Report on underdrain review: Crandon Project waste disposal system: project report 3.2. v. 3.2 March 1982

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REFERENCE

Golder Associates

CONSULTING GEOTECHNICAL AND MINING ENGINEERS

Report on

UNDERDRAIN REVIEW
CRANDON PROJECT
WASTE DISPOSAL SYSTEM
PROJECT REPORT 3.2

Submitted to:

Exxon Minerals Company
Post Office Box 813
Rhinelander, Wisconsin 54501

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March, 1982

786085

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CONSULTING GEOTECHNICAL AND MINING ENGINEERS

March 8, 1982

786085/MA/391
F/N 174.7

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

Attention: Mr. C. E. Fowler

Re: Exxon Crandon Project
Waste Disposal System
Crandon Wisconsin

Gentlemen:

Enclosed for your review and comment is the final draft of Project Report 3.2, Underdrain System Review. This report describes the alternative underdrain systems reviewed and presents our recommendations for an underdrain system, should Exxon elect to use one.

Please call us if you have any questions.

Very truly yours,

GOLDER ASSOCIATES

Gary H. Collison

Gary H. Collison, P.E.
Associates

JFC:GHC:dap

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1.0 INTRODUCTION

This report presents Golder Associates' review of the feasibility of using an underdrain system above a tailings disposal pond liner for the Crandon Project to reduce the amount of seepage through the liner during operation. This study focuses on the design of the underdrain system to act as a filter system to inhibit migration of tailings into the drain, the hydraulic capacity of the underdrain to accomodate estimated seepage volumes, and methods to collect and remove the seepage from the underdrain system. The concepts presented are directed toward designs for the Crandon Project but some details are omitted since they will have to be specific to a given slurry tailings pond.

The primary purpose of an underdrain system is to collect seepage for removal from the disposal system. To do so, the underdrain must be designed to inhibit migration of solid material into the underdrain but allow sufficient hydraulic capacity for the volume of seepage flow. Drainage systems to meet these requirements are commonplace in many water retention dams to prevent piping of the foundation or embankment materials. These drainage systems are designed as soil filters and the design criteria are well known.

An underdrain system may range from a series of collection pipes surrounded by filter material to a complete blanket of filter and/or drain material across a disposal facility. The design of an underdrain system is dependent on the grain size of the disposed waste, in this case the tailings. An underdrain system may be comprised of one, two, or even three layers of material, each filtering the previous layer to allow drainage but not migration of fines.

An underdrain system will reduce the pressure head of pond water acting against a liner beneath the drain. The amount of head reduction depends on the permeability of the tailings and the hydraulic characteristics of the underdrain system. Reducing the head will reduce the driving force of the seepage on the liner and hence reduce the amount of seepage through the liner.

2.0 FILTER DESIGN

2.1 Filter Design Criteria

Several somewhat different sets of criteria exist for the design of filters based on theoretical work and practical applications(Ref. 1,2,3,4). The following are well known criteria proposed by the USBR(Ref. 1) and the U.S. Army Corps of Engineers(Ref. 4):

1) $\dfrac{D_{15}\ \text{filter}}{D_{85}\ \text{base}} \leq$ 5 or less

2) $\dfrac{D_{15}\ \text{filter}}{D_{15}\ \text{base}} \leq 5$ to 40

3) $\dfrac{D_{50}\ \text{filter}}{D_{50}\ \text{base}} \leq 25$

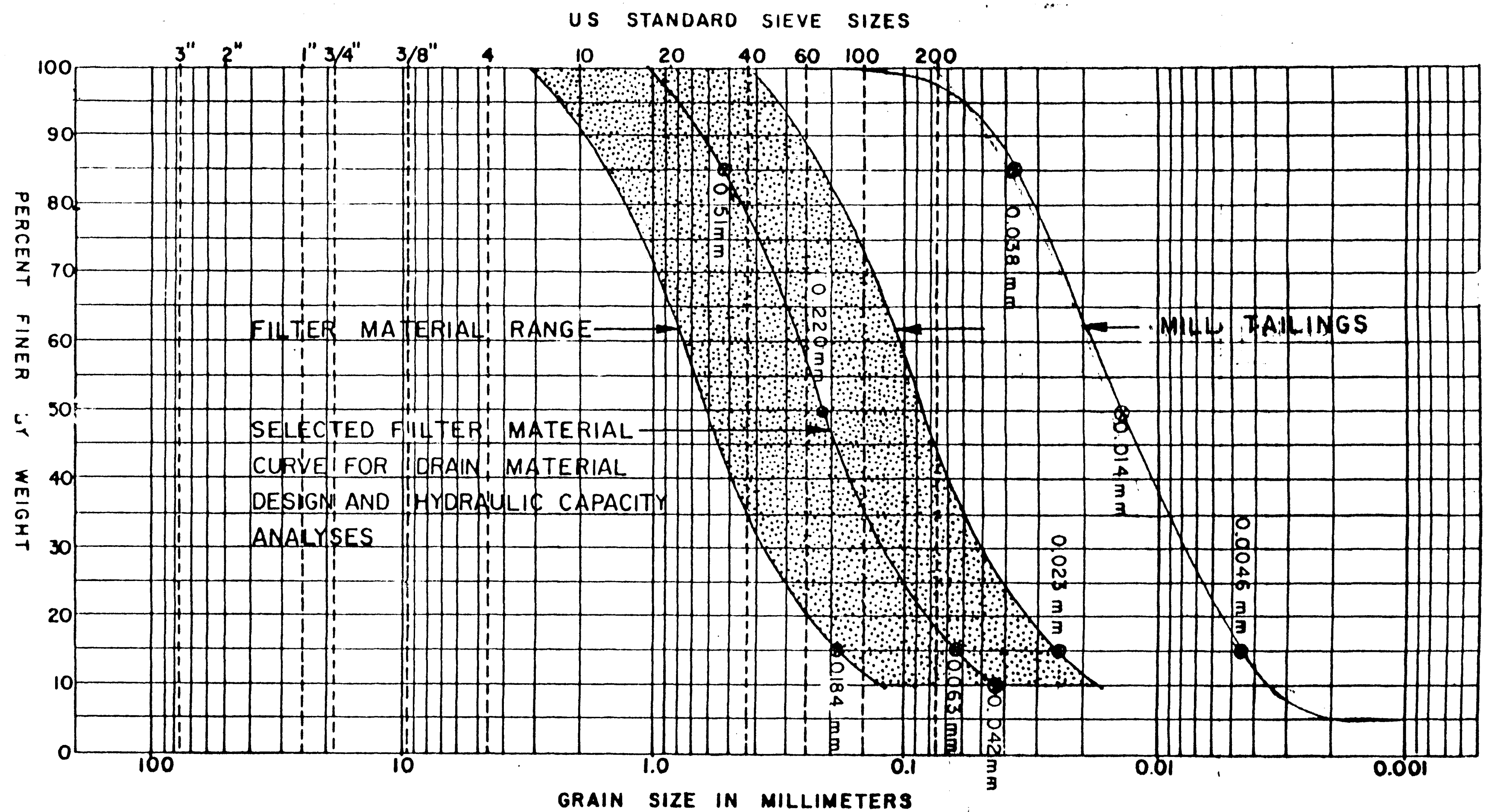
In these expressions, D_{15} is the size at which 15% of the total particles are finer by weight, D_{85} is the size at which 85% of the total particles are finer by weight, and D_{50} is the size at which 50% of the total particles are finer by weight. When more than one filter layer is required, the same criteria are followed with the finer filter considered the "base" for selection of the gradation of the coarser filter.

The intent of criterion 1 is to assure that migration of fines from the base material into the filter material will not occur. For a filter system this criterion is of primary importance since migration of fines will cause clogging of the filter. Criterion 2 is to insure sufficient permeability in filters and drains to prevent the build-up of large seepage forces; this is basically a check on the hydraulic capability of the drain in meeting discharge needs. Commonly, drains are designed with less than 5% of the material passing the #200 U.S. Standard Sieve (0.074 mm) but this is dependent on the grain size of the material being drained. Criterion 3 is to assure that the grain size curve of the filter is roughly parallel to that of the base material so that there is filtering action throughout the range of grain sizes.

2.2 Materials Design

For the Crandon Project application, the base material for underdrain design is the tailings. The size gradation for the tailings, determined from laboratory tests on a sample supplied by Exxon through Lakefield Research of Crandon, is shown on Figure 2.1. Laboratory permeability tests on tailings materials indicate a hydraulic conductivity of about 5×10^{-8} m/s (1.6×10^{-7} ft./sec.) to be a reasonable estimate for design of the tailings facilities[Ref. 6].

The range of filter material gradations which meets Criteria 1 and 2 discussed in Section 2.1. is also shown on Figure 2.1. The coarser end of the band is slightly greater than 25 times the D_{50} of the tailings but the band is roughly parallel to the tailings grain size curve. Because of the very fine grained nature of the tailings, much of the appropriate filter material could have more than 5% finer than the #200 sieve. Because of the fine grain sizes of this filter, a second more permeable layer will be needed to provide sufficient hydraulic capacity for the underdrain system. The details of the hydraulic capacity analyses are presented in Section 4 of this report.



COBBLES	GRAVEL		SAND			FINES	
	COARSE	FINE	COARSE	MEDIUM	FINE	SILT SIZES	CLAY SIZES

D_{15} FILTER $\leq 5(D_{85}$ TAILINGS$) = 5(0.038) = 0.19$ mm

D_{15} FILTER $\geq 5(D_{15}$ TAILINGS$) = 5(0.0046) = 0.023$ mm

D_{15} FILTER $\leq 40(D_{15}$ TAILINGS$) = 40(0.0046) = 0.184$ mm

D_{50} FILTER $\leq 25(D_{50}$ TAILINGS$) = 25(0.014) = 0.35$ mm

GRAIN SIZE DISTRIBUTION
FILTER MATERIAL DESIGN

FIGURE 2.1

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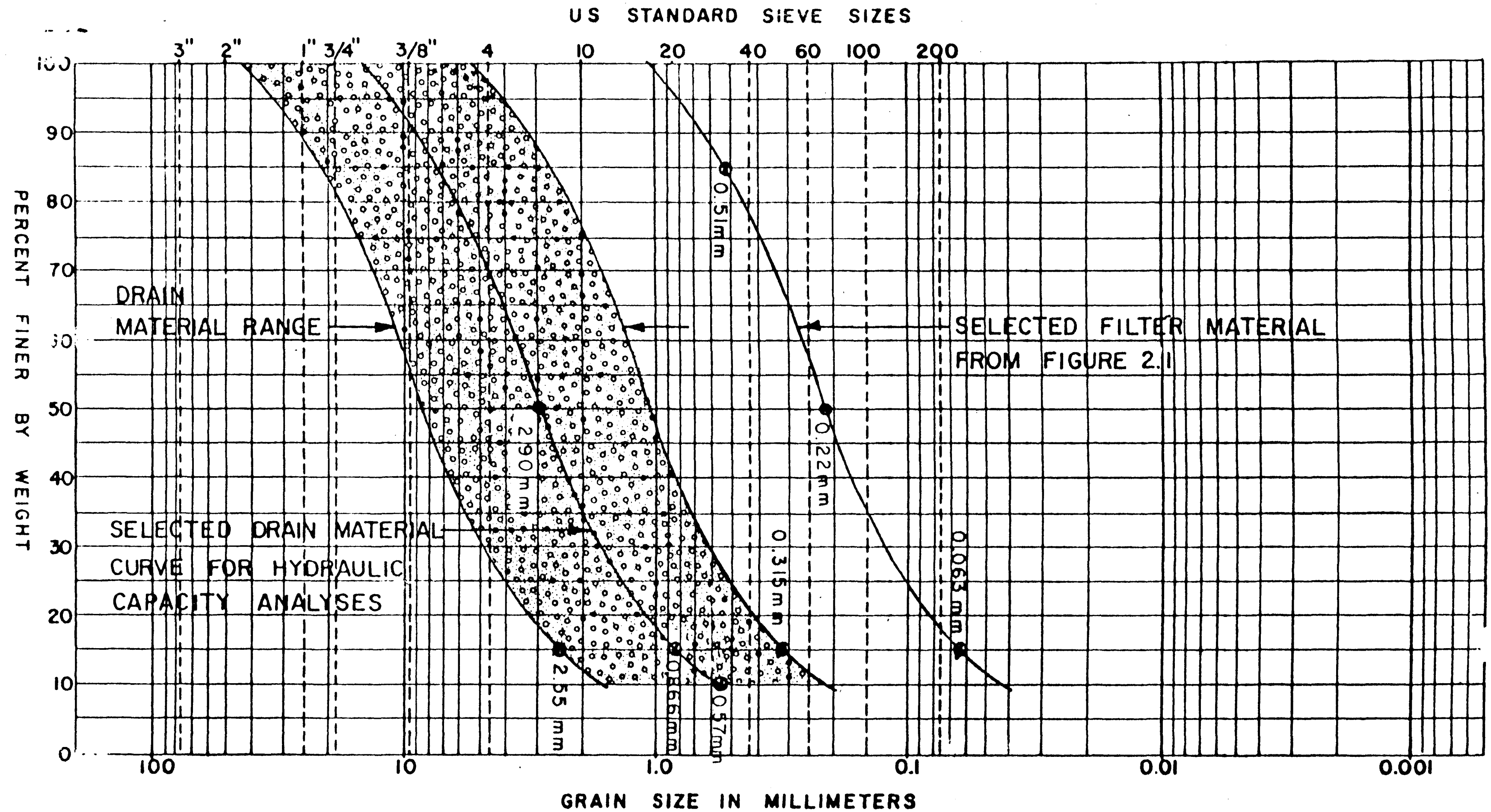
Design of the second material, the drain layer, is based on the gradation of the filter material. However, the range of the gradation of the filter material is wide, and applying the design criteria to both ends of the filter band would yield two bands of drain material. To illustrate the feasibility of the underdrain system, a filter gradation curve has been selected for the design basis of the drain material and it is shown on Figure 2.1 and Figure 2.2. The curve selected is located such that 75% of the filter band at the D_{15} size is coarser, thus having lower hydraulic conductivity than the average gradation of the filter material and hence provides a somewhat conservative estimate of filter thickness. The drain material band determined from the selected filter gradation curve is shown on Figure 2.2. Also shown on Figure 2.2 is the drain gradation curve used in hydraulic capacity estimates. It has been selected such that 75% of this drain band is coarser to provide a somewhat lower than average hydraulic conductivity and hence a more conservative drain layer thickness estimate.

In comparing the filter material gradation band to the gradation curves of till from Site 41, shown on Figure 2.3, it is apparent that the native till will nearly satisfy Criterion 1 for a filter to the tailings. Although less satisfactory for Criterion 2 and 3, these are less important in an underdrain situation than when applied to design of filters for dam embankments. Also, the drain material gradation band shown on Figure 2.2 will essentially satisfy Criterion 1 and 3 using the till as the base material. Thus, there are enough fines in the till to prevent migration of the tailings, and the drain is fine enough to prevent migration of the till. Use of till as filter material could be considered if an extra thickness allowance were



COBBLES	GRAVEL		SAND			FINES	
	COARSE	FINE	COARSE	MEDIUM	FINE	SILT SIZES	CLAY SIZES

D_{15} DRAIN $\leq 5(D_{85}$ FILTER$) = 5(0.51) = 2.55$ mm

D_{15} DRAIN $\geq 5(D_{15}$ FILTER$) = 5(0.063) = 0.315$ mm

D_{15} DRAIN $\leq 40(D_{15}$ FILTER$) = 40(0.063) = 2.52$ mm

D_{50} DRAIN $\leq 25(D_{50}$ FILTER$) = 25(0.22) = 5.5$ mm

GRAIN SIZE DISTRIBUTION
DRAIN MATERIAL DESIGN

FIGURE 2.2

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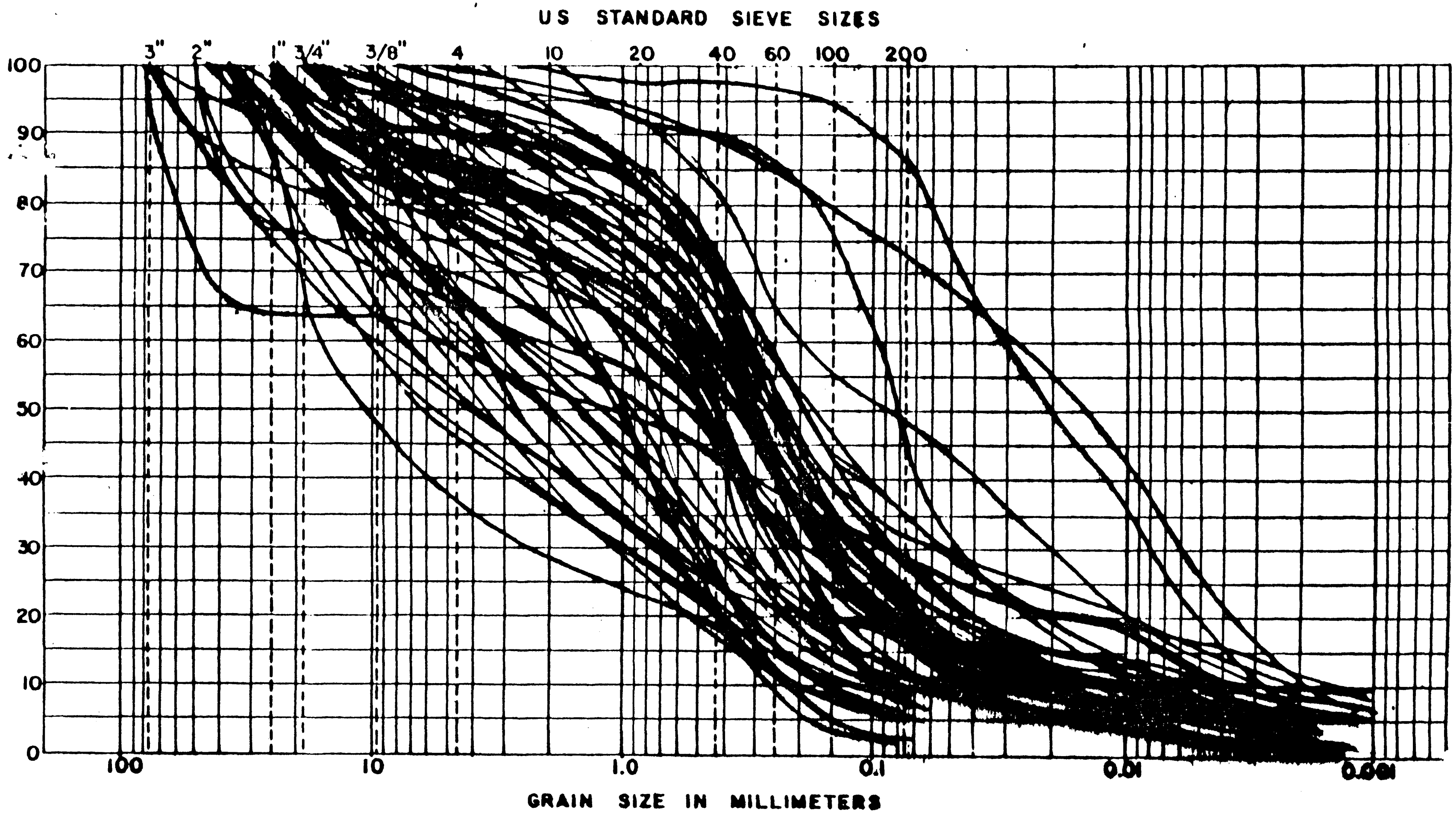
GRAIN SIZE DISTRIBUTION



COBBLES	GRAVEL		SAND			FINES	
	COARSE	FINE	COARSE	MEDIUM	FINE	SILT SIZES	CLAY SIZES

BORING NO.	ELEV. OR DEPTH	W_n	W_L	W_p	I_p	DESCRIPTION OR CLASSIFICATION
-	-	-	-	-	-	Samples of Till from Site 41 (Reference 8)

Drawn
Checked
Reviewed

FIGURE 2.3

made in the drain material to assure that any small amount of fines from the finer grain sized till materials passing into the drain would not clog the drain.

3.0 UNDERDRAIN SYSTEM

3.1 Hydraulic Capacity

The hydraulic capacity of an underdrain system is a measure of the amount of water which the system can transmit for removal. For this project, the concept of the underdrain system is to reduce seepage from the waste disposal pond by reducing the head on the liner beneath the underdrain. An effective underdrain system is one in which the amount of water that can be transmitted by the underdrain is greater than the seepage through the tailings and one which reduces the head acting on the liner to a practical minimum.

Hydraulic capacities of the underdrain systems considered were designed to achieve atmospheric pressure at the bottom of the tailings and honor continuity; outflow through the underdrain must be equal to inflow to the underdrain plus the change in storage within the underdrain. The change in storage in this application was considered a second order effect and taken as zero.

It is presently estimated that the volume of slurry pumped into a pond will be about 900 gallons per minute (5.7×10^{-2} m^3/s) with 690 gallons per minute (4.3×10^{-2} m^3/s) of the slurry being water. This will be a constant rate for most of the life of a pond (lesser during start-up operations). The amount of water contained at any one time in the pore spaces of the settled tailings is about 240 gallons per minute of tailings slurry input (1.5×10^{-2} m^3/s) based on a 50 percent solids (by weight) slurry with an estimated tailings void ratio of 1.1, an estimated tailings dry density of 95 pounds per cubic foot (1522 kg/m^3), and an average tailings specific gravity of

3.22(Ref. 6). Thus, about 450 gallons of water per minute ($2.8x10^{-2}$ m^3/s) will be available for recycle. Of this, about 340 gallons per minute ($2.1x10^{-2}$ m^3/s) could pass through the underdrain system (see Figure 3.1) with about 110 gallons per minute ($0.69x10^{-2}$ m^3/s) becoming ponded water to be decanted.

In addition to the water entering the pond with the tailings, precipitation falling on the pond will also be retained. The average annual precipitation for the area is 30.77 inches (782 mm) and the estimated lake evaporation rate is 23.36 inches (593 mm). Thus, the estimated precipitation retained in a ponded area is 7.41 inches (188 mm). For a 100 acre (40 ha) pond this is equivalent to an average annual amount of about 38 gallons per minute ($2.4x10^{-3}$ m^3/s).

As presently envisioned, the tailings ponds will include separate underdrain and decant systems. The underdrain system will be used to drain and evacuate water seeping through the tailings into the underdrain and water seeping into the underdrain system in areas where free water is ponded. In the ponded water area, the very fine tailings particles enter in suspension and slowly settle out, leaving clarified water at the top. This clarified water will be removed by the decant system. A simple decant system such as a barge mounted pump could be used.

It is not desirable to have the free pond water flow directly into the underdrain system from both a volume and turbidity standpoint. The less water passing through the underdrain, the less is the potential for contamination of underdrain. In order to minimize the volume of water, and to clarify turbid water trying to seep into the underdrain a retarding layer over the filter may be needed. This added retarding layer could be glacial till, waste rock (depending on its gradation), or tailings spigotted down the side slopes of the pond. Either method will suffice and the final selection is somewhat dependent on the shape and operational details of the tailings pond. If glacial till is employed as the filter, it need only be placed thicker to act as both the filter and retarding layer.

3.2 Blanket Underdrain Analysis

Flow estimates of water through the tailings and hence through a blanket underdrain system were made using Darcy's equation:

$$Q=kiA$$

where:

Q = flow (L^3/T)
k = hydraulic conductivity (L/T)
i = hydraulic gradient (L/L)
A = area (L^2)

A more detailed explanation of seepage estimating procedures is presented in Reference 5.

The hydraulic capacity of blanket underdrain systems were assessed in terms of cross-section area (which can be reduced to thickness) for various gradients with the hydraulic conductivities estimated from the filter and drain material bands previously discussed.

3.3 Parallel Pipe Underdrain Analysis

Parallel pipe underdrain systems were not specifically analyzed for the quantity of flow which could be transmitted. The small quantities of flow estimated from the tailings can easily be handled with small diameter pipes, in the 4 to 6 inch (102 mm to 152 mm) range so that the specific size of pipes is a detail left to the final design. The head reduction on the liner for this type of system is related to the spacing between the pipes. Drain spacing and head relationship is defined by the following equation(Ref. 7):

$$W^2 = \frac{4k\ (b^2-a^2)}{q_d}$$

where
W = drain spacing (L)
a = height of drain base above the liner (L)
b = maximum head on liner between drain (L)
k = hydraulic conductivity of tailings (L/T)
q_d = seepage through the tailings per unit area (L/T)

3.4 Combination Underdrain System Analysis

Consideration was also given to a parallel pipe underdrain system connected by a thin blanket of filter material; a combined system. This was done to examine whether a decrease in volume of blanket underdrain material and the number of parallel pipes could achieve a more economic system than could be attained by either system alone. All underdrain systems for this project were analyzed as having at least one collector pipe to channel the water to a discharge point. For purposes of discussion, any other pipe not directly connected to the discharge point is termed a pipe drain.

For combined underdrain systems, the analyses used varying thicknesses of filter material between pipe drains and varying filter bed slopes. Pipe drain spacing could then be determined by adding twice the length of the blanket, as limited by the required hydraulic capacity for a given filter bed thickness, to the pipe drain spacing determined for parallel pipe drains considered alone (see Figure 3.3). The pipe drain size was considered a detail, as previously discussed, and not calculated.

3.5 Analyses Parameters

To compare effectiveness of various underdrain systems, conceptual designs and analyses were applied to a square, nominal 100 acre (40 ha) pond with a maximum tailings depth of 70 feet (21.3 m). A sketch of the pond with dimensions used in the analyses is shown on Figure 3.1.a.

Seepage flow into the blanket underdrain system was estimated separately for the pond bottom area and pond side slope areas. These seepage flow estimates are presented on Figure 3.1.b.

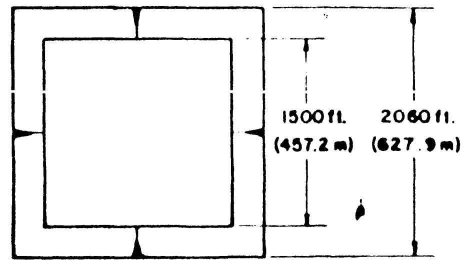
Hydraulic conductivity estimates for the filter material and drain material are given on Figure 3.1.c.

3.6 Underdrain System Analyses

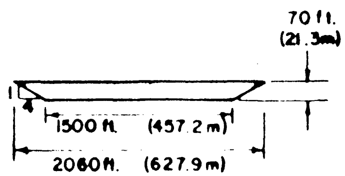
The various bottom underdrain schemes analyzed for this study included: 1) blanket systems with and without bottom slopes and with either a single end or full perimeter collection pipe, 2) pipe drain system with variable pipe spacings, and 3) combination pipe drain and blanket drain systems with varying slopes between the pipes and varying thicknesses of filter material between the pipes. These analyses for the pond bottom systems are presented on Figures 3.2 and 3.3.

Analyses of the underdrain configuration on the pond side slopes included: 1) a single layer filter material blanket, 2) a single layer filter material blanket with parallel pipe drains, and 3) a two layer filter and drain material blanket system. These analyses are presented on Figure 3.4.

a)



PLAN VIEW



CROSS SECTION

TOTAL AREA = 97.4 acres = 39.4 hectares

SLOPE AREA = 2.05×10^6 ft^2 (1.9×10^5 m^2)

BOTTOM AREA = 2.25×10^6 ft.^{2} (2.09×10^5 m^2)

b) SEEPAGE THROUGH THE TAILINGS BY DARCY'S LAW

Q = kiA

ASSUMING:

a. 3 ft.(0.9 m) of WATER OVER TAILINGS

b. MAXIMUM AREA OF FLOW

c. AVERAGE GRADIENT FOR MAXIMUM AREA

WITH:

Q = FLOW (L^3/T)

k = HYDRAULIC CONDUCTIVITY (L/T) OF TAILINGS

= 5.0×10^{-8} m/s (1.6×10^{-7} ft./sec) (REFERENCE 6)

i = HYDRAULIC GRADIENT (L/L)

A = AREA (L^2)

POND BOTTOM:

MAXIMUM DEPTH, TAILINGS = 70 ft. (21.3m)

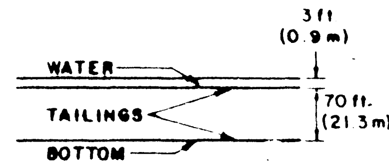
AVERAGE DEPTH, WATER = 3 ft. (0.9 m)

$i = \frac{70 + 3}{70} = 1.04$ say $i = 1.1$

Q = kiA

$= (1.6 \times 10^{-7}$ ft./sec$)(1.1)(2.25 \times 10^6$ ft.$^2)$

= 0.40 cfs (180 gpm)(1.13×10^{-2} m^3/s)



POND SLOPES:

AVERAGE DEPTH, TAILINGS = 35 ft. (10.7m)

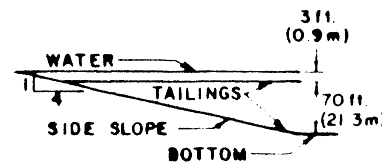
AVERAGE DEPTH, WATER = 3 ft. (0.9 m)

$i = \frac{35 + 3}{35} = 1.08$ say 1.1

Q = kiA

$= (1.6 \times 10^{-7}$ ft./sec$)(1.1)(2.05 \times 10^6$ ft.$^2)$

= 0.36 cfs (160 gpm)(1.02×10^{-2} m^3/s)



c) HYDRAULIC CONDUCTIVITY OF FILTER AND DRAIN MATERIALS

HAZEN'S APPROXIMATION: $k\,(\text{cm/sec}) = [D_{10}(\text{mm})]^2$

FILTER: $k_F = (0.042)^2$

$= (1.8 \times 10^{-3}$ cm/sec$)$

say 1.0×10^{-5} m/s (3.3×10^{-5} ft./sec), rounded to the nearest half order of magnitude

DRAIN: $k_D = (0.57)^2$

$= (3.2 \times 10^{-1}$ cm/sec$)$

say 5.0×10^{-3} m/s (1.6×10^{-2} ft./sec), rounded to the nearest half order of magnitude

JOB NO. 786085	SCALE NOT TO SCALE	CONCEPTUAL ANALYSES PARAMETERS
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CHECKED	DWG. NO. —	
Golder Associates		EXXON MINERALS COMPANY — FIGURE 3.1

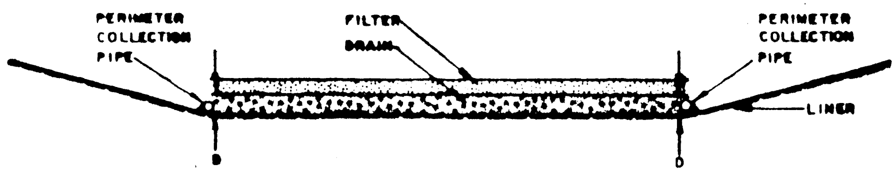
1500 ft. (457.2 m)
FIGURES A THROUGH D

A.) HOR. BOTTOM UNDERDRAIN WITH COLLECTION AT ONE END

A) 0.40 = kiA
0.40 = (1.6×10^{-2})(D/1500)(1500D)
So: D = 5.0 ft (1.5 m)

k = 1.6×10^{-2} ft/sec.
A = D (thickness) x 1500 ft.
i = D/1500

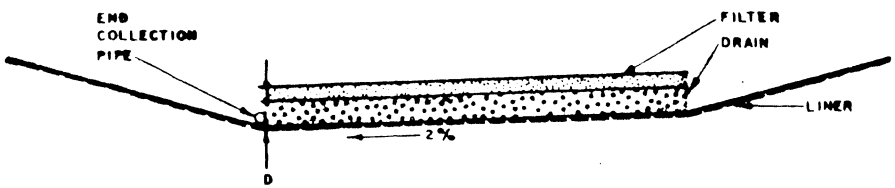
B.) HOR. BOTTOM UNDERDRAIN WITH PERIMETER COLLECTION



B) 0.40 = kiA
0.40 = (1.6×10^{-2})(D/375)(6000D)
So: D = 1.6 ft. (0.5 m)

k = 1.6×10^{-2} ft/sec.
A = D (thickness) (4 x 1500) ft.
i = D/L with L = average flow distance
= $(1500)^2$ / 1500 x 4
= 375 ft. (114.3 m)

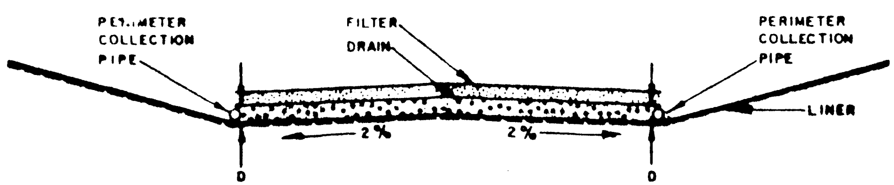
C.) SLOPING UNDERDRAIN WITH COLLECTION AT ONE END



C) 0.40 = kiA
0.40 = (1.6×10^{-2})(0.02)(1500 D)
So: D = 0.8 ft. (0.2 m)

k = 1.6×10^{-2} ft/sec.
A = D (thickness) x 1500
i = 0.02 (bottom slope)

D.) SLOPING UNDERDRAIN WITH PERIMETER COLLECTION



D) 0.40 = kiA
0.40 = (1.6×10^{-2})(0.02)(6000 D)
So: D = 0.2 ft. (0.06 m)

k = 1.6×10^{-2} ft/sec.
A = D (thickness) (4 x 1500)
i = 0.02 (bottom slope)

NOTE:
Hydraulic capacity analysis for side slopes shown on FIGURE 3.4

EQUATIONS: 1. Q = kiA
2. Qin = Qout

Q = flow
k = hydraulic conductivity
i = gradient
A = area

So: Qin = kiA (from the tailings, see Fig. 3.1b)
= 0.40 cfs

With: Qin = Qout (through drain cross section)

JOB NO. 786085	SCALE NOT TO SCALE	BOTTOM BLANKET THICKNESS FOR REQUIRED HYDRAULIC CAPACITY
DRAWN SKB	DATE 7-29-81	
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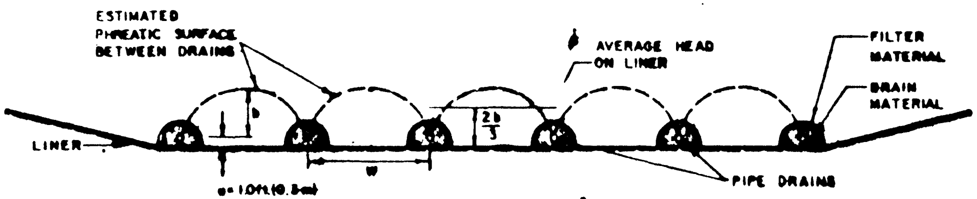
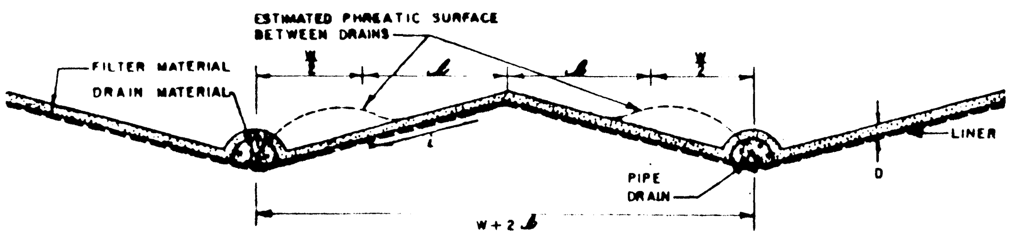
Golder Associates		EXXON MINERALS COMPANY — FIGURE 3.2

A) PIPE DRAIN OR LINE DRAIN SYSTEM



B) COMBINED PIPE UNDERDRAIN AND FILTER BLANKET SYSTEM



EQUATI... in = Q out
Q = k i A
q = k i

Q = flow
q = flow per unit area
k = hydraulic conductivity
i = gradient
A = area

A.) DRAIN SPACING, W, IS ESTIMATED BY:

$$W^2 = \frac{4k\,(b^2 - a^2)}{q_d}$$

$k = 1.6 \times 10^{-7}$ ft/sec. (tailings)

q_d = inflow from tailings per unit area
$= ki$
$= (1.6 \times 10^{-7})(1.1)$
$= 1.8 \times 10^{-7}$ cfs / ft^2

eg: MAXIMUM PHREATIC SURFACE AT SURFACE OF POND, b = 70 ft

$$W = \left[\frac{4(1.6 \times 10^{-7})(70^2 - 1^2)}{1.80 \times 10^{-7}}\right]^{\frac{1}{2}}$$

= 132.0 ft (40.2 m)

So:

b	(ft)	2.0	6.0	10.0	22.0	28.0	41.0	55.0	70.0	83.0
	(m)	0.6	1.8	3.0	6.7	8.5	12.5	16.8	21.3	25.3
W	(ft)	3.3	11.2	18.8	41.4	52.8	77.3	103.7	132.0	156.5
	(m)	1.0	3.4	5.7	12.6	16.1	23.6	31.6	40.2	47.7

B.) ESTIMATED ADDITIONAL SPACE BETWEEN PIPE DRAINS WITH A 2.0 ft. THICK BLANKET OF FILTER MATERIAL OVER THE BOTTOM.

$$Q_{in} = Q_{out}$$

$$k_I\, i_I\, A_I = k_O\, i_O\, A_O$$

eg: D = 2 ft. and i = 25%

$$(1.6 \times 10^{-7})(1.1)(\ell) = (3.3 \times 10^{-5})(0.25)(2)$$

$$\ell = 93.8 \text{ ft. } (28.6 \text{ m})$$

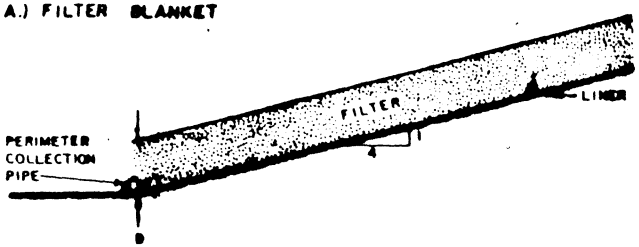
$k_I = 1.6 \times 10^{-7}$ ft/sec
$k_O = 3.3 \times 10^{-5}$ ft/sec
$i_I = 1.1$
i_O = bottom slope
$A_I = 1' \times \ell$
$A_O = 1' \times D$

So:

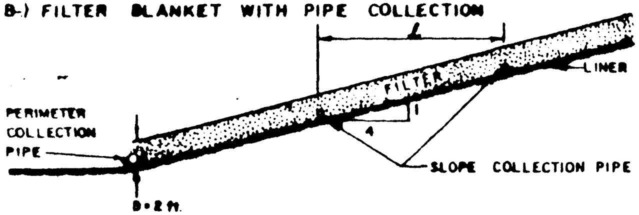
D (ft)	D (m)	i	ℓ (ft)	ℓ (m)
2.0	0.6	0.05	18.8	5.7
		0.10	37.5	11.4
		0.25	93.8	28.6
3.0	0.9	0.05	28.1	8.6
		0.10	56.3	17.2
		0.25	140.6	42.9
4.0	1.2	0.05	37.5	11.4
		0.10	75.0	22.9
		0.25	187.5	57.2
5.0	1.5	0.05	46.9	14.3
		0.10	93.8	28.6
		0.25	234.4	71.4

JOB NO. 786085	SCALE NOT TO SCALE	PIPE DRAIN SPACING FOR REQUIRED HYDRAULIC CAPACITY	
DRAWN SKB	DATE 7-28-81		
CHECKED	DWG. NO.		
Golder Associates		EXXON MINERALS COMPANY	FIGURE 3.3

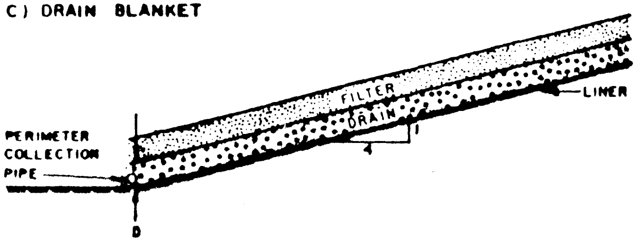
A.) FILTER BLANKET



B.) FILTER BLANKET WITH PIPE COLLECTION



C) DRAIN BLANKET



EQUATIONS: 1. $Q = kiA$ with: Q = flow; k = hydraulic conductivity

2. $Q_{in} = Q_{out}$ i = gradient; A = area

So: $Q_{in} = kiA$ (from the tailings, see Fig 3.1b)

$= 0.36$ cfs

With: $Q_{in} = Q_{out}$ (through the drain cross section)

A) $0.36 = kiA$

$0.36 = (3.3 \times 10^{-5})(0.25)(6000\,D)$

So: $D = 7.3$ ft. (2.2 m)

$k = 3.3 \times 10^{-5}$ ft/sec.

$i = 0.25$ (side slope)

$A = D \times (4 \times 1500)$

B) for: $D = 2.0$ ft.

$= 0.6$ m

$\ell = 93.8$ ft (28.6 m)

(see combined pipe drain and filter blanket calculations for pond bottom, FIGURE 3.3b)

C) $0.36 = kiA$

$0.36 = (1.6 \times 10^{-2})(0.25)(6000\,D)$

So: $D = 0.015$ ft. (0.0045 m)

$k = 1.6 \times 10^{-2}$ ft/sec.

$i = 0.25$ (side slope)

$A = D \times (4 \times 1500)$

NOTE: Flow through filter assumed vertical so its thickness is determined by construction practicality.

JOB NO. 786065	SCALE NOT TO SCALE	SLOPE BLANKET THICKNESS FOR REQUIRED HYDRAULIC CAPACITY
DRAWN SKB	DATE 7-27-81	
CHECKED JFC	DWG. NO.	
Golder Associates		EXXON MINERALS COMPANY — FIGURE 3.4

As shown by the analyses, sloping the pond bottom reduces the thickness of the underdrain system by providing a gradient in addition to that provided by the water flow depth. A minimum 2% slope is considered suitable for a blanket drain system for ponds of the size anticipated for the Crandon Project. Steeper slopes were considered for the combined system.

For analyses purposes, the thickness of the blanket underdrains and blanket portions of combined and side slope underdrains were computed for the section of maximum flow. For blanket underdrains this is at the collection pipe location. For the side slope blanket underdrains it is assumed that there is a collection pipe at the base of the slope. For the combined pipe and blanket underdrains, the distance between drains was calculated based on flow depth limited by the selected thickness of blanket and bottom slope.

4.0 POND SEEPAGE ESTIMATES

Seepage estimates through a liner were made using the nominal 100 acre (40 ha) pond with the dimensions which were shown in Figure 3.1.a. Steady state seepage for operating ponds was estimated using Darcy's equation:

$$Q_S = kiA$$

with

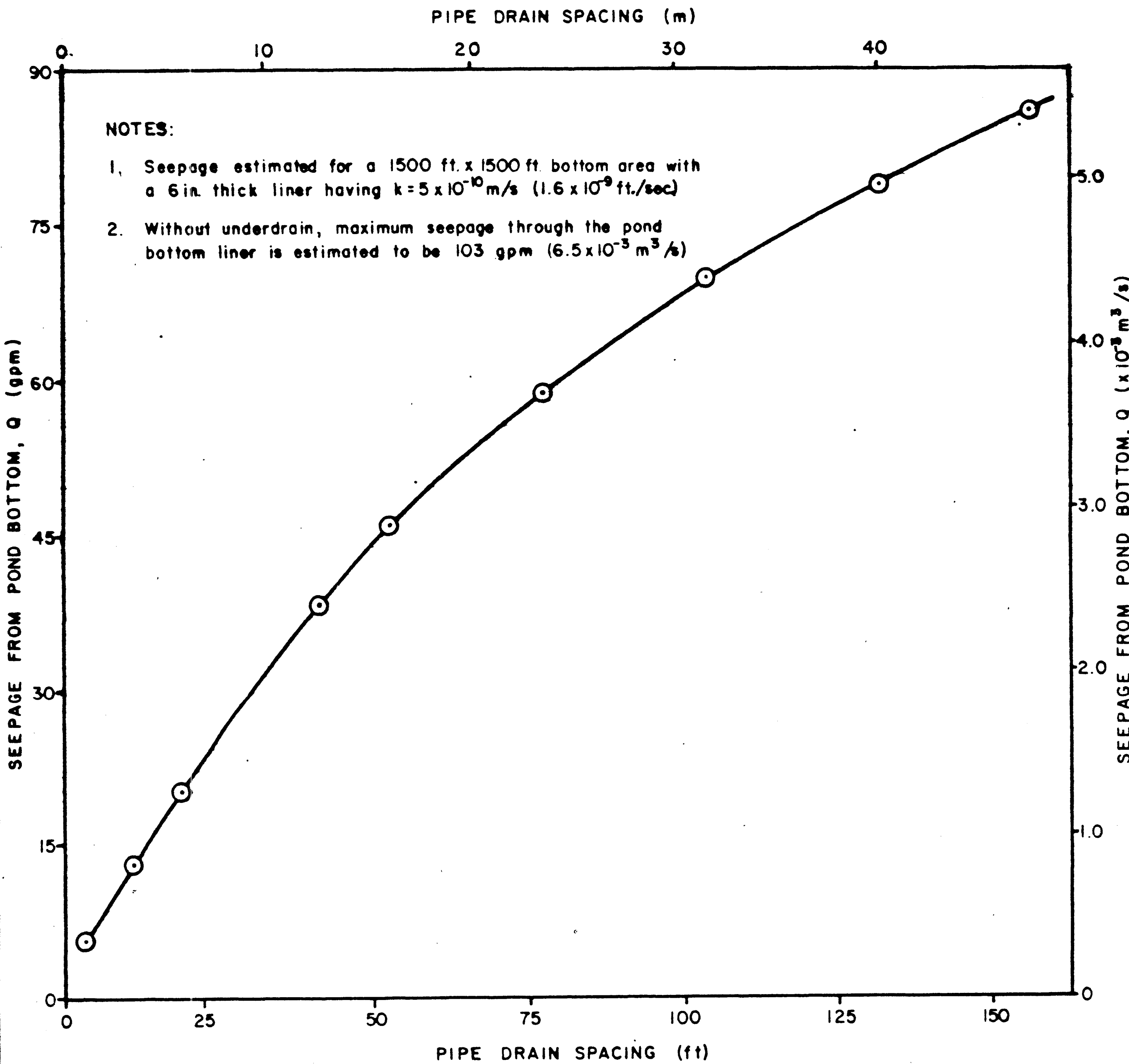
Q_S = the seepage through the liner (L^3/T)
k = the hydraulic conductivity of the liner (L/T)
A = the bottom or slope liner area (L^2)
i = the hydraulic gradient on the liner (L/L)

The hydraulic gradient with blanket drains was estimated using the head on the liner as being equal to the required hydraulic thickness of the drain. For pipe drain systems, 2/3 of the maximum head between the drains was used as an average head across the liner. The hydraulic gradient, i, was calculated as:

$$i = \frac{\text{head + liner thickness}}{\text{liner thickness}}$$

With only pipe drains, the estimated seepage from the pond bottom varies with pipe drain spacing. For the bottom portion of the nominal 100 acre (40 ha) pond, the estimated seepage for varying drain spacing is shown on Figure 4.1. As can be seen from this graph, very close pipe drain spacing is required to significantly reduce the estimated seepage.

Table 4.1 presents seepage estimates for the nominal 100 acre (40 ha) pond with various bottom and side slope



JOB NO. 786085	SCALE AS SHOWN	PIPE DRAIN SPACING vs SEEPAGE FROM POND BOTTOM
DRAWN SKB	DATE 1-6-81	
CHECKED	DWG NO. —	
Golder Associates		EXXON MINERALS COMPANY — FIGURE 4.1

TABLE 4.1
ESTIMATED SEEPAGE THROUGH LINER FOR VARIOUS UNDERDRAIN CONFIGURATIONS

Underdrain Configuration		Seepage Through	Hydraulic Thickness ft. (m)	Gradient	Seepage		
					(10^{-2} cfs)	(gpm)	(10^{-3} m^3/s)
Fig. 3.2 (A):	Hor. bottom blanket w/one end collection	Bottom	5.0 (1.5)	11.0	4.0	18	1.1
Fig. 3.2 (B):	Hor. bottom blanket w/perim. collection	Bottom	1.6 (0.5)	4.2	1.5	6.8	0.43
Fig. 3.2 (C):	Bottom blanket @ 2% slope, one end collection	Bottom	0.8 (0.2)	2.6	0.94	4.2	0.27
Fig. 3.2 (D):	Bottom blanket @ 2% slope, perim. collection	Bottom	0.2 (0.06)	1.4	0.50	2.2	0.14
Fig. 3.3 (A):	Pipe drain @ 132 ft. (40.2 m) centers	Bottom	46.7 (14.2)	1.0	18*	81*	5.1*
Fig. 3.3 (B):	Pipe drain @ 320 ft. (97.5 m) centers, bottom blanket @ 4.0 hor.:1.0 ver. slope	Bottom	2.0 (0.6)	5.0	1.8	8.1	0.51
Fig. 3.4 (A):	Filter blanket	Slope	7.3 (2.2)	15.6	5.1	23	1.4
Fig. 3.4 (B):	Filter blanket w/pipe collection	Slope	2.0 (0.6)	5.0	1.6	7.4	0.46
Fig. 3.4 (C):	Filter and drain blankets	Slope	0.015 (0.0045)	1.0	0.33	1.5	0.09
Liner without underdrain		Bottom	70.0 (21.3)	1.1	23*	103*	6.5*
Liner without underdrain		Slope	35.0 (10.7)	1.1	15*	67*	4.3*

Notes:

Bottom Area = 2.25×10^6 ft.^{2} (2.09×10^5 m^2), Slope Area = 2.05×10^6 ft.^{2} (1.90×10^5 m^2)
Liner Thickness = 6 inches (152 mm), Liner Permeability = 1.6×10^{-9} ft./sec. (5.0×10^{-10} m/s)

*Seepage, $Q = \dfrac{H_t + H_l}{(H_t/k_t) + (H_l/K_l)}$ iA, where, t and l denote tailings and liner respectively, and H denotes head.

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underdrain configurations previously shown on Figures 3.2, 3.3, and 3.4. For comparison purposes, the pipe drain and combined drain systems are shown in Table 4.1 with the pipe drains spaced at 132 foot (40.2 m) centers. Also included in Table 4.1 are seepage estimates for the lined pond bottom and side slopes without an underdrain for comparison.

5.0 CONCLUSIONS

5.1 Seepage Reduction

The underdrain analyses show that dramatic reductions in tailings pond seepage during operation can be obtained with the installation of an underdrain system. The effect of the underdrain system is to reduce the head of water acting on the liner and hence reduce this gradient across the liner. For a given pond size and liner type, the gradient controls the seepage. Changes in gradient can be attained by either making the liner thicker or reducing the head on the liner. To reduce the gradient between one and two orders of magnitude the thickness of the liner would have to be increased by 10 to 100 times; an increase from say 6 inches (152 mm) to between 5 and 50 feet (1.5 m to 15 m). A similar reduction of about one to two orders of magnitude in gradient can be achieved with a blanket underdrain system.

5.2 Two Layer Blanket Underdrain

The conceptual analyses for a nominal 100 acre (40 ha) pond for various underdrain systems indicate that a two layer blanket underdrain is the most feasible system. A single layer of filter material does not have sufficient hydraulic capacity to transmit the seepage using a reasonable material thickness, say less than 5 feet (1.52 m). A coarser material with sufficient hydraulic capacity does not have enough fines to prevent migration of tailings into the drain, which would then clog the drain. Therefore, a coarse bottom drain layer with a filter material layer between it and the tailings appears to be the most functional system. An additional layer of material may be needed to retard short circuiting of large volumes c :larified or unclarified ponded water directly into the drain layer.

5.3 Bottom Slope

The thickness of the drain material can be reduced by sloping the underdrain system. Because of the relatively large aerial extents of the ponds and their relatively shallow depths, steep slopes are not practical. Very flat slopes, 1% or less, are extremely difficult to control over such a large area. A two percent bottom slope is considered a minimum, and it provides an adequate margin for excess hydraulic capacity of the drain system. Somewhat steeper slopes, say 5 to 10 percent may be employed depending on the final pond configuration.

5.4 Pipe Drain and Combined Drain Alternatives

A series of parallel or branching pipe line drains do not seem practical. Pipe drains alone would have to be spaced at about 20 foot (6.1 m) centers to reduce the seepage flow to even 1/5 of the estimated seepage without an underdrain across the same liner. These drains would require a large amount of pipe and drain/filter materials; approximately 22 miles (35 km) of pipe for a nominal 100 acre (40 ha) pond.

Modificiation of the pipe drain system by connecting the drains with filter material (a blanket) would allow widening the drain spacing, but with the added expense of substantial bottom grading. Significant seepage reduction could be attained with a 2 foot (0.61 m) thick layer of filter material including drain pipes spaced at approximately 300 foot (91.4 m) centers and with the filter blanket placed at 4 horizontal to 1 vertical slopes between the drains. Cutting a pond bottom into such a series of ridges would be a more difficult grading job than preparing a flat bottom slope.

If a layer of coarse drain material was added below the filter material in a combined system, it would reduce the underdrain thickness and slopes to the extent that only one pipe down the center would be needed. This, however, is essentially the two layer blanket drain system.

5.5 Inside Embankment Slopes

Alternatives were investigated for draining the 4 horizontal to 1 vertical side slopes. Filter material alone would have to be placed in a fairly thick layer, about 7 feet (2.1 m), to achieve sufficient hydraulic capacity. A modified pipe drain system with pipes placed parallel to the crest on about 90 foot (27.4 m) centers with filter material 2 feet (0.6 m) thick along the entire slope could be used. But, without a similar system on the bottom, there is little reason to install such a complicated system on the slopes. Again, a two layer blanket underdrain system seems most feasible.

5.6 Collection System

Significant reductions in blanket drain material thickness can be achieved by placing the collection system around the perimeter of the pond bottom. This collection scheme will also directly collect the drainage from the side slope so that it does not have to flow through the bottom blanket drain. Finally, it can allow collection of water from the entire pond at any of several discharge points.

6.0 RECOMMENDED UNDERDRAIN SYSTEM

6.1 Description

The recommended underdrain system based on these analyses is a two layer system covering the bottom and side slope areas. The pond bottom, with liner, would be graded generally from the center of the pond down toward the toe of the embankment at a minimum 2% slope.

The drain material would be placed over the liner. The hydraulic capacity of the drain material is so great that only a nominal thickness of less than 6 inches (152 mm) is required in most areas. However, placement considerations on such a large scale dicatate that a drain thickness on the order of 12 inches ±3 inches (305 mm ± 76 mm) may be required.

The drain would be placed without damage to the liner by having the construction equipment working on the previously placed lift of drain and not on the liner. This is a common placement technique when working over liners.

The filter material would be placed over the drain, and tailings will cover it. The filter material is recommended to be on the order of 12 inches ±3 inches (305 mm ± 76 mm) thick on the pond bottom and 6 inches ±2 inches (152 mm ± 51 mm) thick on the side slopes, also based on placement considerations. Both the filter and drain materials need only receive the compaction that occurs during placement. Descriptions of the design for these materials were given in Section 2 and their approximate gradations were shown on Figures 2.1 and 2.2. In order to prevent large volumes of free pond water from entering the underdrain too quickly and to filter turbid free water which does enter, a layer of till, waste rock, or tailings may have to be placed over the filter layer, particularly on the side slopes. If till is used as the filter layer, it would perform both functions.

A collection pipe should be placed around the inside toe of the side slope to collect water from the blanket drain and to conduct this water to the discharge station. A two foot diameter (0.6 m) perforated pipe, laid flat, can conduct 2 to 3 times the estimated flow. Such a collection pipe system has the advantage of being able to conduct all the water reaching the drain to any one (or more) discharge stations, regardless of their location around the perimeter of the pond bottom. Alternatively, the collection pipes could be smaller and sloped to the discharge point. Specifics of the system may be determined during the design phase of the project.

Discharge stations are sump areas from which the underdrain flow will be pumped out of the pond. Multiple stations should be considered to allow backup in case of sump, station access, or collection pipe failure. The unpumped stations could be used to monitor the water levels in the drain in order to evaluate the performance of the underdrain system. If necessary, these extra stations could also be pumped. Should the entire collection pipe collapse the underdrain system could be pumped from the discharge stations like a confined aquifer system. For this reason, discharge stations should include a section of perforated pipe in the sump.

6.2 Efficiency

The efficiency of the proposed underdrain system was reviewed for a nominal 100 acre (40 ha) pond with a storage depth of about 70 feet (21.3 m). Two approaches to efficiency were considered and related to seepage through a 6 inch (152 mm) thick pond liner. The seepage through the liner was estimated based on the head build up over the liner due to:

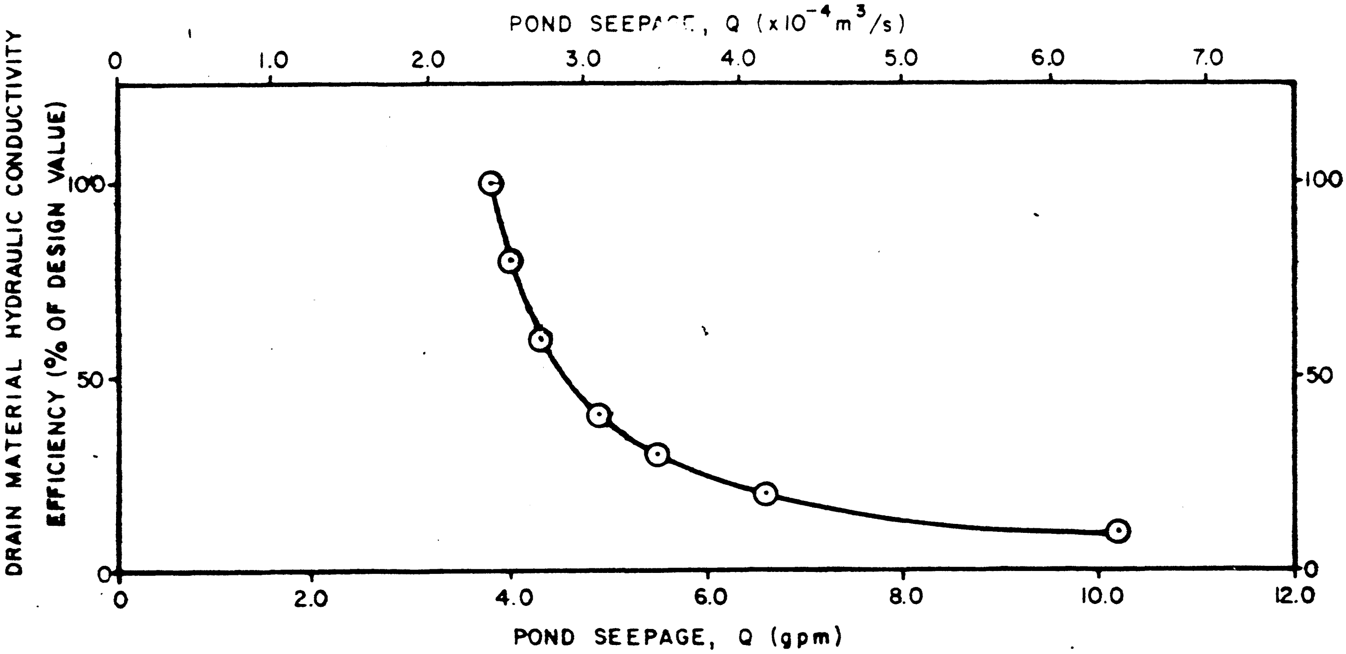
1. a gross reduction in permeability for the entire drain, and

2. total blinding (permeability reduced by clogging) of 100 foot by 100 foot (30.5 m by 30.5 m) areas of the drain.

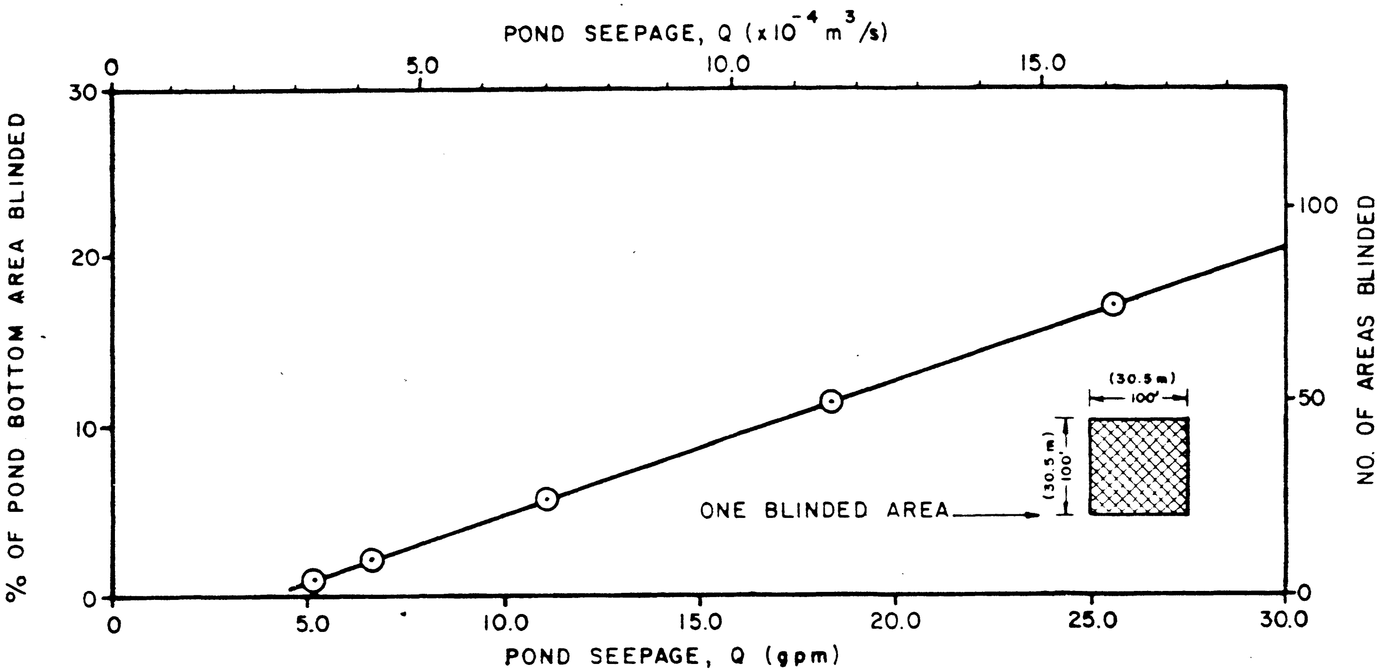
The gradients and hydraulic characteristics used were similar to those previously described in this report. The head build up over blind areas was assumed similar to that occurring between pipe drains 100 feet (30.5 m) apart. The plots of drain efficiency versus seepage are shown in Figure 6.1.

As indicated by Figure 6.1, there is a great deal of excess hydraulic capacity in the underdrain system. If the efficiency of the hydraulic conductivity of the drain is decreased to only 10% of its design value (one order of magnitude lower in permeability), the amount of seepage increases from 4 gpm (2.5×10^{-4} m^3/s) to approximately 10 gpm (6.3×10^{-4} m^3/s) for a nominal 100 acre (40 ha) pond. The effect of blind areas is more severe because of the assumed increase in head on the liner in the blind areas. However, even if 20% of the pond bottom area is covered by 100 foot by 100 foot (30.5 m x 30.5 m) blind areas the seepage through the liner is estimated to increase to approximately 30 gpm (1.9×10^{-3} m^3/s). Given such margin of efficiency in the underdrain system and considering that the drain materials, and possibly the filter materials, will likely be processed materials and will be placed under controlled con-

SEEPAGE THROUGH LINER vs. DRAIN HYDRAULIC CONDUCTIVITY EFFICIENCY



SEEPAGE THROUGH LINER vs. NUMBER OF 100ft. x 100ft. AREAS BLINDED



NOTES:

FIGURES ARE BASED ON:

1. A nominal 100 acre (39.4 hectares), 70 ft. (21.3 m) deep pond as shown on FIGURE 3.1
2. 6 in. (152 mm) thick liner with $k = 5 \times 10^{-10}$ m/s (1.6 x ... $^{-9}$ ft./sec.)

JOB NO. 786085	SCALE AS SHOWN	P... SEEPAGE vs. EFFICIENCY OF UNDERDRAIN SYSTEM
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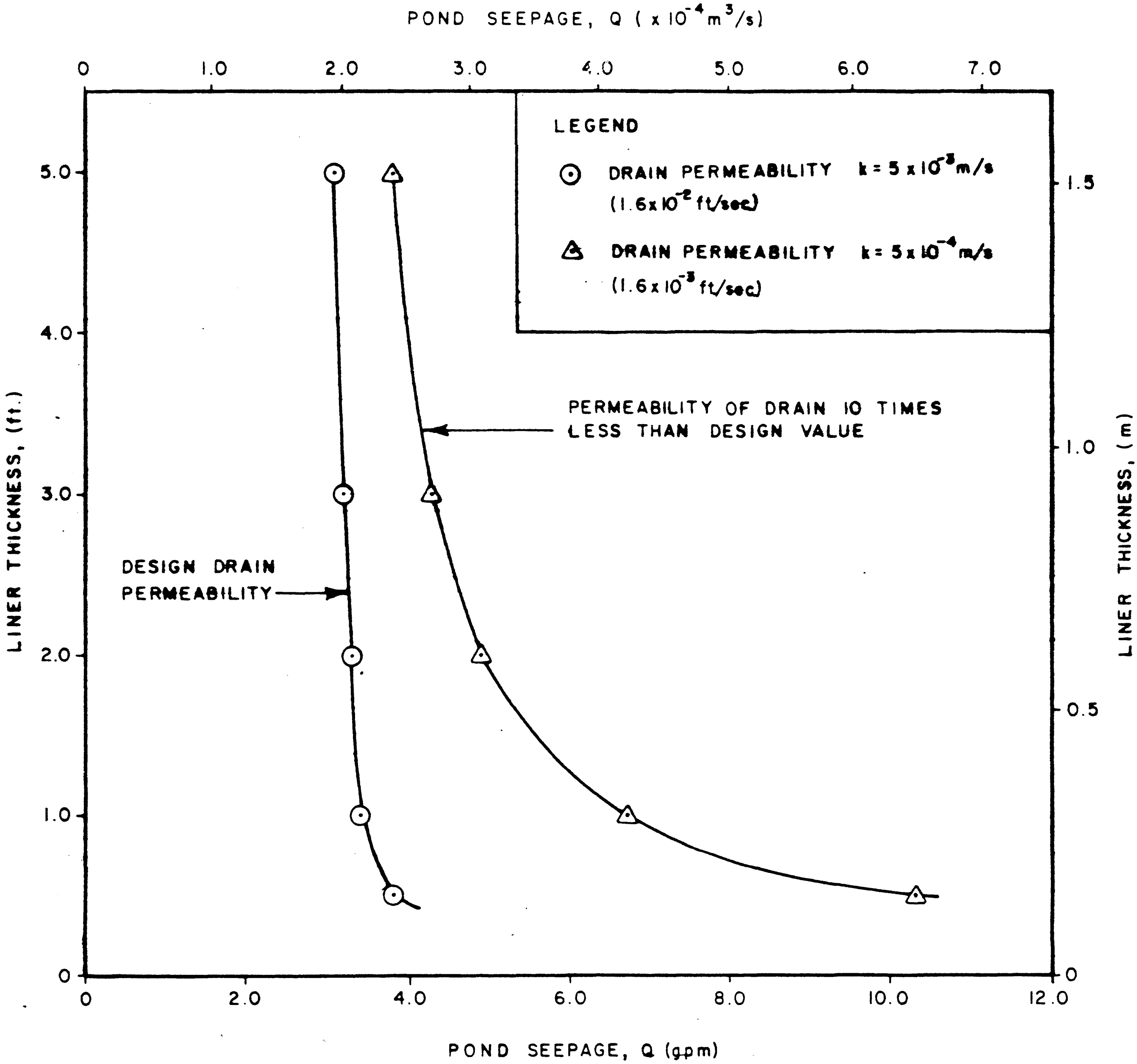
Golder Associates		EXXON MINERALS COMPANY — FIGURE 6.1

ditions the underdrain system should certainly operate successfully in reducing the seepage through the liner.

The combined effect of liner thickness and drain layer permeability on pond seepage are presented graphically on Figure 6.2. For the design drain permeability of $5x10^{-3}$ m/s ($1.6x10^{-2}$ ft./sec.) the rate of seepage is nearly equal for liner thickness varying from 6 inches (152 mm) to 5 feet (1.5 m), less than 4 gallons per minute ($2.5x10^{-4}$ m^3/s). If the drain layer permeability was one order of magnitude less than that used in the design, the resulting seepage quantity would range from approximately 10 gallons per minute ($6.3x10^{-4}$ m^3/s) with a 6 inch (152 mm) thick liner to approximately 4 gallons per minute ($2.5x10^{-4}$ m^3/s) with a 5 foot (1.5 m) thick liner. Thus, for a wide range of drain permeability, the thickness of the liner does not substantially affect the rate of pond seepage. In all cases, the estimated seepage rates from the nominal 100 acre (40 ha), 70 foot (21.3 m) deep pond are considered to be very low.

Although not shown on Figure 6.2, the effect of increasing the drain layer permeability one order of magnitude higher than the design value will not significantly reduce the estimated pond seepage rate. For example, with a drain permeability of $5x10^{-2}$ m/s ($1.6x10^{-1}$ ft./sec.) and a 6 inch (152 mm) thick liner the estimated seepage rate is about 3 gallons per minute ($1.9x10^{-4}$ m^3/s).

The hydraulic capacity of the recommended system is also sufficient to drain the total volume of water being pumped into the pond with the tailings, about 690 gallons per minute ($4.3x10^{-2}$ m^3/s). Using the equation shown on Figure 3.2 part D and a drain material thickness of one foot (305 mm), the hydraulic capacity is 862 gallons per minute



NOTES:

1. A nominal 100 acre (40 hectare), 70 ft. (21.3 m) deep pond, as shown on FIGURE 3.1 is considered in the analyses.
2. Pond seepage quantities include seepage from both the pond bottom and side slopes.
3. Liner permeability $k = 5 \times 10^{-10}$ m/s (1.6×10^{-9} ft./sec)

JOB NO. 786085	SCALE AS SHOWN	EFFECT OF LINER THICKNESS ON SEEPAGE WITH UNDERDRAINS
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Golder Associates		EXXON MINERALS COMPANY — FIGURE 6.2

($5.4x10^{-2}$ m^3/s); greater than the total volume of water input with the tailings plus the average annual retained precipitation. Additional hydraulic capacity is provided by the drain layer on the pond slopes. Using the equation shown on Figure 3.4 part C and a drain material thickness of twelve inches (305 mm), the hydraulic capacity is over 10,800 gallons per minute (0.68 m^3/s). The hydraulic capacity of the drain material on the slopes and pond bottom is over sixteen times the volume of water being pumped into the pond. Thus, there is a great deal of latitude available when final details are established to reduce the underdrain thickness, if adequate placement can be developed, without impacting the ability of the system to drain more water than is supplied.

6.3 Underdrain Materials Availability

Brief consideration has been given to processing waste rock to make the required gradation of filter and drain materials. Some of the factors associated with this approach are as follows:

1. There may be insufficient quantities of waste rock available.
2. The waste rock may not be available at the time needed.
3. The waste rock will probably need three stages of crushing with washing and screening to produce the needed materials.
4. The waste rock may contain sulfide bearing minerals which could produce acidic conditions in the washing operation.
5. The waste rock may be better used for slope protection on the inside pond side slopes.

Based on the above, it is recommended that the waste rock not be used to process filter or drain materials. However, it could be used as a protective cover over the underdrain system where it may not need to be crushed, washed, and screened.

Comparison of the filter and drain material bands proposed in Section 2 of this report (Figures 2.1 and 2.2) to the composite gradation curves of the glacial till soils at the proposed disposal sites, Figures 6.3 and 6.4, suggests that these soils could be used to develop the filter and drain materials. These soils will have to be processed by screening, washing and perhaps some crushing to provide the desired gradations. Such a procedure is technically feasible with available technology. However, the costs associated with such an operation may be high because of the amount of fines (material finer than the #200 sieve) in some of the glacial soils. Also, we are not aware of any mine or commercial aggregate suppliers processing glacial till for graded aggregates on a large scale. Prior to a final decision on processing the glacial soils for filter and drain materials, we recommend additional investigation into practices of commercial aggregate suppliers in the Crandon area and perhaps performing a pilot processing trial by shipping on-site soils to an operating plant.

As discussed in Section 2.2, native till could also be used as a filter material without processing. However, since the range of till grain sizes is slightly wider than the desired filter material gradation, the thickness of the underlying drain, and perhaps the till filter, may have to be greater than for processed filter material because there may be some slight migration of till fines into the drain. This approach is technically feasible, but a cost comparison must be factored into the final decision.

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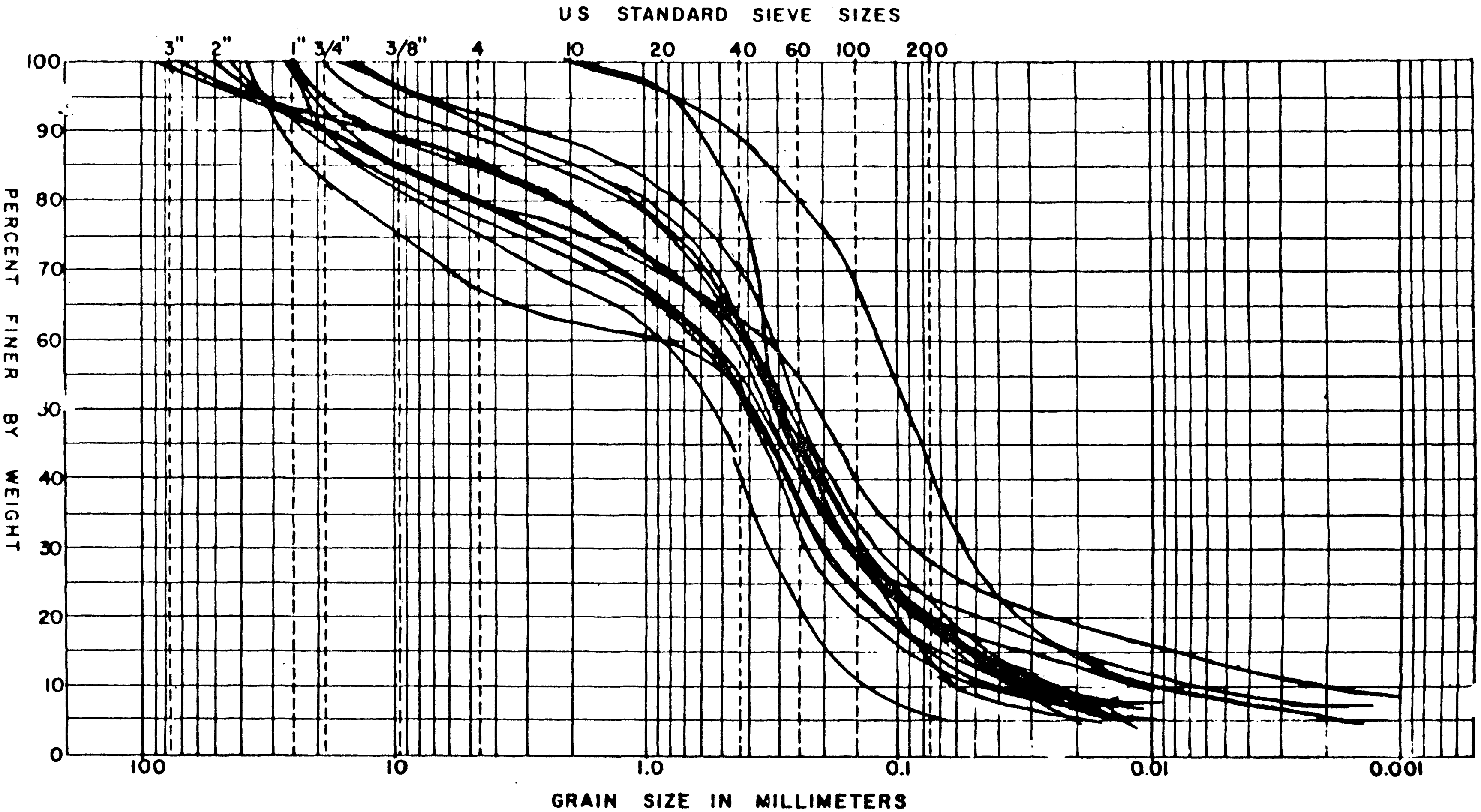
GRAIN SIZE DISTRIBUTION



COBBLES	GRAVEL		SAND			FINES	
	COARSE	FINE	COARSE	MEDIUM	FINE	SILT SIZES	CLAY SIZES

BORING NO.	ELEV. OR DEPTH	W_n	W_L	W_p	I_p	DESCRIPTION OR CLASSIFICATION
-	--	-	-	-	-	Samples of Till from Site 40 (Reference 8)

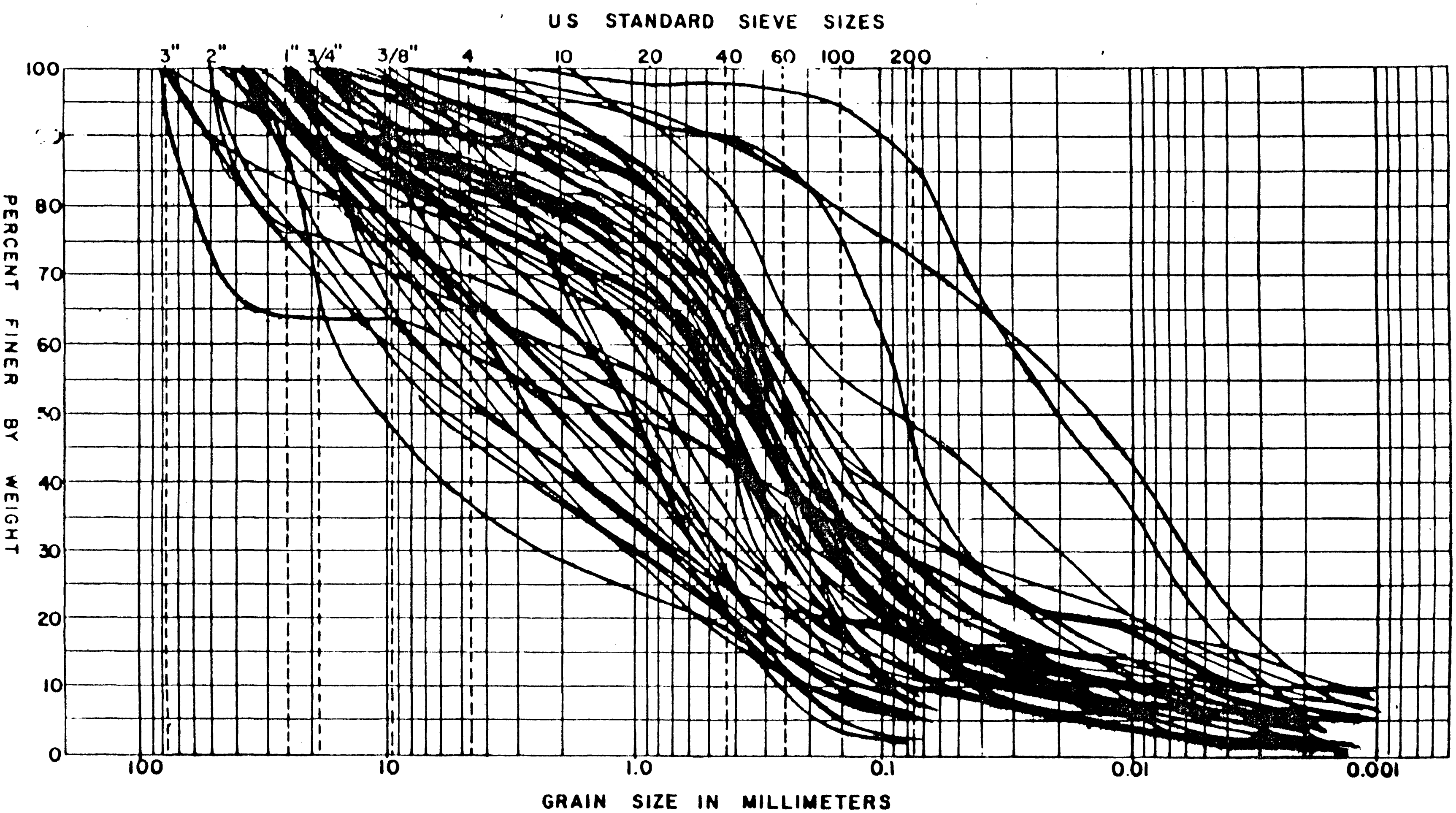
Drawn

Checked

Reviewed

FIGURE 6.3

GRAIN SIZE DISTRIBUTION



COBBLES	GRAVEL		SAND			FINES	
	COARSE	FINE	COARSE	MEDIUM	FINE	SILT SIZES	CLAY SIZES

BORING NO.	ELEV. OR DEPTH	W_n	W_L	W_p	I_p	DESCRIPTION OR CLASSIFICATION
-	-	-	-	-	-	Samples of Till from Site 41 (Reference 8)

FIGURE 6.4

Golder Associates

Date 10-7-81
Job No 786085

Drawn ...
Checked ...
Reviewed ...

7.0 SUMMARY

The addition of an underdrain system above the liner of the tailings ponds at the Crandon Project is a feasible approach for reducing the amount of seepage from the ponds during operation. A two layer blanket underdrain over the pond bottom and side slopes with a perimeter pipe collection system is recommended over other options considered. The underdrain system can be designed and constructed to allow passage of water and retain the tailings materials. The recommended underdrain has sufficient hydraulic capacity to provide a wide margin of efficiency while limiting seepage through the liner. For a nominal 100 acre (40 ha), 70 foot (21.3 m) deep tailings pond, the underdrain system is estimated to reduce the seepage through the liner to less than 4.0 gpm (2.5×10^{-4} m^3/s) compared to an estimated seepage of approximately 170 gpm (107×10^{-4} m^3/s) for the same liner without an underdrain system. The use of an underdrain system to significantly reduce pond seepage is believed to be feasible both technically and from a construction standpoint for the Crandon Project.

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