m^3/s per 40 hectares) being the most likely value.

Therefore, the seepage rate from the pond will not be affected by the advancing wetting front for seepage rates of less than 1800 gallons per minute per 100 acres (0.11 m^3/s per 40 hectares), and is unlikely to be affected by the advancing wetting front for seepage rates less than 6000 gallons per minute per 100 acres (0.4 m^3/s per 40 hectares).

6.3 Mounding of Groundwater to Pond Bottom

6.3.1 General

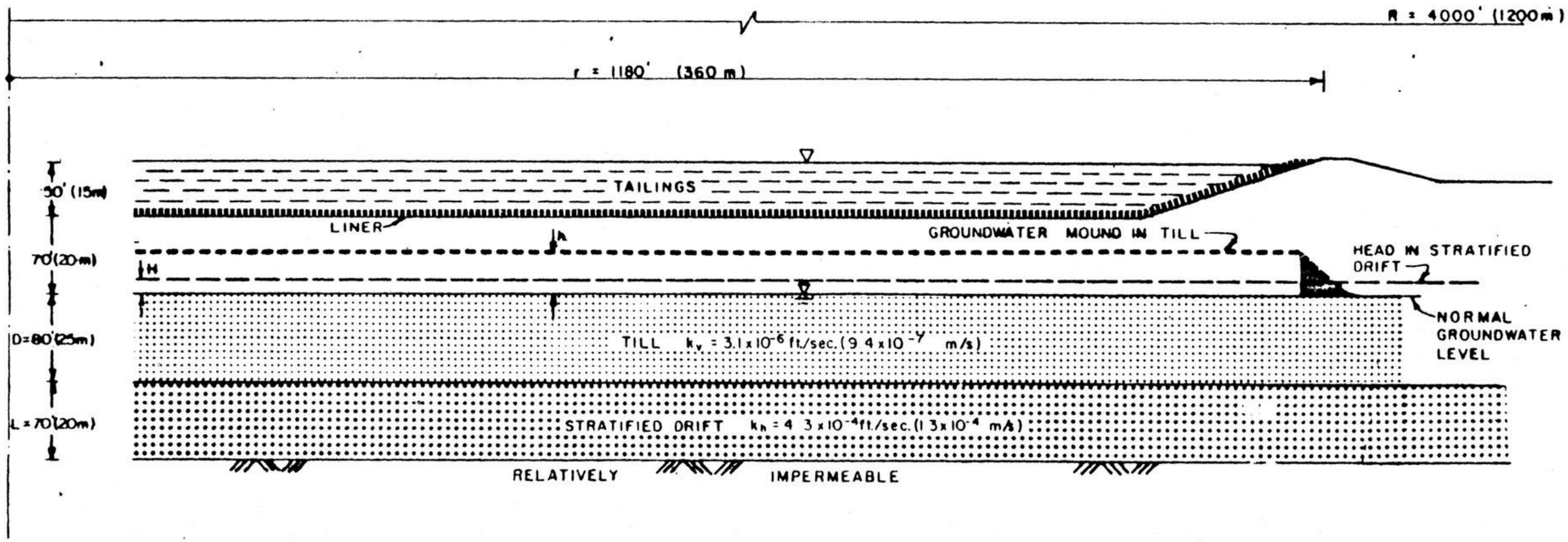
Seepage progressing downward through the unsaturated zone eventually will reach the groundwater. The effect this seepage has on groundwater levels depends on the magnitude of the seepage rate compared to the natural infiltration rate. A reasonable range for the natural infiltration rate in the Crandon Project area is believed to be from 6 to 12 inches per year (150 to 300 mm per year), which is 30 to 60 gallons per minute (0.002 to 0.004 m^3/s) over a 100-acre (40 hectare) area. If the pond seepage rate is approximately equal to the average natural infiltration rate, the seepage will enter the groundwater system and will not substantially affect the groundwater level. If the pond seepage rate is much less than the average natural infilration rate, the local groundwater level may drop. If the seepage rate from a pond substantially exceeds the average natural infiltration rate, the groundwater level will tend to rise under the pond and may eventually rise or mound to the pond bottom.

If the mound rises to the pond bottom it will cause the head at the base of the liner to increase, and consequently decrease the seepage rate from the pond. At that point the seepage rate from the pond becomes a function of the gradients in the groundwater system, as well as the combined resistance to flow of the liner and tailings. If the seepage rate necessary to cause mounding to the pond bottom (Qm) is greater than the maximum seepage rate anticipated from the pond system, the effects of mounding do not need to be considered further. The analyses for estimating this seepage rate is presented in Sections 6.3.2 through 6.3.4 of this report.

6.3.2 Description of Model

A simple model for predicting the height of the groundwater mound as a function of the seepage rate from a pond is illustrated in Figure 6. The derivation of the equations shown on Figure 6 are included in Appendix A. The following assumptions have been made in developing the model:

1. A steady-state seepage condition exists.
2. Horizontal water flow in the till is negligible.
3. The pond can be idealized as circular in plan.
4. Water flow in the stratified drift is radially symmetric.
5. Vertical water flow in the stratified drift is negligible.
6. Water flow in the stratified drift is governed by the steady-state equation for a well in a non-leaky artesian aquifer with a circular constant-head boundary condition (Equation 2 in Figure 6).



LEGEND:

- k_v = Vertical Permeability of the Till
- k_h = Horizontal Permeability of the Stratified Drift
- Q = Seepage Rate from Pond = Seepage Rate into Stratified Drift
- R = Distance to Constant Head Boundary
- H = Excess Head in Stratified Drift
- h = Excess Head in Till
- Q_m = Seepage Rate at which Groundwater Level Rises to Pond Bottom

NOTE:

Seepage through shaded zone at edges of mound is assumed to be insignificant.

EQUATIONS:

$$Q = \frac{2\pi L\, k_h\, k_v\, r^2 h}{2L\, k_h\, (D+h) + k_v r^2 \ln\left(\frac{R}{r}\right)} \qquad (1)$$

$$H = \frac{Q}{2\pi L\, k_h} \ln\left(\frac{R}{r}\right) \qquad (2)$$

MODEL FOR PREDICTING GROUNDWATER MOUNDING	FIGURE 6
Scale 1" = 100' Date 3-23-81 Job No. 786085 — **Golder Associates**	Drawn S.K.B. Checked R.S. Reviewed R.S.

The implications of assuming steady-state seepage conditions will be discussed later in this section. The remaining assumptions are examined below.

The assumption that horizontal flow in the till is negligible is not strictly true. On the edges of the pond the seepage will flow in a generally vertical direction toward the stratified drift, but it will have some horizontal component. Because of the large difference in the permeabilities of the till and the stratified drift, the area affected by the horizontal seepage on the edge of the mound will be insignificant compared to the total area of the mound.

The constant head boundary condition referred to in Item 6 has been assumed to be at a distance of 4000 feet (1200 m) from the center of the pond. This corresponds roughly to the distance from the center of the Sites 40 and 41 to the nearest open bodies of water which are known to be groundwater fed (Ground Hemlock Slough east of Site 41 and the wetland northwest of Rolling Stone Lake for Site 40).

The remaining assumptions given above are all considered to be reasonable first order approximations.

6.3.3 Results and Sensitivity Analyses

In the model shown in Figure 6, the groundwater level will mound to the pond bottom when h equals 70 feet (20 m). The idealized circular pond shown in Figure 6 has a radius of 1180 feet (360 m) which corresponds to a pond area of 100 acres (40 hectares). Applying the model to a 100 acre (40 hectares) pond using the parameters shown in

Figure 6, the groundwater level in the till will mound to the pond bottom when the steady-state seepage rate from the pond exceeds 1800 gallons per minute (0.11 m^3/s) for a sustained period. The steady-state seepage rate from a pond over a sustained period that is expected to cause the groundwater to mound to the pond bottom will be referred to as Q_m.

An inspection of Equation 1 in Figure 6 reveals that the value of Q_m per unit area is dependent on the pond size. For a reasonable variation in pond area from 50 to 300 acres (20 to 120 hectares), Q_m per unit area varies less than 25 percent from Q_m per unit area for a 100 acre (40 hectare) pond. Therefore, it is concluded that the variation in Q_m per unit area is not significant for the pond sizes anticipated for this project. Therefore, Q_m can be considered roughly proportional to pond area.

It is also important to determine the sensitivity of Q_m to variations in the parameters in Equation 1 in Figure 6. The parameters most likely to cause substantial variations in Q_m are R, k_h, and k_v. The effect on Q_m of variations in each of these parameters is evaluated below.

Because of external boundary conditions imposed by the wetlands, lakes, and streams around Sites 40 and 41 that are connected to the groundwater, R may exceed 4000 feet (1200 m) in a particular direction. Larger values of R reduce the value of Q_m. If R is as much as 20,000 feet (6100 m), approximately the distance from Site 41 to the wetland northwest of Rolling Stone Lake or from Site 40 to Ground Hemlock Slough, Q_m becomes 1200 gallons per minute (0.08 m^3/s) which is a decrease of only 33 percent for a five fold increase in R. Therefore, we conclude that Q_m is relatively insensitive to reasonable variations in R.

From the pump test studies (Ref. 3) the range in the horizontal permeability of the stratified drift (k_h) is 2.5×10^{-4} to 7.6×10^{-4} ft./sec. (7.6×10^{-5} to 2.3×10^{-4} m/s). Using this range for k_h in Equation 1 in Figure 6, Q_m varies from 1400 to 2100 gallons per minute (0.09 to 0.13 m^3/s) for a 100 acre (40 hectare) pond. This variation is considered small compared to the corresponding variation in k_h. Therefore, we conclude that Q_m is relatively insensitive to variations in k_h.

The range in the vertical permeability of the till (k_v) interval is 8.8×10^{-7} to 9.9×10^{-6} ft./sec. (2.7×10^{-7} to 3.0×10^{-6} m/s). For this range in k_v, Q_m varies from 700 to 3200 gallons per minute (0.04 to 0.20 m^3/s) for a 100 acre (40 hectare) pond. This variation is considered substantial, and based on the conclusions above, k_v is the only parameter which when varied over a reasonable range of confidence has a substantial affect on Q_m.

In conclusion, it can be stated with considerable confidence that the seepage rate from a tailings pond will not be affected by mounding of the groundwater below the pond as long as the seepage rates are less than 700 gallons per minute per 100 acres (0.04 m^3/s per 40 hectares), and it is unlikely to be affected by mounding for pond seepage rates less than 1800 gallons per minute per 100 acres (0.11 m^3/s per 40 hectares).

6.3.4 Time Required for Groundwater to Mound to Pond Bottom

It was shown in the previous section that the groundwater is likely to mound to the pond bottom if the pond seepage rate exceeds 1800 gallons per minute per 100 acres (0.11 m^3/s per 40 hectares) for a sustained period. In that analysis, it was assumed that steady-state conditions exist, i.e. the mound has risen to the pond bottom and stabilized there. The time required for the groundwater to mound to the pond bottom at a constant pond seepage rate of 1800 gallons per minute per 100 acres (0.11 m^3/s per 40 hectares) is evaluated below. This is important because, if the time required for the groundwater to mound to the pond bottom exceeds the duration of the seepage rates larger than 1800 gallons per minute per 100 acres (0.11 m^3/s per 40 hectares) the mound cannot rise to the pond bottom.

The model shown in Figure 6 can be applied to estimate the time it would take for the groundwater to mound to the pond bottom. It was necessary to assume that steady-state conditions exist over each of a series of time increments. The seepage rate into the stratified drift was computed for each time increment using Equation 1 in Figure 6. The law of conservation of mass was used to obtain the following equation for the increase in h in a time increment.

$$\Delta h_i = \frac{\Delta t_i}{A\, n_s} (Q_{in} - Q_{out})_i \qquad (6.1)$$

where

Δh = increase in h for time increment,

Δt = time increment,

n_s = ratio of volume available for storage in till to the total volume of the mass,

A = area of the pond,

Q_{in} = seepage rate from the pond, and

Q_{out} = seepage rate into stratified drift computed from Equation 1 in Figure 6.

The subscript, i, represents the time increment. The value of Q_{out} for any time increment was computed using the average value of h for the time increment. It was necesary to iterate on each time increment because Q_{out} and h are interrelated.

The method was used to compute the time required for a constant seepage rate of 1800 gallons per minute (0.11 m^3/s) from a 100 acre (40 hectare) pond to mound the groundwater to the pond bottom. The calculation indicates that approximately one year will be required using a value of n_s of 0.07. For a range in n_s of 0.03 to 0.3, the time for the mound to rise to the pond bottom ranges from 6 months to 4 years at a constant seepage rate of 1800 gallons per minute (0.11 m^3/s) from a 100 acre (40 hectare) pond. On the basis of this analysis, it can be concluded that the groundwater level is not likely to mound to the pond bottom unless the seepage rate exceeds 1800 gallons per minute per 100 acres (0.11 m^3/s per 40 hectares) for a period of at least one year.

6.4 Summary and Conclusions

The seepage rate from a pond is influenced not only by the depth of tailings and water in the pond, but also by the piezometric head (h_f) in the till immediately below the pond. Two seepage conditions can develop below the pond which affect h_f. One is the saturation of the zone below the pond bottom as the wetting front advances toward the water table. The other is the development of a mound in the groundwater that rises to the pond bottom.

As the wetting front advances it was shown that the head immediately below the pond (h_f) will not increase above its initial value unless the seepage rate from a 100 acre (40 hectare) pond exceeds the lower bound of 1800 gallons per minute (0.11 m^3/s) and is unlikely to saturate unless the rate from a 100 acre (40 hectare) pond exceeds 6000 gallons per minute (0.4 m^3/s). For a seepage rate of greater than 6000 gallons per minute (0.4 m^3/s) from a 100 acre pond it is likely that h_f will increase above its initial value almost immediately and will continue to increase as the wetting front advances toward the groundwater system. This increase in h_f will cause the seepage rate to decrease with time until the wetting front reaches the groundwater. At that point the seepage rate from the pond becomes very complex and is largely a function of gradients in the regional groundwater system.

It was also shown that the groundwater level will not mound to the pond bottom unless the seepage rate from a 100 acre pond exceeds the lower bound of 700 gallons per minute (0.04 m^3/s) and is unlikely to mound to the pond bottom unless the seepage rate from a 100 acre (40 hectare) pond exceeds 1800 gallons per minute per 100 acres (0.11 m^3/s per 40 ha) for a period of at least one year.

Based on the discussion above, it is concluded that at seepage rates less than 700 gallons per minute per 100 acres (0.04 m^3/s per 40 hectares) the head immediately below the pond will not increase above its initial value of approximately zero and the seepage rate from the pond will not be affected by seepage conditions below the pond. For seepage rates up to 1800 gallons per minute per 100 acres (0.11 m^3/s per 40 hectares) it is unlikely that seepage conditions below the pond will affect the seepage rate from the pond. Therefore, for the remainder of this report, for seepage rates up to 1800 gallons per minute per 100 acres (0.11 m^3/s per 40 hectares), it will be assumed that the head immediately below the pond (h_f) will not increase above its initial value of approximately zero.

7.0 SEEPAGE RATES FROM UNLINED PONDS

7.1 General

The general equation for calculating seepage rates was given in Figure 4. For unlined ponds the equation reduces to the following:

$$Q = \frac{k_t A (D_w + D_t - h_f)}{D_t} \tag{7.1}$$

For unit seepage rates less than 1800 gallons per minute per 100 acres, it was concluded in Section 6.4 that the unsaturated till below the pond does not become saturated and h_f remains approximately zero. Therefore, for unit seepage rates less than 1800 gallons per minute per 100 acres, Equation 7.1 reduces to the following:

$$Q = \frac{k_t A (D_w + D_t)}{D_t} \tag{7.2}$$

7.2 Seepage Rates with Minimal Ponded Water

When the depth of free water ponded on the surface of the tailings is minimal, D_w can be taken as zero and the equation for Q reduces to the following:

$$Q = k_t A \tag{7.3}$$

It is apparent from Equation 7.3 that Q is independent of the depth of tailings (D_t) and that the seepage per unit area (Q/A) is equal to the permeability of the tailings (k_t). This is true because the distance over which the head is dissipated is equal to the head (D_t), i.e. the gradient is one. The fact that the seepage rate is independent of the depth of tailings has important implications on the design of the disposal facilities. It means that the total seepage from an unlined pond may be reduced by reducing the pond area. Therefore, from the standpoint of minimizing seepage, deep ponds with small areas are preferable to shallow ponds with large areas.

The recommended design value (Ref. 5) for the permeability of the tailings (k_t) is 1.6×10^{-7} ft./sec. (5×10^{-8} m/s). Using this value the seepage rate from a 100 acre (40 hectares) pond with minimal ponded water is 310 gallons per minute (0.02 m^3/s). For comparison the range in seepage rate equivalent to the estimated range of natural infiltration is 30 to 60 gallons per minute per 100 acres (0.002 to 0.0004 m^3/s per 40 hectares). The minimum expected value at which pond seepage is affected by seepage conditions in the foundation is 700 gallons per minute per 100 acres (0.04 m^3/s per 40 hectares). Therefore, the seepage rate from unlined ponds with minimal ponded water is independent of seepage conditions in the foundation, and the seepage rate may be computed using Equation 7.3.

7.3 Seepage Rates with Substantial Ponded Water

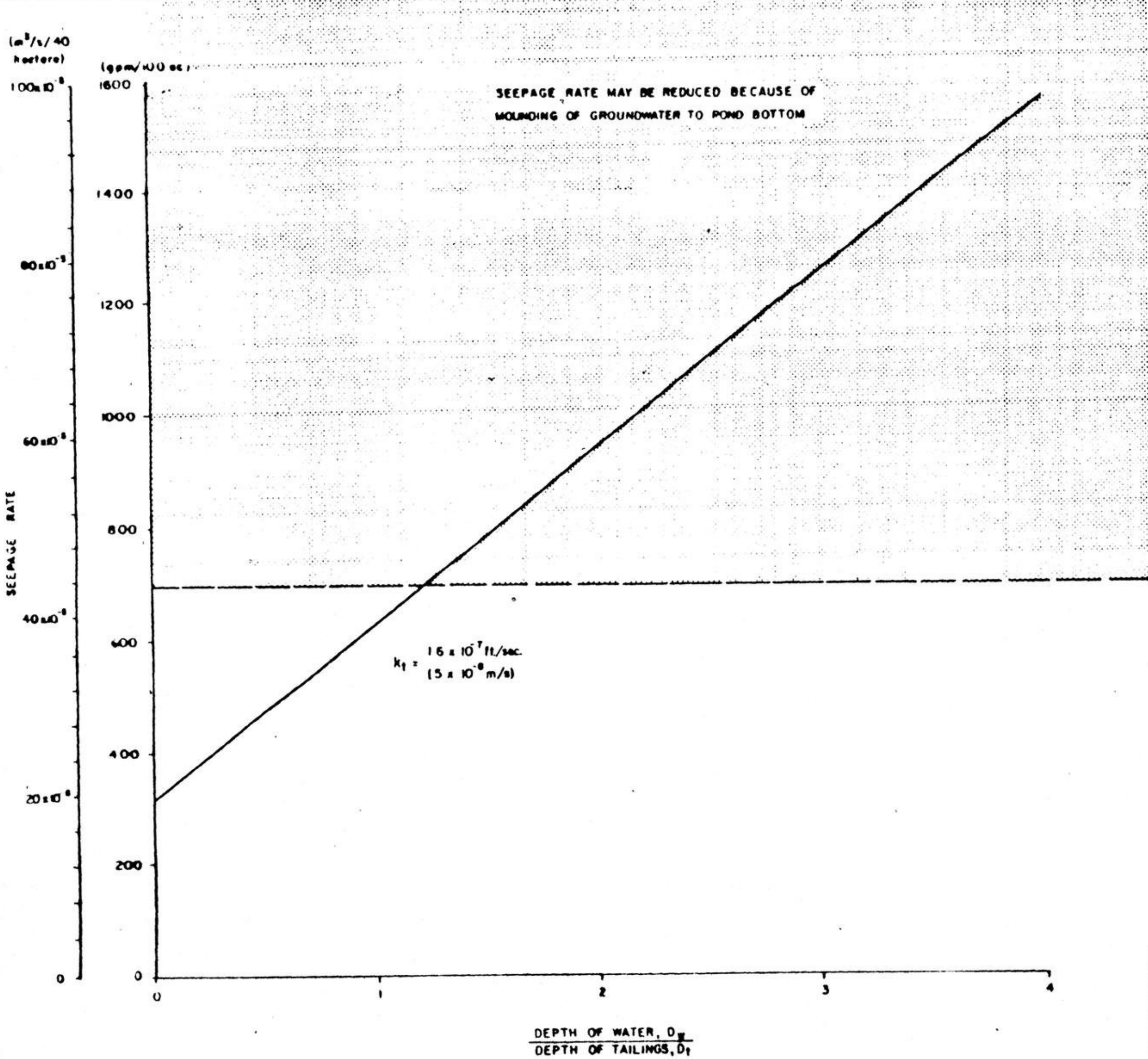
The seepage rate is strongly dependent on the depth of free water ponded on the surface of the tailings (D_w) relative to the depth of tailings (D_t). Equation 7.2 can be rewritten to emphasize the effect of the ratio of D_w/D_t.

$$Q = k_t\, A \left(\frac{D_w}{D_t} + 1 \right) \qquad (7.4)$$

Equation 7.4 is presented in graphical form in Figure 7 for a 100 acre pond and a tailings permeability of 1.6×10^{-7} ft./sec. (5×10^{-8} m/s). It can be seen in Figure 7 that seepage rate increases rapidly as the depth of ponded water increases. For example for a tailings depth of 10 feet the seepage rate increases from 310 to 620 gallons per minute (0.020 to 0.040 m^3/s) as the depth of ponded water increases from 0 to 10 feet (0 to 3m). It can be seen from Figure 7 that the seepage rate may be affected by mounding of the groundwater to the pond bottom when the ratio of the depth of free water to the depth of tailings is greater than about 1.2.

7.4 Seepage Rates from Ponds After Reclamation

The seepage from an unlined pond after reclamation is analogous to the seepage into an underdrain overlying a liner, as long as pumps in the underdrain are operated. The seepage rates from the tailings into an underdrain are evaluated in Appendix C for lined ponds after the reclamation cap is in-place. The conclusions drawn in Appendix C are also considered valid for unlined ponds.



EQUATION FOR CURVE

$$Q = k_t A \left(\frac{D_w}{D_t} + 1 \right)$$

LEGEND:

A = Pond Area
Q = Seepage Rate
k_t = Permeability of tailings
k_L = Permeability of liner
D_t = Depth of tailings
D_L = Thickness of liner
D_w = Depth of free water

SEEPAGE RATES vs RATIO OF WATER DEPTH TO TAILINGS DEPTH FOR UNLINED PONDS		FIGURE 7
Scale AS SHOWN Date 3-27-81 Job No. 786085	Golder Associates	Drawn SKB Checked R.S. Reviewed RS

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8.0 SEEPAGE RATES FROM LINED PONDS

8.1 Introduction

Seepage rates for ponds during operation and after reclamation are presented in this section. Evaluations are made for ponds with liners ranging from a 0.5 ft. (0.15 m) soil-bentonite liner with a permeability of 1.6×10^{-9} ft./sec. (5×10^{-10} m/s) to a 40 mil synthetic liner with a permeability of 3.3×10^{-14} (1.0×10^{-14} m/s). During operation, seepage rates were calculated for tailings depths ranging up to 80 feet. The reduction in the seepage rate after the pond has been reclaimed and the long-term or steady-state seepage rate for reclaimed ponds are also evaluated.

8.2 Seepage Rates During Operation

8.2.1 General

The general equation for calculating seepage rates was given in Section 5.1 and is as follows:

$$Q = \frac{(D_w + D_t + D_L - h_f)A}{\frac{D_t}{k_t} + \frac{D_L}{k_L}} \qquad (8.1)$$

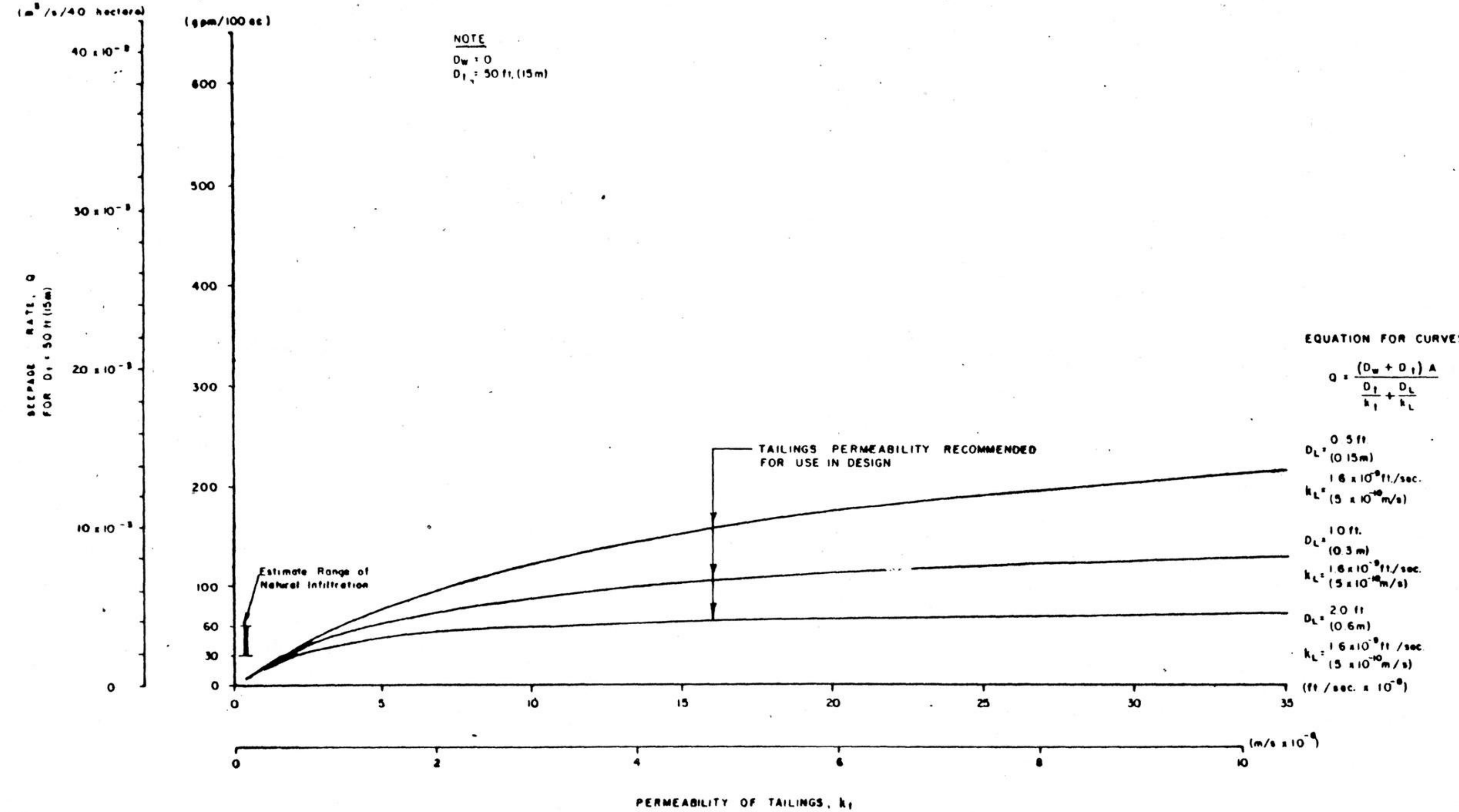
The equation can be simplified somewhat for lined ponds at the Crandon site. For unit seepage rates less than 1800 gallons per minute per 100 acres, (0.11 m^3/s per 40 hectares) it was shown in Section 6.0 that the unsaturated till below the pond does not become saturated and the piezometric head at the base of the liner (h_f) remains approximately zero.

The liner thicknesses being considered for this project range from a fraction of an inch to several feet. The contribution of the liner thickness (D_L) to the head causing seepage is insignificant (D_L is much less than $D_w + D_t$) during most of the operating life of the pond. Therefore, the equation for computing seepage rates for unit seepage rates less than 1800 gallons per minute per 100 acres (0.11 m^3/s per 40 hectares) reduces to the following by setting the piezometric head at the base of the liner (h_f) to zero and by assuming that the thickness of the liner (D_L) does not contribute significantly to the head causing seepage.

$$Q = \frac{(D_w + D_t)\ A}{\frac{D_t}{k_t} + \frac{D_L}{k_L}} \tag{8.2}$$

8.2.2 Effect of Tailings on Seepage Rate

Equation 8.2 shows that all the variables which influence the seepage rate can be controlled by either the design or operation of the pond system, except for the permeability of the tailings. Although a specific value for tailings permeabilty has been recommended for use in design, it is still considered important to evaluate the effect of variations in the permeability of the tailings on the seepage rate. The seepage rates from a 100 acre (40 hectare) pond with a 50 foot (15 m) depth of tailings are plotted versus tailings permeability in Figure 8 for soil-bentonite liners with thicknesses ranging from 6 inches (152 mm) to 2.0 feet (0.61 m). For comparison the range in seepage rate equivalent to the estimated range in the natural infiltration rate is also shown in Figure 8.



LEGEND:

- Q = Seepage Rate
- k_t = Permeability of tailings
- k_L = Permeability of liner
- D_t = Depth of tailings
- D_L = Thickness of liner
- D_w = Depth of free water

SEEPAGE RATES vs. TAILINGS PERMEABILITY FOR 50ft (15m) DEEP POND

FIGURE 8

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Job No. 786085

Golder Associates

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The following general conclusions can be drawn about the effect of variations in tailings permeability on pond seepage:

1. The influence of the permeability of the tailings on the seepage rate decreases as the liner's flow resistance ($^{D}L/k_L$) increases.

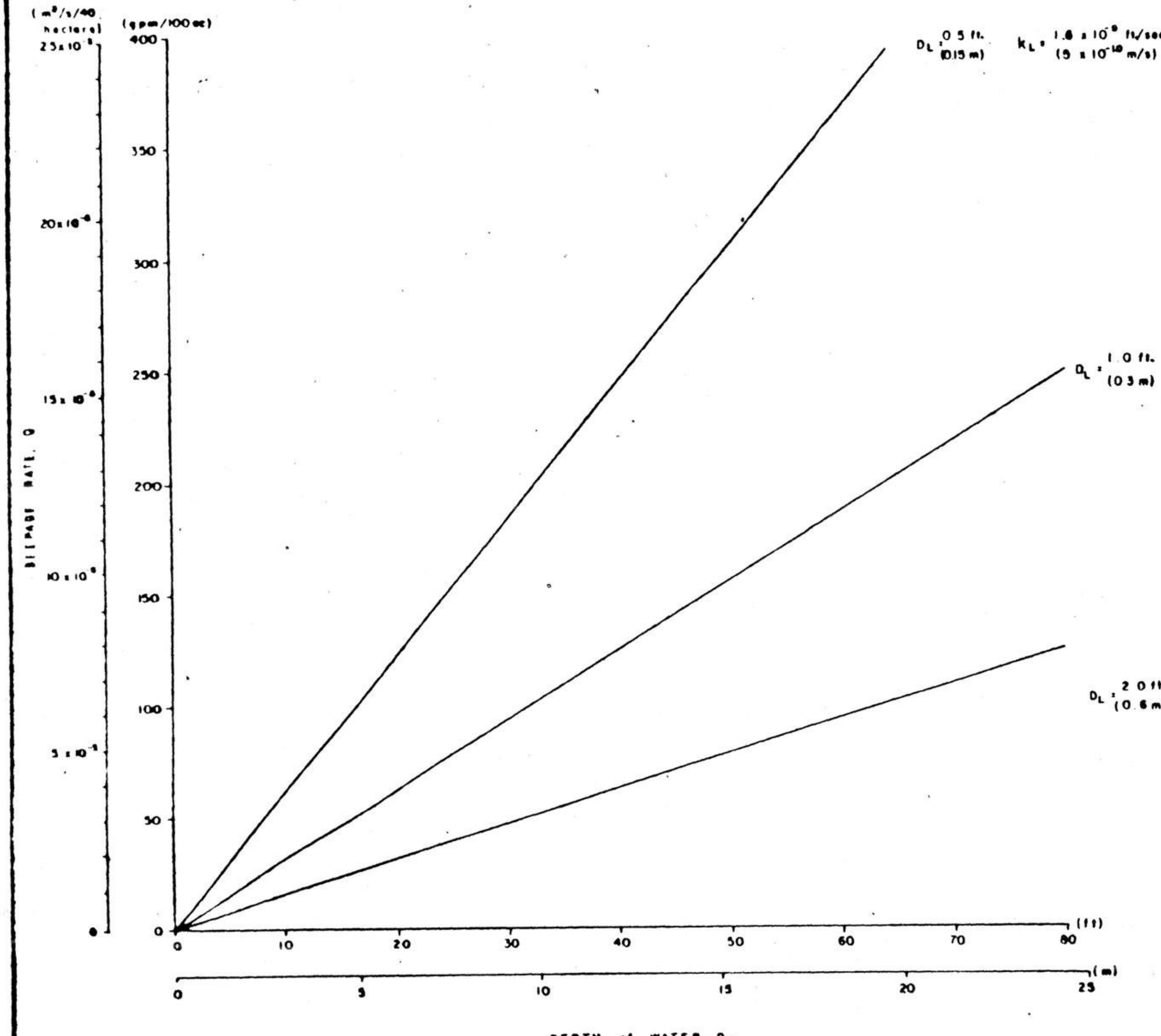
2. For the liners considered for this project the seepage rate is very nearly independent of the tailings permeability for tailings permeabilities equal to or greater than the value recommended for use in design (1.6×10^{-7} ft./sec. = 5×10^{-8} m/s).

3. The seepage rate is substantially reduced by the tailings for tailings permeabilities less than about one-half the value recommended for use in design.

8.2.3 Effect of Pond Depth

The seepage rate as a function of head was calculated for two cases. In each case a pond area of 100 acres (40 hectares) was used and four liner types ranging from a 6 inch (152 mm) soil-bentonite liner with a permeability of 1.6×10^{-9} ft./sec. (5×10^{-10} m/s) to a 40 mil (1 mm) synthetic liner with a permeability of 3.3×10^{-14} ft./sec. (1×10^{-14} m/s) were considered.

In the first case the ponds were assumed to contain water only. The results of the calculations are plotted in Figure 9. The seepage rates for this case represent an upper bound for each of the three soil-bentonite liners shown. The curve for the 40 mil (1 mm) synthetic liner is



EQUATION FOR CURVES

$$Q = \frac{(D_w + D_t)\,A}{\frac{D_t}{k_t} + \frac{D_L}{k_L}}$$

LEGEND:

Q = Seepage Rate

k_t = Permeability of tailings

k_L = Permeability of liner

D_t = Depth of tailings

D_L = Thickness of liner

SEEPAGE RATES FOR LINED PONDS STORING WATER ONLY	FIGURE 9

Scale AS SHOWN
Date 11-19-81
Job No. 786085

Golder Associates

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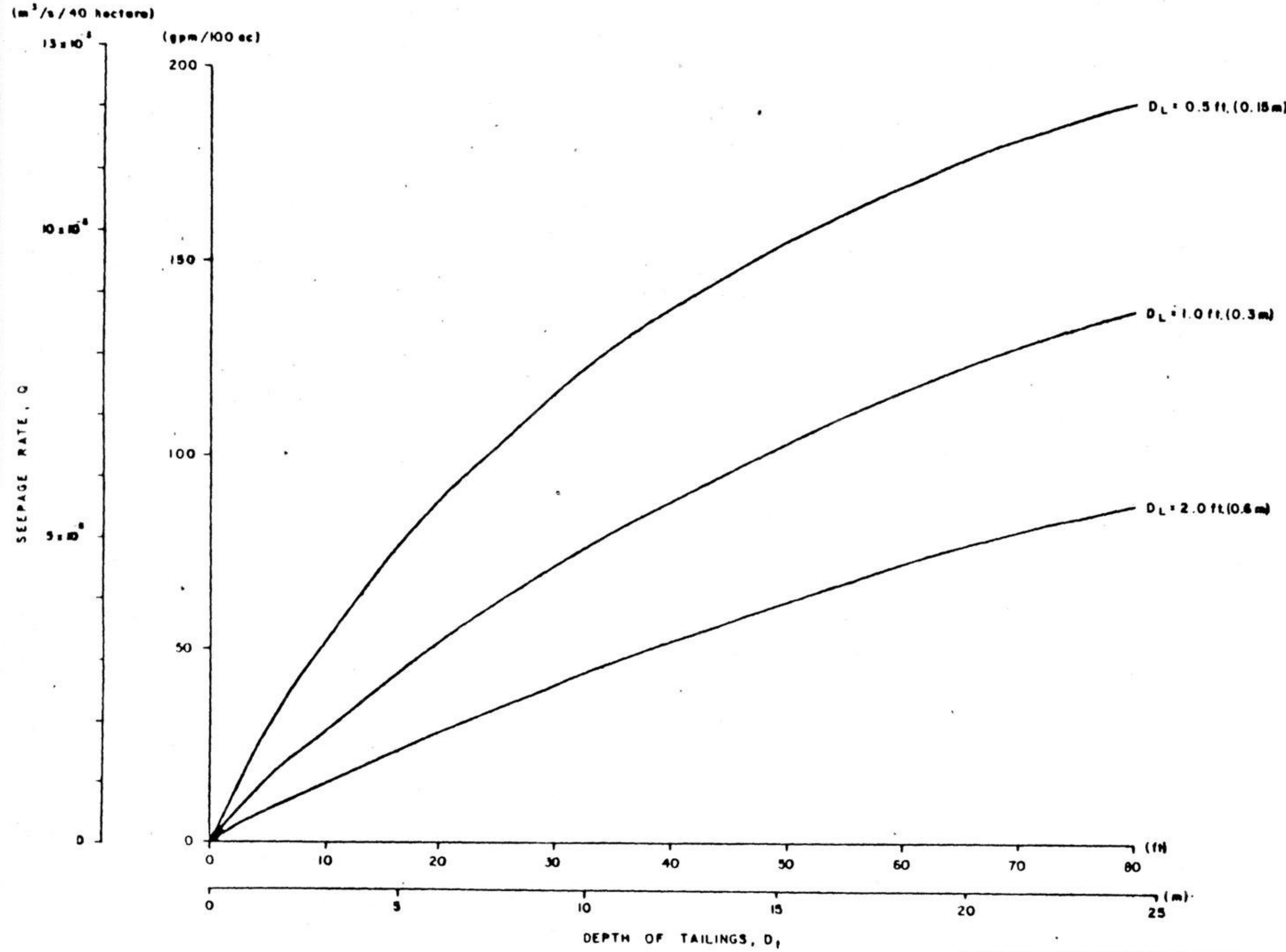
not shown on Figure 9 or on the figure for the other case because the seepage rate, even at a head of 80 feet (24 m), is only about 2 gallons per minute per 100 acres (0.0001 m^3/s per 40 hectares). The seepage rate for a water depth of 50 feet (15 m) ranges from 80 gallons per minute per 100 acres (0.005 m^3/s per 40 hectares) for a 2 foot thick soil-bentonite liner to 310 gallons per minute per 100 acres (0.02 m^3/s per 40 hectares) for a 6 inch (152 mm) thick soil-bentonite liner.

In the second case, seepage rates were computed for various depths of tailings and the same liners using a tailings permeability of 1.6×10^{-7} ft./sec. (5×10^{-8} m/s). The depth of water over the tailings was assumed to be minimal. The results are plotted in Figure 10. The seepage rates for a tailings depth of 50 feet (15 m) range from 60 gallons per minute per 100 acres (0.004 m^3/s per 40 hectares) for a 2 foot thick soil-bentonite liner to 160 gallons per minute per 100 acres (0.01 m^3/s per 40 hectares) for a 6 inch (152 mm) thick soil-bentonite liner.

A comparison of Figures 9 and 10 further confirms the conclusion above that the tailings have a major effect on seepage rates for low resistance liners and very little effect for high resistance liners.

Another important conclusion can be made by comparing Figures 9 and 10. In lined ponds filled with tailings, an increase in the depth of tailings (and consequently an increase in head) causes a less than proportional increase in the seepage rate. This effect becomes more pronounced as the tailings permeability decreases. Therefore the same



EQUATION FOR CURVES

$$Q = \frac{(D_w + D_t)\,A}{\frac{D_t}{k_t} + \frac{D_L}{k_L}}$$

NOTE:

$k_L = \frac{1.6 \times 10^{-9} \text{ ft/sec.}}{(5 \times 10^{-10} \text{ m/s})}$

$k_t = \frac{1.6 \times 10^{-7} \text{ ft/sec.}}{(5 \times 10^{-8} \text{ m/s})}$

LEGEND:

- Q = Seepage Rate
- k_t = Permeability of tailings
- k_L = Permeability of liner
- D_t = Depth of tailings
- D_L = Thickness of liner

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SEEPAGE RATES FOR LINED PONDS STORING TAILINGS ONLY

EXXON MINERALS COMPANY — FIGURE 10

conclusion can be made for lined ponds as was made for unlined ponds. From the standpoint of minimizing seepage during operation, deep ponds with small areas are preferable to shallow ponds with large areas.

8.3 Seepage Rates from Ponds After Reclamation

8.3.1 General

It was previously discussed in Section 5.2.1 that drainage of the tailings will be controlled by one of two factors: (1) the combined resistance to flow of tailings and liner, or (2) the rate at which water will drain from the pores of the tailings. The first factor controls if the combined resistance to flow of the tailings and liner retard the drainage sufficiently that complete drainage of water from the pores can occur as the piezometric level drops. If the combined resistance of the tailings and liner would allow the piezometric level to drop faster than water will drain from the pores of the tailings, the second factor controls.

The rate of drainage and the corresponding decrease in seepage rate can be evaluated for conditions where the first factor controls using the model in Figure 5. Predictions made using the model, along with the concepts discussed in Appendix C can be used to evaluate which of the factors above will control the rate of drainage of the tailings for a particular set of conditions.

It was concluded in Appendix C that a reasonable best estimate of the time for a 50 foot (15 m) deep tailings pond with an underdrain to reach steady-state conditions is 6 years, provided the long term infiltration rate is in the range of 1 to 4 inches per year (25 to 100 mm/yr.). According to the concepts in Appendix C, the time to reach steady-state is approximately proportional to the thickness of the tailings. Therefore, the time to reach steady-state for a one foot (300 mm) layer of tailings would be about 0.12 years (6 yrs./50 ft.), or taking the inverse, a thickness of about 8 feet (2.4 m) of tailings would reach steady-state in one year. If the piezometric level in a lined pond, with an infiltration rate in the range of 1 to 4 inches per year (25 to 100 mm/yr.) as determined by the model in Figure 5, drops at a rate faster than 8 feet per year (2.4 m/yr.), complete drainage of the pores (drainage to the volumetric water content corresponding to the infiltration rate) would not occur as the piezometric level drops. Therefore, under these conditions, the rate of drainage would be controlled by the rate at which water will drain from the pores of the tailings. On the other hand, if the piezometric level under the same conditions drops at a rate slower than 8 feet per year (2.4 m/yr.), complete drainage of the pores would occur as the piezometric level drops, and the rate of drainage would be controlled by the combined resistance to flow of the tailings and liner.

The model in Figure 5 predicts that for infiltration rates of greater than 1 inch per year (25 mm/yr.) the drop in the piezometric level in a pond with a depth of 50 feet (15 m) during the first year after reclamation will be less than 8 feet (2.4 m) for all the liners considered in this report. In subsequent years the model predicts that the piezometric level would drop even more slowly. For ponds with tailings depths less than 50 feet (15 m) the rate the piezometric level drops would be less than the rate for a 50 feet (15 m) tailings depth. For ponds with tailings depths greater than 50 feet, up to the 80 foot (24 m) maximum considered in this report, the model for some cases predicts drops in the piezometric level that are slightly larger than 8 feet (2.4 m) in the first few years after reclamation, but decrease to about 8 feet (2.4 m) or less in subsequent years. The rate at which water will drain from the voids of the tailings may control the drainage of the tailings in ponds deeper than 50 feet (15 m) for the first few years after reclamation, but this is not expected to have a substantial effect on the time required to reach steady-state or on the seepage rates during drainage of the tailings. Therefore, the controlling factor in the rate of drainage of lined ponds considered in this report is expected to be the combined resistance to flow of the tailings and liner, and not the rate at which water will drain from the pores of the tailings. This conclusion is valid for tailings depths up to about 80 feet (24 m) and for infiltration rates of 1 to 4 inches per year (25 to 100 mm/yr.). The effect of the conclusion is that the model in Figure 5 can be used to estimate seepage rates after reclamation for any tailings depth and liner considered in this report, and for infiltration rates in the range presently considered reasonable for the reclamation cap.

8.3.2 Time to Reach Steady-State Conditions

For the piezometric level in the pond to drop the infiltration rate through the cap (q) must be less than the seepage rate from the pond. Eventually, as the piezometric head drops, the seepage rate from the pond becomes equal to the infiltration rate, i.e. steady-state seepage conditions are reached. According to the model in Figure 5 an infinite amount of time is required to reach steady-state conditions. Therefore it is necessary to define a time where the piezometric head in the pond has dropped almost to the steady-state level (x_{ss}). We chose to define a time (t_{95}) as the point where the piezometric head has dropped 95 percent of the distance from its original level (at the surface of the tailings) to the steady-state level (x_{ss}).

The value of x corresponding to t_{95} is as follows:

$$x_{95} = 0.95\ x_{ss} + 0.05\ (D_t + D_L)$$

By substituting the above equation for x_{95} for x in Equation 2 in Figure 5 and simplifying, the following equation was obtained:

$$t_{95} = n_D \quad \frac{D_L\ (k_t - k_L)\ (3\ k_t - 0.95\ q)}{k_L\ (k_t - q)^2} + \frac{0.95\ (D_t + D_L)}{k_t - q}$$

It is considered that t_{95} is a practical estimate of the time required for the pond to reach steady-state seepage conditions.

Values of t_{95} for soil-bentonite liners with thicknesses of 6 inches (152 mm), 1.0 feet (304 mm), and 2.0 feet (0.61 m), are plotted in Figure 11 versus the infiltration rate into the tailings. A tailings permeability of 1.6×10^{-7} ft./sec. (5×10^{-8} m/s), a drainable porosity of 0.3 and a tailings depth of 50 feet (15 m) were used in calculating the values of t_{95} in Figure 11. It is apparent that the value of t_{95} is not strongly affected by the infiltration rate, but it is strongly influenced by the flow resistance of the bottom liner. For example, at an infiltration rate of 2.0 inches per year (50 mm/yr.) t_{95} varies from about 12 years for a 6 inch (152 mm) soil-bentonite liner to about 41 years for a 2 foot (0.61 m) soil-bentonite liner. The time to reach steady-state for a pond

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NOTE

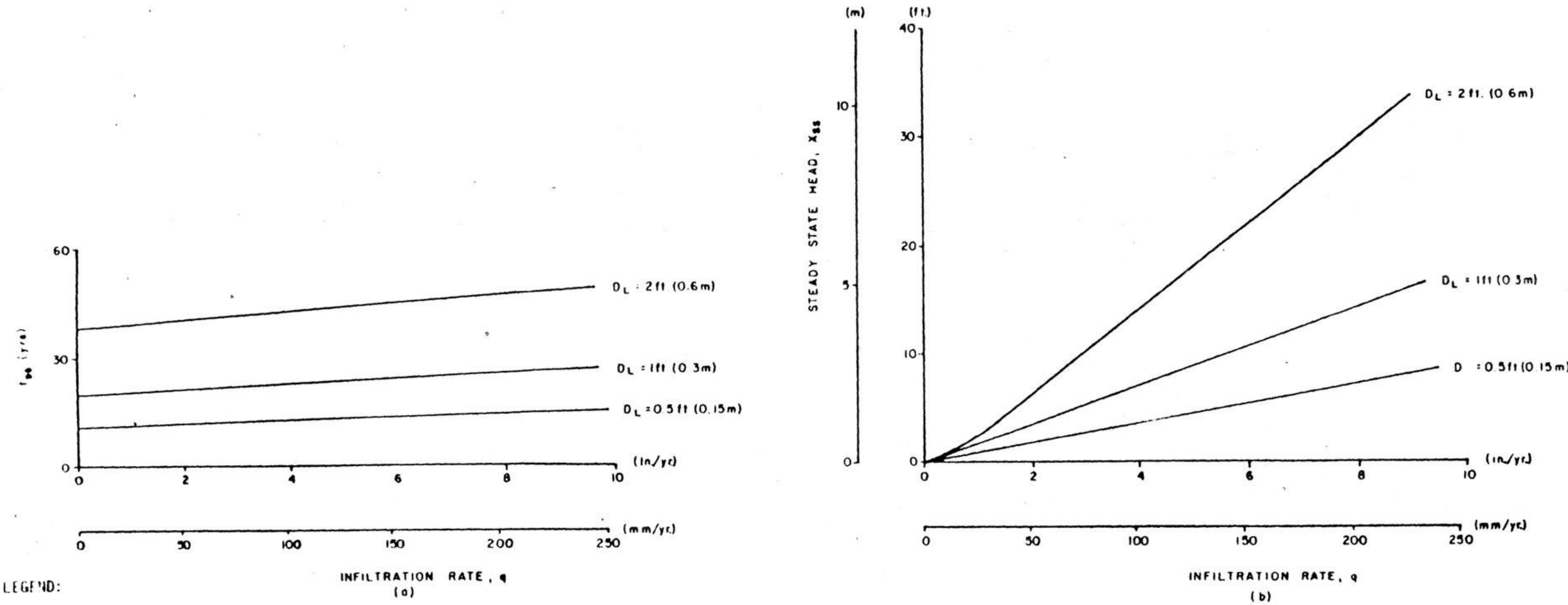
(for both (a) and (b))

$k_L = 1.6 \times 10^{-9}$ ft/sec. (5×10^{-10} m/s)

$k_t = 1.6 \times 10^{-7}$ ft/sec. (5×10^{-8} m/s)

D_t = 50 ft. (15 m)

n_D = 0.30



LEGEND:

Q = Seepage Rate

k_t = Permeability of tailings

k_L = Permeability of liner

D_t = Depth of tailings

D_L = Thickness of liner

n_D = Drainable porosity of tailings

q = Infiltration rate

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with a 40 mil (1.0 mm) synthetic liner with a permeability of 3.3×10^{-14} ft./sec. (1.0×10^{-14} m/s) could not be shown conveniently in Figure 11, because at an infiltration rate near zero t_{95} exceeds 100 years.

8.3.3 Piezometric Levels at Steady-State

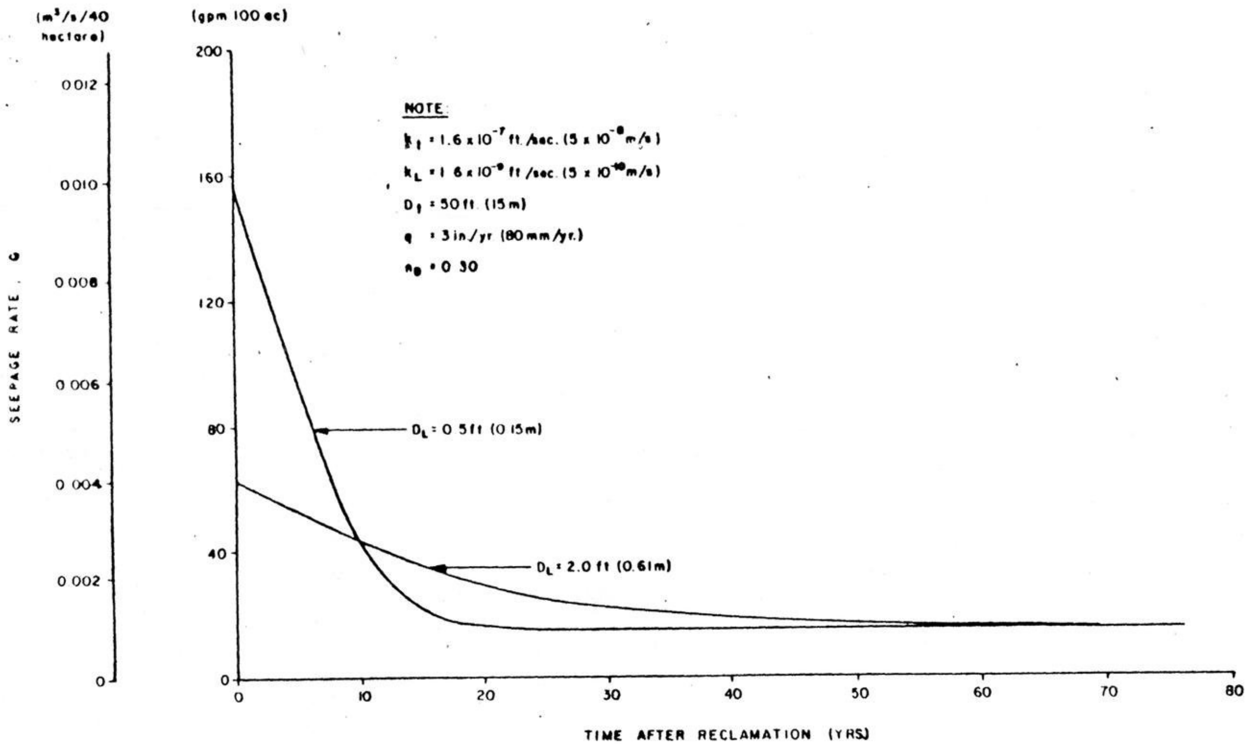
The piezometric head remaining in the pond when steady-state seepage conditions (x_{ss}) are reached at a given infiltration rate are shown in Figure 11. Figure 11 also shows that the steady-state head, and consequently the saturated depth of the tailings, varies considerably with variations in the infiltration rate, as well as with liner type.

For any tailings-liner system there is an infiltration rate at which the head in the pond will remain at the surface of the pond. That rate is the maximum possible for the system. The maximum infiltration rates for lined ponds range from 30 inches per year (760 mm/yr.) for a 6 inch (152 mm) soil-bentonite liner to about 0.2 inches per year (5 mm/yr.) for a 40 mil (1 mm) synthetic liner. A tailings permeability of 1.6×10^{-7} ft./sec. (5×10^{-8} m/s) and a tailings depth of 50 feet (15 m) were used in calculating these values. For comparison the estimated range of natural infiltration rate ranges from 6 to 12 inches per year (152 to 304 mm/yr.).

For any pond/liner system there is also an infiltration rate at which most of the tailings in a pond will desaturate. As an example, the infiltration rate at which a 5 foot (15 m) depth of tailings will remain saturated under long-term steady-state conditions was evaluated. The rate ranges from 6 inches per year (152 mm/yr.) for a 6 inch (152 mm) thick soil-bentonite liner to 2 inches per year (50 mm/yr.) for a 2.0 foot (0.61 m) thick soil-bentonite liner and to 0.02 inches per year (0.5 mm/yr.) for a synthetic liner. These analyses indicate that if substantial desaturation of the tailings is considered desirable, the reclamation cap chosen for a pond is dependent on the bottom liner in the pond.

8.3.4 Variation in Seepage Rate with Time

The decrease in seepage rate after the pond has been reclaimed is shown in Figure 12 for two cases. An infiltration rate of 3.0 inches per year (50 mm/yr.) was assumed. The two cases shown were chosen to illustrate the effect the liner has on the decrease in seepage with time. The seepage rate from a pond wih a synthetic liner would be about 1 gallon per minute (0.0001 m^3/s) at the end of reclamation for the case in Figure 12 and that the seepage rate would not decrease significantly over the time scale used in Figure 12.



LEGEND:

Q = Seepage Rate

k_t = Permeability of tailings

k_L = Permeability of liner

D_t = Depth of tailings

D_L = Thickness of liner

n_D = Drainable porosity of tailings

q = Infiltration rate

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Golder Associates		EXXON MINERALS COMPANY — FIGURE 12

9.0 SEEPAGE RATES FROM PONDS WITH UNDERDRAINS

9.1 General

The estimates of seepage rates for ponds with underdrains have been made for a pond with an area of 100 acres (2100 feet x 2100 feet) and a bottom graded generally from the center of the pond downward toward the perimeter at a slope of 2 percent. To keep the estimates as generic as possible and to allow comparison with the seepage rates given in this report for ponds without underdrains, the side slopes of the pond have not been considered in the analyses below.

9.2 Seepage Rates During Operation

Seepage rates for ponds with underdrains and liners were calculated using a depth of water in the underdrain equal to the estimated hydraulic thickness of the underdrain. The method for determining the required hydraulic thickness of the underdrain was explained in detail in Reference 9. Using a tailings permeability of 1.6×10^{-7} ft./sec. (5.0×10^{-8} m/s) and an underdrain permeability of 1.6×10^{-2} ft./sec. (5.0×10^{-3} m/s), the required hydraulic thickness is 3 inches (76 mm) for a 100 acre (40 hectare) pond with a minimal amount of ponded water (average hydraulic gradient through the tailings of 1.0) over the tailings. The required hydraulic thickness is 6 inches (152 mm) for a 100 acre pond (40 hectares) with substantial ponded water over the tailings (average hydraulic gradient through the tailings of 2.0).

Seepage rates during operation for ponds with an underdrain and liner are summarized in Table 1. Values are given for 6 inch, 1.0 foot, and 2.0 foot, (152 mm, 0.30 m, and 0.61 m) thick soil-bentonite liners and for a 40 mil

TABLE 1

SEEPAGE RATES DURING OPERATION FROM PONDS
WITH UNDERDRAINS AND BOTTOM LINERS

		Seepage Rate	
Liner Type	Liner Thickness ft. (m)	h=0.25' (0.076 m) gpm ($m^3/s \times 10^{-4}$)	h=0.5' (0.15 m) gpm ($m^3/s \times 10^{-4}$)
Soil-bentonite	0.5 (0.15)	5 (3)	6 (4)
Soil-bentonite	1.0 (0.30)	4 (3)	5 (3)
Soil-bentonite	2.0 (0.61	3 (2)	4 (3)
Synthetic	0.003 (0.001)	0.005 (0.003)	0.01 (0.006)

Notes: 1. h = the average depth of water in the underdrain

2. Soil-bentonite liner permeability = 1.6×10^{-9} ft./sec. (5.0×10^{-10} m/s)

3. Synthetic liner permeability = 3.3×10^{-14} ft./sec. (1.0×10^{-14} m/s)

synthetic liner. Seepage rates for each liner are given for both a 3 inch (76 mm) and a 6 inch (152 mm) head of water in the underdrain. These two cases correspond to gradients through the tailings of 1.0 and 2.0 respectively.

Table 1 shows that seepage rates from ponds with underdrains and liners are very small during operation. The maximum seepage rate for the conditions considered in Table 1 is 6 gallons per minute per 100 acres (0.0004 m^3/s per 40 hectares). It can be seen from Table 1 that the seepage rate during operation is relatively insensitive to variations in the thickness of the soil-bentonite liner. On the other hand, the seepage rate during operation is substantially less with a synthetic liner than it is with the soil-bentonite liners.

9.3 Seepage Rates After Operation

After active disposal of tailings in a pond has ceased, it will be important to continue operating the pumps in the underdrain during the time the tailings are draining. Continued operation of the pumps while the tailings are draining is important to prevent the seepage rate through the bottom liner from increasing substantially from the rate during operation, and to allow the tailings to drain as rapidly as possible. In the discussions below, it has been assumed that operation of the pumps in the underdrain continues until drainage of the tailings is substantially complete.

The seepage rate through the liner in a pond with an underdrain and liner is related to the seepage rate into the underdrain from the tailings. The seepage rate from the tailings into the underdrain during drainage of the tailings was evaluated in Appendix C.

The conclusions drawn in Appendix C are as follows:

1. For a period of about 6 months after the reclamation cap is completed, the seepage rate from the tailings is expected to be about 310 gallons per minute per 100 acres (0.02 m^3/s per 40 ha).

2. After this 6 month period the seepage rate from the tailings is expected to gradually decrease over a period of about 5 years to a rate approximately equal to the infiltration rate into the reclamation cap, i.e. the long-term, steady-state seepage rate.

3. Our best estimate of the time to reach steady-state conditions, after the reclamation cap is complete, is 6 years. Considering a reasonable degree of uncertainty in the variation in tailings permeability as the tailings drain, it is our judgment that the time to reach steady-state conditions, after the reclamation cap is in place, is not likely to exceed 15 years.

These conclusions are considered valid for infiltration rates into the reclamation cap of about 1 to 4 inches per year (25 to 100 mm/yr.) and for a tailings depth of about 50 feet (15 m). The time to reach steady-state conditions would be shorter for smaller infiltration rates and tailings depths, and longer for larger infiltration rates and tailings depths. The time to reach steady-state conditions is expected to be roughly proportional to the tailings depth. It is expected to be less sensitive to variations in the infiltration rate.

As the seepage rate from the tailings into the underdrain decreases during drainage of water from the pores of the tailings, the seepage rate through the liner will essentially remain constant, or may decrease slightly, as long as the seepage is pumped from the underdrain. Therefore, during this period the seepage rate through the liner will be equal to or slightly less than the rates shown in Table 1 for various liners, none of which are larger than 6 gallons per minute per 100 acres (0.0004 m^3/s per 40 hectares).

Under long-term conditions, after drainage of the tailings are substantially complete and pumping from the underdrain has ceased, a head of water will build up over the liner to a level sufficient to produce seepage through the liner that is equal to the infiltration rate into the reclamation cap. The seepage rate for this long-term, steady-state condition may be greater or less than the seepage rate during operation, depending on the infiltration rate through the cap into the tailings. For high infiltration rates and high resistance (D_L/k_L) liners, the head of water above the liner may rise back into the tailings, causing that part of the tailings to re-saturate. The estimated depth of tailings that would be saturated under long-term, steady-state conditions for a range of infiltration rates and various bottom liners is given in Table 2. The seepage rates through the bottom liner from a 100 acre (40 hectares) pond are also given in Table 2 for each infiltration rate. In calculating the saturated depth of tailings, it has been assumed that the combined thickness of the filter and underdrain is 2 feet (0.61 m). The saturated depths of tailings for a pond with a synthetic liner are not shown in Table 2 because even at an infiltration rate of as little as 0.2 inches per year (5 mm/yr.) the saturated depth of tailings would be 50 feet (15 m).

TABLE 2

SATURATED DEPTH OF TAILINGS UNDER
LONG-TERM CONDITIONS
FOR LINED PONDS WITH UNDERDRAINS

Infiltration Rate in./yr. (mm/yr.)	Seepage Rate gpm (m^3/s)	Saturated Depth of Tailings D_L=0.5' ft. (m)	D_L=1.0' ft. (m)	D_L=2.0' ft. (m)
1 (25)	5 (0.0003)	0	0	0
2 (50)	10 (0.0006)	0	1 (0.3)	1 (0.3)
4 (100)	20 (0.001)	2 (0.6)	4 (1)	10 (3)
6 (150)	30 (0.002)	3 (1)	8 (2)	18 (5)
9 (230)	50 (0.003)	7 (2)	14 (4)	30 (9)

Notes:

1. D_L = the thickness of soil-bentonite liner with a permeability of $1.6x10^{-9}$ ft./sec. ($5.0x10^{-10}$ m/s).
2. The seepage rates given are for a 100-acre pond.
3. The combined thickness of the filter and underdrain was assumed to be 2 ft. (0.61 m).

Two important conclusions can be drawn from Table 2:

1. For the long-term seepage rate to be no larger than the expected magnitude of the seepage rate during operation (10 gallons per minute per 100 acres), the infiltration rate through the reclamation cap must be less than about 2 inches per year (50 mm/yr.).

2. At relatively high infiltration rates (greater than about 6 inches per year = 150 mm/yr.), a substantial depth of tailings will re-saturate under long-term conditions for any of the liners considered in this report except the 6 inch (152 mm) thick soil-bentonite liner.

10.0 COMPARISONS OF SEEPAGE CONTROL FEATURES

Seepage rate estimates have been presented for unlined ponds, lined ponds without underdrains, and lined ponds with underdrains. Estimates have been made for ponds both during their operating life and after they are reclaimed. These included estimates of seepage rates long after the ponds are reclaimed, when steady-state conditions exist.

The estimated maximum seepage rates during operation for a 100 acre (40 ha), 50 foot (15 m) deep pond are summarized in Table 3. Seepage rates are given for ponds with the liner types discussed above, both with and without an underdrain. The seepage rates for each liner type, with and without an underdrain, are compared in Table 3 to the seepage rate from an unlined pond. This comparison shows clearly the effectiveness of the underdrain in reducing the maximum seepage rate from a pond during operation. It also shows that increasing the thickness of the soil-bentonite liner in ponds with underdrains does not have a substantial effect on the maximum seepage rate during operation. However, the seepage rate from a pond with an underdrain can be reduced substantially by using a synthetic liner instead of a soil-bentonite liner.

Seepage histories for a single 100 acre (40 hectare) pond with a 50 foot (15 m) storage depth are shown in Figure 13 for an unlined pond, a pond with a 6 inch (152 mm) soil-bentonite liner, and a pond with an underdrain and a 6 inch (152 mm) soil-bentonite liner. The pond was assumed to be filled at a uniform rate over a 7.5 yr. period and the reclamation cap was assumed to be in place one year after the pond is filled to capacity. The infiltration rate after the reclamation cap is in place was assumed to be 2 inches per year (50 mm/yr.). The seepage history for

TABLE 3

ESTIMATED MAXIMUM SEEPAGE RATES
FOR A 100 ACRES (40 HECTARE), 50 FOOT (15 METER) DEEP POND

LINER MATERIAL	D_L ft. (m)	LINER ONLY			LINER AND UNDERDRAIN		
		Q gpm	Q ($m^3/s \times 10^{-4}$)	R %	Q gpm	Q ($m^3/s \times 10^{-4}$)	R %
Unlined	0	310	(200)	100	310	(200)	100
Soil-Bentonite	0.5 (0.15)	160	(100)	52	5	(3)	2
Soil-Bentonite	1.0 (0.30)	100	(60)	32	4	(3)	1
Soil-Bentonite	2.0 (0.61)	63	(40)	20	3	(2)	1
Synthetic	0.003 (0.001)	1	(0.6)	0.3	0.005	(0.003)	0.002

Notes: R = Ratio of Q for any liner and underdrain condition to Q for an unlined pond

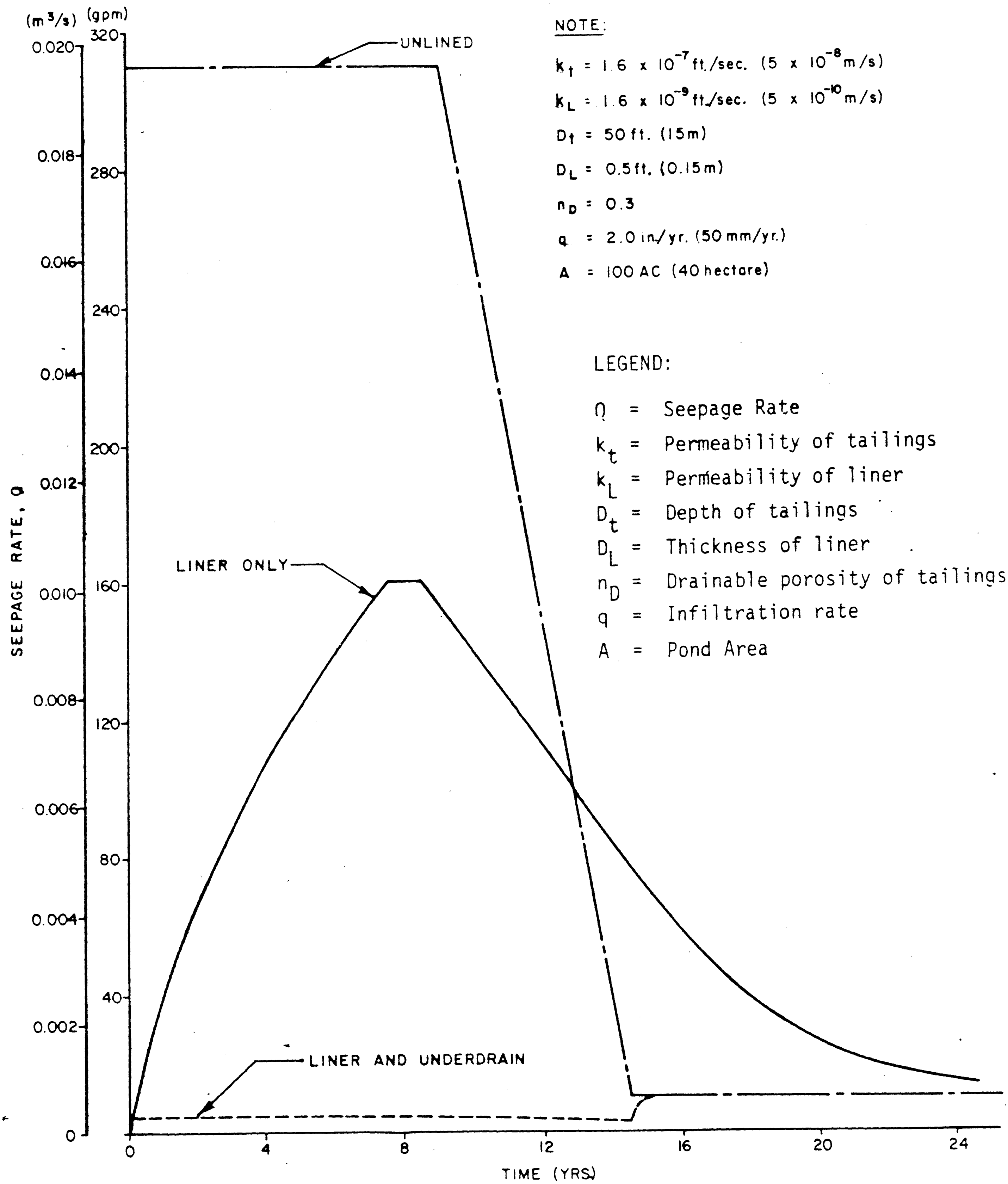
D_L = liner thickness

Q = seepage rate

Tailings permeability = 1.6×10^{-7} ft./sec. (5×10^{-8} m/s)

Soil-Bentonite liner permeability = 1.6×10^{-9} ft./sec. (5×10^{-10} m/s)

Synthetic liner permeability = 3.3×10^{-14} ft./sec. (1×10^{-14} m/s)



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the pond with an underdrain was developed on the assumption that pumping from the underdrain continues until seepage from the tailings reaches steady-state conditions.

Over any period of time the area under the curve for each of the seepage histories shown in Figure 13 represents the total volume of seepage from the pond. It is clear from Figure 13 that the 6 inch (152 mm) soil-bentonite liner substantially reduces the total volume of seepage below that from the unlined pond. Similarly the liner and underdrain reduce the total volume of seepage still further. The total volume of seepage from the pond with 6 inch (152 mm) soil-bentonite liner is estimated to be about 50 percent of the volume from the unlined pond during the 20 year period beginning at the start of its operation. Over the same period the total volume of seepage from the pond with a liner and underdrain is estimated to be about 3 percent of the volume from the unlined pond, and about 6 percent of the volume from the pond with a liner and no underdrain.

11.0 SEEPAGE HISTORY FOR AN EXAMPLE WASTE DISPOSAL SYSTEM

A framework has been presented which will allow a reasonable estimate of the seepage history of a single waste disposal pond. For this study to be more meaningful, it must be integrated into an overall waste disposal plan which will allow the seepage history of the entire disposal system to be estimated.

In keeping with the generic nature of this report, the seepage history of an actual proposed waste disposal system will not be evaluated. Instead seepage histories will be presented for an idealized system consisting of four 100-acre (40 hectare) ponds, 50 feet (15 m) deep. Each pond was assumed to be filled at a uniform rate over a 7.5 year period (for a total project life of 30 years), and the reclamation cap was assumed to be in place one year after the pond is filled to capacity. The infiltration rate after the reclamation cap is in place was assumed to be 2 inches per year (50 mm/yr.).

Two seepage histories for the system described above are shown in Figure 14. One of the seepage histories is for a pond system with a 6 inch (152 mm) thick soil-bentonite liner and no underdrains. The other is for a pond system with an underdrain and a 6 inch (152 mm) thick soil-bentonite liner. The seepage history for the system with underdrains was developed on the assumption that pumping from the underdrain continues until seepage from the tailings reaches steady-state conditions. These seepage histories show dramatically the effectiveness of the underdrain in reducing the overall seepage from the waste disposal system.

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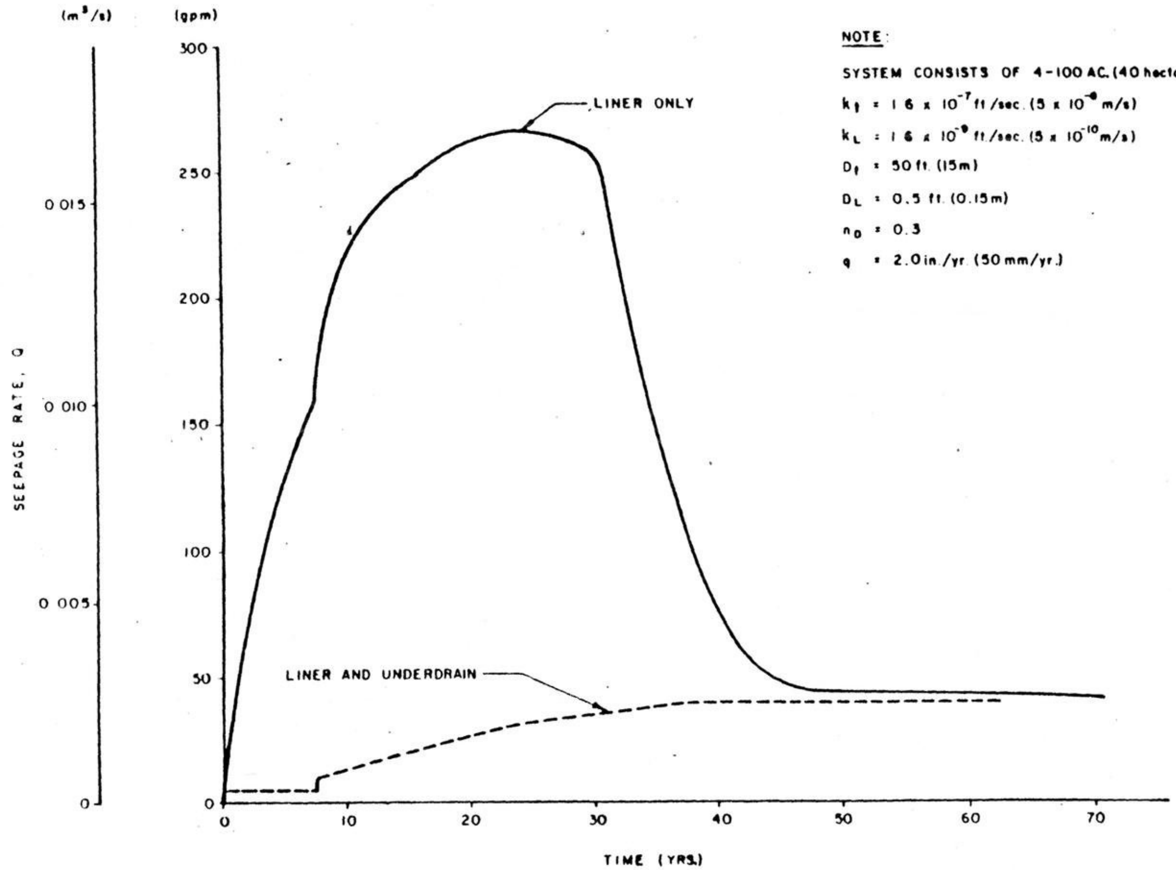

NOTE:

SYSTEM CONSISTS OF 4-100 AC. (40 hectare) PONDS

k_t = 1.6×10^{-7} ft/sec. (5×10^{-8} m/s)

k_L = 1.6×10^{-9} ft/sec. (5×10^{-10} m/s)

D_t = 50 ft. (15m)

D_L = 0.5 ft. (0.15m)

n_D = 0.3

q = 2.0 in./yr. (50 mm/yr.)

LEGEND:

Q = Seepage Rate
k_t = Permeability of tailings
k_L = Permeability of liner
D_t = Depth of tailings
D_L = Depth of liner
n_D = Drainable porosity of tailings
q = Infiltration rate
A = Pond Area

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12.0 SUMMARY

This report presents analytical methods for estimating seepage rates and the results of those estimates for slurried tailings disposal facilities of the approximate size required for the Crandon Project. The report presents estimated seepage rates during the time a facility is in operation and after the facility has been reclaimed. The types of disposal facilities considered were unlined ponds, lined ponds with no underdrains, and lined ponds with underdrains above the liner.

The theoretical principles used in this report to estimate seepage rates are applicable to any waste disposal facility. In applying these principles to disposal facilities at the Crandon site, certain assumptions have been made. These assumptions always considered the inherent variations in geologic conditions and material properties, and the parameters expected to have a substantial effect on the seepage rate. However it should be recognized that virtually no empirical evidence is available to guide judgments of this kind. Golder Associates considers the seepage rate estimates presented in this report to be consistent with the state-of-the-art in making such estimates.

The methods presented in this report for estimating seepage rates, as well as the estimates themselves, are considered applicable to proposed waste disposal Sites 40 and 41 for the Crandon Project. Conclusions for other sites, based on this report, may not be valid.

Seepage rates from tailings ponds may be affected by the subsurface conditions below the pond. It was shown that the seepage rate will not be affected by the subsurface conditions for seepage rates less than 700 gallons per minute per 100 acres (0.04 m^3/s per 40 hectares) and is not likely to be affected for seepage rates up to 1800 gallons per minute per 100 acres (0.11 m^3/s per 40 hectares). It was also shown that no lined ponds, and only unlined ponds with a substantial amount of ponded water, will have seepage rates greater than 700 gallons per minute per 100 acres (0.04 m^3/s per 40 hectares). Thus, the subsurface conditions are not expected to affect seepage rates, except in the case of an unlined pond with substantial ponded water.

The seepage rate from an unlined pond with minimal ponded water is independent of the depth of tailing and was estimated to be 310 gallons per minute per 100 acres (0.02 m^3/s per 40 hectares). The seepage rate from an unlined pond with substantial ponded water may be 1000 gallons per minute or more per 100 acres (0.06 m^3/s per 40 hectares). If an unlined pond has substantial ponded water, seepage from the pond greater than 700 gallons per minute per 100 acres (0.04 m^3/s per 40 hectares) may cause the groundwater to mound to the pond bottom.

The seepage rate during operation from a lined pond without an underdrain was estimated to range from less than 2 gallons per minute per 100 acres (0.0001 m^3/s per 40 hectares) for a pond with a synthetic liner to a maximum of 500 gallons per minute per 100 acres (0.03 m^3/s per 40 hectares) for a pond that is filled with water to a depth of 80 feet (24 m) and has a 6 inch (152 mm) thick soil-bentonite liner. The seepage rate from a pond with a tailings depth of 50 feet (15 m) and a minimal depth of water on the tailings was estimated to range from 60 gallons per minute per 100 acres (0.004 m^3/s per 40 hectares) for a 2 foot (0.61 m) thick soil-bentonite liner to 160 gallons per minute per 100 acres (0.011 m^3/s per 40 hectares) for a 6 inch (152 mm) thick soil-bentonite liner.

Seepage rates from lined ponds without underdrains will gradually decrease after the reclamation cap is in-place. Prior to completion of the reclamation cap the seepage rate is expected to be approximately the same as the maximum rate during operation. The seepage rate will gradually decrease after the reclamation cap is in place, eventually reaching a unit rate equal to the rate of infiltration of water through the reclamation cap (i.e., steady-state conditions). The estimated time required to effectively reach this long-term, steady-state seepage rate, assuming infiltration rates in the range of 1 to 4 inches per year (25 to 100 mm/yr.) and a tailings depth of 50 feet (15 m), ranges from about 12 years for a pond with a 6 inch (152 mm) thick soil-bentonite liner to about 41 years for a pond with a 2.0 foot (0.61 m) thick soil-bentonite liner. The time required to effectively reach steady-state conditions in a pond with a synthetic liner was estimated to exceed 100 years even at an infiltration rate near zero. While the time to effectively reach steady-state conditions is expected to be great for thick soil-bentonite liners or synthetic liners, it should be recognized that the seepage rates with these liners are also much lower.

The depth of tailings that remains saturated under long-term conditions is dependent on both the liner resistance (D_L/k_L) and the infiltration rate. In general the depth of tailings remaining saturated under long-term conditions will be greater for higher infiltration rates and liners with greater resistances to flow. An infiltration rate can be calculated for any liner that will result in a 5 foot (1.5 m) depth of tailings remaining saturated under long-term conditions. That infiltration rate ranges from 6 inches per year (152 mm/yr.) for a 6 inch (152 mm) thick soil-bentonite liner to 2 inches per year (50 mm/yr.) for a 2.0 foot (0.61 m) soil-bentonite liner to 0.02 inches per year (0.5 mm/yr.) for a synthetic liner. These analyses indicate that if substantial desaturation of the tailings is considered desirable, the reclamation cap chosen for a pond must be consistent with the bottom liner in the pond.

Seepage rates from ponds with an underdrain and liner were estimated to be very small during operation. The seepage rates during operation were estimated to range from 0.005 gallons per minute per 100 acres ($3x10^{-7}$ m^3/s per 40 hectares) for a pond with a synthetic liner to 5 gallons per minute per 100 acres (0.0003 m^3/s per 40 hectares) for a pond with a 6 inch (152 mm) thick soil-bentonite liner. These seepage rates were calculated assuming minimal ponded water on the tailings. However, the estimated seepage rates are not much greater if the pond has substantial ponded water.

It has been assumed in the seepage estimates in this report that pumps in the underdrain are operated until drainage of the tailings is substantially complete, i.e., until steady-state conditions are effectively reached. The estimate of the time to effectively reach steady-state conditions, after the reclamation cap is in place, is 6 years. Considering a reasonable degree of uncertainty in the variation in tailings permeability as the tailings drain, it is judged that the time to reach steady-state conditions, after the reclamation cap is in place, is not likely to exceed 15 years. These conclusions are valid for infiltration rates of 1 to 4 inches per year (25 to

100 mm/yr.) and for a tailings depth of 50 feet (15 m). The time to reach steady-state conditions is expected to be roughly proportional to the tailings depth. It is expected to be less sensitive to variations in the infiltration rate.

Seepage rates from ponds with an underdrain and liner, after the reclamation cap is in place but before steady-state conditions are reached are expected to be less than the rates during operation, provided pumping from the underdrain is continued. The seepage rate for long-term, steady-state conditions (after pumping from the underdrain has ceased) will be equal to the rate of infiltration over the pond area. This seepage rate may be greater or less than the seepage rate during operation. Infiltration rates of 1 to 4 inches per year (25 to 100 mm/yr.) correspond to seepage rates of 5 to 20 gallons per minute per 100 acres (0.0003 to 0.0013 m^3/s per 40 hectares). This indicates that for the long-term seepage rate to be no larger than the expected magnitude of the seepage rate during operation (10 gallons per minute per 100 acres), the infiltration rate through the reclamation cap must be less than about 2 inches per year (50 mm/yr.).

Comparisons of the total volume of seepage from a 100 acre, 50 foot (15 m) deep pond were made for three liner conditions: a pond with no liner, a pond with a 6 inch (152 mm) thick soil-bentonite liner and no underdrain, and a pond with an underdrain and a 6 inch (152 mm) thick soil-bentonite liner. The comparisons show that over the 20 year period beginning with the operation of the pond, the total volume of seepage from the pond with a 6 inch (152 mm) soil-bentonite liner was estimated to be about 50 percent of the volume from the unlined pond. Over the same period the total volume of seepage from the pond with a liner and underdrain was estimated to be about 3 percent of the volume from the unlined pond, and about 6 percent of the volume from the pond with a liner and no underdrain.

Seepage histories were presented for an idealized waste disposal system consisting of four 100 acre (40 hectare) ponds, 50 feet (15 m) deep. The two seepage histories presented are for ponds with 6 inch (152 mm) soil-bentonite liners, with and without underdrains. These seepage histories show dramatically the effectiveness of the underdrain in reducing the overall seepage from the waste disposal system.

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EQUATIONS FOR PREDICTING GROUNDWATER MOUNDING

The derivation of the equations for predicting groundwater mounding is given below. Refer to Fig. 6 for the definitions of the terms.

The equation for steady-state flow to a well in a confined aquifer is assumed to be applicable to the flow in the stratified drift from the pond. The equation is as follows:

$$Q_1 = \frac{2\pi L k_h H}{\ln\left(\frac{R}{r}\right)} \tag{1}$$

The flow through the till into the stratified drift can be computed by Darcy's Law as follows:

$$Q_2 = \frac{k_v (h-H)\pi r^2}{D+h} \tag{2}$$

At steady-state Q_1 must equal Q_2. Equating Q_1 and Q_2 and simplifying yields the following equation for H:

$$H = \frac{k_v r^2 h \ln\left(\frac{R}{r}\right)}{2Lk_h(D+h) + k_v r^2 \ln\left(\frac{R}{r}\right)} \tag{3}$$

Substituting for H in Equation 1 yields the following equation for the steady-state seepage rate:

$$Q = \frac{2\pi L k_h\ k_v\ r^2 h}{2Lk_h(D+h) + k_v r^2 \ln\left(\frac{R}{r}\right)} \tag{4}$$

EQUATIONS FOR COMPUTING SEEPAGE RATES AFTER RECLAMATION

The derivation of the equation for computing seepage rates as a function of time after reclamation is given below. Refer to Figure 5 for definitions of terms.

The sources of seepage are the water draining from the tailings and a constant unit infiltration rate, q. The equation relating the sources of flow and the seepage rate out of the pond is as follows:

$$Q = -n_d \frac{dx}{dt} A + qA \tag{1}$$

The seepage rate out of the pond must also satisfy Darcy's Law. Darcy's Law applied to a layered system is as follows:

$$Q = \frac{xA}{\frac{D_L}{k_L} + \frac{x - D_L}{k_t}} \tag{2}$$

Combining Equations 1 and 2 yields the following differential equation:

$$-\frac{dx}{dt} = \frac{k_L\, k_t}{n_D} \left[\frac{x}{k_L\,(x-D_L) + k_t\, D_L} - \frac{q}{k_L\, k_t} \right] \tag{3}$$

Separating variables in Equation 3 yields the following:

$$dt = n_D \left[\frac{k_L x + D_L\,(k_t - k_L)}{q\, D_L\,(k_t - k_L) - k_L x\,(k_t - q)} \right] \tag{4}$$

Integrating Equation 4, applying the boundary condition that $x = D_t + D_L$ at $t = 0$, and simplifying yields the following:

$$t = n_D \left[\frac{D_L\, k_t\,(k_t - k_L)}{k_L\, b^2} \ln \frac{k_L b (D_t + D_L) - c}{k_L b\, x - c} + \frac{D_t + D_L - x}{b} \right] \tag{5}$$

where

$$b = k_t - q$$

$$c = D_L\, q\,(k_t - k_L)$$

At steady-state seepage conditions the seepage rate into the pond must equal the seepage rate out of the pond and the change in head in the pond (dx/dt) must be zero. Substituting zero into Equation 3 for dx/dt yields the following equation for the head in the pond (x) at steady state:

$$x_{ss} = \frac{q\ D_L\ (k_t - k_L)}{k_L\ (k_t - q)} \tag{6}$$

or,

$$x_{ss} = \frac{c}{k_L\ b}$$

APPENDIX C

GRAVITY DRAINAGE OF TAILINGS IN A POND WITH AN UNDERDRAIN

Introduction

Gravity drainage is the drainage of water from the pore space of the tailings. Substantial gravity drainage is not expected to occur until after the reclamation cap on the pond is in place. Provided pumping from the underdrain continues during gravity drainage of the tailings, the seepage rate through the liner is expected to be less than the seepage rate through the liner during operation. On the other hand, if pumping from the underdrain ceases during the early stages of gravity drainage, a substantial increase in the seepage rate through the liner is expected to occur. The purpose of this appendix is to estimate the rate of gravity drainage, and thus, the time required for complete drainage to occur.

Conceptually, the analysis presented below divides gravity drainage into two stages. During the first stage the piezometric level in the tailings drops from the surface of the tailings to below the pond bottom. This is accompanied by a decrease in the volumetric water content of the tailings. The second stage consists of the gravity drainage of tailings that are now partially saturated. One of the factors influencing the rate of gravity drainage is the rate of infiltration through the reclamation cap. During gravity drainage the seepage rate from the tailings gradually declines, eventually reaching a unit rate equal to the infiltration rate, i.e. steady-state conditions are reached.

Stage 1

During the first stage the seepage rate can be estimated using Darcy's Law. Seepage is controlled by the saturated permeability of the tailings, and the gradient through the tailings is one. Throughout the first stage the unit seepage rate would be equal to the saturated permeability of the tailings. This corresponds to a seepage rate of 310 gpm per 100 acres (0.02 m^3/s per 40 hectares). The time required for completion of the first stage can be calculated using the following equation which was derived using a simple mass balance:

$$t = \frac{(n-\theta_o)D_t}{k_t-q} \tag{1}$$

where

n = porosity or volumetric water content at saturation
θ_o = volumetric water content at the end of the first stage
D_t = tailings depth
k_t = saturated permeability of the tailings
q = rate of infiltration through the reclamation cap.

For a 50 foot (15 m) tailings depth and infiltration rates ranging from 0.5 to 9 inches per year (13 to 200 mm/yr.), the estimated time for completion of the first stage ranges from 6 to 7 months. The volumetric water content was assumed to decrease from 0.5 at saturation to 0.45, as the piezometric level drops past any point.

A check on the reasonableness of the estimated time for completion of Stage 1 can be made using the first of the methods of analysis (Method 1) described below for Stage 2 gravity drainage. The Method 1 analysis can be used to calculate an upper bound on the time required for the volumetric water content to decrease a given amount. The analysis shows that an upper bound on the time for the volumetric water content to decrease from 0.5 (saturation) to 0.45 is about 9 months. This indicates that the estimated time of 6 to 7 months given above for completion of Stage 1 is a reasonable estimate.

Stage 2

The second stage of gravity drainage begins with a partially saturated mass of tailings which is assumed to be at a uniform volumetric water content of 0.45. Seepage through the tailings can still be estimated using Darcy's Law. However the permeability (the permeability of a partially saturated material will hereafter be referenced to as the effective permeability) is a function of the volumetric water content which decreases continuously during the second stage of gravity drainage. Furthermore, the volumetric water content during the second stage is dependent on the seepage rate. It is clear that the seepage rate, the effective permeability, and the volumetric water content are interdependent during the second stage of gravity drainage.

An empirical equation relating effective permeability (k_e) and volumetric water content (θ) was presented in Reference 10. The equation is as follows:

$$k_e = k_t \left(\frac{\theta - \theta_r}{n_D}\right)^{\frac{2+3\lambda}{\lambda}} \qquad (2)$$

where

θ = volumetric water content

θ_r = residual volumetric water content, i.e. the lowest water content that can be achieved by purely mechanical means

n_D = drainage porosity ($n - \theta_r$)

λ = pore-size distribution index; ranges from 1.8 to 3.7 for soils tested

k_t = saturated permeability of the tailings

This equation is based on laboratory data and correlation in Reference 6. The laboratory testing was done on a variety of materials, including two soils described as silt loam and silty clay loam. The data in Reference 6 suggest that for a silt-size material, such as the Crandon tailings, a reasonable value of λ is 2.0 and a reasonable estimate of θ_r is 0.2. A value of 0.3 is considered to be a reasonable estimate of the drainable porosity. These values will be used in subsequent analyses.

Under long-term, steady-state conditions, the unit seepage rate is equal to the infiltration rate. The unit seepage rate must also be equal to the effective permeability (assuming a uniform volumetric water content at steady-state). Thus, under steady-state conditions the effective permeability is equal to the infiltration rate. This fact, along with Equation 2, can be used to determine the volumetric water content at steady-state (θ_q) for any given infiltration rate. The results for selected infiltration rates (q) are as follows:

q, (in./yr.)	θ_q
0.5	0.29
1.0	0.31
2.0	0.33
4.0	0.35

These values represent the minimum volumetric water content that will occur for the corresponding infiltration rate.

Two methods have been used to estimate the decrease in seepage rate with time during the second stage. The two methods are believed to bracket the actual performance of the system.

In the first method, it has been assumed that the volumetric water content decreases with time uniformly through the tailings, i.e. θ is a function of time, but not of depth. It can be shown that for a uniform volumetric water content less than saturation, the hydraulic gradient through the tailings is unity. Therefore, at any time, the unit seepage rate will be equal to the effective permeability at that time.

The rate at which the volumetric water content decreases using the first method of analysis can be calculated using the following equation:

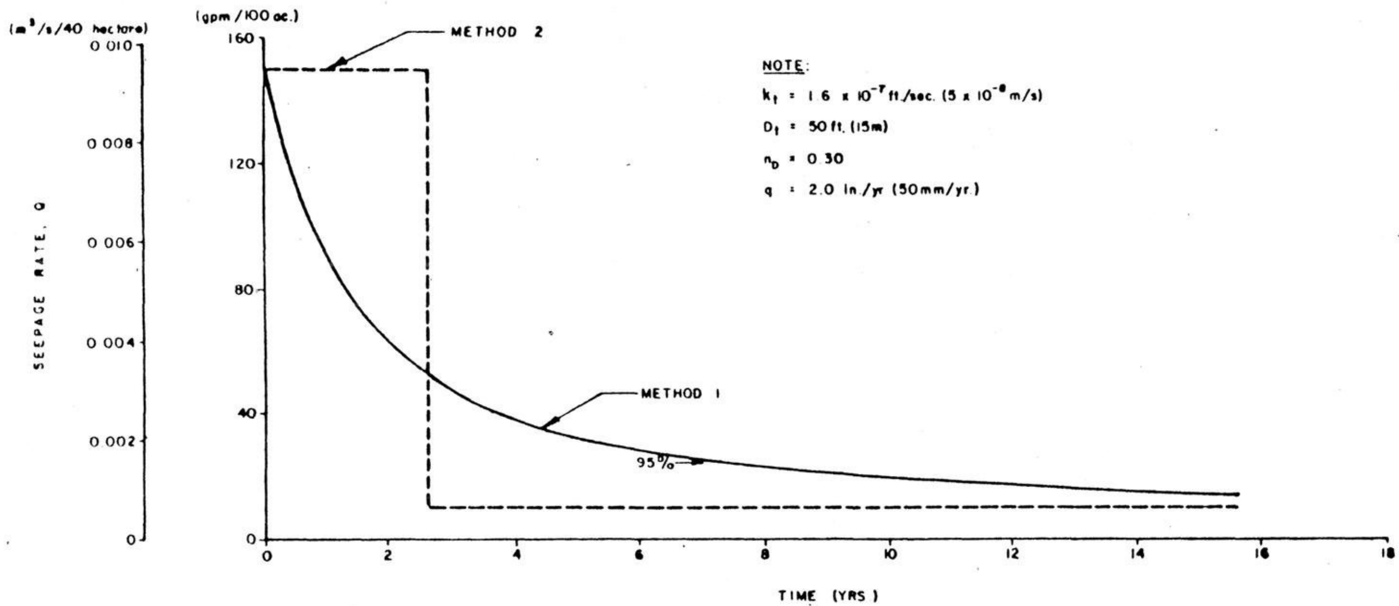
$$k_e \Delta t = q \Delta t + \Delta \theta D_t \quad (3)$$

where

Δt = a time increment
$\Delta \theta$ = change in θ over time increment Δt

The other variables are as previously defined.

This equation can be solved iteratively (because k_e is dependent on θ) by taking finite time increments to produce a relationship between θ and t. This can be easily translated into a relationship between the seepage rate and time. This relationship is plotted in Figure C1 for a tailings depth of 50 feet (15 m), and an infiltration rate of 2 inches per year (50 mm/yr.).



LEGEND:

- Q = Seepage Rate
- k_t = Permeability of tailings
- k_L = Permeability of liner
- D_t = Depth of tailings
- D_L = Depth of liner
- n_D = Drainable porosity of tailings
- q = Infiltration rate
- A = Pond Area

JOB NO. 786085	SCALE AS SHOWN	SEEPAGE RATES FROM THE TAILINGS DURING STAGE 2 OF GRAVITY DRAINAGE
DRAWN SKB	DATE 1-21-82	
CHECKED WRS	DWG. NO. —	
Golder Associates		EXXON MINERALS COMPANY — FIGURE C 1

Method 1 shows the seepage rate decreasing to 25 gallons per minute (0.0016 m^3/s) in about 7 years after the start of the second stage. This corresponds to 95 percent of the decrease from the maximum of 310 gallons per minute (0.020 m^3/s) during the first stage to 10 gallons per minute (0.0006 m^3/s) at steady-state.

The second method of analysis made the assumption that the drainage occurs as a front moving downward through the tailings. Above the front it is assumed that the volumetric water content has decreased to the steady-state value (θ_q) and below the front the volumetric water content is assumed to be equal to the final value at the end of the first stage (θ=0.45). These assumptions mean that (1) the zone above the front is not contributing any water from drainage of its pores, and (2) the seepage rate from the bottom of the tailings is equal to the effective permeability at a volumetric water content of 0.45. The analysis yields a time of 2.6 years for the full 50 foot (15 m) depth of tailings to drain to a volumetric water content corresonding to an infiltration rate of 2 inches per year (50 mm/yr.). The variation in seepage rate with time is plotted in Figure C1.

The actual variation in seepage rate with time is expected to be between those calculated by the two methods described above. The actual rate of gravity drainage of the tailings is expected to be faster than calculated in the first method of analysis and slower than calculated in the second method of analysis. Method 1 produces a slower rate of drainage because of the assumption that the volumetric water content decreases with time, but is uniform with depth. With this calculation method the volumetric water content of the lower part of the tailings - the part which controls the seepage rate - is lower at any time than actually expected. Therefore, the calculated seepage rate at any time is lower than expected, and consequently the calculated rate of drainage is slower than expected. Method 2 produces a faster rate of drainage than is actually expected, because the volumetric water content of the lower part of the tailings is assumed to remain at a constant, relatively high value throughout drainage, and consequently the seepage rate remains at a constant rate throughout drainage. The actual seepage rate is expected to decrease with time and the average seepage rate during drainage is expected to be lower than the constant rate assumed in Method 2. Therefore, the rate of drainage predicted with Method 2 is faster than is actually expected to occur.

It can therefore be concluded that for a given set of tailings properties, tailings depth, and infiltration rate the actual rate of drainage during the second stage is expected to be between those predicted by Methods 1 and 2. For the tailings properties, depth, and infiltration rate used, the time to essentially reach steady-state as predicted by Method 1 is about 7 years and the time to reach steady-state as predicted by Method 2 is about 3 years. For the case analyzed, Golder Associates considers 5 years to be a reasonable best estimate of the time required for the completion of the second stage of gravity drainage. Sensitivity analyses, varying the infiltration rate, suggest that this estimate is valid for infiltration rates in the range of 1 to 4 inches per year (25 to 100 mm/yr.).

Summary and Conclusions

The following conclusions are considered valid for infiltration rates of 1 to 4 inches per year (25 to

100 mm/yr.) and for a tailings depth of about 50 feet (15 m).

1. For a period of about 6 months after the reclamation cap is completed, the seepage rate from the tailings into the underdrain is expected to be about 310 gallons per minute per 100 acres (0.02 m^3/s per 40 hectares).

2. After this 6 month period the seepage rate from the tailings into the underdrain is expected to gradually decrease over a period of about 5 years to a rate approximately equal to the infiltration rate into the reclamation cap, i.e. the long-term,steady-state seepage rate.

3. The estimated time to reach steady-state conditions, after the reclamation cap is complete, is 6 years. Considering a reasonable degree of uncertainty in the variation in tailings permeability as the tailings drain, it is judged that the time to reach steady-state conditions, after the reclamation cap is in place, is not likely to exceed 15 years.

The time to reach steady-state conditions is expected to be roughly proportional to the tailings depth. It is expected to be less sensitive to variations in the infiltration rate.

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