REVIEW OF USE OF AN ELEVATED WATER TABLE AS A METHOD TO CONTROL AND REDUCE ACIDIC DRAINAGE FROM TAILINGS

MEND Report 2.17.1

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FINAL REPORT

REVIEW OF USE OF AN ELEVATED WATER TABLE AS A METHOD TO CONTROL AND REDUCE ACIDIC DRAINAGE FROM TAILINGS

Prepared for:

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CANMET Scientific Authority: Gilles A. Tremblay

Prepared by:

SENES Consultants Limited
121 Granton Drive
Unit 12
Richmond Hill, Ontario
L4B 3N4

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EXECUTIVE SUMMARY

Methods such as subaqueous disposal are available to control and reduce acidic drainage from tailings and can be applied to many, but not all tailings management facilities. These available methods have various drawbacks and in particular high cost. There is a need for alternate methods which can reduce the cost of closure and perhaps eliminate some of the drawbacks associated with the available methods. This report reviews one such alternate method that is increasingly being considered for the closure of sulphide tailings impoundments - the application of elevated water table concepts.

The concept of using an elevated water table within tailings is of great interest as available data suggests that the rate of oxidation of sulphide tailings, in conditions where the water table approaches the surface of the tailings, is very low and similar to the rate of oxidation of sulphide tailings maintained under water cover. There are three basic approaches that can be applied to raise the elevation of the water table and the associated capillary zone within tailings:

1) Modifying the water balance of the tailings;
2) Enhancing the water retention ability of the tailings; and
3) Constructing groundwater flow barriers within the tailings.

Modification of the water balance involves increasing water input into, or decreasing water losses from, the tailings. Water retention can be improved by enhancing the physical characteristics of the tailings prior to placement - thickened tailings which provide a very high level of saturation and considerable capillary zone height represent one means of achieving this objective. The concept of a groundwater flow barrier involves the installation of a barrier within tailings to reduce the horizontal and often preferential downgradient flow of pore water within the tailings. The suitability of these approaches is dependent upon site specific conditions.

Not all tailings management facilities are well suited for the application of elevated water tables. Tailings stacks were historically designed to minimize the water level within the tailings and maintain as small a surface pond as possible. The application of elevated water table concepts to raised stacks presents a considerable challenge. The application of the concept to other tailings impoundments (e.g. valley dam impoundments) is possible and may be economically beneficial in comparison to other closure options.

Elevated water tables have been an intrinsic component of closure strategies for tailings management facilities but have only recently become proposed or applied as a principal basis of closure plans. As such, experience in the application and performance assessment of elevated water tables is recent and being accumulated. The developing state of knowledge is evidenced by the relatively limited data available regarding the application of elevated water tables to sulphide tailings impoundments. Nine sites, however, provide relevant but preliminary data:

- Five sites (the Elura mine in Australia, the Greens Creek mine in Alaska, the Cluff Lake mine in Saskatchewan, Les Mines Selbaie in Québec, and the Kidd Creek metallurgical site in Ontario) involve the ongoing or discontinued disposal of thickened tailings. These sites represent a broad range of site conditions, and tailings disposal and closure strategies.

- Three sites (the Falconbridge New Tailings site, the Dona Lake mine site, and the Stanrock mine site - all in Ontario) involve the modification of the water balance of the tailings. At the Falconbridge New Tailings site, research has been carried out to investigate the important relationships between oxygen consumption rates within tailings, the degree of saturation, and depth to the tailings water table. At the Dona Lake site, a closure plan is being implemented which relies in part on the elevation of the water table within the coarse tailings beach area. The proposed approach for the historic Stanrock tailings stack is based on replacing spigotted tailings dams with engineered water retaining structures - this would ultimately allow the water table within the tailings to rise and inhibit acid production from much of the tailings. Chemical treatment of acidic drainage from the Stanrock tailings would continue for an interim period following the construction of the new containment structures.

! The Sturgeon Lake site in Ontario involves a combination of a modified water balance and a groundwater flow barrier.

Chemical treatment of acidic drainage may be required, in some instances, after the application of an elevated water table concept. Key sources of acid production could include sulphide solids in the near surface and not sufficiently saturated zone, and fluctuations in the water table elevation. The effect of water table fluctuation could be mitigated in some cases by the use of a cover to reduce evaporative losses, increase infiltration, or to elevate the water table to the cover. The additional and interim use of chemical treatment may be cost beneficial when compared to other options.

Numerical modelling techniques are being used to predict the performance of elevated water table concepts in controlling or reducing acidic drainage. These techniques draw upon soil science and civil engineering methods of predicting water movement in soil, and can be complemented by numerical models for the prediction of acidic production in tailings. These models are important as they provide a means of preliminarily assessing the performance of a closure option, and of addressing the effect of changes in ambient conditions (e.g. drought conditions).

Preliminary and conceptual cost comparisons were carried out based on the closure of three types of tailings impoundments: a tailings stack; a valley impoundment underlain by a pervious zone; and a valley impoundment underlain by an impervious zone. Closure options included the perpetual collection and treatment of acidic drainage, the use of an engineered cover, and applications of elevated water table concepts. The first order estimates of closure costs indicate that elevated water table concepts, when suitable, can provide significant closure cost saving in comparison to collection and treatment, and the use of an engineered cap.

SOMMAIRE

Certaines méthodes, comme la déposition subaquatique, permettent de contrôler et de réduire la production de drainage acide en provenance de résidus. Ces méthodes ne peuvent s'appliquer à toutes les installations de gestion des résidus; cependant, elles conviennent à un grand nombre d'entre elles. Ces méthodes présentent divers inconvénients, notamment leur coût élevé. Il faut donc trouver des solutions de rechange qui peuvent réduire le coût de fermeture, et peut-être même éliminer certains des inconvénients associés aux méthodes actuelles. Le présent rapport fait état d'une méthode de rechange qui consiste à utiliser une nappe phréatique surélevée; cette méthode est de plus en plus considérée pour la fermeture de parcs à résidus sulfurés.

L'utilisation d'une nappe phréatique surélevée dans les résidus présente un grand intérêt et les données publiées sur le sujet font état d'un très faible taux d'oxydation des sulfures, semblable au taux d'oxydation dans les résidus sulfurés couverts d'eau, là où la nappe phréatique atteint presque la surface des résidus. Les trois méthodes suivantes visent à mettre en application le principe de la surélévation de la nappe phréatique et de la zone de capillarité s'y rapportant dans les résidus :

1) modification du bilan hydrique dans le parc à résidus;
2) amélioration de la capacité de rétention d'eau des résidus;
3) construction de barrières freinant l'écoulement de l'eau souterraine.

La modification du bilan hydrique consiste à accroître l'apport d'eau ou à réduire les pertes en eau des résidus. On peut accroître la capacité de rétention d'eau des résidus en améliorant leurs caractéristiques physiques avant la mise en place. L'une des façons de parvenir à un niveau de saturation élevé consiste à épaissir les résidus, ce qui permet de porter à une hauteur relativement élevée la zone de capillarité. Par ailleurs, la construction d'une barrière freinant l'écoulement de l'eau souterraine comporte l'installation d'une barrière à l'intérieur des résidus de manière à réduire l'écoulement horizontal des eaux interstitielles qui s'effectue souvent d'amont en aval à l'intérieur des résidus. Le choix de la méthode dépend des conditions particulières du site.

Toutes les installations de gestion des résidus ne conviennent pas à l'utilisation d'une nappe phréatique surélevée. Les tas de résidus étaient à l'origine conçues pour réduire le niveau d'eau à l'intérieur des résidus et pour maintenir un étang de surface qui soit le plus petit possible. L'application du principe de la nappe phréatique surélevée aux tas de résidus constitue un défi de taille. L'application du principe à d'autres types de parcs à résidus (p. ex. Digues dans une vallée) est possible et peut être avantageuse sur le plan économique, si on la compare à d'autres options de fermeture.

Les nappes phréatiques surélevées sont une composante intrinsèque des stratégies de fermeture des installations de gestion des résidus; cependant, elles ne sont que depuis récemment proposées ou appliquées à titre d'élément principal des plans de fermeture. À ce titre, l'expérience de l'application et de l'évaluation du rendement de ces dernières sont récentes et on procède actuellement à la cueillette d'information. L'état des connaissances en développement est mis en lumière par le nombre relativement limité de données concernant l'application du principe des nappes phréatiques surélevée aux parcs à résidus sulfurés. Toutefois, des données pertinentes, quoique préliminaires, ont été recueillies à neuf sites :

! À cinq sites (la mine Elura en Australie, la mine Greens Creek en Alaska, la mine Cluff Lake en Saskatchewan, Les Mines Selbaie au Québec et le site métallurgique Kidd Creek en Ontario), on a mis en application le confinement continu ou interrompu de résidus épaissis. Ces sites présentent un grand éventail de conditions différentes et permettent d'appliquer des stratégies de confinement des résidus et de fermeture différentes.

! À trois sites (le parc à résidus New Tailings de Falconbridge, le site minier Dona Lake et le site minier Stanrock - tous en Ontario), on a appliqué le principe de la modification du bilan hydrique dans les résidus. Au site de Falconbridge, on a effectué des recherches visant à étudier les relations importantes qui existent entre le taux de consommation d'oxygène à l'intérieur des résidus, le degré de saturation et la profondeur de la nappe phréatique. Au site Dona Lake, on procède actuellement à la mise en oeuvre d'un plan de fermeture fondé en partie sur le principe de l'utilisation d'une nappe phréatique surélevée à l'intérieur de la zone de la plage de résidus à grain grossier. La méthode proposée pour le parc à résidus de Stanrock est fondée sur le remplacement des digues construites à partir de résidus par des digues imperméables afin de retenir l'eau - ce qui permettrait la surélévation de la nappe phréatique, empêchant par le fait même la production d'acide dans la majeure partie des résidus. Le traitement chimique du drainage acide des résidus de Stanrock se poursuivrait temporairement après la construction de nouvelles structures de confinement.

! Au site Sturgeon Lake en Ontario, la stratégie comporte à la fois le principe de modification du bilan hydrique et la construction de digues contre l'écoulement de l'eau souterraine.

Il peut être nécessaire de traiter chimiquement le drainage acide, dans certains cas, après l'application de la méthode de la nappe phréatique surélevée. Les sources clés de production d'acide pourraient comprendre la présence de matières solides de sulfures près de la surface, la présence d'une zone qui n'est pas suffisamment saturée, ainsi que des fluctuations de l'élévation de la nappe phréatique. Dans certains cas, il serait possible d'atténuer les effets de la fluctuation de la nappe phréatique en utilisant une couverture, de manière à réduire les pertes dues à l'évaporation, accroître l'infiltration ou pour élever la nappe phréatique jusqu'à la couverture. Le recours à un traitement chimique additionnel et temporaire peut être avantageux sur le plan économique si on le compare à d'autres options.

Des techniques de modélisation numérique sont employées pour prévoir le rendement des nappes phréatiques surélevées en matière de contrôle ou de réduction du drainage minier. Ces techniques mettent à contribution la science des sols et les méthodes de génie civil visant à prévoir les mouvements de l'eau dans les sols et peuvent être accompagnées de modèles numériques pour la prévision de production d'acide dans les résidus. Ces modèles sont importants parce qu'ils constituent un moyen d'évaluer de façon préliminaire le rendement d'une option de fermeture et de régler le problème de l'effet des changements des conditions ambiantes (p. ex. dans des conditions de sécheresse).

Les comparaisons des coûts préliminaires et des coûts de conception sont fondés sur la fermeture de trois types de parcs à résidus, d'un tas de résidus, d'une digue dans une vallée reposant sur une zone perméable et d'une digue reposant sur une zone imperméable. Les options de fermeture comprennent la collecte et le traitement à perpétuité du drainage acide, l'utilisation d'une couverture multi-couches et des applications du principe de la nappe phréatique surélevée. Les estimations de premier ordre des coûts de fermeture indiquent que l'application du principe de la nappe phréatique surélevée, là où les conditions s'y prêtent, peut permettre de réaliser des économies importantes quant aux coûts de fermeture, comparativement à la captation, au traitement et à l'utilisation d'une couverture multi-couches.

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1.0 INTRODUCTION

1.1 OVERVIEW

Ongoing research and developments in the prediction, prevention, and control of acid mine drainage (AMD) indicate that the generation of acidic drainage from reactive tailings can be prevented or effectively controlled by limiting the diffusion of atmospheric oxygen through interstitial pore spaces in tailings to sulphide solids. An elevated water table within reactive tailings is a relatively new concept which makes effective use of the low rate of diffusion of oxygen through saturated or near saturated pore spaces.

Elevated water tables may be very useful in developing passive decommissioning strategies for reactive tailings, or at least mitigating acidic drainage treatment requirements by reducing the quantity of sulphide mineralization available for oxidation. The use of elevated water tables as a means of reducing the quantity of sulphide minerals available for oxidation has been studied at only a few tailings management facilities, and has been proposed for use at a few other sites.

This study focusses on the use of an elevated water table and is meant to serve as a useful reference document. It describes relevant theories, elevated water table concepts, and summarizes the limited empirical and scientific data currently available. In concept, elevated water tables are ideally suited for application in Canada due in large extent to typical net precipitation conditions. This concept is also attractive as it addresses many of the key concerns associated with the use of moisture retaining dry covers and wet covers. The major problem identified in this study was limited data and case histories respecting the use of elevated water tables as a means of controlling or reducing acidic drainage from tailings.

1.2 REPORT ORGANIZATION

The physicochemical properties of the tailings and the physical characteristics of the tailings management facility ultimately determine whether or not a tailings basin will be suitable for an elevated water table. The key factors that need to be characterized when determining whether or not an elevated water table would be suitable for a tailings basin, and assessing a potential elevated water table application are discussed in Section 2.0.

Concepts that may be applied to raise the water table and the associated capillary zone within reactive tailings are identified and described in Section 3.0. These concepts include: modifying the water balance of the reactive tailings, enhancing the water retention ability of the tailings, and constructing groundwater flow barriers within tailings - the latter is a concept developed by the project team. The modelling of the concept of groundwater flow barriers within tailings is new and was done as part of this study. The two dimensional modelling of groundwater flow barriers was completed by R.V. Nicholson and P. Tibble of the Waterloo Centre for Groundwater Research, at the University of Waterloo. Sites that provide relevant field experience (empirical findings) and data are described in Section 4.0.

Section 5.0 presents an evaluation of decommissioning options for three types of tailings management facilities: a tailings stack; a tailings deposit contained in a valley naturally underlain by pervious materials; and a tailings deposit contained in a valley naturally underlain by impervious materials. The decommissioning options considered include the long term collection and treatment of acidic drainage, construction and maintenance of moisture retaining dry covers, and the application of the elevated water table concepts. These scenarios serve to highlight the potential cost saving benefits of the elevated water table concepts.

A discussion of findings is provided in Section 6.0. Priorities for further technology development are also presented.

1.3 ACKNOWLEDGEMENTS

The Director and Manager of this study (Randall Knapp and David Orava, respectively) acknowledge the diverse and important contributions made by the multi-discipline study team which included Henny Guttman, Carol Pettit, Jeffrey Martin, and specialist consultants at other organizations: Fred Brackebusch, a specialist in the area of paste fill; Iain Bruce and Claude Bédard, geotechnical engineers with considerable experience with mine tailings impoundments; and Ronald V. Nicholson of the University of Waterloo, Centre for Groundwater Research. Suggestions and comments received from external reviewers (Bob Michelutti at Falconbridge, Bernie Swarbrick at Kidd Creek, Brain MacQuarrie at Inco in Thompson, Steve Reitzel now at Klohn Crippen, and Leonard Sinclair at Saskatchewan Environment and Resource Management) and the guidance received from Gilles Tremblay of MEND were all most useful to the study team and their contributions are also well appreciated.

Mining companies and other organizations made considerable and likely the most

important contributions to the study by providing much of the recent information used in the report. Contributions from Steve Heppner of the Admiralty National Monument in Alaska, and Debbie Bryant of Les Mines Selbaie in Québec are noteworthy.

2.0 ELEVATED WATER TABLE CONSIDERATIONS

Elevated water table concepts involve the raising of the level of the saturated zone within tailings impoundments so that reactive tailings are maintained in a saturated or sufficiently near-saturated state to inhibit the oxidation of the sulphide minerals. Key factors that need to be taken into account when considering or developing an elevated water table program are addressed in this section.

2.1 BACKGROUND

A typical groundwater profile found in soils including tailings is presented in Figure 2.1. The water table represents the divide between the vadose zone and the phreatic zone. Freeze and Cherry (1979) and Domenico and Schwartz (1990) describe the water table as the surface at which the fluid pressure in the pores of the porous medium equals the atmospheric pressure.

The capillary fringe or tension-saturated zone occurs immediately above the water table and results from a combination of the surface tension of water and the ability of water to wet the surface of the medium. The vertical height of this zone above the water table depends on the interstitial pore size which is directly related to the particle grain-size distribution. Specifically, the smaller the pore size the greater the surface tension and consequently the higher the capillary rise above the water table.

Tailings are crushed rock particles - a waste byproduct resulting from the comminution of ore. Tailings typically contain a grain-size distribution ranging from medium sand to clay sized particles with 70 to 90% of the material less than 74   m (200 mesh) in size (Figures 2.2A to 2.2C). During tailings placement, beach type deposits are formed as the particles are hydraulically separated by grain size, density, and shape. Relatively coarse-grained and denser material settles closer to the discharge point(s) while fine-grained and less dense tailings particles including slimes settle further downgradient as indicated in Figure 2.3.

The hydraulic conductivity (K), which is a measure of the ease with which water passes through a particular medium, of the tailings decreases with distance from the source. Porosity is a measure of the water storage capacity of a medium. The porosity of unconsolidated tailings is largely dependent upon the packing of the grains, their arrangement, and size distribution.

FIGURE 2.1

GROUNDWATER PROFILES

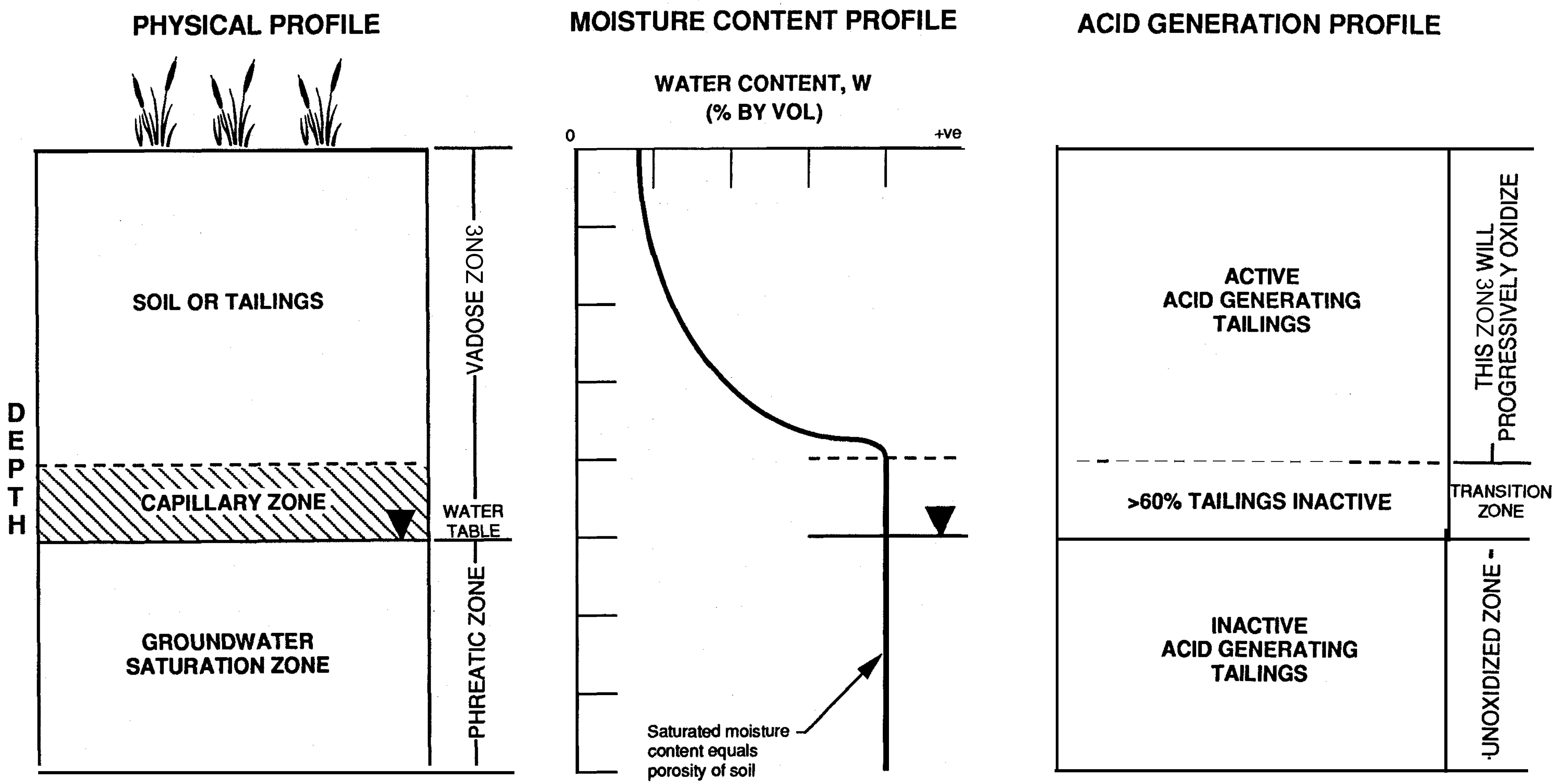


FIGURE 2.2

GRAIN SIZE DISTRIBUTION

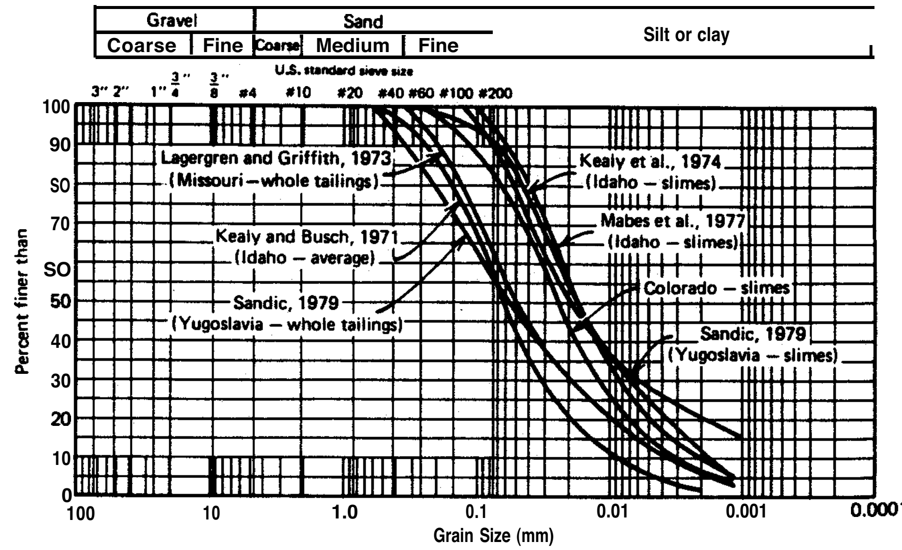


FIGURE 2.2A GRADATIONS OF LEAD-ZINC TAILINGS

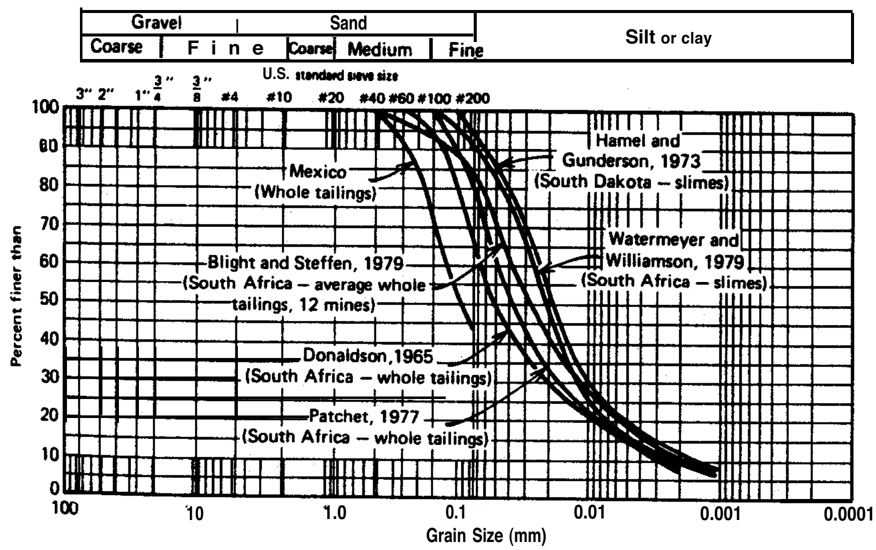


FIGURE 2.28 GRADATIONS OF GOLD-SILVER TAILINGS

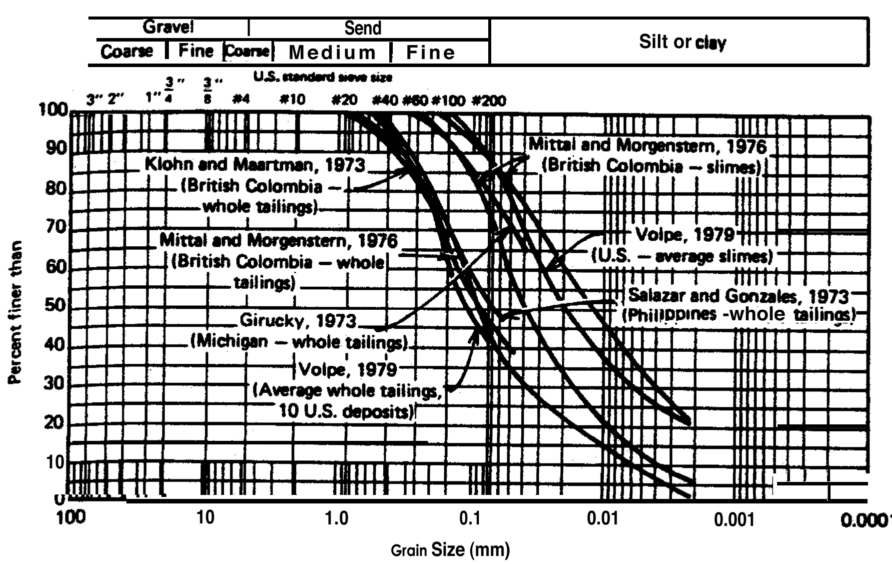
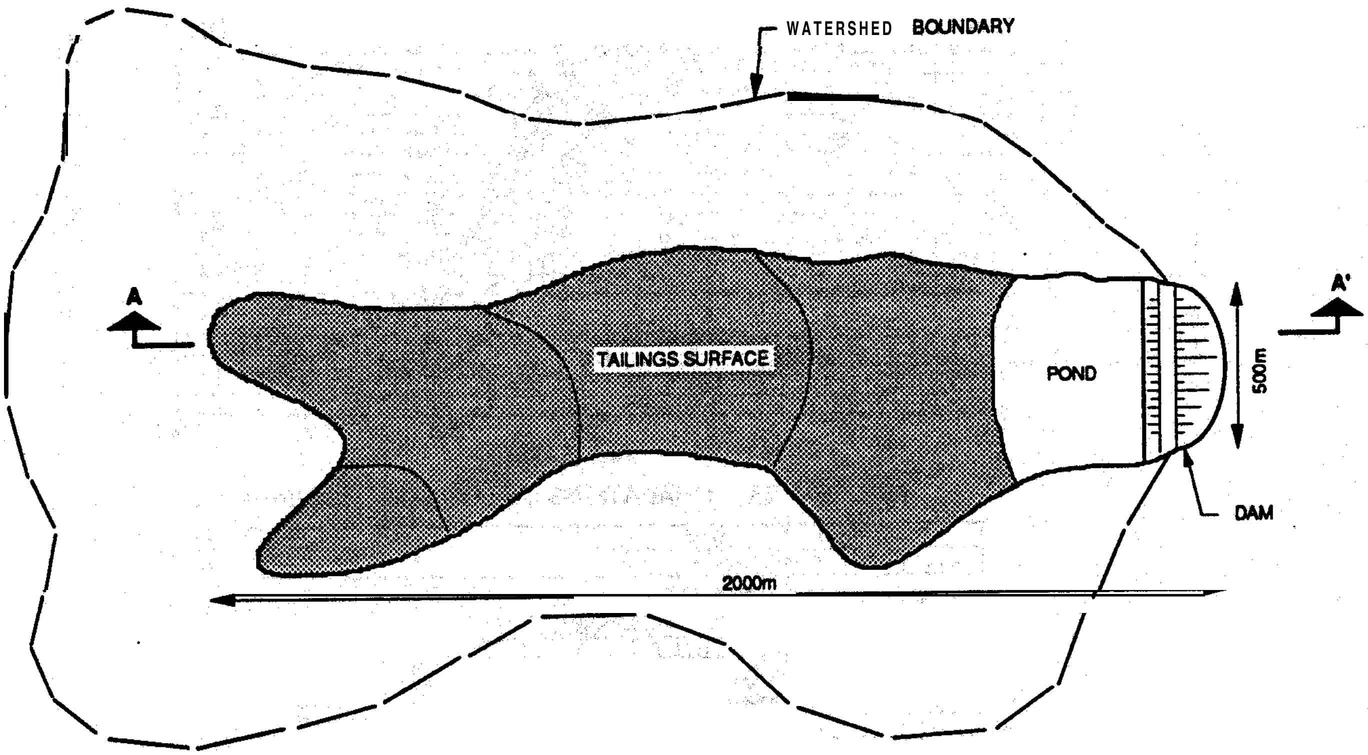


FIGURE 2.2C GRADATIONS OF COPPER TAILINGS

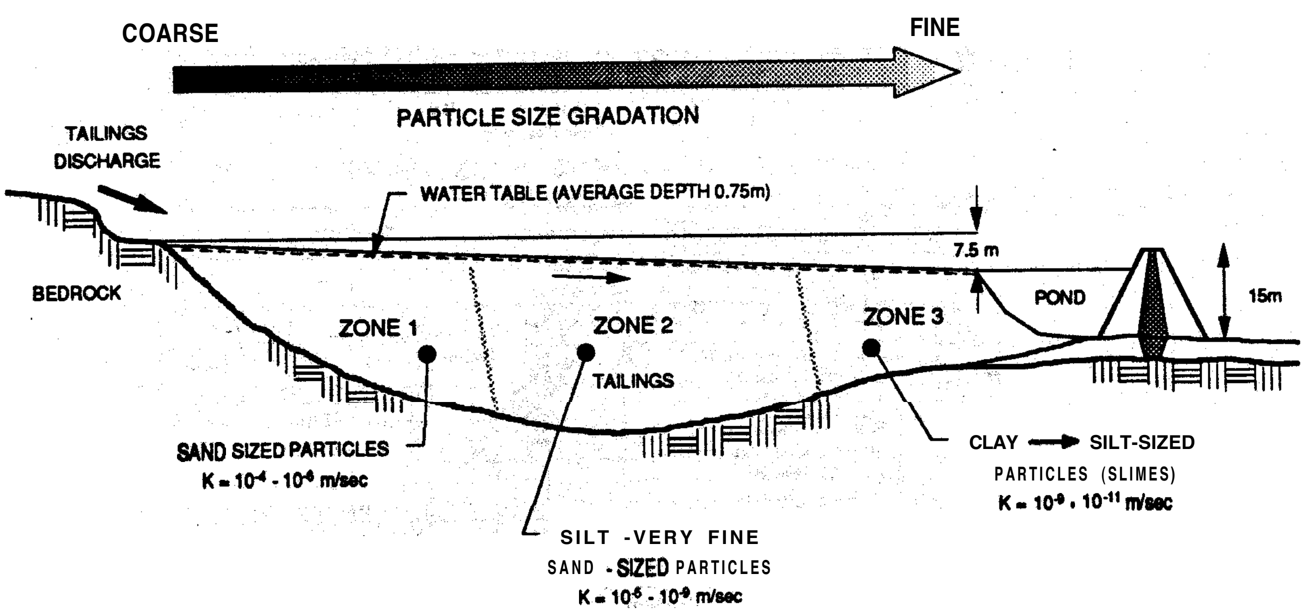
SOURCE: REVISED FROM VICK, 1990

FIGURE 2.3

PARTICLE - SIZE DISTRIBUTION AND HYDRAULIC CONDUCTIVITY WITH DISTANCE FROM SOURCE



PLAN VIEW



SECTION A-A
(NOT TO SCALE)

For the purpose of this report, an elevated water table concept is defined as an engineered practice designed to reduce the depth of the unsaturated zone overlying the main saturated zone.

The primary role of an elevated water table in reactive tailings is to reduce the total depth of unsaturated tailings exposed to oxygen as the elevated water table acts as a diffusion barrier to atmospheric oxygen. The primary mode of atmospheric oxygen transport to the surfaces of sulphide minerals in the tailings is by molecular diffusion through interstitial pore spaces and as such the diffusion of oxygen through the tailings pore space is a strong function of the moisture content. From experimental data in tailings, which can be generalized to other porous media, a useful expression for the effective diffusion coefficient (D_e) as the function of the degree of saturation is as follows (Elberling et al., 1993):

$$D_e = D_a \tau (1 - S)^{\alpha} + \frac{D_w \tau S}{H} \tag{2.1}$$

where:

D_e	=	effective diffusion coefficient in cover material ($m^2 s^{-1}$)
D_a	=	diffusion coefficient of oxygen in air ($m^2 s^{-1}$)
D_w	=	diffusion coefficient of oxygen in water ($m^2 s^{-1}$)
τ	=	experimental parameter
S	=	degree of saturation (volume of water/volume of pore space)
H	=	modified Henry's constant
α	=	experimental parameter

Chao et al. (1991) devised a mass spectrometer - based method for the rapid measurement of the effective diffusion coefficient in till covers. For compacted till covers, the fitted parameter values were J = 0.032 and " = 3.92. The effective diffusion coefficient with field samples varied from 5.64 x 10^{-7} m^2 s^{-1} to 1.66 x 10^{-8} m^2 s^{-1}, depending on the degree of saturation (0.20 to 0.86).

The dependence of the effective diffusion coefficient (D_e) on the degree of saturation as shown in Equation 2.1 and the fitted parameter values determined above (" = 3.92) suggests that the diffusion coefficient can vary over five orders of magnitude. However, the most significant attenuations in D_e occur at saturation levels above 0.6. This means that nearly saturated tailings (being in excess of about 60% saturation) in the upper zone can provide orders of magnitude decrease in diffusive oxygen transport to the underlying tailings. The elevation of the phreatic surface within reactive tailings can therefore substantially reduce the inventory of exposed and drained sulphide tailings available for acid generation.

The position of the water table has two effects on the oxidation of sulphide minerals. The first is to effectively limit the oxidation of sulphides to the tailings zone above the water table. The second effect relates to the higher moisture levels immediately above the water table which may extend significantly close to the surface when the water table is sufficiently shallow or when there is strong capillary action. Fine-grained tailings can retain more moisture at higher elevations above the water table and will therefore exhibit lower oxidation rates than coarser tailings with a similar depth to the water table.

The depth from the surface of the tailings to the water table that is sufficient to reduce oxidation rates is not immediately obvious. An elevation that is closest but below the tailings surface is best from the perspective of reducing the diffusion of oxygen into the tailings. However, such a condition has two principal drawbacks:

1) a water table at surface can lead to physical instability of the tailings surface; and

2) a shallow water table can lead to the discharge of near surface tailings pore water to surface runoff during precipitation events.

With respect to item 1), granular porous media such as tailings are most stable when drained or at least under negative pore pressure. In tailings, this condition occurs above the water table. As the water table elevation in tailings increases, the effective stress in the media decreases and the shear stress required to move the tailings decreases. This increases the potential for the tailings to flow as a result of a disturbance. As such, tailings containment structures must be capable of safely accommodating the raising of the water level within the tailings, and in a water pond (if present). With respect to item 2), this is a less understood drawback. The phenomenon of rapid discharge of shallow tailings pore water during rainfall events at the Nordic tailings at Elliot Lake, Ontario was reported by Blowes and Gillham (1988).

As a guideline, the depth to the elevated water table should not fall below a depth equivalent to the Air Entry Value (AEV) of the tailings at the surface. The AEV value is a measure of the suction pressure created to begin draining water from the tailings. This suction can pull water from the water table upwards thus creating near saturated conditions well above the actual water table. Measurements of thickened or non-segregated tailings indicate that these tailings have very high suction values (in the order of several metres) and have the potential to retain a very high moisture content above the water table.

Nicholson et al. (1991) proposed a relationship to estimate the AEV from the d_{10} grain size - a parameter that is straightforward to measure. In general, coarser tailings require a shallower water table condition than fine-grained tailings to achieve the same reduction in oxidation rates.

The rates of sulphide oxidation below an elevated water table would be expected to be similar to rates under a surface water cover. Theoretical analysis suggests that these rates will be controlled by the infiltration of water containing dissolved oxygen rather than by diffusion of atmospheric oxygen. Under saturated conditions, the diffusion rates become so low that infiltration dominates but still at very small rates. According to Nicholson et al. (1989), these rates would be on the order of 0.09 mol-0_2 m^{-2} a^{-1} (based on 10 mg L^{-1} of dissolved oxygen and an infiltration rate of 0.3 m a^{-1}).

At active tailings sites, the surface layer of sulphide tailings is regularly wetted and the tailings water table is recharged as new tailings are deposited. Once tailings deposition ceases, the degree of saturation of the interstitial pore spaces in the near surface tailings typically decreases, and this allows atmospheric oxygen to diffuse into and react with available sulphide minerals. This process has been observed at many sites.

The following three conceptual approaches to creating an elevated water table are presented in Section 3.0.

1) Create a Positive Water Balance in Tailings
2) Enhance the Water Retention Ability of the Tailings
3) Construct Groundwater Flow Barriers within Tailings

2.2 REQUIRED CHARACTERIZATION

A tailings management facility (TMF) being considered as a potential elevated water table site needs to be well characterized. A holistic perspective should be taken and the data collection should include both technical and nontechnical factors important for project planning and approvals. Key factors that need to be addressed are listed in Table 2.1. Site specific conditions could require that additional factors be considered.

It is important that a characterization study assess spatial variations in properties within the tailings mass, both above and below the water table, and across the tailings basin (e.g. in areas having coarse tailings, medium to fine grained tailings, and slimes).

Table 2.1

CHARACTERIZATION REQUIREMENTS

Factor	Technical Aspect
Acid Generation Potential of Tailings	Static and kinetic testing. Mineralogy. Extent of oxidation (if any). Metal concentrations.
Physical Characteristics of Tailings Solids	Grain size distribution, permeability, density, porosity.
Tailings Pore Water	Depth to water table. Height of capillary zone. Temperature profile. Pore water quality.
Hydrogeology	Groundwater quality and use. Hydrogeological regime of the basin including seepage from containment structures.
Surface Water	Surface water quality and use (include the tailings pond, adjacent surface water bodies, and flows to/from the tailings basin). Hydrology of tailings pond. Storm water management.
Tailings Management Facility	Tailings distribution within the TMF. TMF design. Closure planning. Land use. Site specific factors.

2.2.1 Acid Generation Potential of Tailings

Acidic drainage is the result of the combined chemical and biological oxidation of sulphide minerals and the concomitant release of associated metals, such as iron, aluminum, manganese, uranium and other heavy metals. The oxidation of pyrite, the predominant sulphide mineral, can be expressed by the following stoichiometric equations:

Pyrite Oxidation:

$$FeS_2 + \frac{7}{2}O_2 + H_2O \rightarrow Fe^{2+} + 2SO_4^{2-} + 2H^+ \tag{2.2}$$

$$or,\ 2FeS_2 + 7O_2 + 2H_2O \rightarrow 2FeSO_4 + 2H_2SO_4 \tag{2.3}$$

Ferrous iron (Fe^{2+}) is oxidized to its ferric state as follows.

$$2\ Fe^{2+} + \frac{1}{2}\ O_2 + 2H^+ \rightarrow 2Fe^{3+} + H_2O \tag{2.4}$$

The reaction given by Equation 2.4 is dependent upon the pH of the solution and presence of catalysts such as *Thiobacillus ferroxidans* and other acidophilic bacteria. Under acidic conditions (pH 2 to 3), the biological oxidation rate is greater than the chemical rate.

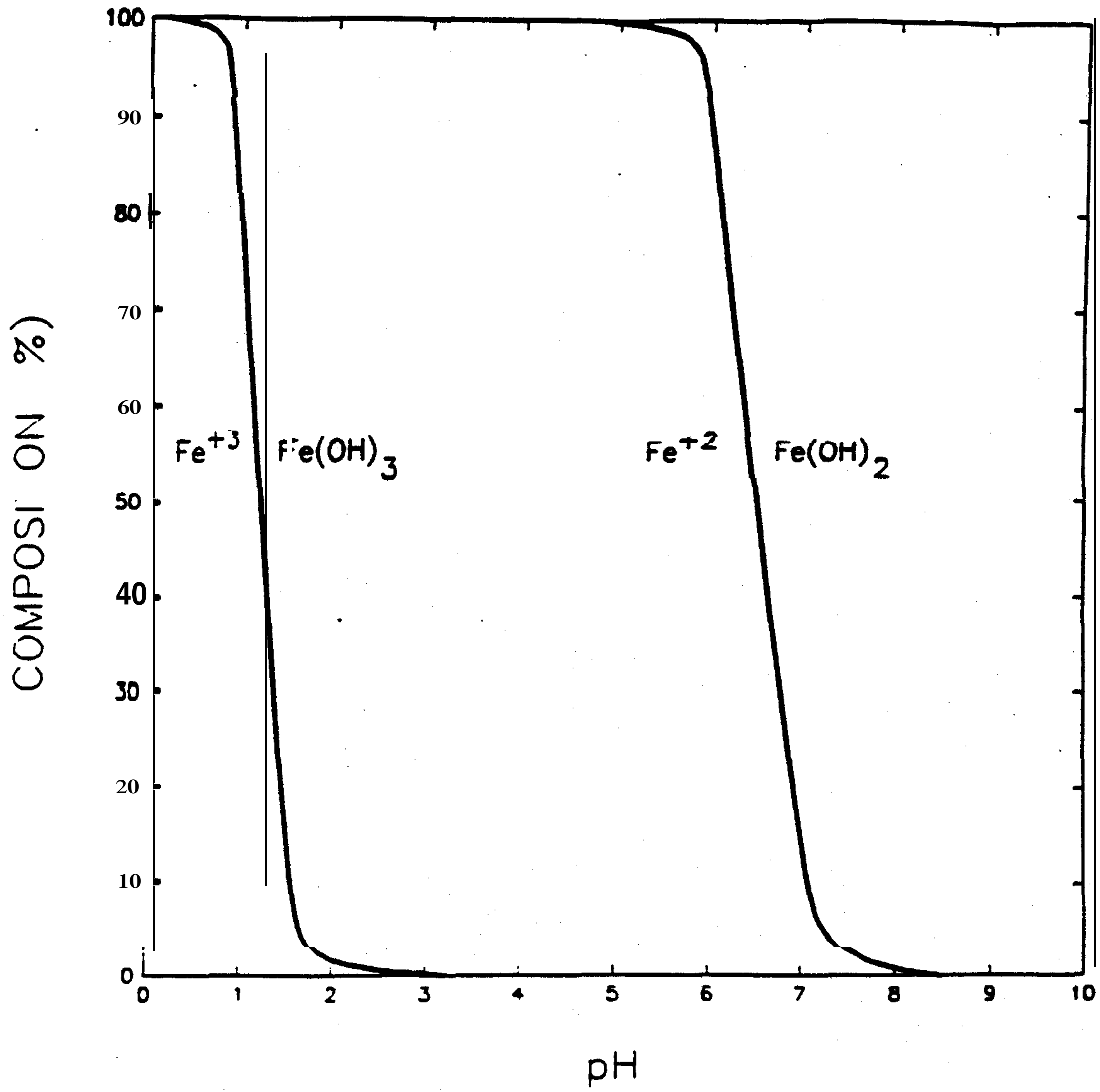
The dependence of the dissolved ferric iron to variations in pH is shown in Figure 2.4. Ferric iron does not remain in solution much above pH 2 to 3 where it is hydrolysed to $Fe(OH)_3$.

$$Fe^{3+} + 3H_2O \rightarrow Fe(OH)_3 + 3H^+ \tag{2.5}$$

Ferric iron is an excellent oxidant, under low pH conditions available ferric iron acts as an oxidizing agent to produce additional sulphate and hence sulphuric acid. The

FIGURE 2.4

DISTRIBUTIONOFFERROUS AND FERRIC IRON AS A FUNCTION OF pH



SOURCE: TAKEN FROM FIGURES 11.7 AND 11.8, RITCEY, 1989 anoxic oxidation of pyrite is as follows:

$$14Fe^{3+} + FeS_2 + 8H_2O \rightarrow 15Fe^{2+} + 2SO_4^{2-} + 16H^{+} \qquad (2.6)$$

Sulphide minerals, other than pyrite, may have different reaction mechanisms, stoichiometries, and reaction rate limiting factors.

The acid generation potential of a waste can be determined through conventional acid base accounting and kinetic testing. Several MEND reports have been prepared to assist the mining industry and government in the characterization of reactive mine wastes (i.e. SENES, Golder, and Laval, 1994; SRK, 1990; Coastech, 1991).

The extent to which near surface oxidation of reactive tailings has occurred is also of importance. The collection of this data would involve field work to determine:

- the depth of the zone of tailings that has been oxidized; and

- an assessment based on mineralogical evaluations and static and dynamic testing of the oxidized zone of the residual acid generation potential of the oxidized zone of tailings.

2.2.2 Physical Characteristics of Tailings Solids

Characterization of the tailings solids is critical as the data is required for the prediction of the height and effectiveness of the capillary zone and the selection of a suitable water table elevation. Two key parameters, grain size and permeability, are discussed below.

Grain Size:

Grain size and size distribution affect:

- the rate of acid generation;

- ! the reactivity of buffering minerals - reactive surface area being a factor;
- ! tailings moisture retention ability;
- ! permeability - vertical and horizontal components; and
- ! mechanisms of contaminant transport (diffusive/convective).

When characterizing tailings solids, mineralogical and chemical testing should be completed for various screen sizes. Of specific importance is acid base accounting data relative to grain size - it is typically found that acid producing and acid consuming materials are present in different particle size fractions.

Hydraulically deposited tailings form beaches consisting of coarse-grained material proximal to the discharge point grading into clay-size particles at the distal end. Spigot or end-of-pipe discharge methods can produce highly heterogeneous beach deposits. Vertical bedding or alternating layers of coarse and fine tailings material are, however, characteristic of many tailings deposits. Slimes sedimentation is controlled to a large extent by vertical settling. Consequently, the physical properties of tailings can vary significantly throughout a tailings management facility.

Permeability:

Permeability is a measure of the ease that water can move through a medium (e.g. tailings). For example, high permeabilities are found in well sorted gravel, while very low permeabilities are found in dense crystalline rock. The permeability is largely controlled by grain-size distribution in unconsolidated materials.

The vertical permeabilities in tailings are characteristically one to two orders of magnitude lower than the horizontal values. Vick (1990) reported ratios of horizontal to vertical permeabilities ranging from 2 to 10 for uniform beach sand deposits and underwater deposited slimes. As such, it is expected that in many conventional hydraulically deposited tailings, pore water moves preferentially in the horizontal direction (e.g. parallel to the surface) while also migrating downward.

The permeability (k) of saturated tailings can be estimated by grain size analysis, through laboratory pereameter tests, or through field piezometer tests. Permeability may vary with time as the following three phenomena occur within tailings:

1) permeability may be reduced due to secondary mineral precipitation (e.g. formation of sticky precipitates such as gypsum, or impermeable layers known as hardpans);

2) permeability may be reduced due to the consolidation of the tailings over time; and

3) alternately, permeability may increase due to the dissolution of secondary minerals (e.g. gypsum $CaSO_4 \cdot 2H_2O$).

2.2.3 Tailings Pore Water

The tailings pore water may be acidic from the oxidation of sulphide minerals prior to the implementation of the elevated water table concept. Experience has demonstrated that in some cases, acidic pore water may be naturally neutralized by available alkalinity within the tailings mass and/or in underlying geologic formations as the water migrates through these materials. Predictive modelling techniques can be used to assess the quality of future seepage.

Several types of predictive geochemical models are currently available (Perkins et al., 1995). Examples include geochemical equilibrium models such as MINTEQA2, and acid generation models such as RATAP and WATAIL. MINTEQA2 can be used for estimating water quality changes that may occur in a tailings pond with pH modification or leaching by groundwaters. RATAP and WATAIL are useful for evaluating long term behaviour of unsaturated reactive tailings.

Conventional testing such as pore water sampling, sequential leaching tests, and humidity cells can be used to establish pore water (source concentration) characteristics, leachable fractions, and possible long term (ultimate) concentrations. Empirical expressions can be developed to predict the change in contaminant concentrations over time.

2.2.4 Hydrogeology

The hydrogeology of the TMF is a critical factor in assessing the applicability of an elevated water table concept, and dictates what engineered controls would be necessary.

Important considerations are:

- the permeability of containment structures, the underlying or enclosing sediments and bedrock;
- location and gradient of the impoundment groundwater table;
- sources of groundwater recharge;
- local and regional groundwater flow paths; and
- downstream water use and potential receptors.

An ideal elevated water table application would be a natural basin contained by low-permeability bedrock and/or sediments and low-permeability containment structures which would ensure that the reactive tailings remain saturated and that water transport is restricted to the surface of the tailings. There would be minimal infiltration or groundwater discharge. Few facilities are ideal, however, conceptual approaches to creating and maintaining an elevated water table in non-ideal situations are available - several such approaches are presented in Section 3.0.

An assessment of the water balance of the tailings at a particular site represents the first step towards determining what is the most appropriate and cost effective method for establishing an elevated water table. As indicated previously, the water balance variables are inflows such as precipitation, and runoff from watershed drainage areas and outflows such as evaporation, seepage, and direct discharge.

Modelling (hydrology, geochemical) can be conducted to assist in the evaluation of the effectiveness of a particular approach under various water balance conditions to reduce the amount of acid generating material contained within the unsaturated zone.

2.2.5 Surface Water

The management of surface water flows through a TMF is extremely important, and measures proposed to raise the water table should be assessed to determine what potential impact, if any, they may have on the hydrology of the tailings basin.

Surface Water Flows:

Many of the measures that can be taken to create an elevated water table, can have an effect on the hydrology of a tailings basin. The diversion of additional surface flows (either runoff or stream flow) to a TMF would increase the volume of water reporting to the surface of the tailings and would require that the surface water management strategy be reviewed and revised if necessary to ensure that surface flows are safely controlled. Computerized water balance models such as WATBAL (Welch et al., 1992) can be used to predict flows to tailings management facilities, the rise in water pond levels, and the rate of discharge.

Surface Water Quality:

There is no unique water balance for a tailings basin as input parameters can vary from day to day, month to month, and even yearly (Welch et al., 1992). For instance, precipitation varies considerably, as does evaporative loss. As such, it is expected that the water table within tailings will fluctuate - the degree would depend heavily on site specific conditions. A drop in the water table level at a decommissioned tailings basin where reactive tailings are close to surface, could result in a decrease in the saturation of pore spaces and subsequently acid generation. This situation would be unacceptable in most cases, however, mitigative measures can be taken. Preventative measures could include raising the elevation of the water table to a level higher than normally required using a surface layer or cover made of non-acid generating material that would allow capillary rise sufficiently above the reactive tailings. The use of a top layer may also allow the surface to be vegetated thereby reducing surface erosion and suspended solids levels in runoff flows.

Runoff water quality may initially be affected by the discharge of near surface pore water but as a general comment, the quality of runoff from a tailings management facility would be expected to improve over time. The prediction of tailings runoff quality over time is an area where further study is required.

Measures that can be taken to elevate the water table may be beneficial to the quality of adjacent surface water bodies. For instance, the use of seepage cutoffs along perimeter containment structures may significantly reduce or eliminate adverse impacts to the quality of nearby waterbodies.

Efficient surface water management can be achieved by: diverting additional runoff to a TMF; raising the level of a water pond; and taking measures to reduce losses of tailings pore water. If these proactive measures are optimized, it may be possible to develop an elevated water table in a basin with minimal discharge to the environment.

2.2.6 Tailings Basin

Not all existing tailings facilities are suited for the elevated water table concepts. Tailings basins were historically designed as raised stacks or valley impoundments. Tailings stacks were designed to minimize water tables by creating well drained coarse sand dams and by maintaining as small a surface pond as practical. For these types of facilities the application of an elevated water table represents a significant challenge. However, such applications are possible and could prove to be economically attractive in comparison with other closure options.

Valley impoundments often used lakes and swamps with valley dams to provide increased containment and settling ponds. These types of structures intrinsically have elevated water tables and the relative degree of saturation within the tailings depends upon site specific physical and environmental factors.

Decommissioning concepts may be incorporated into the planning and design of new tailings management facilities. For new basins, the incorporation of an elevated water table through both the design of the TMF and the modification of the physical properties of the tailings (e.g. improving the AEV through the use of thickened tailings) are possible alternatives to current technologies.

The applicability of the concept will ultimately be determined by the site specific parameters. Consideration must be given to the short term and long term environmental implications. Every site is unique and may have constraints related to groundwater quality and use, surface water quality and use, and sensitive ecological communities.

As evidenced by the use of water covers, it is reasonable to state that maintenance of tailings in the saturated state is generally well received by regulators. A remaining concern, however, relates to the long term maintenance of water retaining dams. The use of an elevated water table concept would minimize this concern when it can be demonstrated that a tailings pond will not be required over the long term, and that the containment structures can safely accommodate an elevated water table. As a rule, geotechnical studies should be carried out to assess the effect of an elevated water table on the stability (erosion, liquefaction) of the tailings, and the containment structures.

2.3 OTHER OPTIONS

The use of an elevated water table should be compared to other options. All options considered appropriate for the particular site should be thoroughly evaluated. The results of the studies described would be considered in the analysis. Proposed options can be systematically rated with the objective of determining the most appropriate approach.

The technical evaluation should include a prediction of the inventory of potentially acid generating tailings contained within the unsaturated zone. The use of an elevated water table alone may be insufficient to completely inhibit the production of acidic drainage from all the reactive tailings and in such cases it may be beneficial to add a surface layer of non-acid producing tailings or other material that provides the required physical properties to decrease evaporation and allow the capillary zone to extend sufficiently above the reactive tailings.

A reduction in the total volume of acidic drainage produced at some sites, particularly historic properties, may be beneficial as it could mitigate long term acidic drainage treatment requirements.

3.0 ELEVATED WATER TABLE CONCEPTS

This section describes the following three conceptual approaches to creating an elevated water table within tailings impoundments.

1) Modifying the water balance of the tailings;
2) Enhancing the water retention ability of the tailings; and
3) Constructing groundwater flow barriers within the tailings.

3.1 MODIFIED WATER BALANCE

At some sites, the water balance of a tailings management facility can be modified to increase the elevation of the water table within the tailings. The water input must be higher, or output lower, to effect a rise in the water table elevation. Precipitation, runoff flowing to the tailings, groundwater, mill discharge, and local surface water drainage systems represent potential sources of water to tailings, while evaporation, runoff flowing from the tailings, groundwater flow, water pond discharge or recycle, and seepage represent water losses (Figure 3.1).

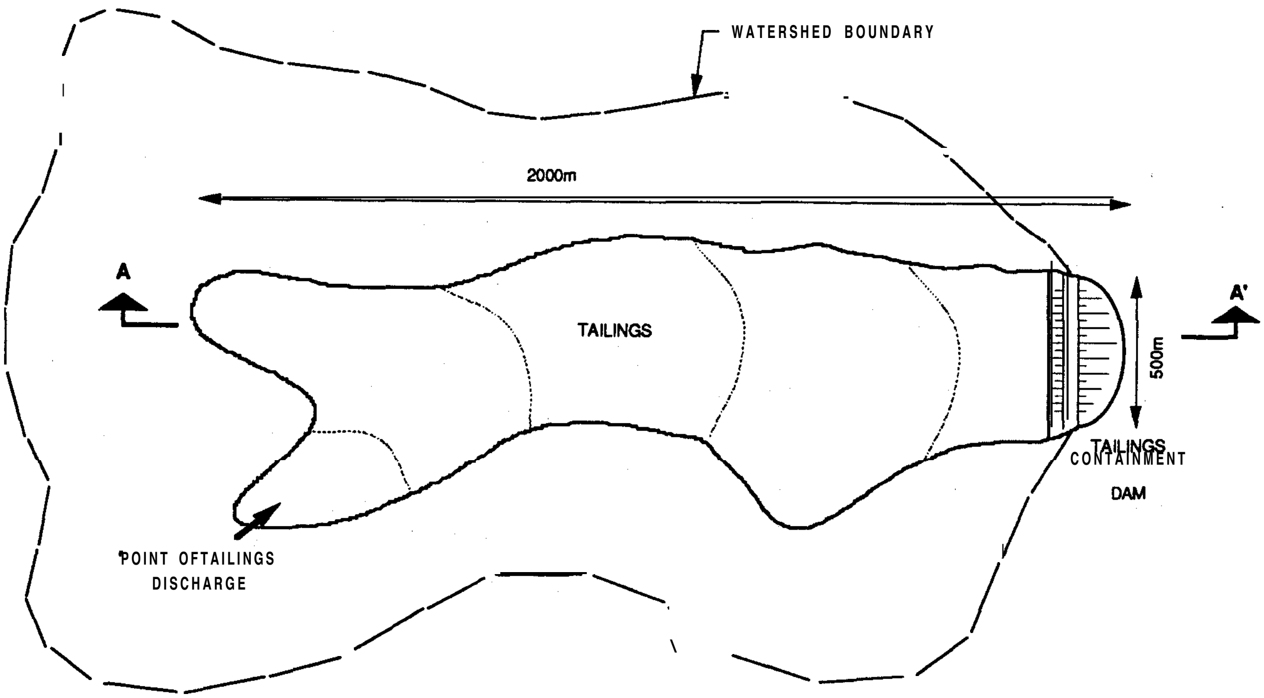
There are several computer models available to evaluate water table conditions within tailings including FLONET (discussed further in Subsection 3.3). The geometry of the tailings deposit, hydraulic conductivities of tailings and surrounding terrain, and local climatic conditions play important roles in the water balance; therefore, models need to be calibrated to suit site specific conditions. The tailings water balance may be modified by:

! Increasing water input to the tailings through the diversion of a natural drainage system to the tailings including the collection of runoff from the surrounding watershed;

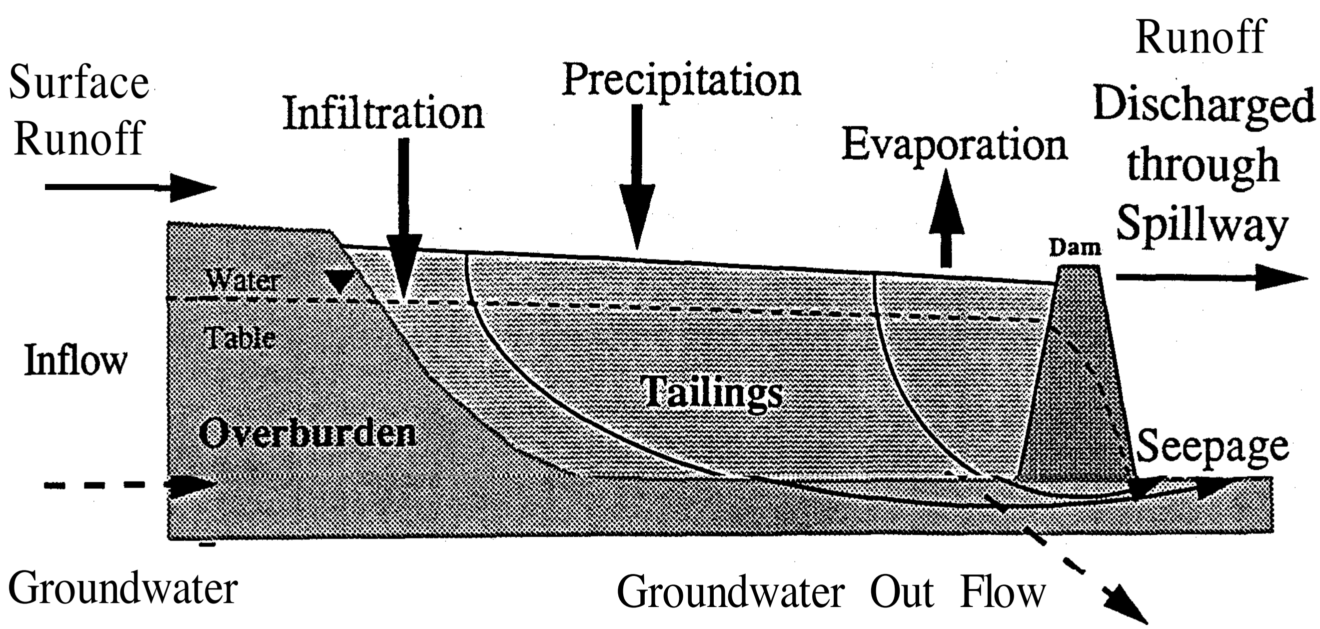
! Reducing tailings pore water seepage losses through the construction of low permeability perimeter containment dams and/or perimeter seepage barriers; and

FIGURE 3.1

TAILINGS POREWATER INPUTS AND LOSSES



PLANVIEW



SECTIONA-A'

SHOWING TAILINGS POREWATER INPUTS AND LOSSES

(NOT TO SCALE)

- Reducing water loss due to evaporation and/or improving infiltration.

3.1.1 Increasing Input

Runoff from areas that would not normally drain to a tailings management facility can be diverted and used to provide additional water to the tailings impoundment. Variations of this approach include:

- Diversion of runoff from the local watershed; and
- Diversion of runoff from adjacent watershed(s).

At the Quirke tailings basin in Elliot Lake, Ontario, runoff from local and adjacent watersheds were diverted to the tailings basin to maintain a water cover, about one metre in depth, over the tailings. The water cover will be maintained in perpetuity.

This diversion of local runoff involves the use of a runoff collection system, a water level control weir, and a permanent channel to ensure an adequate supply of water to the tailings.

The principal objective of this approach is to obtain a reliable, long term source of water to the tailings impoundment. Site specific conditions would determine whether or not an elevated water table could be maintained during extended drought. Drawbacks to this approach include: the alteration and diversion of a natural drainage system, and potential perpetual maintenance and control. The diversion of runoff from an adjacent watershed to the tailings has also been proposed for use at tailings basins in areas having dry climates to provide water to augment low runoff flows into the tailings basin (e.g. Neves Corvos, Portugal).

3.1.2 Reduced Seepage

Seepage is generally controlled by constructing water retention type dams or raised embankments with internal impervious zones and drains as perimeter containment structures. These types of structures enable positive control of the phreatic surface and allow for the storage of water against the upstream face of the dams.

Water retention dams are constructed to their full height prior to beginning of discharge of tailings into the impoundment. These structures include an impervious core, drainage zones, filters, and rip rap. These dams are designed to survive seismic events, and their use requires significant upfront planning.

Bedrock can be grouted to reduce seepage. This approach has been used at many sites to treat exposed bedrock foundations along new dam alignments. Measures taken during new dam construction to provide a good contact between the rock foundation and the dam core include: the removal of debris from the rock surface; consolidation grouting of near surface joints and fracture zones; and the application of slush grout to infill surface discontinuities.

Raised embankments differ from conventional water retention type structures in that construction of the embankment is staged over the life of the impoundment. Following construction of a starter dyke, subsequent embankment raises are scheduled to keep pace with the rising elevation of tailings and required ponded water storage capacity. The principal advantages of raised embankments compared to water-retention type dams include staged construction, and lower initial capital costs.

Slurry walls are commonly used in construction activities, and have been used to reduce seepage flows into underground facilities, as barriers to leachate flow around waste disposal areas, and as cutoff walls to reduce seepage below dams. A slurry trench wall or cutoff consists of a continuous trench excavated by excavator, or dragline or combination of the two. The trench is continuously filled with bentonite slurry as the excavation progresses. The trench is normally 1 to 3 m wide and the maximum depth depends on the capability of excavating equipment. A large excavator is capable of reaching 8 to 10 m, a dragline 20 to 25 m.

The backfill consists of a slurry formed from bentonite mixed with the excavated waste.

The bentonite usually constituents 15% by weight of the mix. The excavated soil is mixed and broken down on the site by windrowing, dozing and blading. A bentonite slurry is then added by further windrowing or by a batch plant mixer. The backfill is then pushed into the trench if it is not too deep or lowered in by clamshell if the excavation is deep, to prevent segregation. A full description of the process is provided in Fell, MacGregor and Stapledon (1992). Slurry wall construction costs vary greatly ranging from less than \$100/m^2 for shallow walls to more than \$300/m^2 for deep walls. Costs can be severely affected by the presence of boulders and necessity for keying the slurry wall into bedrock.

3.1.3 Reduced Evaporation

Evaporation is a dominant mechanism for the loss of water from the surface layer of fine-grained materials. Evaporation may be significantly reduced by the placement of a coarse cover such as rip rap to act as an evaporation barrier and to allow precipitation and runoff water to percolate down to the tailings surface. The material also provides for the condensation of water vapour released from the surface of the tailings.

3.2 ENHANCED WATER RETENTION ABILITY

3.2.1 Thickened Tailings

Thickened tailings are comprised of greater than 50% solids and are disposed in cone shaped mounds with a surface slope of 2 to 6%. According to Robinsky (1975, 1978), and (Robinsky et al. (1991) and Barbour et al. (1993), tailings disposal by the thickened, sloped, discharge scheme provides the following advantages over conventional disposal of tailings:

- greater placement volume for a given height of containment dyke;
- minimal to no requirement for high perimeter dams;
- the elimination of slime ponds and decant systems; and
- a homogeneous tailings mass with low hydraulic conductivity.

With respect to acid generation, the most important characteristic of thickened tailings is the formation of a homogeneous mass of low hydraulic conductivity and high moisture content. Robinsky et al. (1991) indicated that thickening promotes the development of a shallow water table and the near-saturation of surface tailings. This approach is used at the Kidd Creek tailings area in Timmins, Ontario.

Thickened tailings create a very high level of saturation with the capillary fringe extending near surface. In concept, thickened non-acid generating tailings could be used to cap existing tailings during the final years of operation. The near surface tailings would have excellent water-retention properties which would in turn substantially reduce the depth of oxidation. Tailings stability could be enhanced by minimizing the beach slope. Furthermore, following closure of the mine, a soil layer could be placed over the tailings for the purposes of reducing water losses due to evaporation, encouraging capillary rise into the cover, reducing runoff, and encouraging vegetation growth.

3.2.2 Paste Addition

Paste is a high density mixture of fine solid particles and a relatively low water content of 10% to 25% (Brackebusch, 1994). Cement and larger particles of aggregate can be added to a paste without greatly changing the pipeline transport characteristics of the tailings. A paste may bleed water when it is allowed to remain undisturbed for several hours. The angle of repose of paste ranges from 5% to nearly 30%.

The advantages of paste technology for tailings disposal are reduced land usage and lower retaining structures because of the stackability. The lack of particle segregation or size classification is an important difference from conventional deposition of tailings. These properties result in a homogenous tailings deposit which compacts and can support reclamation vehicle traffic. The low permeability of consolidated paste assists in the inhibition of sulphide mineral oxidation.

The aluminum industry has adopted paste technology to stack red mud tailings. At several sites, tailings are dewatered to stiff pastes using belt, vacuum or pressure filtration and hauled to impoundments.

3.3 GROUNDWATER FLOW BARRIERS WITHIN TAILINGS

3.3.1 Approach

As part of this study, an alternate approach to creating an elevated water table was conceived and then evaluated using two dimensional computer modelling techniques. In brief, the approach involves the construction of flow barriers within tailings to reduce the horizontal and often preferential downgradient flow of pore water. The envisaged effect would be to raise the water table in the areas upgradient of the barriers.

The elevation of a water table is a function of the water balance in the deposit and the permeability of the tailings. For modelling purposes, the principal input of water to the tailings was considered to be precipitation where a fraction of the precipitation infiltrated the tailings. The water losses (output) from the tailings include evaporation, seepage from the subsurface, and discharge at a spillway. The water table elevation increases if either the input rate is increased or the output rate is decreased.

A number of options were considered to attain an increase in the water table elevation in a typical tailings impoundment. These included decreasing outflow by reconstruction of a perimeter dam, decreasing evaporation to increase infiltration, and use of groundwater flow or hydraulic barriers constructed *in-situ*. The modelling study investigated the relative magnitude of effect of each of these options in elevating the water table. The results show that all of the methods considered can provide an increase in water table elevation.

The model that was used to estimate the relative change in water table elevation for a typical tailings scenario is a steady-state groundwater flow model known as FLONET (Waterloo, 1994) which has been tested and applied to many groundwater flow scenarios.

FLONET is a steady-state flow model that solves the groundwater flow problem using the dual formulation method (Frind and Matanga, 1985) in terms of hydraulic potential and stream functions. This results in a highly accurate and informative flownet representation of the groundwater flow system.

The FLONET model represents flow in a two dimensional cross-section and can be applied to flow systems that have relatively simple perimeter boundaries, as is the case with many tailings impoundments. The model requires information on the properties of the subsurface media including permeability (or hydraulic conductivity), the boundary conditions around the model section, and the physical dimensions of the section. The model was selected because it allows the input flux of water at the water table (or other boundaries) to be specified and the resulting steady-state water table elevation to be calculated. It allows simulation of the water table elevation resulting from changes in boundary conditions or internal properties/conditions in the flow regime.

3.3.2 Scenarios Modelled

Several scenarios were modelled. A base case was generated to evaluate the effects of the modelled amendments on a *typical* site. Simulations were then made for:

1) increased infiltration;
2) decreased permeability of a downgradient dam; and
3) the installation of hydraulic barriers within the tailings.

In excess of thirty model simulations were run to assess the sensitivity of water table elevation to various tailings characteristics and boundary conditions. The output of the model provided flownet diagrams showing head distribution and flowlines. These have been summarized in the schematic diagrams that follow in the subsections below (only the water table elevations and selected flowlines are shown for clarity).

Base Case:

A generalized tailings impoundment underlain by glacial overburden and a low permeability clay is shown in Figure 3.2. Hydraulic conductivities within the tailings were derived from data collected at a tailings impoundment near Sudbury, Ontario (David, 1993; David and Nicholson, 1995). Pertinent values used in the model are summarized in Table 3.1.

Horizontal and vertical hydraulic conductivities were calculated using a harmonic mean (for equivalent vertical hydraulic conductivity) and a geometric mean (for equivalent horizontal hydraulic conductivity values) of d_{10} grain size values from several test trenches in tailings. Infiltration was set at a value typical of that of the northern Ontario climate. The tailings portion of the impoundment was sectioned into three zones to mimic the grain size segregation that typically occurs between the tailings spigot area or beach to the pond (Figure 2.3). The zone closest to the spigot usually contains the most coarse-grained material and the zone nearest the dam contains the most fine-grained tailings. The hydraulic characteristics of the tailings dam were set to simulate a structure that was designed for physical stabilization (such as the underflow of cycloned tailings) rather than a water retaining structure. In effect, the simulated dam was made of coarse tailings that offered little resistance to flow in comparison to the tailings zone immediately upgradient of it. A summary of hydraulic conductivities in the tailings and dam is given in Table 3.2. Hydraulic heads or water levels in the region downgradient of the dam were specified to be at ground level elevation to simulate seepage runoff through and beneath the tailings containment dam.

The base case for the *typical* tailings scenario results in a water table elevation of about 12.5 m above the datum or base of the flow system (Figure 3.2). The slope on the water table is similar to that of the tailings surface. In the base case, the discharge of water is primarily through and below the perimeter dam.

Increased Infiltration:

The ambient infiltration (or volumetric flux) rate was selected to correspond to an average annual rate of 365 $mm \cdot a^{-1}$. The specified rate of infiltration or flux entering through the surface of the tailings impoundment was increased to simulate a decrease in evaporation. In practice, this could be accomplished by constructing a coarse sand or gravel layer over the tailings.

FIGURE 3.2

SCHEMATIC CROSS-SECTION OF THE MODEL SCENARIO SELECTEDASTHEBASECASE

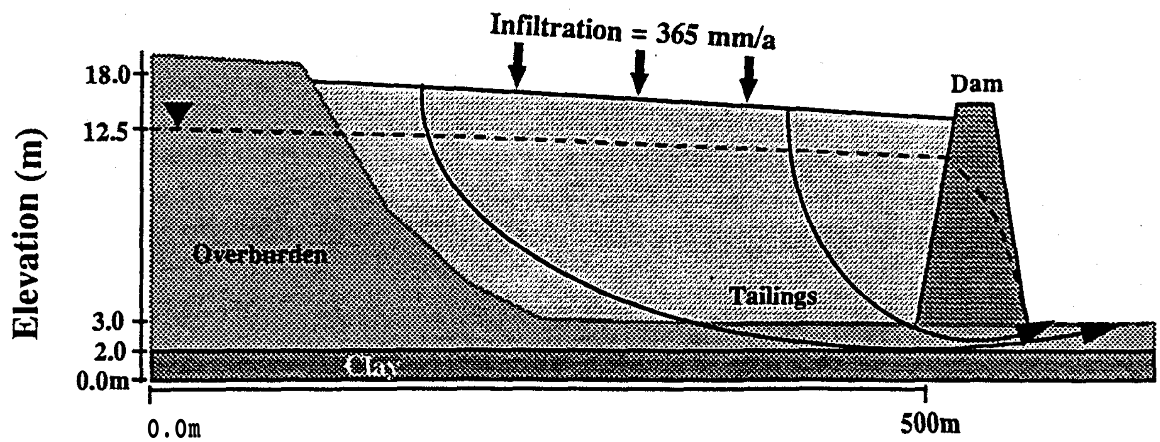
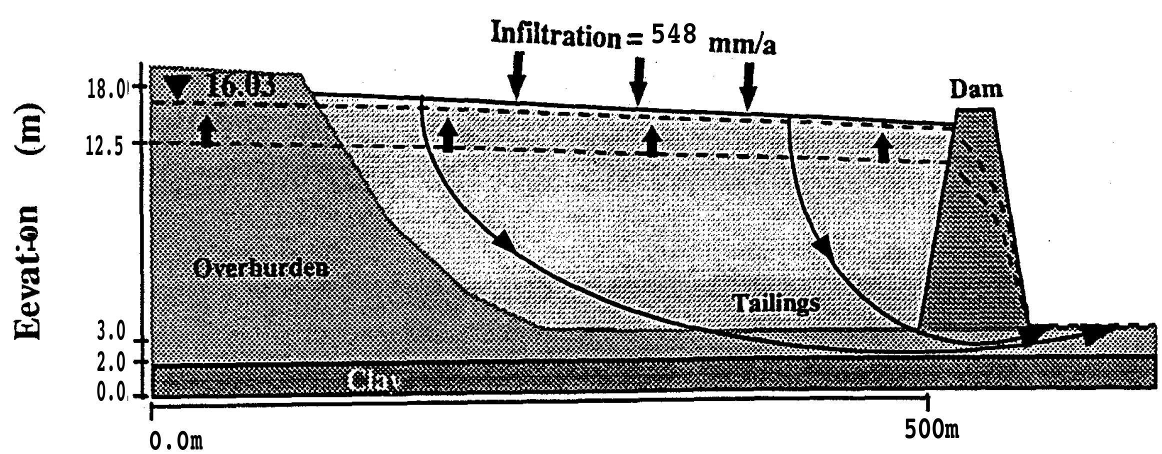


FIGURE 3.3

THE WATER TABLE CONFIGURATION WHEN THE INFILTRATION RATE IS INCREASED BY 50% ABOVE THE BASE CASE VALUE



RESULT: ELEVATION INCREASE OF 3.5m

Table 3.1

SUMMARY OF TAILINGS CHARACTERISTICS USED IN THE MODELLING OF SCENARIOS USING THE FLONET MODEL

Simulation	**Infiltration ($mm \cdot a^{-1}$)**	**Water Level at Dam (m)**	**Depth of Barrier Wall (m)**	**Hydraulic Conductivity of Barrier Wall ($m \cdot s^{-1}$)**
Base Case	365	3	0	N/A
Infiltration + 50%	**548**	3	0	N/A
3 m rise at Perimeter Dam	365	**6**	0	N/A
5 m rise at Perimeter Dam	365	**8**	0	N/A
Partial Barrier	365	3	**6**	4.6×10^{-9}
Full Barrier	365	3	**8**	3.5×10^{-8}

Table 3.2

SUMMARY OF HYDRAULIC CONDUCTIVITIES OF THE TAILINGS, DAM AND UNDERLYING CLAY LAYER

Tailings Zone	**$K_{horizontal}$ ($m \cdot s^{-1}$)**	**$K_{vertical}$ ($m \cdot s^{-1}$)**	**K_H/K_v**
1 (beach)	4.7×10^{-5}	1.4×10^{-7}	340
2 (intermediate)	2.4×10^{-5}	6.9×10^{-8}	340
3 (pond/dam)	1.2×10^{-5}	3.5×10^{-8}	340
Dam	4.7×10^{-5}	4.7×10^{-5}	1
Clay	1×10^{-10}	1×10^{-10}	1

Table 3.3

MODELLED WATER TABLE ELEVATION AND NET RISE IN WATER TABLE

Simulation	Water Table Elevation at Beach (m)	Potential Rise in Water Table Elevation Relative to Base Case (m)
Base Case	12.5	0
Infiltration + 50%	16.0	3.5
3 m rise at Perimeter Dam 1	17.3	4.8
5 m rise at Perimeter Dam	18.3	5.8
Partial Barrier	14.1	1.6
Full Barrier	25.9	13.4

When the infiltration increased from 365 to 548 $mm \cdot a^{-1}$, the water table at the beach increased by about 3.5 m in elevation (Figure 3.3). This may represent a significant increase in some tailings impoundments that already have relatively shallow water table conditions. The results also suggest that it is necessary to evaluate the effect of water balance changes, such as a decrease in evaporation, on a site specific basis.

Dam Modifications:

Two scenarios were used to assess the effect on the water table elevation arising from an increase in the hydraulic head at the tailings containment dam. The first scenario simulated a 3 m rise in the hydraulic head, above that of the base case, at the dam (Figure 3.4). The second scenario simulated a 5 m rise (Figure 3.5). These scenarios were used to simulate dam modifications that would result in the dam being made relatively impermeable up to a selected elevation.

When the water level at the perimeter dam was raised from 3 to 6 m, a difference of 3 m, the water table at the beach increased by about 5 m (Figure 3.4).

A 5 m increase in the water level at the dam, from 3 m to 8 m, produced about a 6 m rise in the water table at the beach (Figure 3.5). The relative water table elevation increase at the beach decreases as the dam water level increases (Table 3.3).

Hydraulic Barriers:

Water levels occur deeper below the tailings surface in the beach area as opposed to the pond area because the beach ground surface is at a higher elevation and the coarse grained tailings are more permeable and transmit flow and drain more readily than the fine material. A unique concept for raising the water table within tailings was considered to specifically raise the water levels in the beach and other

FIGURE 3.4

THE WATER TABLE CONFIGURATION WHEN THE WATER LEVEL AT THE DAM IS INCREASED BY 3m ABOVE THE BASE CASE LEVEL

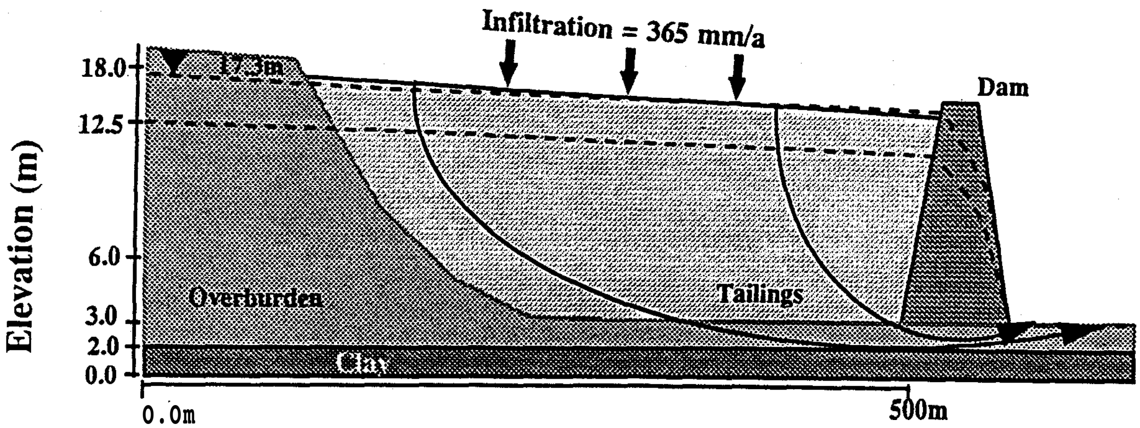
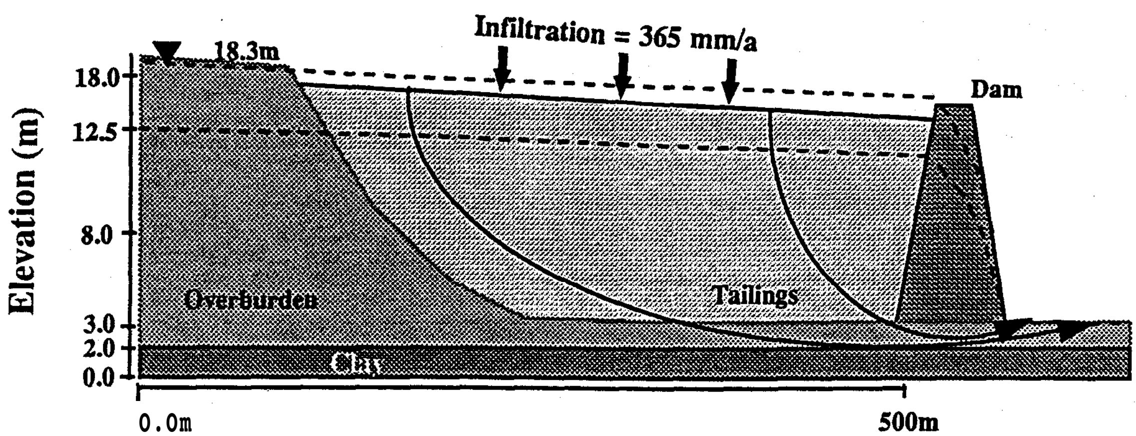


FIGURE 3.5

THE WATER TABLE CONFIGURATION WHEN THE WATER LEVEL AT THE DAM IS INCREASED BY5m ABOVE THE BASE CASE LEVEL



tailings areas having a deep water table. The hydraulic barrier is based on the concept of creating a greater resistance to the horizontal groundwater flow component within the tailings. Because the hydraulic conductivity (K) of tailings is often greatest in the horizontal direction and is much lower in the vertical direction, the principal objective of the barrier is to reduce horizontal hydraulic conductivity.

The ratio of $K_{horizontal}/K_{vertical}$ is commonly 100 to 400 in tailings. This occurs because of the grain size segregation and layering that results from hydraulic discharge. This means that the major flux of water in tailings will occur along horizontal pathways represented by the high permeability layers. If the horizontal pathways can be interrupted, horizontal flow rates can be reduced and higher water levels would be expected to develop upgradient from the groundwater flow barrier. In concept, the mixing of coarse-grained and fine-grained layers across a vertical section of tailings would reduce the horizontal hydraulic conductivity to a value representative of unsegregated tailings. This could represent a decrease of $K_{horizontal}$ by a factor of 10 to 100 times. Therefore, if a vertical zone was established within the tailings and extended orthogonally across the nominal flow direction, water levels upgradient of the flow barrier should increase. The relative increase in water level upgradient of the barrier was addressed through modelling.

In the simulations, the barrier was placed approximately in the middle of the tailings impoundment (with the beach area located upgradient) to investigate the effects on the water table in the thicker vadose zone. In one set of simulations, the barrier was *constructed* to a depth of approximately three-quarters of the tailings depth and in the second set of simulations, the barrier was *constructed* to the base of the tailings.

The modelling results suggest that a hydraulic barrier is much more effective if it is installed to the base of the tailings. With a low permeability barrier placed to a depth representing 75% of the tailings thickness, the water table rise in the beach area was less than 2 m (Figure 3.6). In this case, a significant portion of horizontal flow was diverted below the barrier at relatively high rates. In comparison, a 1 m thick vertical barrier that extends to the low permeability base of the tailings more than doubled the water table elevation at the beach (Figure 3.7) even though the barrier has a hydraulic conductivity equivalent to that of tailings near the dam (about 3.5×10^{-8} m$\cdot$s^{-1} or 0.003 m$\cdot$d^{-1}). Although the water level is shown to be above the ground surface upgradient of the barrier, the water table would only rise to the tailings surface.

These results suggest that the groundwater flow barrier concept may provide favourable benefits for enhancing water table elevations in elevated beach areas of tailings. The modelling results also indicate that it is more important to construct the vertical barrier so that it fully penetrates the tailings even with higher hydraulic conductivity than it is to construct an impermeable boundary with only partial penetration (Table 3.3). The hydraulic conductivity of a barrier can be similar to that of a mixed or unsegregated tailings and still provide benefit. This means that costly amendments such as bentonite may not be required. The actual procedure that could be used to construct such a groundwater flow barrier in tailings has not been developed. In concept, however, construction of a barrier could involve the mixing of the tailings to the base (along a section across the tailings basin and without actually removing tailings) to create a homogeneous mixture of tailings - the objective being to remove the horizontal layering and homogenize the grain-size distribution. If field tests indicated that not enough fine-grained tailings exist at the barrier location to achieve the required hydraulic conductivity, fine material such as tailings slimes could be added. Potential construction methods include hydraulic displacement, dragline, and auger methods. Additional work is required in this area to better identify suitable methods.

The construction cost of such a barrier can be compared to the area of tailings that are effectively saturated. Consider a 1 km wide tailings area in which the barrier is emplaced 500 m downslope from the beach: the barrier would be 1000 m long and the area potentially saturated by the elevated water table would be 50 ha (1000 m x 500 m). If the average depth of the tailings was 20 m then the area of the wall would be 20,000 m^2. If a bentonite/tailings barrier could be constructed *in-situ* by

FIGURE 3.6

THE WATER TABLE CONFIGURATION WHEN AN IMPERMEABLE BARRIER WALL IS PLACED TO A DEPTH OF 75% OF THE TOTAL TAILINGS DEPTH

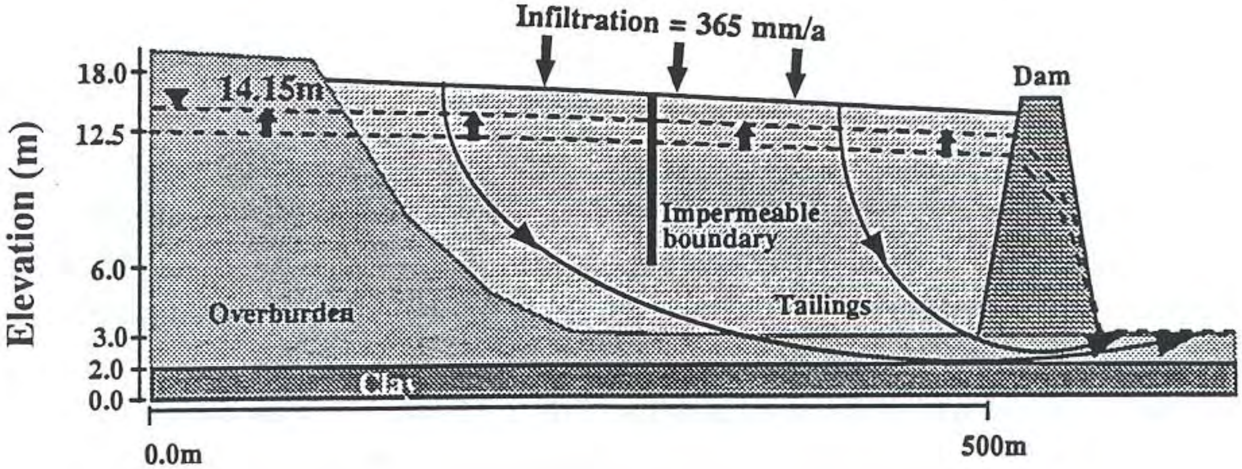
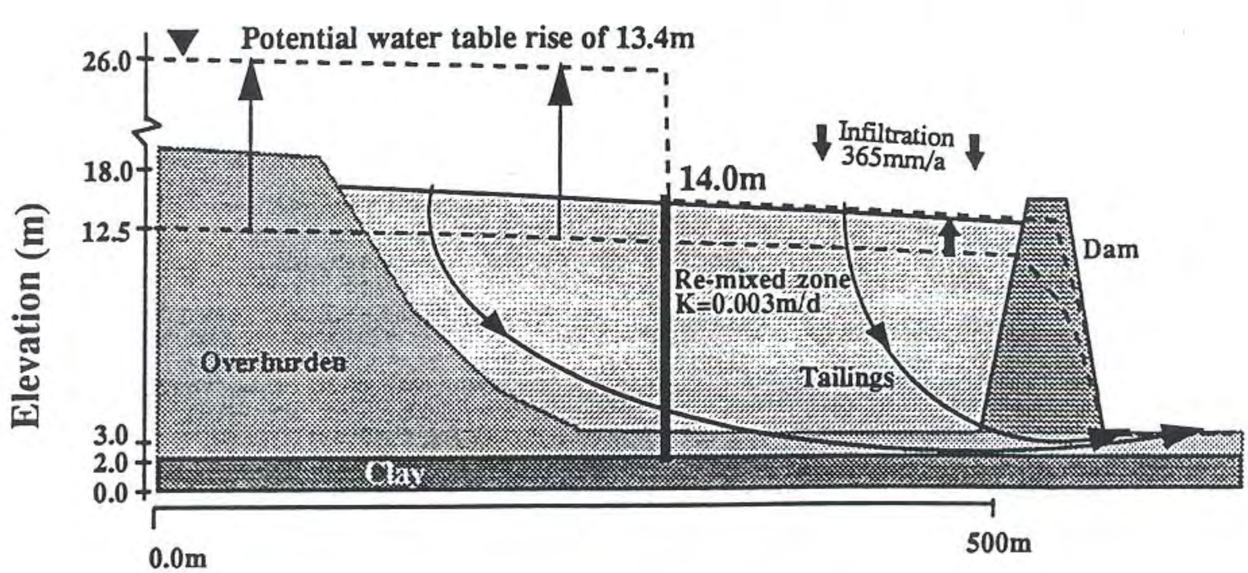


FIGURE 3.7

THE WATER TABLE CONFIGURATION WHEN A "MIXED TAILINGS" BARRIER WALL IS PLACED TO THE BASE OF THE TAILINGS



augering at a cost of $40/m^2, the cost of the barrier would be in the order of $800,000 - equivalent to a unit a cost of $16,000 per hectare of tailings with an elevated water table.

Synopsis:

The modelling study has shown that elevating the water table in tailings can be achieved to varying degrees by different approaches. Raising the water level at perimeter dams will likely raise the water table in the beach areas by a similar amount. Reducing evaporation to enhance infiltration will result in an increase in the water table elevation. An increase in infiltration of 50% resulted in a maximum water table increase of only 12%. The relative increase of the water table at the beach would be greater in tailings with lower hydraulic conductivity.

Reducing evaporation from the tailings may provide other benefits, such as maintaining high moisture contents in fine-grained layers near the tailings surface, thereby assisting in effectively reducing oxygen influx to the tailings.

Two dimensional computer modelling of groundwater flow barriers within tailings has indicated that this method will provide an increase in the water table elevation upgradient of the flow barrier. This elevated water table concept may be useful in inhibiting acidic drainage in elevated beach areas of tailings.

4.0 SITES THAT PROVIDE RELEVANT EXPERIENCE

Current research suggests that tailings with a water table that approaches the surface behave in a similar manner to tailings that are under a water cover in so far as oxidation rates are minimized. There are, however, limited data to confirm this. There have been few focussed attempts to raise the water table in tailings other than the construction of perimeter dams and one case of slurry wall construction.

Nine sites provide some degree of relevant experience, either empirical findings or scientific data, respecting elevated water tables and/or thickened tailings (see Table 4.1). Five sites (Elura, Greens Creek, Cluff Lake, Les Mines Selbaie, and Kidd Creek) have used or are using thickened tailings. The modified water balance concept has been considered or proposed for the Falconbridge New Tailings site, the Dona Lake mine, and the historic Stanrock mine. The ninth site, the Sturgeon Lake property, involved the combined use of elevated water table concepts and a flow barrier.

Table 4.1

SITES THAT PROVIDE RELEVANT EXPERIENCE

Site Study m	Mine Site	Approximate Location	Elevated Water Table Concept
1	Elura	New South Wales, Australia	Thickened Tailings
2	Greens Creek	Alaska, USA	Thickened Tailings
3	Cluff Lake	Lake Athabaska District, Saskatchewan	Thickened Tailings
4	Les Mines Selbaie	Joutel, Québec	Thickened Tailings
5	Kidd Creek	Timmins, Ontario	Thickened Tailings
6	Falconbridge New Tailings	Falconbridge, Ontario	Modified Water Balance
7	Dona Lake	Pickle Lake, Ontario	Modified Water Balance
8	Stanrock	Elliot Lake, Ontario	Modified Water Balance
9	Sturgeon Lake	Ignace, Ontario	Combination of a Modified Water Balance and a Groundwater Flow Barrier

At most of these sites, results are inconclusive; however, useful information can be obtained from their study.

4.1 SITE STUDY m 1 - ELURA MINE, AUSTRALIA

The Elura site is of interest as it employs the use of thickened tailing in a dry climate. Although an elevated water table is not present, the tailing have a high degree of saturation. Much of the following information is based on a technical paper by Williams (1992).

4.1.1 Background

The Elura lead zinc mine is located near Cobar in New South Wales, Australia. The mine began production in 1983 at a rate of 1.1 million t of ore per year.

The central thickened tailings disposal method was selected to minimize the need for extensive containment embankments. The tailings disposal area (Figure 4.1.1) is located on ground sloping slightly to the south. An earthfill ramp was constructed to the designed height of the centre of the cone and used to carry the discharge pipeline. Radial embankments subdivide the cone into three disposal areas: the m 1 area which covers about 125E of arc, the m 2 area located to the north and covering approximately 60E of arc, and the m 3 area which covers the remaining 175E.

At the m 1 area, the perimeter containment structures are less than 1 m in height. This area has been filled and contains approximately 5.2 million tonnes of tailings stacked to a height of approximately 12 m. The decant pond is located to the south of the m 1 area. Circa 1992, the m 1 area was closed and tailings disposal switched to the m 2 area.

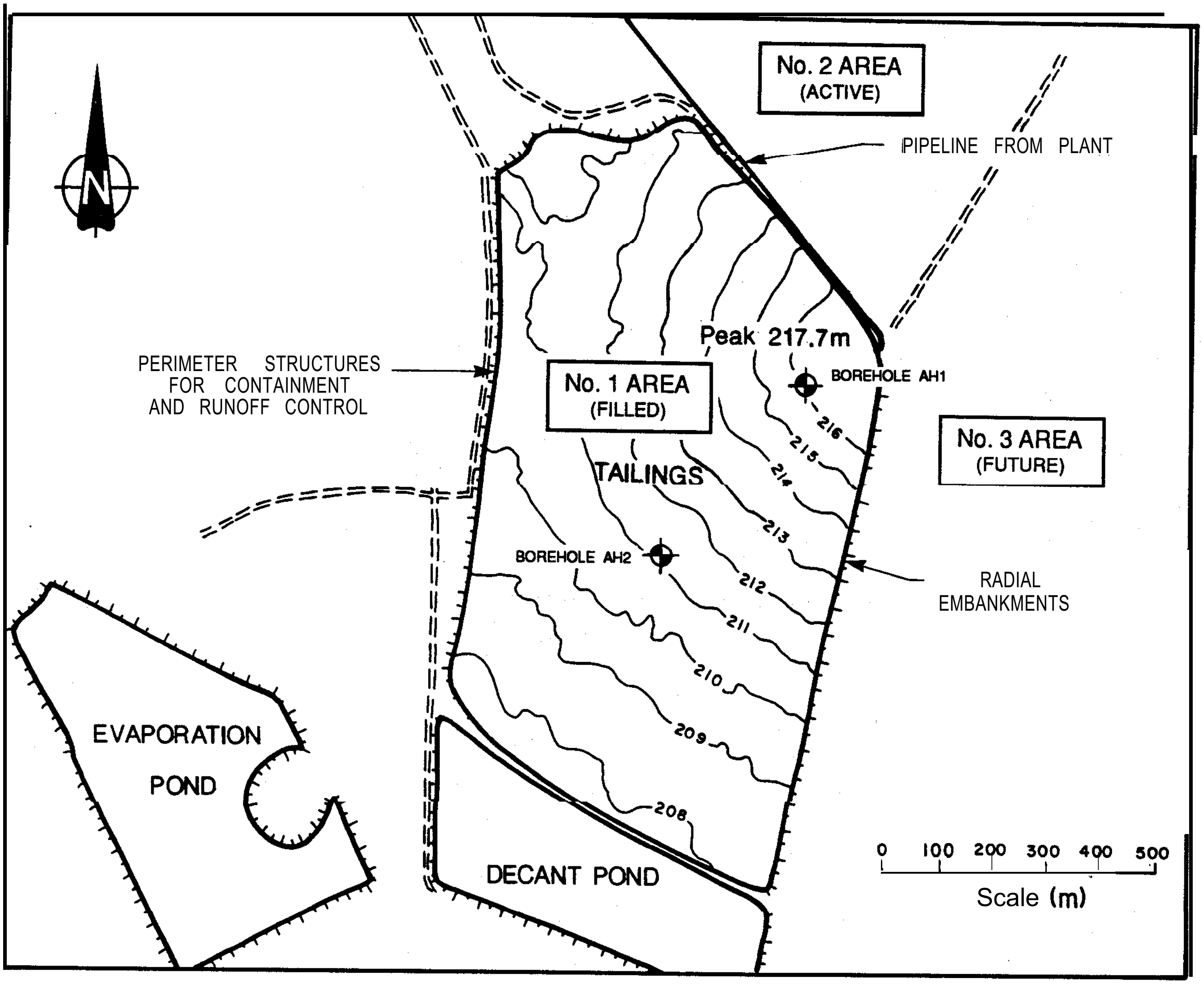
A significant feature of the tailings in the m 1 area is the uniformity of the gradient of the tailings beach at between 1.6 to 1.7% only flattening slightly at the toe. The grain size distribution of the Elura tailings is similar to those for other lead/zinc deposits presented in Figure 2.2A (Section 2.1) with 80 to 90% less than 74 m.

4.1.2 Rehabilitation of the m 1 Area

Investigations were carried out to determine appropriate rehabilitation measures for

FIGURE 4.1.1

PLAN VIEW OF ELURA MINE NO. 1 TAILINGS AREA



NOTE:

CONTOURS ARE BASED ON AN AERIAL SURVEY OF THE TAILINGS STACK COMPLETED IN SEPTEMBER, 1988

SOURCE: MODIFIED FROM FIGURE 9 (WILLIAMS, 1992) the m 1 area. The works undertaken included drilling, sampling, and testing of the tailings and the modelling of soil covers.

Two boreholes (identified as AH1 and AH2 in Figure 4.1.1) were drilled to a depth of 5 m with tailings samples collected at 0.5 m intervals. Parameters measured were moisture content, paste pH, and density.

As indicated in Figure 4.1.2, moisture content results were found to be below 18.4% the saturation moisture content for the average tailings density of 2.37 t/m^3. It was inferred that the stack has a uniform moisture content of approximately 65% of saturation. Based upon work by Nicholson et al. (1991), at this level of saturation and higher, major reductions occur to oxygen diffusion into tailings.

The tailings have a high sulphur content and have strong net acid producing potential. The pH in the decant pond located south of the m 1 area was 2.9 a year after tailings deposition commenced. Available buffering has resulted in a relatively high tailings stack pH of 5 to 5.5 (except near surface where pH is in the range of 2). Profiles of pH over the depths of boreholes AH1 and AH2 are shown in Figure 4.1.3.

Thickened tailings are stable when first formed and subsequent events, such as sedimentation and evaporation lead to increased density and strength. Deep seated static slip failure is not a concern at the low slope angles, but liquification remains an issue (Williams, 1992).

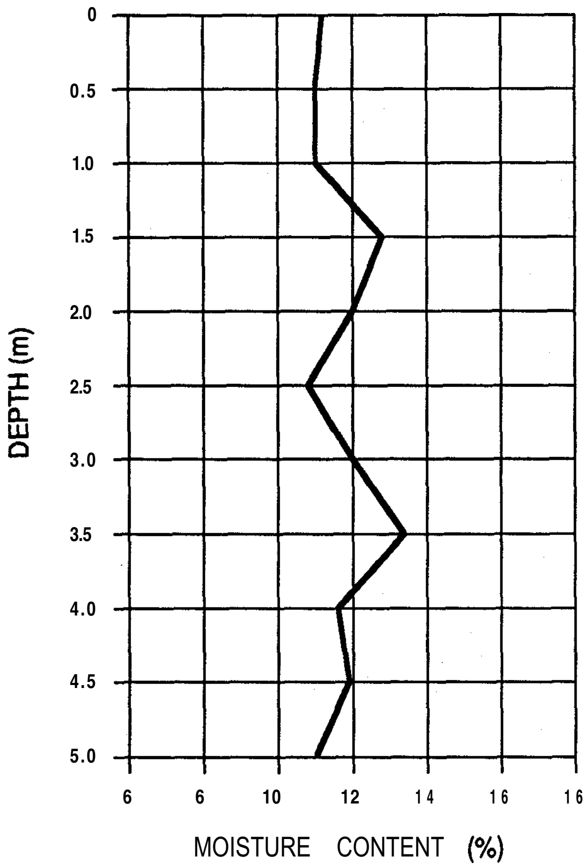
4.1.3 Decommissioning Strategy

The decommissioning objective was to prevent the infiltration of rainfall into the tailings thereby preventing movement of water through the tailings and the transport of oxidation products.

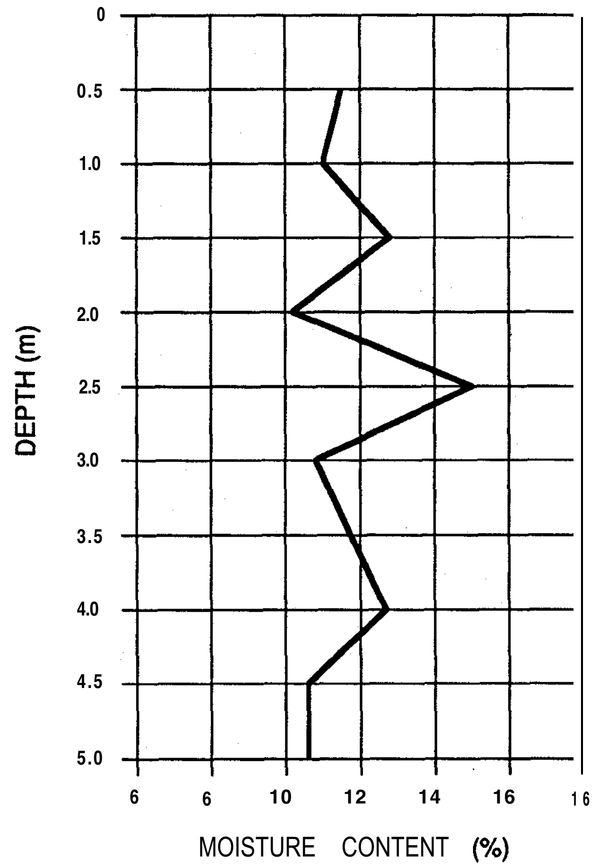
The performance of soil cover options were modelled using the U.S. Environmental Protection Agency HELP computer program. The HELP program models

FIGURE 4.1.2

MOISTURE CONTENT vs. DEPTH IN TAILINGS IN AREA NO. 1



BOREHOLE AH1

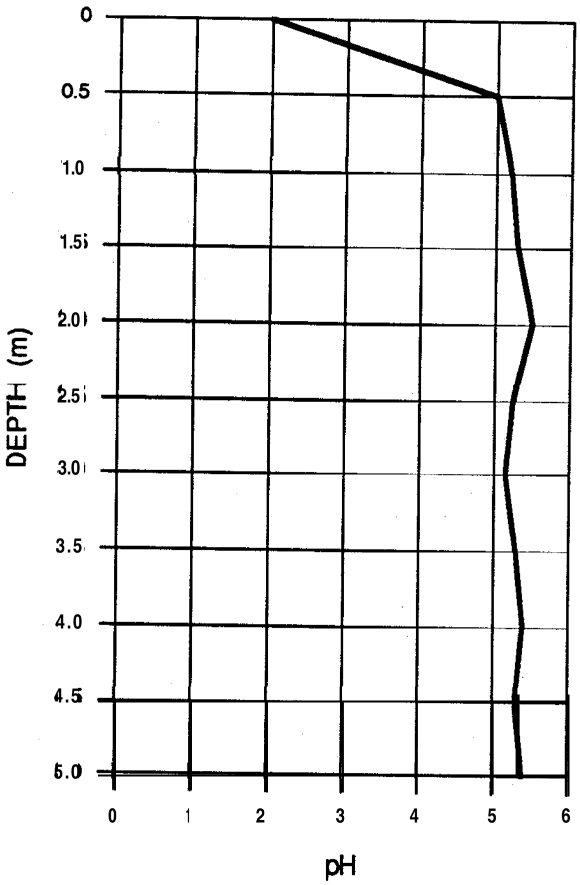


BOREHOLE AH2

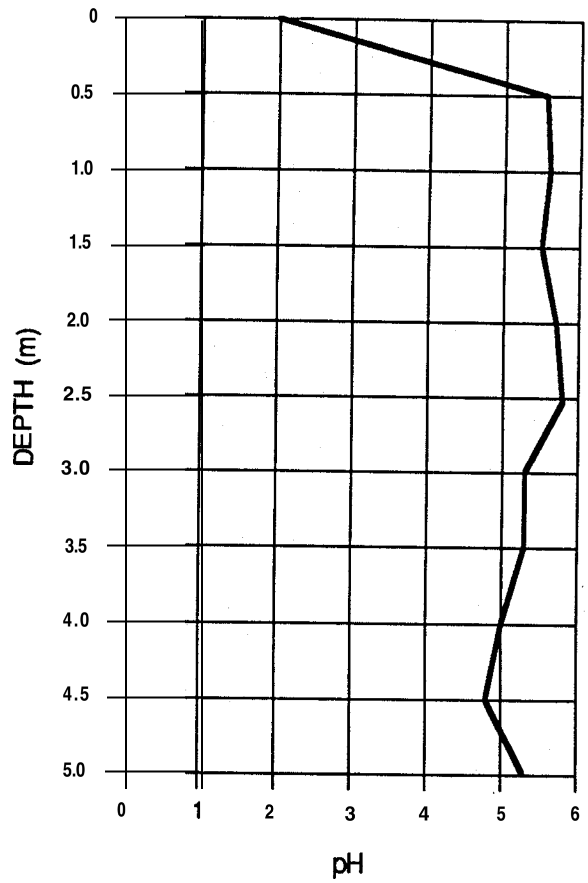
SOURCE: FIGURE 11 (WILLIAMS, 1992)

FIGURE 4.1.3

pH vs. DEPTH
IN TAILINGS IN AREA No. 1



BOREHOLE AH1



BOREHOLE AH2

SOURCE: FIGURE 13 (WILLIAMS, 1992)

infiltration, runoff, and evapotranspiration. The model was used to estimate (for various cover thicknesses) the flux of rainfall infiltration into the tailings, and the flux of evapotranspiration. Results are summarized in Table 4.1.1.

Table 4.1.1

RESULTS FROM HELP MODELLING

Soil Cover Thickness (cm)	Water Flux at Cover: Tailings Interface (mm yr^{-1})	Deep Infiltration to Tailings (mm yr^{-1})
15	70	0
25	25	0
35	7	0
50	1	0

Source: Table 1 (Williams, 1992).

The modelling was based on the use of gravelly clay obtained from the as-yet-developed m 3 area. Physical properties of the material were obtained through laboratory testing. Information respecting the HELP program is available in Schroeder et al. (1994). Based on the modelling results, a 0.50 m cover with an additional 15 cm of topsoil was recommended.

The closure plan developed is suitable for this dry climate area. However, as indicated by the field data, moisture contents in the thickened tailings at 65% of saturation were quite high and may well be higher if moisture input was enhanced rather than curtailed. The use of a coarse sand cover to raise the level of saturation by maximizing infiltration and reducing evaporative losses could have been an alternate closure option.

4.2 SITE STUDY m 2 - GREENS CREEK MINE

The Greens Creek mine tailings facility is an example of thickened tailings deposition. Elevated water tables were not considered in the original closure design, however, such an approach could be considered at this site.

4.2.1 Background

The Greens Creek Mine is located on the northern extension of Admiralty Island located south of Juneau, Alaska. The deposit was discovered in 1975 by joint venture companies Noranda Exploration, Marietta Resources International, Exalas Resources Corporation, and Texas Gas Exploration.

Underground exploration and diamond drilling were carried out between 1978 and 1980. Environmental baseline studies were also carried out leading to the development of a Draft Environmental Impact Statement in 1982, and a Final Environmental Impact Statement (FEIS) - the latter was approved by the U.S. Department of Agriculture (USDA) in 1983 (USDA, 1988).

Tests to assess the acid generation potential of Greens Creek ore and tailings samples were carried out in 1982 prior to the completion of the FEIS. Two of three major geological components of the orebody referred to as Black and White were found to not have acid generation potential. The third component referred to as Massive was a confirmed acid producer. Tailings were found to be acid consuming (USDA, 1988).

The Plan of Operations for the development of the project, which was approved in 1984, outlined how the 3.1 million tonnes of recoverable ore (Ag, Au, Zn, Pb) was to be mined and milled, and described the proposed waste management plan.

In 1986, Amselco Minerals Inc. assumed control of the project. The company revised the work plan for 1987 - revisions included significant changes to the methods of mining and tailings disposal. The revised work plan was accepted by the USDA, Forest Service and the mine operated from 1988 to 1992.

In 1993, a new mineralized zone was discovered. There are plans to reopen the mine in 1997. The project is currently owned by Greens Creek Mining Company.

4.2.2 Waste Management Plan

The tailings disposal plan initially proposed for the project was based on the construction of a wet tailings facility at the Cannery Muskeg. The tailings basin would have a storage capacity of 2.6 million m^3 and the tailings would be slurry discharged into a settling pond within a tailings basin having an area in the range of 60 ha (Greens, 1995). A plan of the wet tailings basin is provided in Figure 4.2.1.

The revised mining method proposed by Amselco Minerals Inc. required that mine backfill (tailings) be placed and compacted to a density adequate to allow equipment operation within a few days. The mine opted to construct a dry tailings facility. The overall economic viability of the project was significantly enhanced with the adoption of the revised program. The revised plan reduced the disturbed area occupied by the tailings basin to approximately 13 ha which included a 12 ha dry tailings facility and a 1 ha tailings effluent sedimentation pond (Figure 4.2.2).

As part of the dry tailings disposal plan, dewatered tailings not used for mine backfill were truck transported to the dry tailings facility and spread and compacted in lifts.

The dry tailings stack would contain centre line and finger drains, and a rockfill embankment at the toe. The tailings stack would be constructed to a height of approximately 24 m, and the tailings would be further stabilized by main and saddle embankments of less than 8 m in height. Of the 880 t of tailings produced per day, 640 t were placed underground as mine backfill. The remaining tailings were hauled to the dry tailings facility in trucks. Approximately 320,000 t of tailings were deposited in the tailings management facility.

During the USDA (1988) environmental assessment review of the proposed changes to the general plan of operation, it was noted that preliminary testing carried out

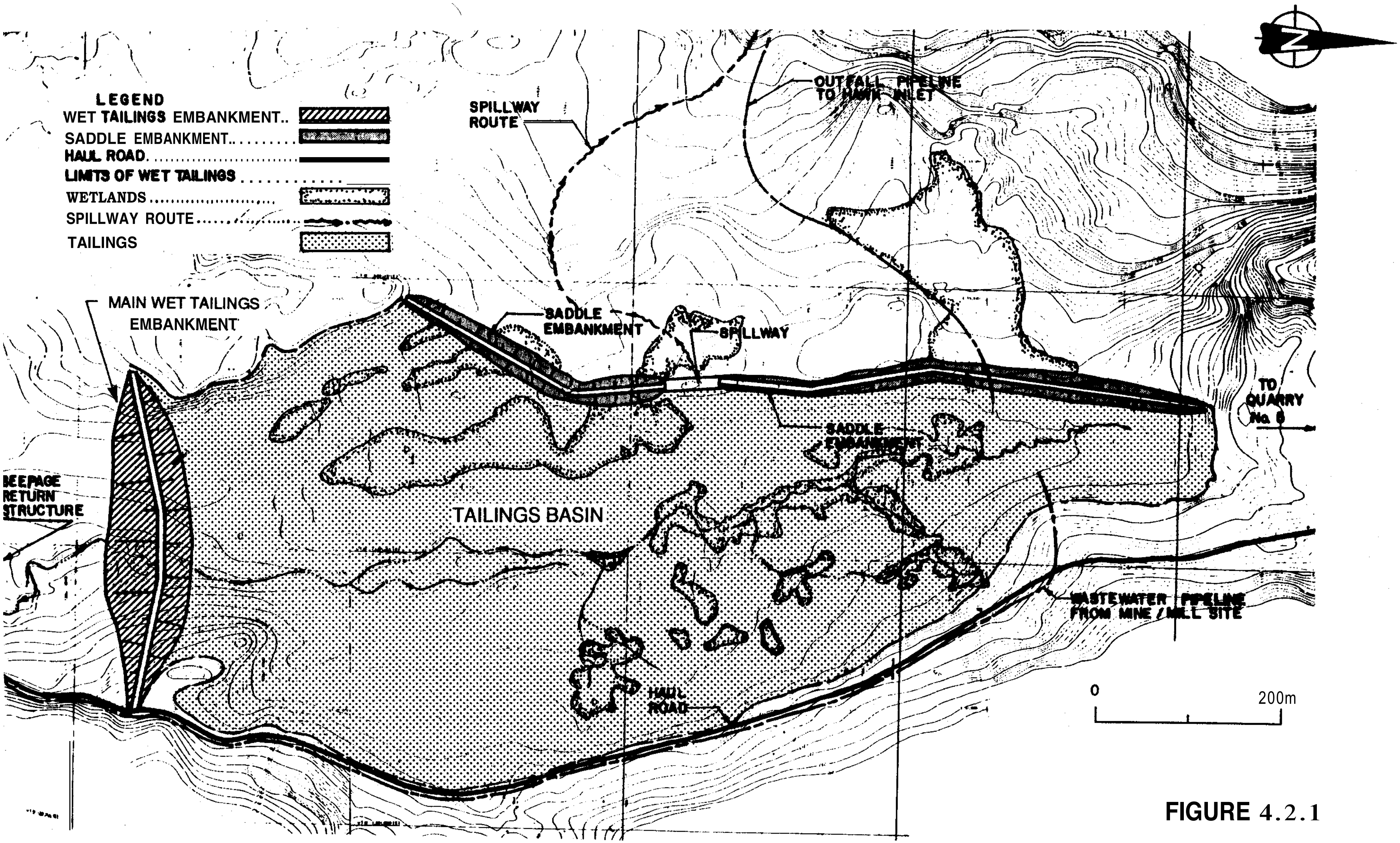


FIGURE 4.2.1

GREENS CREEK MINE
CANNERY MUSKEG TAILINGS BASIN
WET TAILINGS DISPOSAL

SOURCE: FIGURE 3 (USDA, 1988), FIGURE 2-7(USDA, 1983)

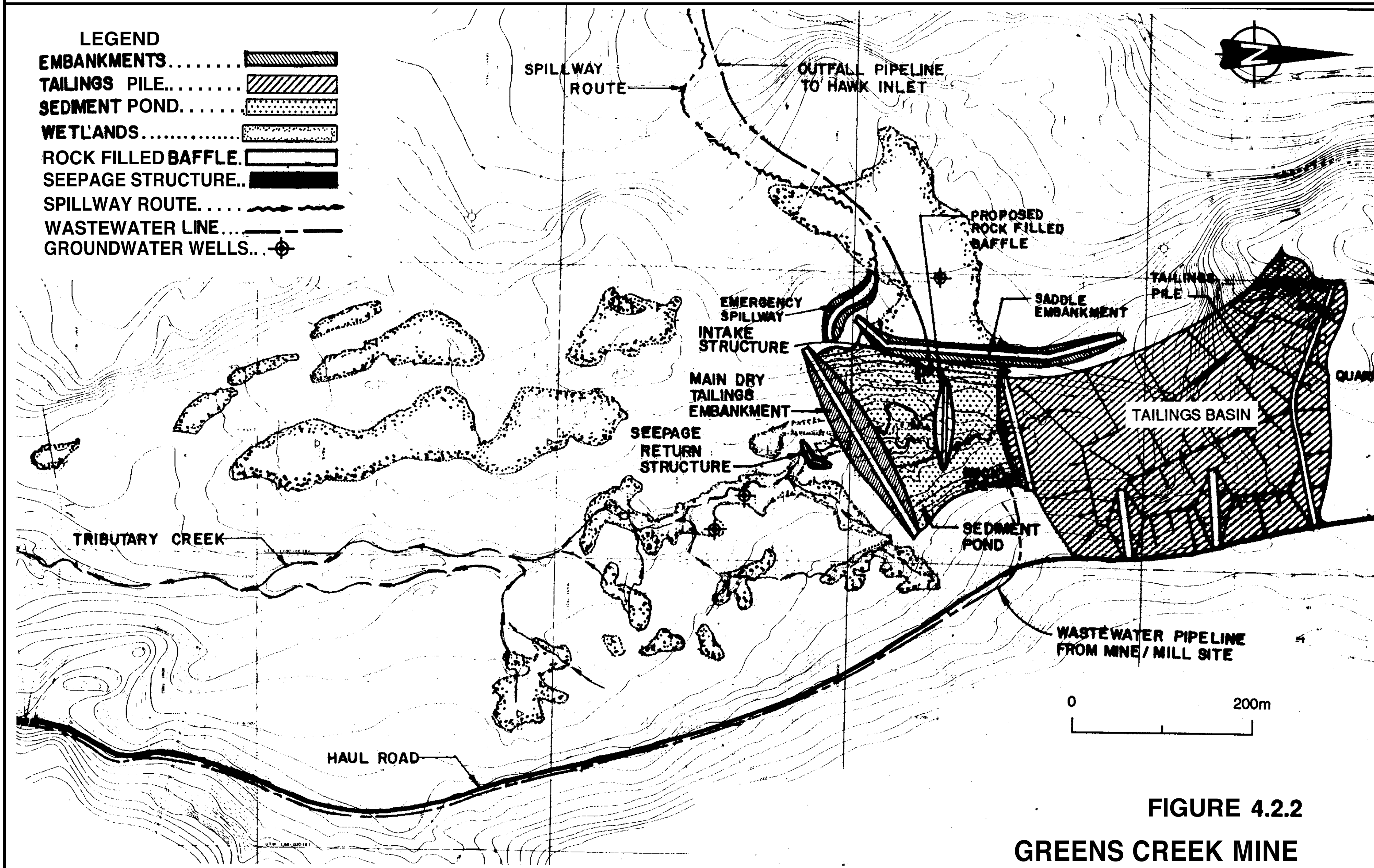


FIGURE 4.2.2

GREENS CREEK MINE
CANNERY MUSKEG TAILINGS BASIN
DRY TAILINGS DISPOSAL

SOURCE: FIGURE 4 (USDA, 1988)

on representative tailings samples indicated that acid production and acid leaching potential were low. Additional testing using actual mill tailings were proposed to be carried out later during the first year of mine operation. Such additional tests would be used to further characterize the acid generation potential of the tailings.

The dry tailings disposal plan included measures to avoid acid generating conditions. These measures included:

- grading, compaction, and sealing to reduce water infiltration through the dry tailings stack;

- contouring of the tailings stack and collection of runoff in interception ditches to reduce infiltration into the tailings; and

- the capping and vegetation of filled sections.

It is noteworthy that the mine also had a comprehensive plan to address acidic drainage from waste rock dumps as most recently described in Kennecott (1995).

During the licensing stage the dry tailings disposal method was considered the preferred method of tailings disposal. The tailings facility is located within an environmentally sensitive region, and the approach minimized both the total disturbed area and subsequent potential impact on the local environment.

The tailings were dewatered using pressure filters and deposited at a moisture content of between 9 and 11%. Following placement in 0.4 m lifts, the thickened tailings were compacted by the haul trucks. The tailings facility was divided in sections whereby once filled to capacity each section was sloped and reclaimed with a cap of waste rock and revegetated.

4.2.3 Monitoring and Testing

Preoperational acid generating potential and leaching tests (pre-1985) indicated that the tailings would be net acid consumers. The company indicated that chemical treatment measures would be implemented if future tests indicated that some tailings were acid generating.

While the mine was in operation, two tests were used to assess the chemical status of the deposited tailings (Greens, 1995):

- monthly pH measurements of leachates in the finger drains under the tailings stack. Readings were taken on a monthly basis from July 1989 to January 1991 - measurements were typically in the pH range of 6 to 6.8; and

! a leach test to characterize the acid production potential of the tailings. The leach test was initiated in October 1989 and continued in excess of 500 days. Leach test procedures included: particle size analyses; geochemical analyses; and a leach test for soils.

Particle size analyses determined that 73.8% of the tailings solids are minus 53 m (270 mesh). Key chemical components were determined to be SiO_2 (32.5%), Fe_2O_3 (13.9%), CaO (9.3%), and MgO (5.3%). Moisture content was determined to be 11% (by wt).

The final pH of the leach solution used in the synthetic precipitation leach test was 6.62 and resulted in the solubilization of 247 mg/L of calcium, and 67.9 mg/L magnesium. Lead, manganese, and zinc values were 0.47, 4.5, and 42.6 mg/L respectively.

The tailings were found to be marginally acid producing. Selected test result data are summarized below (Greens, 1995):

! acid consumption determined using Bruynesteyn and Duncan, and Sobek methods were 94 and 270 kg H_2SO_4/t.

! potential acid production calculated from pyritic sulphur (10%) was 338 kg H_2SO_4/t.

Acid/base accounting and shake flask tests carried out by Cominco Engineering Services in 1994 (Greens, 1995) also indicated that the dry tailings have a potential for acid production.

4.2.4 <u>Synopsis</u>

The mine continues to monitor the tailings management facility and is re-evaluating strategies for future tailings disposal. This operation used a dry (thickened) tailings concept primarily to enhance the quality of backfill and not to encourage the formation of an elevated water table. The tailings were deposited in compacted lifts as compared to a thickened tailings cone. At present, insufficient data precludes drawing conclusions as to the effectiveness of the thickened tailings method to inhibit oxidation reactions at this site.

Significant benefits were achieved from the use of the dry tailings disposal method at this site including reductions in the total area disturbed by the development of the tailings management facility, and tailings basin construction costs. The Green Creek site appears to be well suited to the use of an elevated water table concept given the high rainfall and presence of thickened tailings. A shallow cover may be sufficient to provide adequate evaporation protection and allow for the discharge of clean runoff.

4.3 SITE STUDY m 3 - CLUFF LAKE

The Cluff tailings basin is another example where thickened tailings were used to assist in creating a suitable closure plan. Although the elevated water table is not integral to the system performance, such a condition is created by the design which controls acid drainage at this site.

4.3.1 Background

The Cluff Lake uranium mine is located in northern Saskatchewan approximately 97 km south of Lake Athabasca and 35 km east of the Saskatchewan-Alberta border. The Cluff Lake deposits were discovered circa 1968. Two distinct grades of mineralization existed and the site was developed as follows:

- Phase 1 (May 1980 to February 1983) involved the mining and milling of the high-grade D orebody;
- Phase 1 extension (March 1983 to July 1984) involved the reprocessing of gravimetric tails; and
- Phase 2 (commenced August 1984) involved the mining and milling of low-grade orebodies.

Construction of the Phase 1 facilities began in the fall of 1978 and production from the D orebody in May, 1980. The D orebody was depleted in 1983. The Phase 2 program which initially focussed on three deposits (Claude Lake, OP, and N40) began in August 1984.

4.3.2 <u>Acid Generation</u>

The pyrite content of the tailings is very low. It is unlikely that the tailings will produce highly acidic seepage but pH levels can be expected within the 4 to 6 range.

4.3.3 <u>Tailings Management Facility</u>

The Tailings Management Facility (TMF) includes a primary tailings pond with an impervious retaining dam and a secondary effluent treatment system (Figure 4.3.1). The main dam includes a bentonite slurry cutoff wall into the bedrock and a compacted bentonite admixture liner to control seepage from the tailings area into Snake Lake.

During Phase 1, high grade ore was crushed and fed to a grinding circuit and subsequently to leaching. Leaching produced a reject referred to as leach tails which were placed into concrete containers. At the end of Phase 1, approximately 6,475 t of leach tails were contained in concrete vaults. Medium grade ore was upgraded by a gravity concentration process. Rejects from the upgrading process (gravimetric residue) were stockpiled in two gravimetric tailings ponds. Gravimetric residues were reprocessed during the Phase 1 extension period (Saskatchewan Research Council, 1991).

As such, only small quantities of solids (mainly iron cake) were deposited into the tailings facility during Phase 1. The principal discharge into the facility was neutralized liquid. About 53,000 t of tailings were deposited into the tailings facility during Phase 1 extension operations. These tailings were deposited in the north end of the tailings facility.

In 1984, a divider dyke was completed to separate the TMF into the liquids pond and the solids pond (later to become the lower and upper solids pond).

The mill process was modified to suit the Phase 2 processing of lower grade ore and the reprocessing of Phase 1 leach tails. At the commencement of Phase 2, tailings were deposited in a similar manner to that used during the Phase 1 extension. Subsequent mill modifications allowed separate discharge of tailings solids and neutralized liquid. Since January 1987, thickened tailings solids (>50% by wt.) have been disposed in the tailings facility upstream of the neutralized liquid influent. This method eliminated the segregation of the tailings solids into coarse and fine reactions (Saskatchewan Research Council, 1991).

During the reprocessing of leach tails at the commencement of Phase 2, a sandy till berm was constructed across the tailings basin to ensure that the enriched tailings produced during the reprocessing were retained as far upstream within the TMF as possible (Figure 4.3.1). The enriched tailings were subsequently covered, as planned, by other thickened Phase 2 tailings.

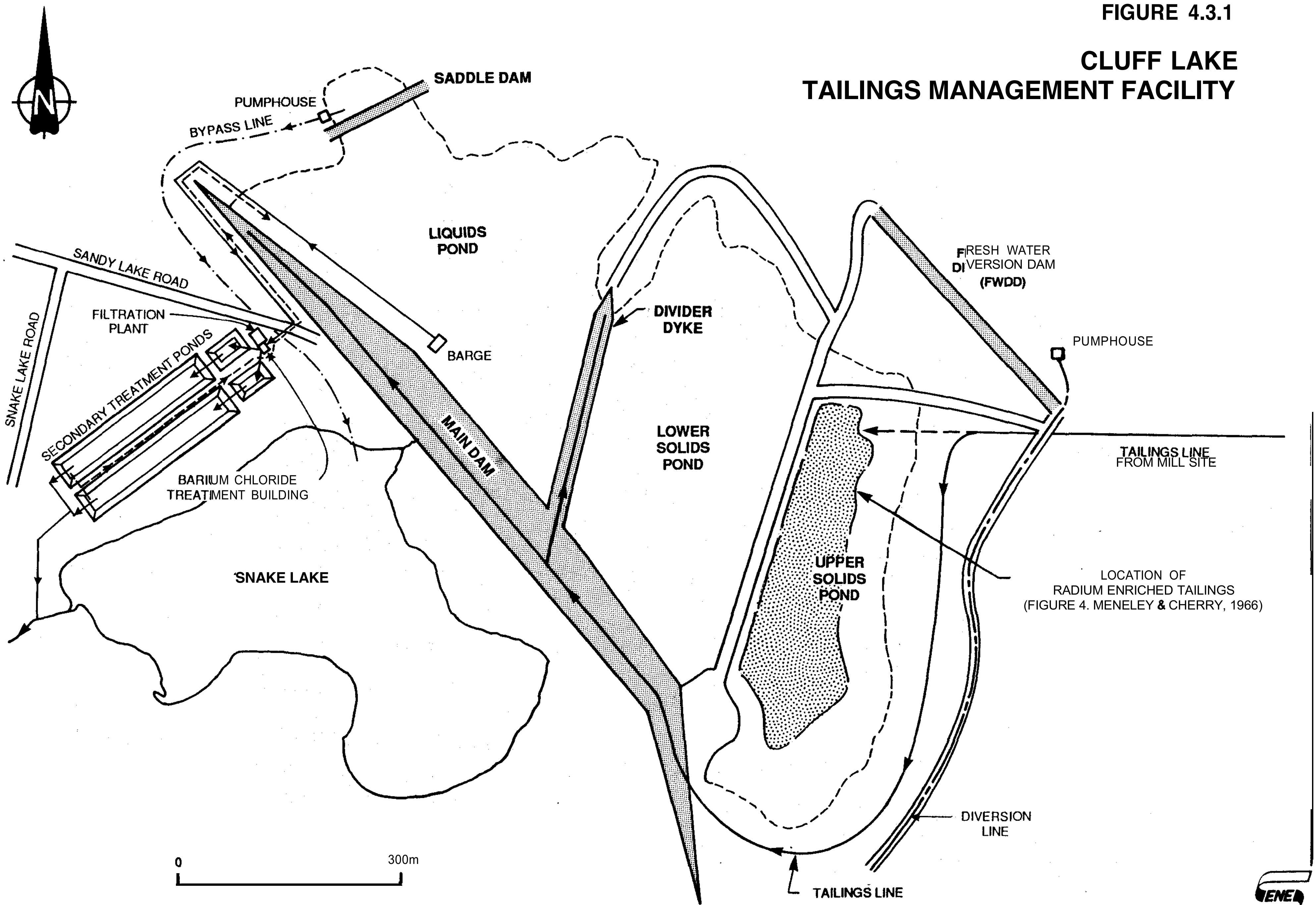
By February 1987, about 450,000 t of Phase 2 tailings has been deposited in the TMF. The mill operated intermittently between 1987 and July 1989. The flushing of lines which accompanied each shutdown resulted in some segregation of the tailings.

4.3.4 TMF Decommissioning Strategy

The conceptual decommissioning plan for the Cluff Lake TMF was developed from 1983 through 1986 (Amok, 1986, Meneley and Cherry, 1986). In 1990, the plan was reviewed with respect to the placement of thickened tailings. The long term closure plan is to develop a uniform slope using thickened tailings on the solids pond section of the facility followed by the placement of a cover over the tailings extending westward to the divider dyke. The water level in the liquids section will be lowered by constructing a spillway in the northwestern abutment of the main dam. An upstream diversion channel will reduce groundwater inflow into the

FIGURE 4.3.1

CLUFF LAKE TAILINGS MANAGEMENT FACILITY



tailings basin.

Thickened tailings will be used to form a relatively uniform slope of approximately 1 to 3% over the solids pond. This practice will significantly reduce particle segregation resulting in a relatively homogeneous material with similar physical properties. The bulk of the surface cap will be comprised of crushed waste rock to produce a free-draining layer to enhance infiltration into the tailings and inhibit surface runoff. The 1 m thick cover will also reduce the effects of gamma radiation and minimize tailings erosion and frost heaving.

In 1993, thickened tailings were placed in the area south of the Fresh Water Diversion Dam (FWDD). Deposited tailings have remained saturated except for a surficial desiccated layer near the active tailings area.

To ensure that little or no segregation occurs within the solids pond and to reduce the hydraulic conductivity of the tailings an additional thickener was added to the mill discharge in 1994. This produces specially thickened tailings with a solids content of approximately 65 %. Low density slimes that had accumulated against the divider dyke were fed into the thickener. The TMF which has a capacity of approximately 2,669,000 m^3 will contain about 2,460,000 m^3 of tailings at the closure of the facility circa 2002.

Surface runoff on the tailings is encouraged to infiltrate (SENES, 1986). Although AMD is not a material issue at this site, the use of thickened tailings below the crushed rock cover would result in a near saturated layer that would reduce or eliminate any acid production. Should acid be produced in the near surface tailings it would be consumed by buffering minerals.

4.3.5 <u>Monitoring And Modelling</u>

In 1986, information from geotechnical and geochemical studies and modelling results from a seepage and transport model developed at the University of Saskatchewan were utilized to predict future Ra_{226} release rates from the TMF following decommissioning and the subsequent impact on Snake Lake. The research predicted a maximum Ra_{226} release rate of 1.55 Bq/L and a maximum concentration of approximately 0.06 Bq/L in Snake Lake, 4,000 years after decommissioning.

In 1993, a new source concentration function was included in the seepage transport model which provided information on peak release rates from different components of the model at different times. The previous versions of the model required a uniform leaching rate over the entire tailings mass. This version predicted a peak release concentration of Ra_{226} of 2.2 Bq/L 5,000 years after decommissioning (Cogema, 1993).

In 1994, monitoring wells were placed in the tailings to monitor changes in the density of tailings and the migration of Ra_{226} and non-retarded ions beneath the tailings mass (Cogema, 1994). A surface water sampling program continues to monitor the levels of radionuclides (Ra_{226} and U), trace elements (As, Ba, Bi, Cd, Co, Cr, Mo, and Se), and major ions (Ca, Cl, Na, and SO_4) in the surrounding surface waterbodies. Based on available reference data collected between 1981 and 1992, the concentrations on the various ions in Island Lake, located immediately downstream of Snake Lake, have remained relatively constant during the last five years except for uranium which has steadily declined.

4.4 SITE STUDY m 4 - LES MINES SELBAIE

Selbaie is another example where thickened tailings may prove beneficial in controlling long term AMD from the tailings management facility.

4.4.1 Background

The polymetallic Zn-Cu-Ag-Au deposit is located 82 km northwest of Joutel, Québec. The Selbaie ore deposits were discovered in 1974-75 by joint venture partners Selco Inc. and Pick and Mather and Co. In July 1981, the underground mining operation commenced at a production rate of 1,650 t of ore per day and a mill discharge rate of 1,567 t of tailings per day. In 1985, ownership changed to 55% BP Canada Resources Inc, 35% Esso Minerals, and 10% TransCanada Pipelines Ltd. The mine was subsequently purchased by Billiton Metals Canada Inc.

Production at the open pit commenced in 1987; the daily ore production and mill discharge rate increased to 6500 tonnes and 6175 tonnes, respectively. Since 1993, the mill discharge rate has risen to approximately 7600 tonnes per day. The underground mine was closed in 1993. Production continues from the open pit.

The vein-type mineralization is characterized by predominantly three main types:

- A1 - silicified ore with laminated veins consisting of alternating layers of quartz, sphalerite, pyrite, and minor chalcopyrite;
- A2 - quartz vein stockwork mineralization consisting of chalcopyrite veinlets with minor sphalerite; and
- B - a network of closely spaced quartz-carbonate-chlorite veins containing varying amounts of chalcopyrite, chalcocite, and minor sphalerite with minor amounts of bornite, covellite, and native copper within the zone of supergene alteration.

4.4.2 Tailings Management Facility

The tailings basin is located approximately 1 km south of the mill (Figure 4.4.1). Tailings at 15 to 20% solids were pumped to a 45 ft thickener located at the north end of the basin. Thickener overflow was discharged to the tailings pond and the thickened tailings (thickener underflow) were pumped to a tailings cone. The original concept was to develop a thickened tailings cone with a 6% slope. In concept, the thickened tailings would be discharged from a single point to form a stable consolidated coned beach and eliminate the need for large perimeter dams. The homogeneous nature of the thickened tailings would also enhance water retention and inhibit oxygen diffusion to sulphide solids.

The design density (65% solids) of the tailings could not be achieved and typical operating densities varied between 58 to 60% solids. The lower densities resulted in segregation of slimes and high solids loading to the tailings pond. The higher than desired flow from the single discharge point also resulted in gully erosion of beaches and the flattening of the beach slope. In 1986, the thickened tailings cone method was discontinued and replaced by conventional spigotting from the northeast end of the basin. Internal dykes were constructed using waste rock to contain slimes and provide for improved capacity without a major raising of the perimeter dams. The raising of the dams produced a large pond with a capacity of about 1×10^6 m^3 providing a settling time of approximately 30 days during average flow conditions. In 1987, the tailings capacity was estimated at approximately 20×10^6 t.

Freezing of spigots during the winter months forced the company to abandon multiple spigots and to utilize a lower operating density with a single end of pipe discharge. This significantly reduced the viability of maintaining steep beaches during the winter operations.

4.4.3 <u>Physicochemical and Mineralogical Characteristics of the Tailings</u>

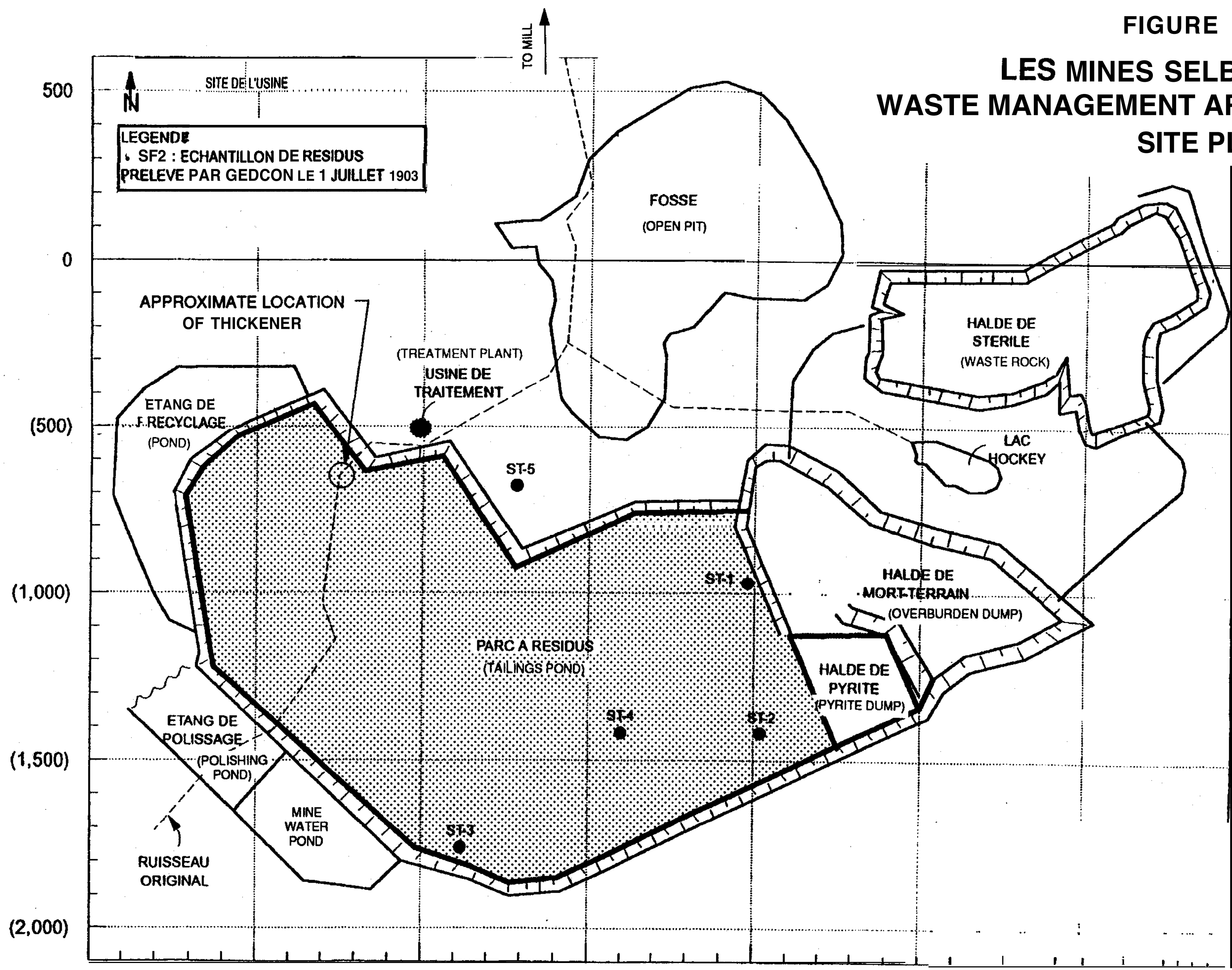
This section presents results of drilling programs completed within the tailings area by GEOCON (1993) and Fournier (1994).

The tailings are comprised of 77 to 80 % quartz, 3 to 4 % sericite, varying amounts of chlorite, gypsum, and limonite, 10 to 15 % pyrite, and trace amounts of other sulphide minerals. Although microscopic investigations revealed pervasive limonite staining indicative of a strongly oxidizing environment, the pyrite appeared fresh. The pyrite particle size ranges from 5-200 m with approximately 90 % of the sample less than 90 m and a d_{10} value of approximately 4 m. The results of moisture content determinations are presented in Table 4.4.1. The data suggests that the tailings are remaining saturated.

ABA testing and kinetic tests using humidity cells were conducted on an old,

FIGURE 4.4.1

LES MINES SELBAIE WASTE MANAGEMENT AREA SITE PLAN



SOURCE: MODIFIED FROM FIGURE 1 (LES MINES SELBAIE, 1995) oxidized tailings sample and a fresh tailings sample. The average sulphide content measured 3.9 % with a maximum content of 8.3 %. The ABA test results indicate that the tailings are intermediate to strongly acid generating (Table 4.4.2). The humidity cell tests were run for approximately 3 months. Although the pH of leachate collected from the old oxidized sample remained low the concentrations of metals and sulphate decreased with time suggesting that the pyrite was relatively stable chemically considering that the sample contained no carbonate. Similarly for the fresh sample, the metal levels in the leachate declined with time. The pH, however, remained above 5.0 and is expected to fall following consumption of the 1.5 % carbonates in the tailings.

4.4.4 Long-term Disposal Plans

The Selbaie tailings are excellent candidates for application of the elevated water table concept. The tailings were thickened, fine grained and appear to have natural water contents that approach saturation even in the near surface zone. With the low permeability foundation conditions (high local water table) and high net precipitation, a simple cover to maximize infiltration and minimize evaporative loss could be a suitable closure strategy.

Table 4.4.1

LES MINES SELBAIE
TAILINGS MOISTURE DETERMINATIONS

Sample m	**Sample Depth (m)**	**Water Content (%)**	**Total Volumetric Weight (kg/m^3)**	**Dry Weight (kg/m^3)**	**Sample Colour After Drying (as an indication of oxidation)**
94-8	4.57	42.1	1868	1315	Pale Grey
94-8	7.62	34.2	1855	1383	Pale Grey
94-8	9.91	24.3	2059	1659	Dark Grey
94-8	12.19	29.4	1887	1459	Pale Grey
94-9	7.62	21.1	2013	1664	Dark Grey
94-7	5.33	27.7	1948	1526	Dark Grey

Source: Fournier (1994).

Table 4.4.2

LES MINES SELBAIE
ABA ANALYSIS OF TAILINGS SAMPLES

Analysis Date	Sample ID[1]	Paste pH	% S Total (%)	% S SO_4 (%)	% S Sulphide (%)	AP ($CaCO_3$) (kg/t)	NP ($CaCO_3$) (kg/t)	NNP ($CaCO_3$) kg/t)	NP/AP
9 Aug 93	ST-1	6.4	8.22	0.21	8.31	257	33	-224	0.13
9 Aug 93	ST-2	8.1	2.24	<0.01	2.05	70	25	-45	0.36
14 Sep 93	ST-3	7.1	1.21	0.05	0.99	38	16	-22	0.42
9 Aug 93	ST-4	8.2	2.4	0.02	2.37	75	14	-61	0.19
9 Aug 93	ST-5A	4	4.25	0.57	3.57	133	-3	-136	-0.02
9 Aug 93	ST-5B	4	5.36	0.43	4.89	168	0	-168	0.00
9 Aug 93	ST-6	6.7	5.39	0.25	5.24	168	18	-150	0.11
Maximum		8.2	8.22	0.57	8.31	257	33	-22	0.42
Minimum		4	1.21	<0.01	0.99	38	-3	-224	-0.02
Mean		6.4	4.15	0.22	3.92	130	15	-115	0.17
Standard Deviation		1.6	2.23	0.20	2.29	70	12	68	0.16

[1] Selected sample locations are shown in Figure 4.4.1.

Source: GEOCON (1993).

This site is worthy of future study to address the benefits of thickened tailings in controlling acid production in potentially highly acidic tailings.

4.5 SITE STUDY m 5 - KIDD CREEK

4.5.1 Background

At the Kidd Creek metallurgical site in Timmins, Ontario tailings are deposited using the thickened tailings disposal method. The tailings are discharged from a central location within a 1,200 ha tailings basin to form a tailings cone (Figure 4.5.1). This approach was developed by Robinsky (1975, 1978) and the tailings cone is also referred to as the Robinsky cone.

4.5.2 Technical Studies

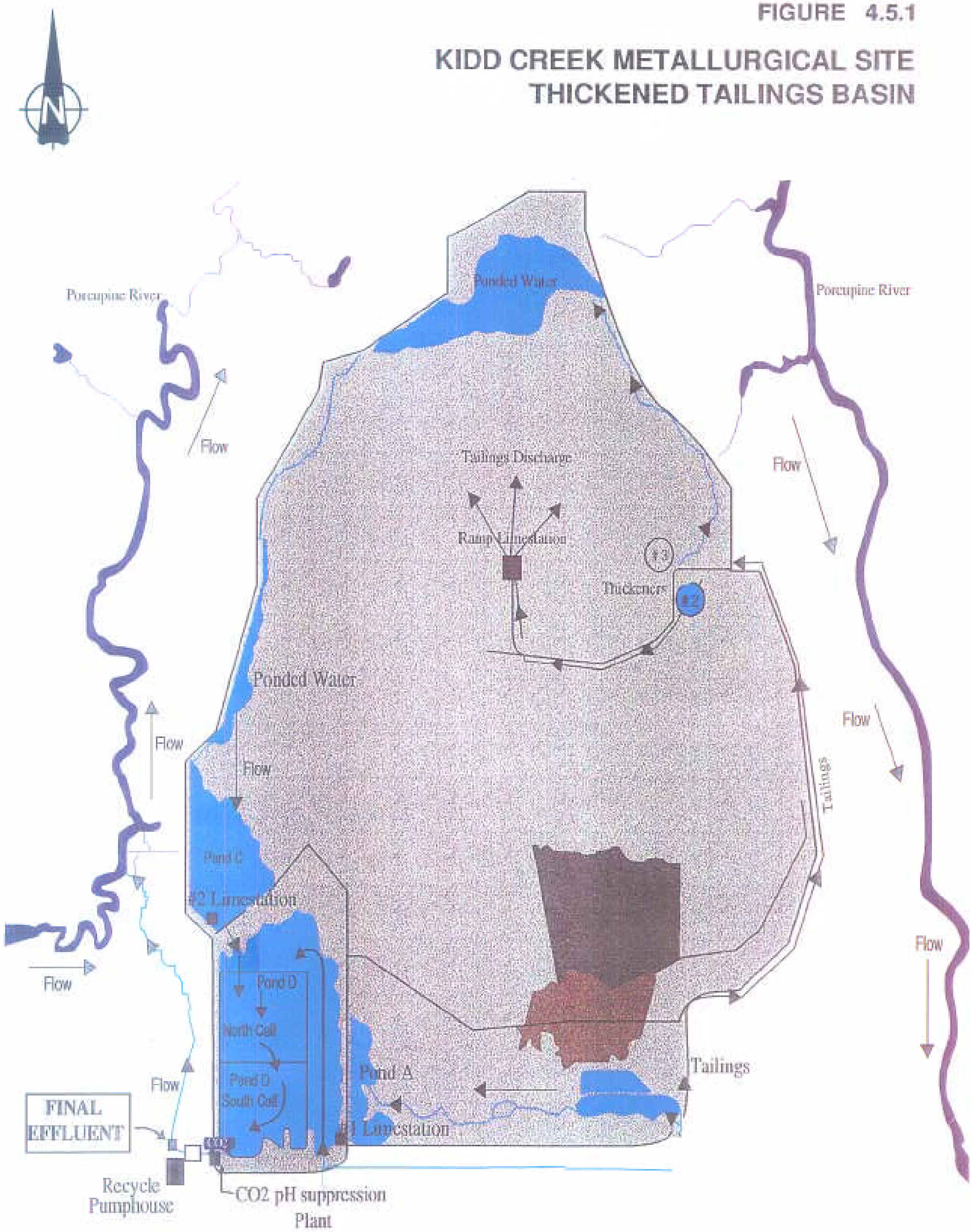
There is considerable information on the hydrologic characteristics of the thickened tailings disposal method at Kidd Creek. While there are data on pore water chemistry in the Kidd Creek tailings, the rates of acid generation or sulphide mineral oxidation have not been clearly defined or compared to rates in other tailings disposed conventionally. Published sources of information include, but are not limited to: Robinsky et al. (1991), Barbour et al. (1993), Al et al. (1994a, b), Woyshner and St-Arnaud (1994) and Al and Blowes (1995).

The tailings slurry has a low water content (approximately 30% by mass) during discharge and remains unsegregated as the slurry forms a cone with a 1 to 2% grade. The lack of segregation creates a relatively homogeneous tailings that have characteristics that are favourable for high moisture retention above the water table (high capillary tension). Although the tailings deposit was not designed to maintain a high water table, this condition occurs from time-to-time. This, and the high moisture retention above the water table, has implications for lower oxidation rates in the tailings.

In 1993, St-Arnaud and Woyshner completed an extensive technical study which

FIGURE 4.5.1

KIDD CREEK METALLURGICAL SITE THICKENED TAILINGS BASIN



SOURCE: FALCONBRIDGE LIMITED, KIDD CREEK DIVISION, 1995 had the general objective of verifying the hydrology of the Kidd Creek thickened tailings disposal site. Hydrologic and hydrogeologic data were obtained and assessed, and tailings pore water sampling and analyses were carried out. Selected findings by St-Arnaud and Woyshner (1993) are summarized below:

(1) During water table recharge conditions, following summer drawdown, the height of the capillary fringe was observed to be 4 m. A maximum height of 5 to 6 m is expected at the apex of the tailings cone during summer drawdown.

(2) An infiltration deficit was predicted for extremely dry conditions which would result in tailings surface dewatering. Above normal precipitation would likely replenish the deficit.

It was concluded that (St-Arnaud and Woyshner, 1993):

(1) Considering the tailings cone as is, then following closure, tailings saturation and water table position is expected to resemble that presently observed in areas of the cone where deposition is not active.

(2) De-watering during a drought year is expected to have little impact on long-term saturation of the tailings. However during these periods, oxidation is promoted deeper in the surface tailings.

(3) Release of contaminants from the tailings site to the environment should remain at present rates because pore water velocities are slow, and because of the sustained presence of near-surface saturated conditions.

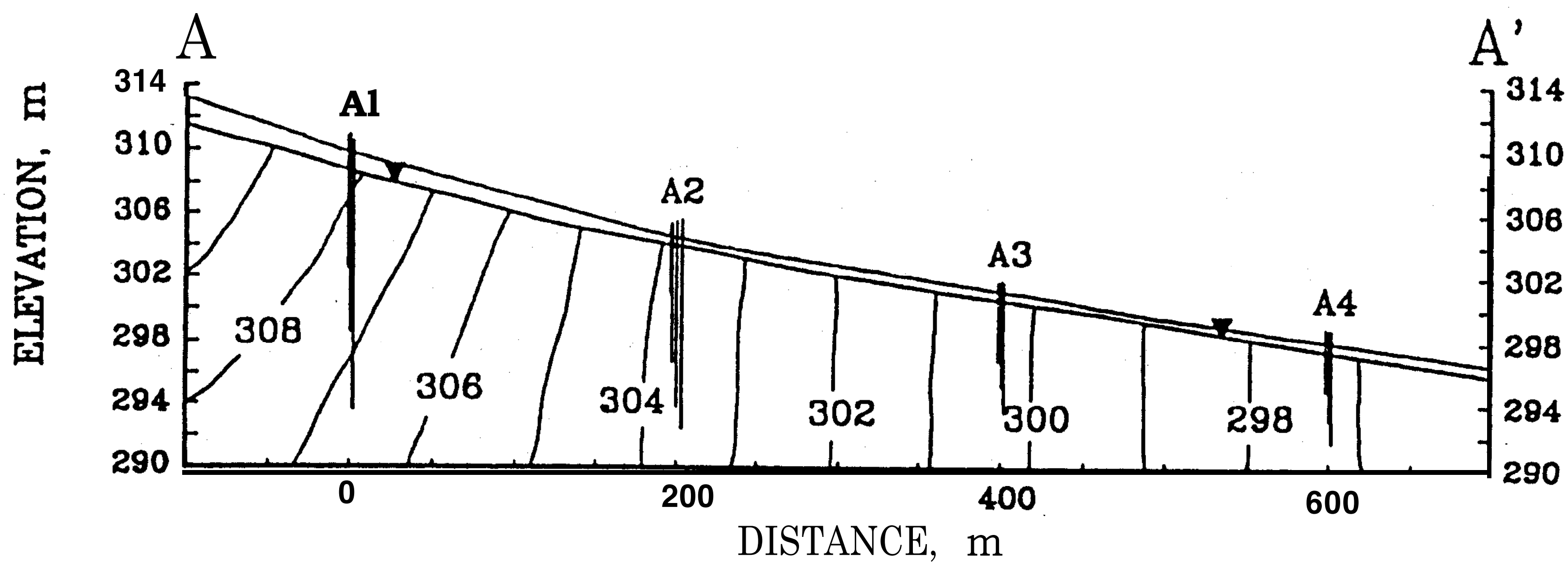
A grain-size distribution envelope presented by Barbour et al. (1993) indicated that the d_{10} values varied between 1 and 5 microns, values that are approaching clay-sized particles. The measured hydraulic conductivity were generally in the 8×10^{-8} to 5×10^{-7} $m \cdot s^{-1}$ range. A simple modelling analysis of moisture content above the water table as a function of evaporation showed that lower evaporation rates can contribute to near saturated conditions up to the AEV value (6 m) and that even with high steady-state evaporation rates of 6 mm/day, the saturated conditions can be maintained with a water table at 4.5 m below the tailings surface. At an estimated summer evaporation rates of 2.5 mm/day, saturated conditions to the surface could be maintained with a water table depth of 5.5 m below ground surface.

An extensive field study by Al et al. (1994a, b) showed that the range in hydraulic conductivity (K) was 5×10^{-9} to 1×10^{-6} $m \cdot s^{-1}$ with in excess of 70% of the measured values in the limited range of 1 to 5×10^{-8} $m \cdot s^{-1}$. The water table elevation across the site varied dramatically with the seasons at the apex of the pile and more moderately near the base of the pile. While the water table was almost at the tailings surface in the spring, the depth of the water table extends to about 5 m below ground surface at the apex of the pile to less than 2 m below surface in the flatter lying areas closer to the pile perimeter (Figure 4.5.2). The moisture content remains near saturated values to within 0.3 to 0.4 m of the surface even when the water table drops to 6.5 m below surface (near the centre of the cone). Although only preliminary data are available in the study, the zone of oxidation appears to be restricted to the near surface zone extending to depths from 0.3 to 0.5 m below ground surface. Solute velocities in the subsurface that migrate with the pore water are 0.6 $m \cdot a^{-1}$ vertically near the apex of the cone.

The water balance for the Kidd Creek tailings impoundment include annual values of precipitation (P) of 860 mm, runoff (RO) of 0.42 x P, evapotranspiration of 0.51 x P, and infiltration of 0.07 x P (Woyshner and St-Arnaud, 1994). Horizontal groundwater velocities were estimated to be on the order of 10 $cm \cdot a^{-1}$. The capillary fringe or zone of tension saturation, that occurs above the water table was reported to be within 1 m of the tailings surface at the apex of the cone even when the water table occurred at a depth of 6 to 7 metres below surface. A drainage curve for the Kidd Creek tailings reveals an air entry value (AEV) of approximately 6 m of water

FIGURE 4.5.2

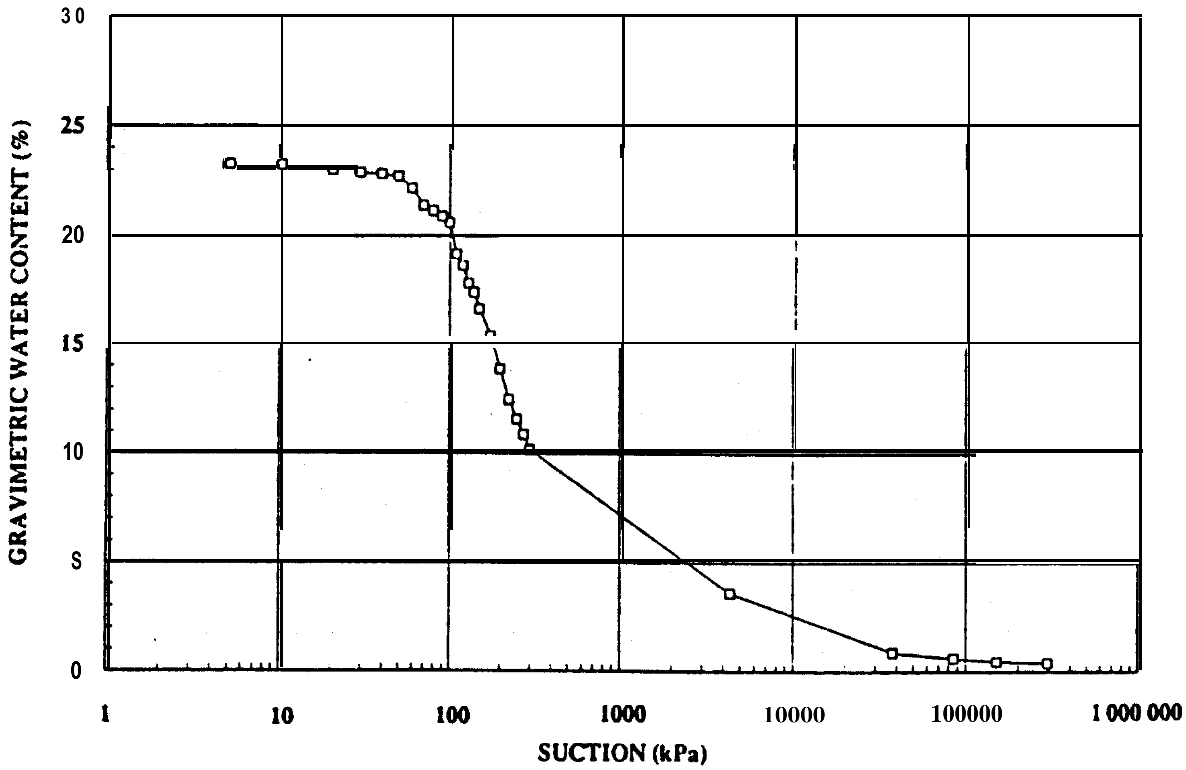
CROSS-SECTION OF THE KIDD CREEK TAILINGS SHOWING THE APEX OF THE DISCHARGE CONE WHERE THE DEEPEST WATER LEVELS ARE OBSERVED



SOURCE: (WOYSHNER AND ST-ARNAUD, 1994)

FIGURE 4.5.3

MOISTURE RETENTION CHARACTERISTIC CURVE FOR THICKENED TAILINGS FROM KIDD CREEK USING THE PRESSURE-PLATE METHOD



NOTE:

1. 1 kPa IS EQUIVALENT TO 0.1 m OF WATER

SOURCE: (BARBOUR et al, 1993)

(or 60 kPa) as shown in Figure 4.5.3. This indicates that the tailings will remain effectively saturated up to 6 m above the water table. The high AEV and observed high moisture content above the water table confirms that very little water addition is required to raise the water table.

4.5.3 Synopsis

The depth to the water table varies from 6.5 m below surface near the apex of the cone to within 1 m of the surface in the flatter areas around the perimeter of the cone. The moisture content of the tailings appears to remain saturated well above the water table. Kidd Creek tailings remain largely unsegregated and have d_{10} values on the order of a few microns. This results in strong capillarity action. Lower moisture contents near the surface are likely due to evaporative losses that can affect the topmost 1 m of the tailings.

Chemical studies suggest that oxidation of the tailings has been quite limited. As tailings placement is ongoing highly saturated conditions are maintained by continuous tailings and water discharge. As such, the Kidd Creek tailings may not represent a good example of elevated water table control on the oxidation rate. Given the current conditions, it appears that lower oxidation rates are actually related to the high moisture levels maintained through capillary action.

The water balance for the tailings suggest that infiltration is less than 10% of local precipitation any evaporative losses are estimated to be about 50% of precipitation. This suggests that designing a surface layer to reduce evaporation could increase infiltration and thereby raise the water table, especially in these tailings that maintain a high moisture content even during the summer months. Very little added water is required to raise the water table under the near-saturated conditions present at this site. Even if the water table is not raised to the surface, added infiltration and less evaporation will result in higher degrees of saturation near the tailings surface and this will result in lower oxidation rates. Indeed, it may be advantageous to keep the water table further below the surface to maintain physical stability.

4.6 SITE STUDY m 6 - NEW TAILINGS, FALCONBRIDGE

4.6.1 Background

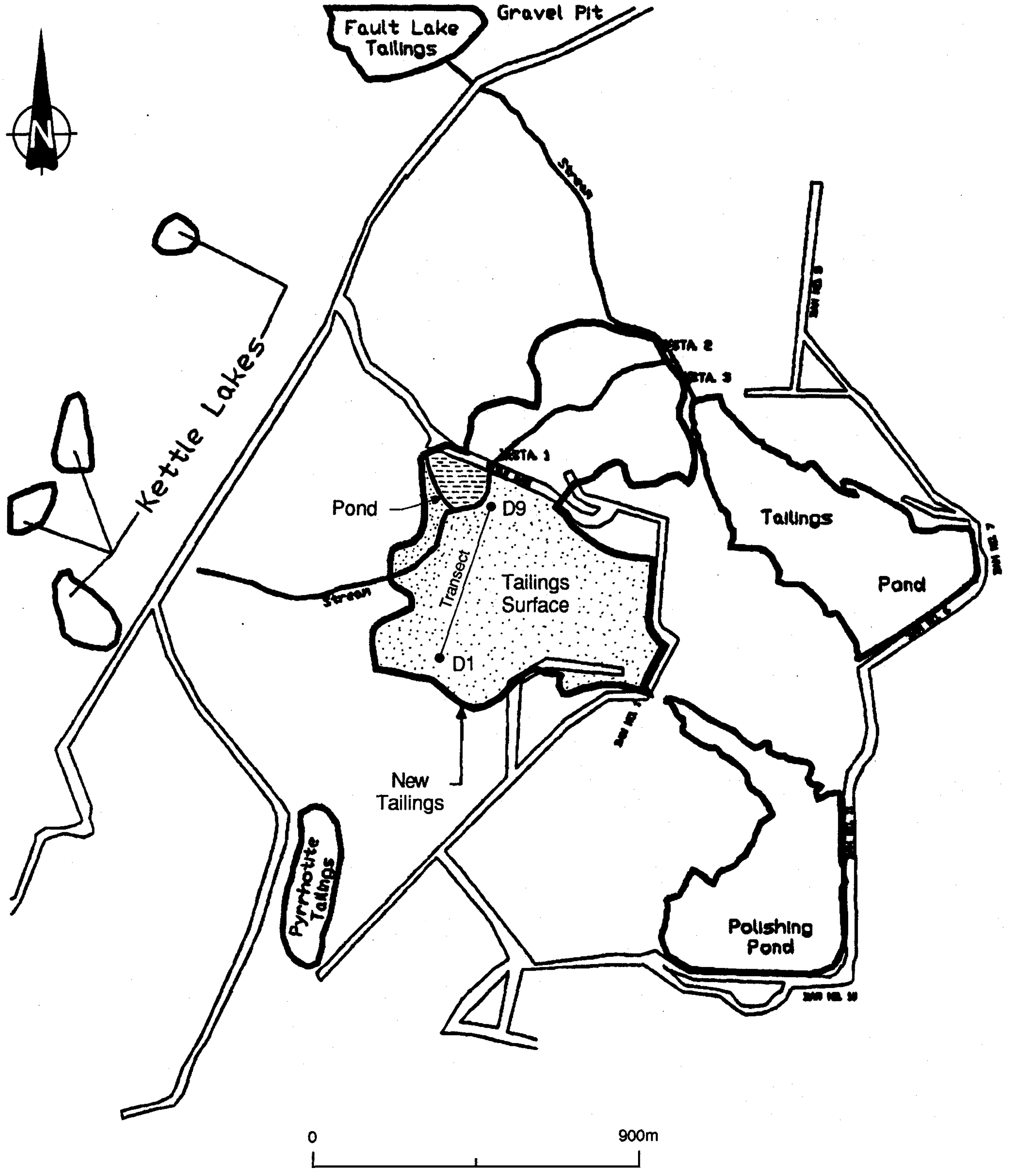
The New Tailings site is situated at the northernmost part of Falconbridge's East Mine property northwest of Falconbridge, Ontario. In the range of 3 million cubic metres of tailings generated from the East Mine operations were deposited at the New Tailings impoundment from 1978 to 1985 and low-sulphur, fine-grained slimes were deposited from 1985 to 1987. The impoundment is currently inactive and closure is planned using passive treatment to minimize sulphide oxidation and acid generation.

The New Tailings site has provided a good opportunity to study the effects of a number of controlling variables on the rate of acid generation in sulphide tailings. Tailings deposition ended in 1987, well before most of the above studies were conducted. The tailings were discharged to develop a beach near the spigot location and slimes migrated towards the pond at the far end of the impoundment (Figures 4.6.1 and 4.6.2). During the final year of operation, however, a floating intermediate earth-fill berm was constructed about midway between the beach and the original pond. Low sulphur slimes (cyclone overflow) were deposited in the final two years of operation. The slimes layer was not uniform and wind erosion caused the partial removal of the cover in the south-west region of the beach. The intermediate dam also retained a shallow pond that maintained a shallow water table to the beach. This was an ideal site to study the effects of fine-grained moist cover-layers (low-sulphur slimes) that may act as oxygen barriers to gas diffusion. It was also useful for the study of effects of shallow water table conditions (1 m depth at the beach to 0 m at the pond edge) maintained by the intermediate dam in the south-west area of the tailings.

A number of detailed studies have been conducted at the New Tailings impoundment to investigate the rate of sulphide mineral oxidation. One such study assessed the effect of depth to the water table on the rate of oxidation. It is evident that as the depth to the water table increases, the rate of oxidation also increases for shallow water table conditions. Beyond a certain depth, the water table elevation does not have an effect on oxidation rates. This happens when the oxidation zone, that is controlled by a combination of the intrinsic oxidation rate and the diffusive resistance of the tailings is above the water table. The following

FIGURE 4.6.1

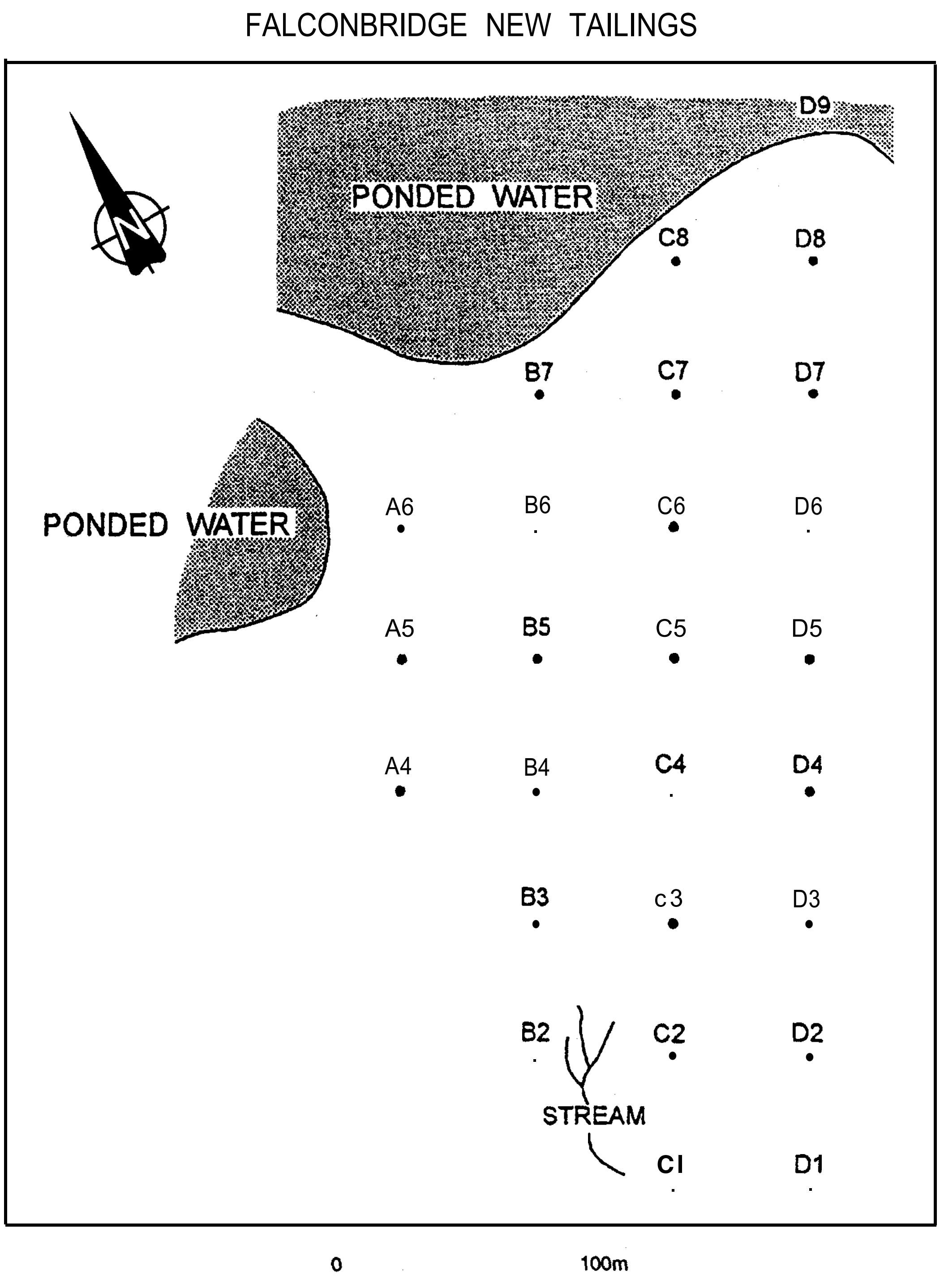
FALCONBRIDGE NEW TAILINGS SITE PLAN VIEW



SOURCE: (NICHOLSON et al, 1995a)

FIGURE 4.6.2

DETAILED PLAN OF STUDY AREA WITHIN THE IMPOUNDMENT



SOURCE: (NICHOLSON et al, 1995a)

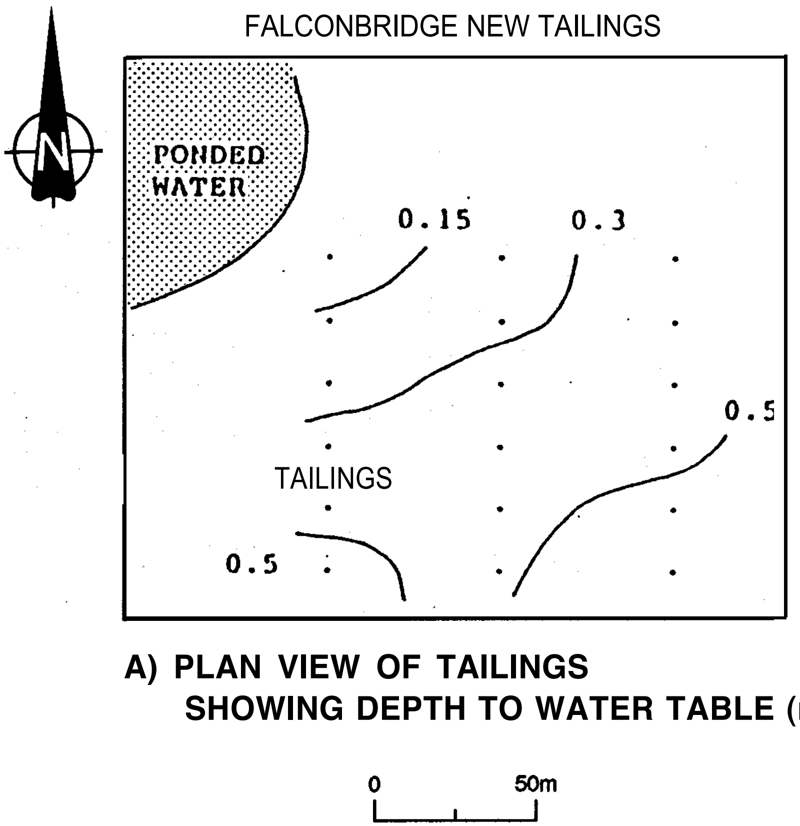
reports provide information on the New Tailings site: Nicholson and David (1991), David and Nicholson (1993), David (1993), Elberling et al. (1994), David and Nicholson (1995), Nicholson et al. (1995a), and Elberling and Nicholson (1996).

Laboratory experiments have demonstrated the link between oxygen flux through the surface and the rate of oxidation products released in sulphide tailings (Elberling, et al., 1994). Assuming that the oxygen flux reflects the relative oxidation rate, the sensitivity of the oxidation rates to different remediation designs can be evaluated. Depth to water table and oxidation values close to ponded water in a tailings impoundment were plotted as shown in Figure 4.6.3. The values of the oxidation rates decrease from 300 to less than 0.038 mol/m^2 per year over a distance of less than 150 m. It is reasonable to conclude that the change in relative oxidation rates by a factor of 1000 is a result of an increase in saturation resulting from increasing water table levels as the pond is approached. This result is in accordance with David's (1993) conclusion that a shallow water cover appears to provide the most favourable environment for a reduction in overall oxidation rates.

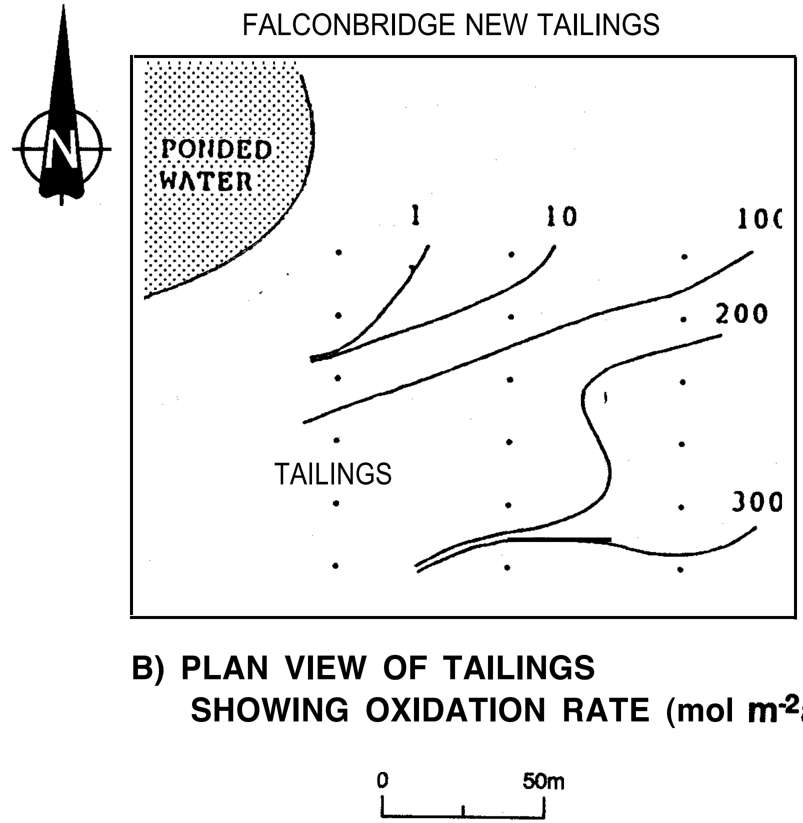
In a later study by Nicholson et al., (1995a), measured oxygen consumption rates were monitored at 26 test sites over a 10 ha area in the tailings impoundment. The test sites represented a range of diffusion coefficients that included the presence of fine-grained moist layers and variation in the depth to the saturated zone in the tailings. The oxygen consumption rates were monitored several times over a two-month period (at nine sites along a transect along the flow direction toward the pond). Results are summarized in Figure 4.6.4. The pore gas oxygen concentration decreased from atmospheric concentration (20.9%) to less than 2% within the upper 0.6 m of all profiles measured. The decreasing oxygen concentration with depth resulted from the limited supply of oxygen controlled by the diffusivity of the tailings in which uptake of oxygen occurs by sulphide oxidation. The depth to the water table at the beach was approximately 0.65 m below ground surface and low degrees of saturation in the tailings were observed near the surface. Although variation in the distribution of sulphide minerals is partly a result of the history of the tailings deposition, the beach site provided a typical profile with an upper oxidized zone and a lower unoxidized zone. The zones are separated by a transition zone where sulphide minerals are currently being oxidized and oxygen is consumed. Towards the pond, the water table is located closer to the ground surface and this limits the transport of oxygen to greater depths. Thus, the extent of the oxidized zone was limited.

FIGURE 4.6.3

THE FLUX OF OXYGEN CALCULATED FROM FICK'S FIRST LAW USING OXYGEN CONCENTRATION GRADIENTS AND CALCULATED DIFFUSION COEFFICIENTS BASED ON MEASURED MOISTURE CONTENTS



A) PLAN VIEW OF TAILINGS
SHOWING DEPTH TO WATER TABLE (m)

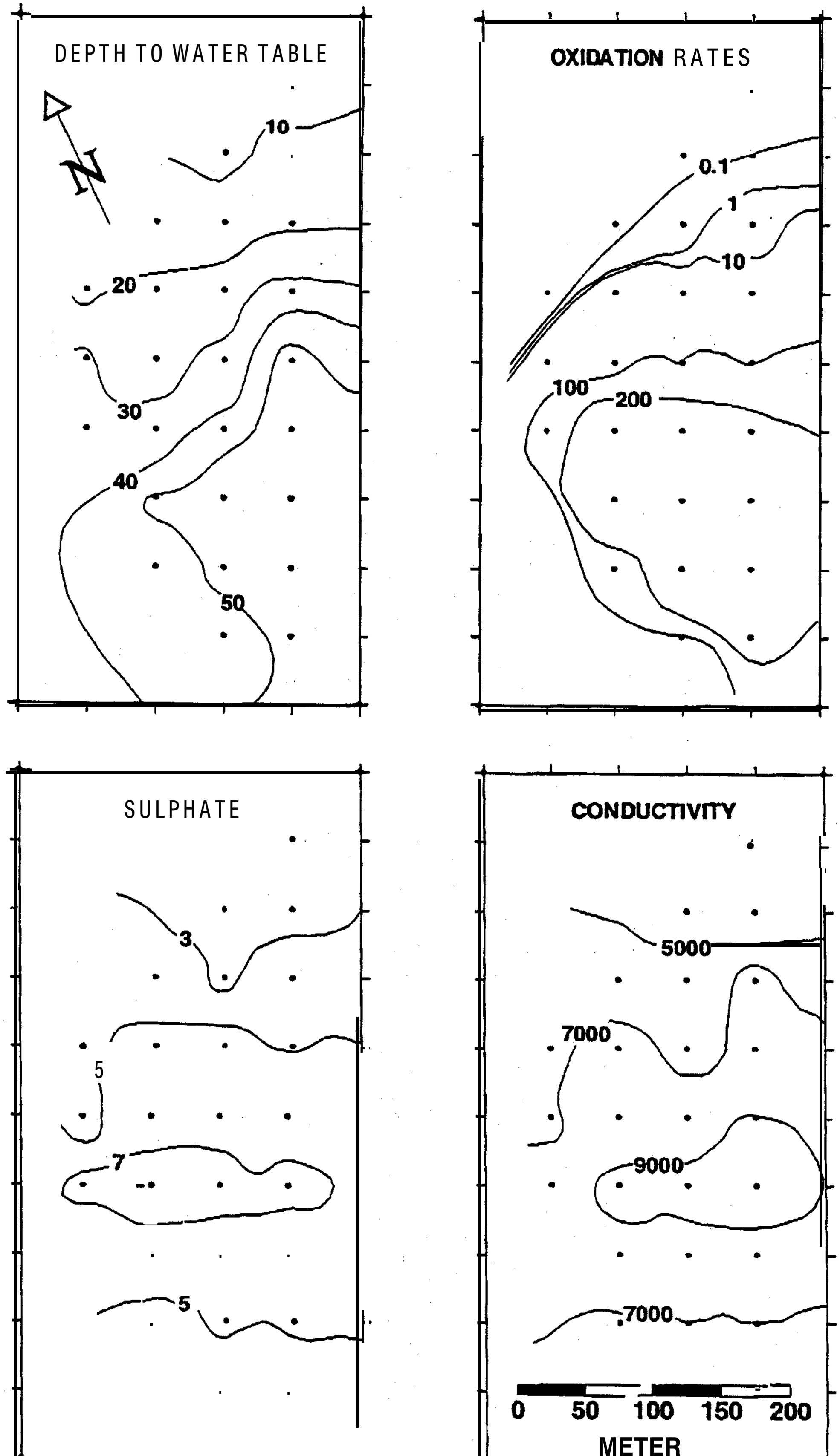


B) PLAN VIEW OF TAILINGS
SHOWING OXIDATION RATE (mol $m^{-2}a^{-1}$)

SOURCE: (ELBERLING ETAL, 1994)

FIGURE 4.6.4

OXIDATION RATES MEASURED WITHIN THE STUDY AREA



SOURCE: (NICHOLSON et al, 1995a)

The results from the oxygen consumption measurements along the main transect along the flow direction towards the pond are summarized in Figure 4.6.5. The oxygen consumption varies from 250 moles-$O_2 \cdot m^{-2}a^{-1}$ at sites where the water table is below the oxidation zone to less than 0.2 moles-$O_2 \cdot m^{-2}a^{-1}$ near the pond where the water table approaches ground surface.

The vertical diffusion coefficient at sites D2 to D9 was also evaluated based on diffusion rates of an unreactive tracer gas. In contrast to the oxygen measurements, the decrease in tracer gas concentrations in the gas reservoir is due only to the soil diffusivity. The change in CO concentration was evaluated by a non-steady mathematical equation. The site at the beach represented the most homogeneous site with the maximum measured diffusivity D_{eff} of approximately $2 \times 10^{-6}\ m^{-2}s^{-1}$ which corresponds to a degree of saturation of 22% (Figure 4.6.6). In contrast, a site close to the pond exhibited the lowest estimated D_{eff} of approximately $3 \times 10^{-8}\ m^{-2}s^{-1}$, representing a degree of saturation of about 80%.

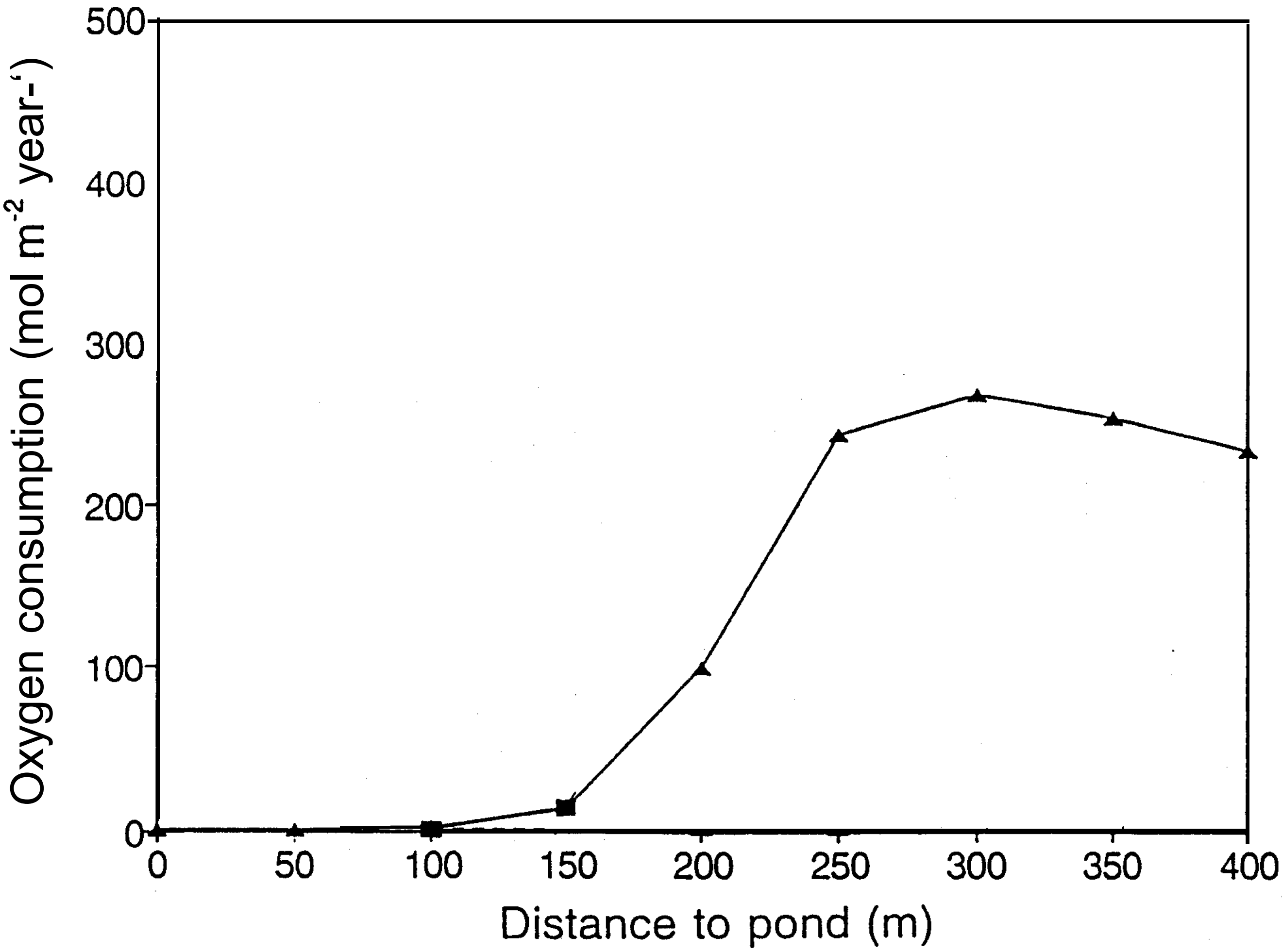
4.6.2 Synopsis

Recent investigations have provided direct measurements of oxygen consumption rates across the tailings area on the New Tailings site (Nicholson et al, 1995b) which are indicative of rates of oxidation in the tailings. The data have been reported as flux of oxygen as mol-$O_2 \cdot m^{-2}a^{-1}$ but are readily converted to either tonnes of H_2SO_4 per hectare per year (t-$H_2SO_4 \cdot ha^{-1}a^{-1}$) or tonnes of $CaCO_3$ per hectare per year (t-$CaCO_3 \cdot ha^{-1}a^{-1}$). Values up to 1100 mol-$O_2 \cdot m^{-2}a^{-1}$ (550 t-$H_2SO_4 \cdot ha^{-1}a^{-1}$) have been observed in fresh high pyrrhotite tailings with a detection limit of about 0.1 mol-$O_2 \cdot m^{-2}a^{-1}$ (0.05 T-$H_2SO_4 \cdot ha^{-1}a^{-1}$), giving a range of measured values of four orders of magnitude.

On the New Tailings site with low sulphur tailings, the flux values range from about 300 mol$\cdot m^{-2}a^{-1}$ at the beach with a water table depth of 0.65 m to less than the detection limit of 0.1 mol-$O_2 \cdot m^{-2}a^{-1}$ at the edge of the pond, a distance of 400 m from the beach. This shows that a three order-of-magnitude change occurs between the ponded area and the well drained coarse beach tailings with a relatively shallow

FIGURE 4.6.5

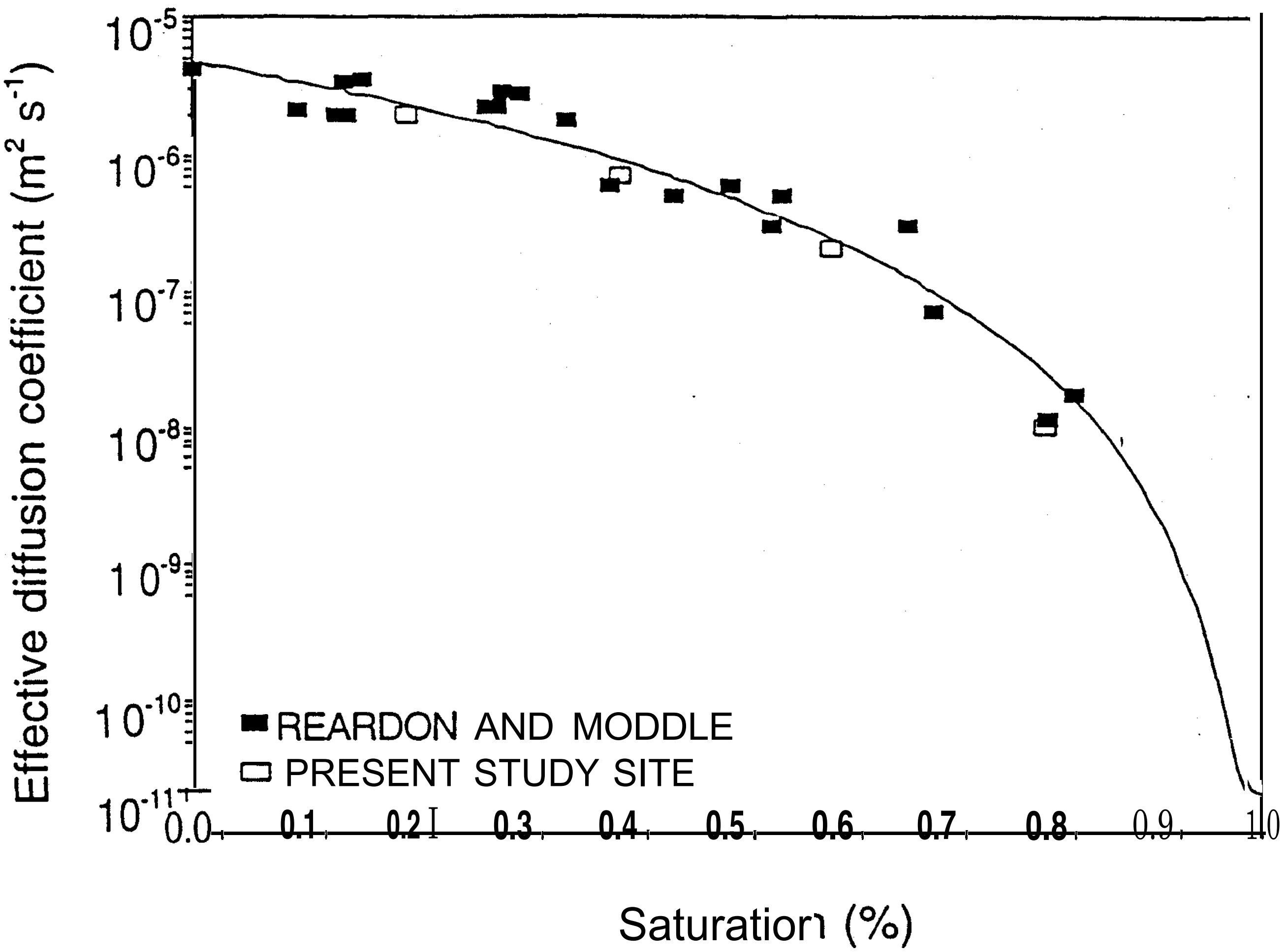
OXYGEN CONSUMPTION RATES ALONG A TRANSECT FROM THE BEACH TO AN INTERMEDIATE POND ON THE NEW TAILINGS AT FALCONBRIDGE



SOURCE: (N HO et al, 199

FIGURE 4.6.6

THE EFFECTIVE DIFFUSION COEFFICIENT IN TAILINGS AS A FUNCTION OF THE DEGREE OF SATURATION



NOTE:

1. **S = VOLUME OF WATERNOLUME OF VOIDS**

SOURCE: (ELBERLING and NICHOLSON, 1996)

water table. This suggests that the water table depth as small as 1 m does not prevent oxidation or reduce it significantly in the early years of oxidation. In this case, the 1 m deep water table was associated with coarse tailings that do not retain significant moisture above the water table. This means that the effective diffusion coefficients remain high under these conditions. If the tailings contained more fine-grained material, more water would be maintained by capillary action above the water table. Indeed, most tailings have sufficient fine material to sustain a saturated state up to two metres above the water table when they remain unsegregated. If such material were present in the beach area, then it is probable that much lower oxygen flux values would have been observed

4.7 SITE STUDY m 7 - DONA LAKE TAILINGS

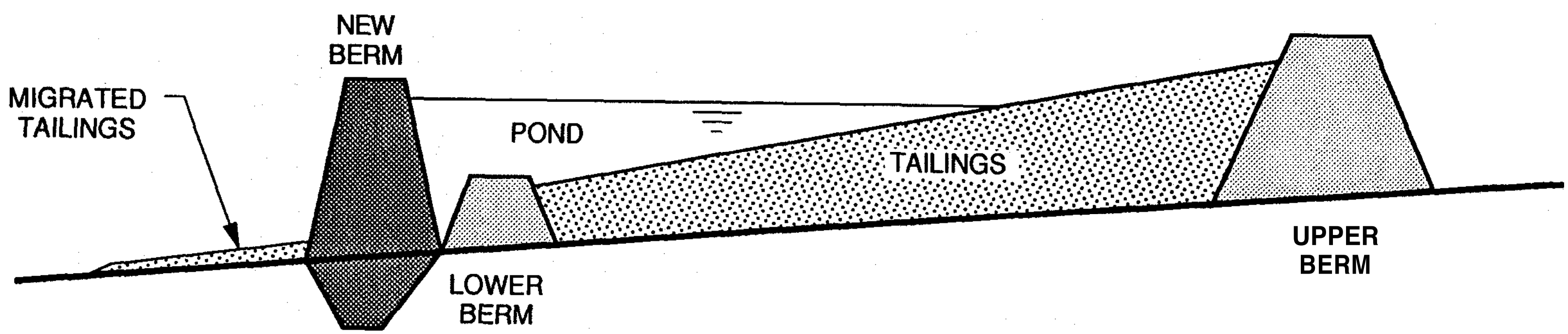
The Dona Lake mine provides an example of a current application of an elevated water table concept to the decommissioning of a tailings management facility. The mine site is located in northwest Ontario near Pickle Lake.

Partway through the mine life it was determined that the tailings have the potential to produce acidic drainage. Efforts were made to contain the tailings within a section of the TMF in an effort to reduce the future closure cost. An intermediate tailings containment structure referred to as the lower berm (Figure 4.7.1) was constructed over peat in the early 1990's and effectively contained the tailings to a smaller area within the TMF.

The physical characteristics of the tailings impoundment are not conductive to underwater tailings disposal. The performance of the tailings impoundment was modelled under various closure scenarios. Results indicated that the tailings should remain in a saturated or near saturated condition to inhibit oxidation and the production of acidic drainage (Bews et al., 1994). As indicated by Placer Dome International (1995), researchers at the University of Saskatchewan determined that if the water table within the tailings remains at a high elevation, maintaining near saturated conditions in the tailings should not be a problem whether the tailings are uncovered, capped, or vegetated. If the water table was low, acidic

FIGURE 4.7.1

DONA LAKE TAILINGS SYSTEM CROSS SECTION



SOURCE: PLACER DOME INTERNATIONAL (1995) drainage could occur in the top 1 m layer of fine tailings located near the lower berm. Desaturation of the coarse grained tailings near the upper berm was predicted to be more likely. If the water table within the tailings was less than 2 m from the surface, acidic drainage was not expected as neutralization would be available from the saturated tailings.

In the fall of 1994, a new water retaining berm was constructed approximately 50 m downstream of the permeable lower berm at a cost of $1,700,000. The new berm will allow the lower areas of the tailings to be flooded, and will raise the water table in the upper tailings beach (Placer Dome International, 1995).

The tailings impoundment area is in the process of flooding naturally and the pond is expected to rise to the design level in the spring of 1996. Field monitoring involving piezometers, neutron probe measurements of moisture within the tailings, and matrix suction profile measurements (in the upper tailings beach area) are ongoing. The SOILCOVER (U of S, 1993) numerical modelling program will be calibrated using field data. Surface flux boundary conditions obtained through SOILCOVER will be input to a SEEP/W model. Results will be used by researchers at the University of Saskatchewan to evaluate the performance of the system and possible refinements to the closure plan (Okane, 1996).

4.8 SITE STUDY m 8 - STANROCK MINE

4.8.1 Background

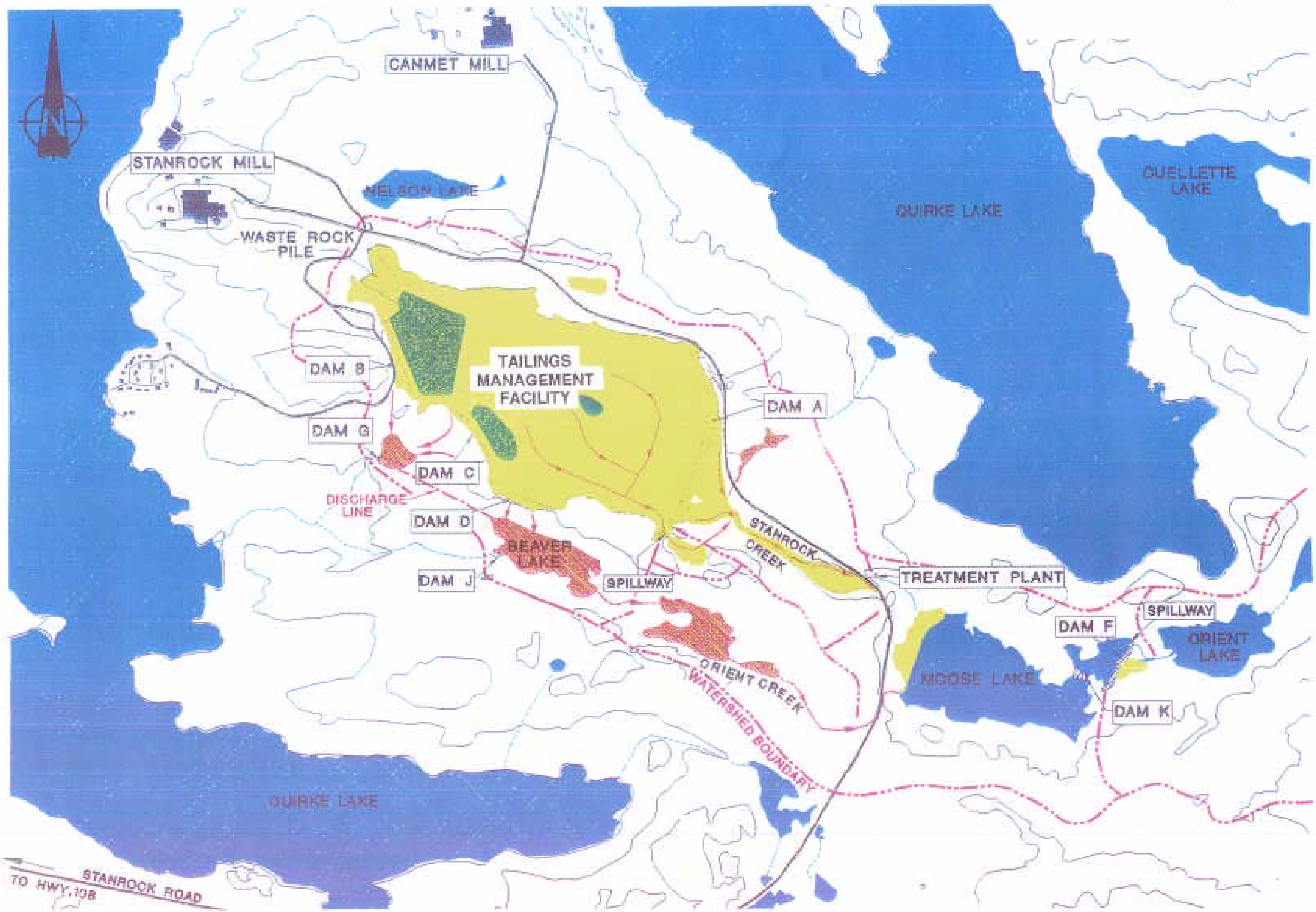
The historic Stanrock uranium mine is located northeast of the City of Elliot Lake, Ontario. A general site plan of the tailings management facility (TMF) is provided in Figure 4.8.1. Production at the mine began in March, 1958 with a design capacity of 2995 tonnes per day. Underground mining was suspended in 1964. Between 1958 and 1964 the TMF received about 5.7 million t of tailings from both the Stanrock Mine and the adjacent CANMET Mine - the latter operated between 1957 and 1960. The TMF has not received any tailings solids since 1964.

4.8.2 Historic TMF

Tailings from the CANMET mill were discharged into the north side of the TMF

FIGURE 4.8.1

STANROCK SITE PLAN, 1992



and were also used to form the starter dyke for Dam A along the eastern perimeter of the basin (Figure 4.8.1). Tailings from the Stanrock mill were spigotted into the basin from the southern rim and were used to build Dams B, C and D. The discharge of tailings at these locations resulted in long tailings beaches which sloped inward and then eastward from the discharge locations towards Dam A. Process water and runoff ponded at the east end of the TMF and was removed by decant structures at Dam A.

In all, nine containment structures have been constructed since 1957 to control tailings and surface runoff. All of the structures have been built, altered or upgraded since tailings deposition ceased in 1964. Eight of the structures are still operative. Of the eight, only four (Dams A, B, C and D) retain the tailings in the TMF. These dams are pervious structures built with spigotted tailings. As a result, they do not maintain the water table in the tailings mass but instead allow seepage to flow out while retaining the tailings solids in the basin.

Presently Dams G and J, constructed in 1970 and 1979, respectively, are used to collect the seepage from Dams B, C and D, and divert it to a treatment plant constructed in 1977 at the upstream end of Moose Lake. The plant adds lime slurry and barium chloride solution to the seepage and surface runoff from Dam A.

4.8.3 Development of a Suitable Decommissioning Strategy

In 1992, a study was carried out to evaluate potential closure options and develop a conceptual closure plan which would be consistent with regulatory requirements. The options study was broad based; however it limited the scope to four basic concepts:

Method A - Base Case
Method B - Water Cover
Method C - Soil Cover
Method D - Removal

The Base Case option was to retain the status quo at the site. Necessary repairs and remedial actions would be initiated to stabilize dams and ensure the seepage collection and treatment systems continued to function. The plan, however, did little to address acid generation, long term treatment requirements, sludge production and long term care and maintenance. As a result, the Base Case was rejected as it was not consistent with regulatory requirements.

The remaining options were reviewed and water cover was selected as the preferred alternative. The water cover option included:

- construction of a new tailings basin in Moose Lake. This includes 5 perimeter dams with maximum heights of up to 30 m;
- relocation of all tailings from the TMF to Moose Lake; and
- the construction of a new treatment plant.

The advantage of this plan was that all tailings would be under water and thus future acid production would be stopped. Interim treatment would be required to manage existing acid inventories and provide for radium removal but for the longer term treatment could be stopped. Furthermore, with tailings under water, gamma radiation, dusting, and radon release from the new basin would be effectively eliminated.

One of the concerns with any removal project is the effectiveness of the clean-up as well as the cost. Residual contamination would be left in the basin though the level of contamination or potential concern is difficult to predict. The costs would be relatively high as the tailings are as much as 30 m deep, and there are substantial quantities of waste rock which will require separate handling. In addition, the base of the tailings area contains peat which could be contaminated. The relocation of 5.7×10^6 t of tailings plus on additional 1×10^6 t of waste peat and spills at a unit rate of $5/t direct costs plus indirect and contingency would alone cost more than $50,000,000. Basin development costs would substantially add to this estimated cost.

Given the substantial cost and the potential for practical limitations of the relocation plan, the mining company believed it would be prudent to further assess the *in-situ* management of the tailings within the existing Stanrock basin. In this regard, SENES and Golder (1994) developed an *in-situ* management proposal. The objective of the *in-situ* management concept was to provide a cost-effective plan which satisfactorily addressed all concerns associated with the existing Stanrock site conditions and/or the Base Case option presented in the 1992 decommissioning study (Golder, 1992).

The conceptual design, as illustrated in Figure 4.8.2, encourages the formation of an elevated water table along the fringes of the tailings deposit thereby reducing the amount of unsaturated tailings. In brief, the proposed plan includes:

! reconstruction of new Dams A, B, C and D as conventional low permeability dams with till cores and grouted foundations;

! elimination of a seepage collection system. The need for pumping and treating this water would be eliminated;

! construction of surface drainage works (lined channels) to safely transport surface water from the TMA basin;

! vegetation of the tailings surface; and

! refurbishment of the treatment plant to ensure adequate levels of interim treatment.

These changes are illustrated in Figure 4.8.3.

The proposed plan is designed to achieve:

! an 88% reduction in future acid release from the site due to the significant reduction in the amount of unsaturated tailings;

! a significant reduction in treatment costs;

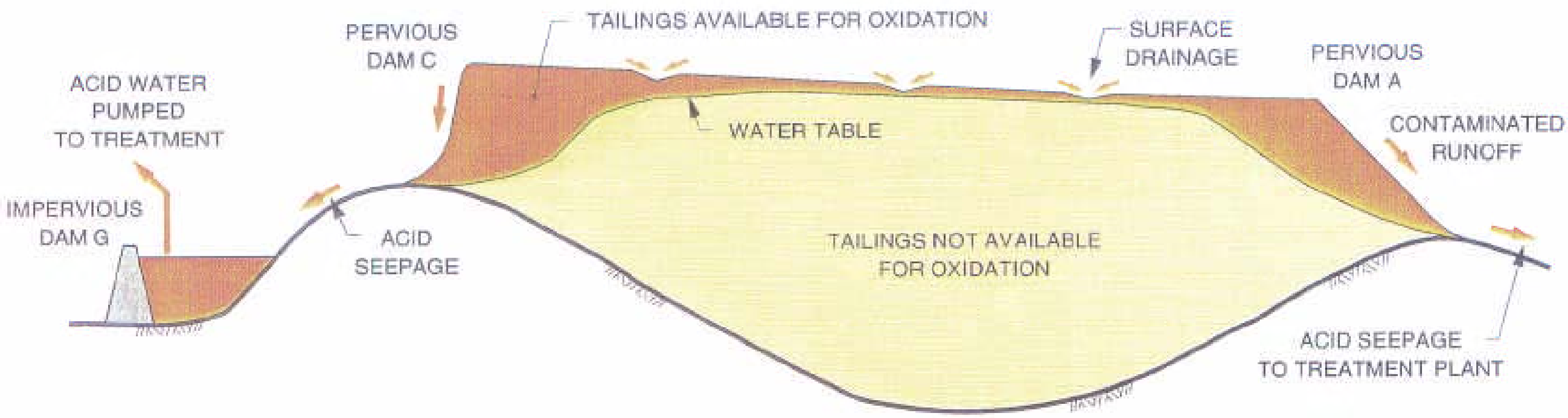
! a significant reduction in long term care and maintenance requirements although a program would be required to ensure the continued physical integrity of the decommissioned TMF;

! effective elimination of wind and water erosion of tailings through revegetation of the oxidized tailings surface; and

FIGURE 4.8.2

CONCEPTUAL SECTIONS
STANROCK TAILINGS MANAGEMENT AREA

PRE RECLAMATION



POST RECLAMATION

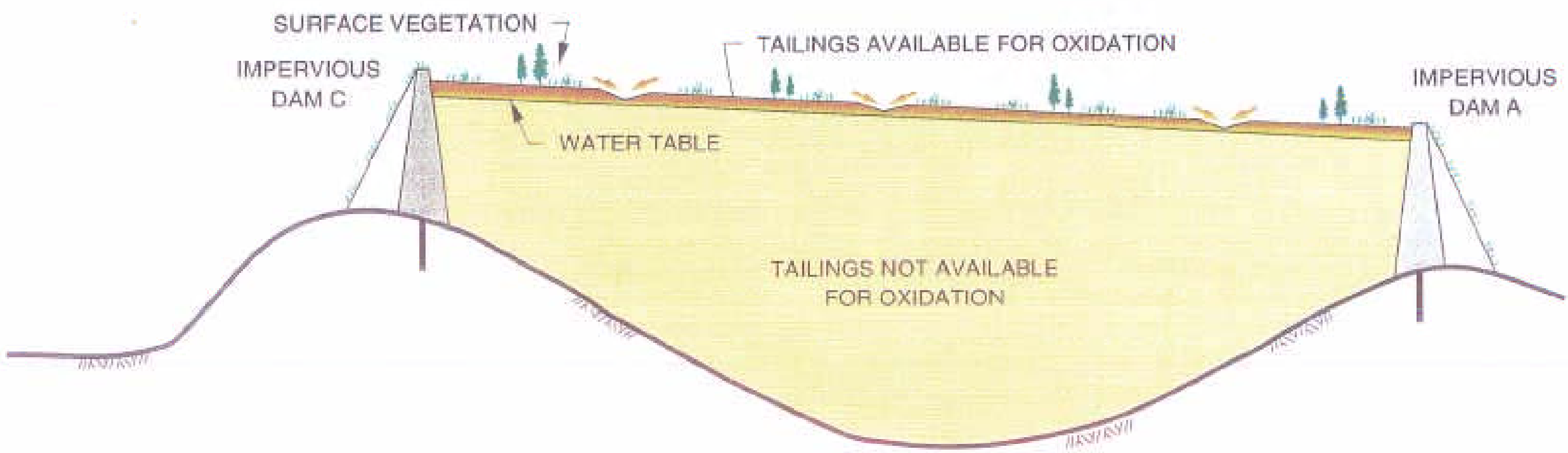
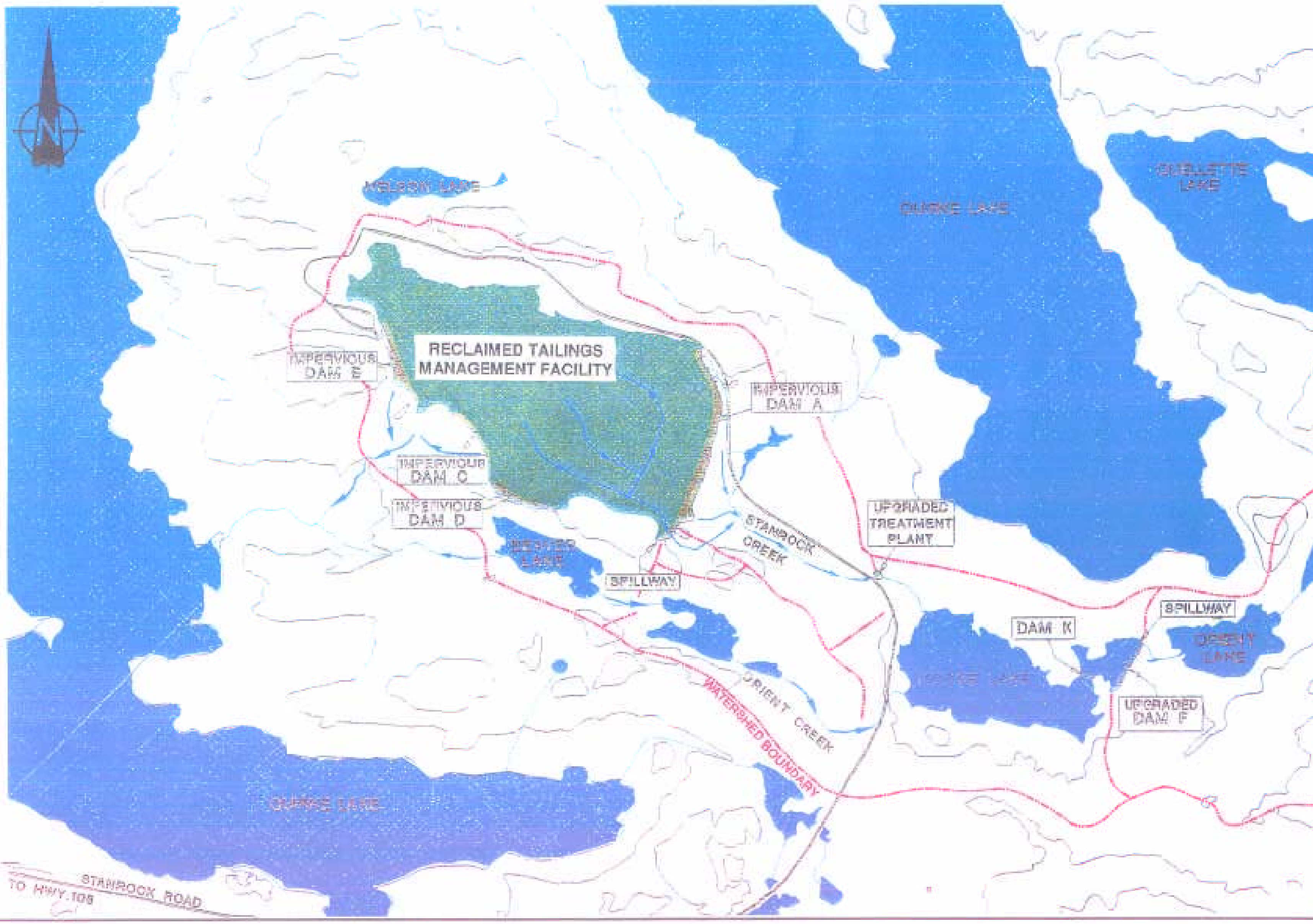


FIGURE 4.8.3

STANROCK SITE PLAN AFTER RECLAMATION



! the elevated water table would effectively reduce radioactive dust and radon emissions.

4.9 SITE STUDY m 9 - STURGEON LAKE

4.9.1 Background

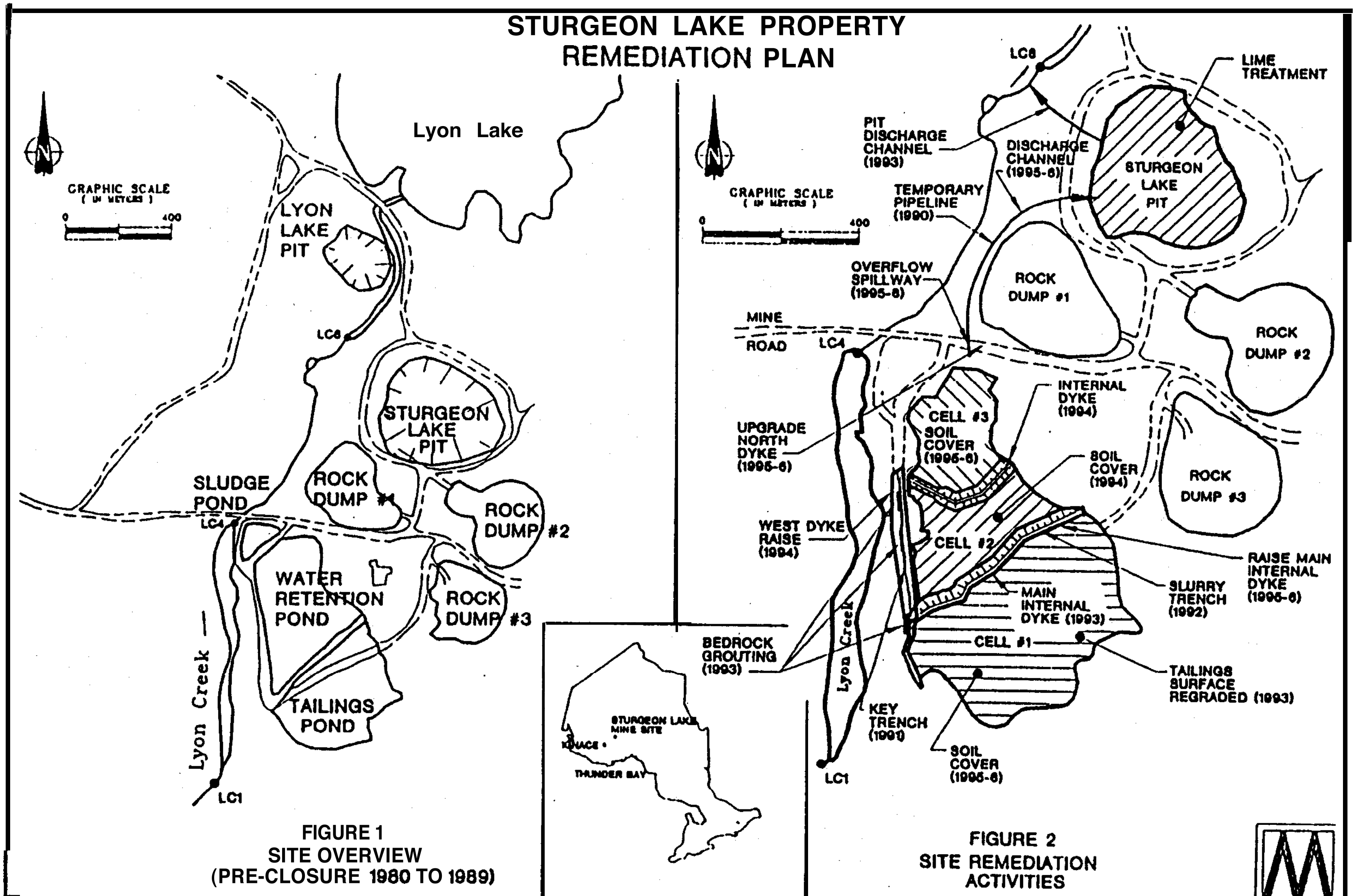
The Sturgeon Lake property is located approximately 90 km northeast of Ignace, Ontario. Between 1974 and 1980, approximately 3.6 million tonnes of copper, lead and zinc ore were mined by Corporation Falconbridge Copper (CFC). In 1986, the property was acquired by Metall Mining Corporation (formerly Minnova) and in 1988 initial monitoring began toward the development of a remediation plan. One feature of the remediation plan was the construction of a slurry wall to bisect the tailings pond dividing cell 1 from cell 2 (Figure 4.9.1). The completed trench was 465 m in length and extended to a maximum depth of 12 m (Martel and Dickson, 1995). Excavation was completed using a large clam shell and trench wall stability was maintained by the addition of a bentonite slurry. This slurry was displaced by a bentonite till mixture which in turn was capped by a compacted till cap.

The approximate cost for the construction of the slurry trench was $666,000 (Martel, 1995). The large volume of bentonite used in the slurry trench was a major cost, estimated to be approximately 25% of the total cost.

The slurry wall was assumed to have raised the water level by approximately 2 m but little data are available. Further remediation tasks are planned to develop a ponding of approximately 1 m of water over the coarse tailings cell. Permission to utilize the local watershed has been obtained to divert runoff to the tailings.

FIGURE 4.9.1

PLAN VIEW OF THE STURGEON LAKE TAILINGS IMPOUNDMENT SHOWING THE LOCATION OF THE SLURRY TRENCH CONSTRUCTED TO RAISE WATER LEVELS IN CELL 1



SOURCE: (MARTELAND DICKSON, 1095)

5.0 EXAMPLE APPLICATION OF ELEVATED WATER TABLES

5.1 OVERVIEW

This section provides a first order evaluation of the application of elevated water tables for AMD control at reactive tailings sites.

The evaluation is based on reactive tailings having the following characteristics:

- specific gravity 3.0, tailings dry bulk density 1.5 t/m^3.
- sulphur content 5%, net acid generation potential 130 kg/t.
- grain size 50%, minus 325 mesh.
- typical average permeability 2 x 10^{-5} cm/s.

The assumed climatic factors are:

- an annual precipitation of 800 mm.
- an annual potential lake evaporation of 500 mm.
- a typical net precipitation of 375 mm (e.g., runoff).

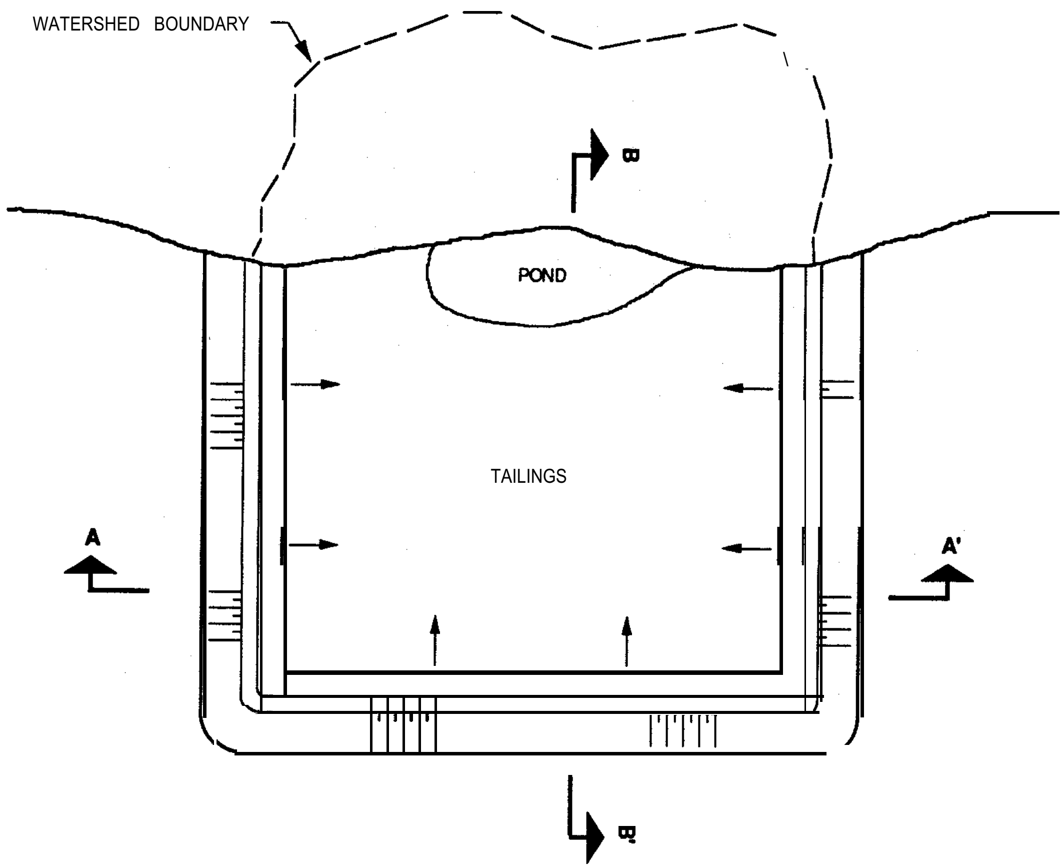
For the purposes of this evaluation, the tailings basin capacity was calculated based upon a 15 year mine life at a production rate of 3,000 tpd equivalent to 15.8 x 10^6 t in total. Three tailings basin development options are considered:

1) The use of a raised stack;
2) The use of a valley dam on pervious aggregate; and
3) The use of a valley dam on bedrock.

The key characteristics of these options are shown schematically in Figures 5.1.1, 5.1.2 and 5.1.3.

FIGURE 5.1.1

TYPICAL TAILINGS STACK



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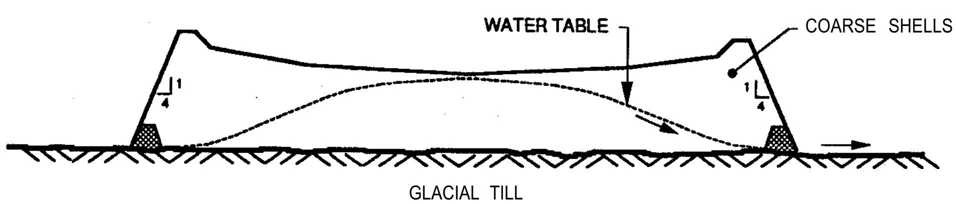
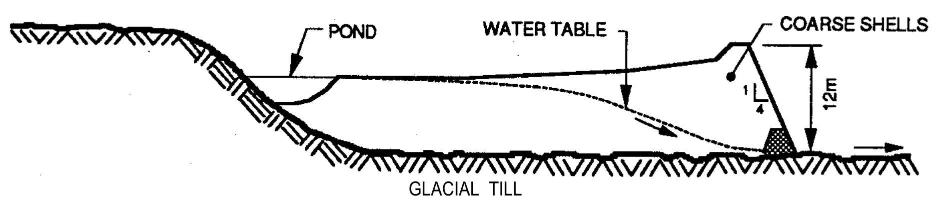


SECTION A-A



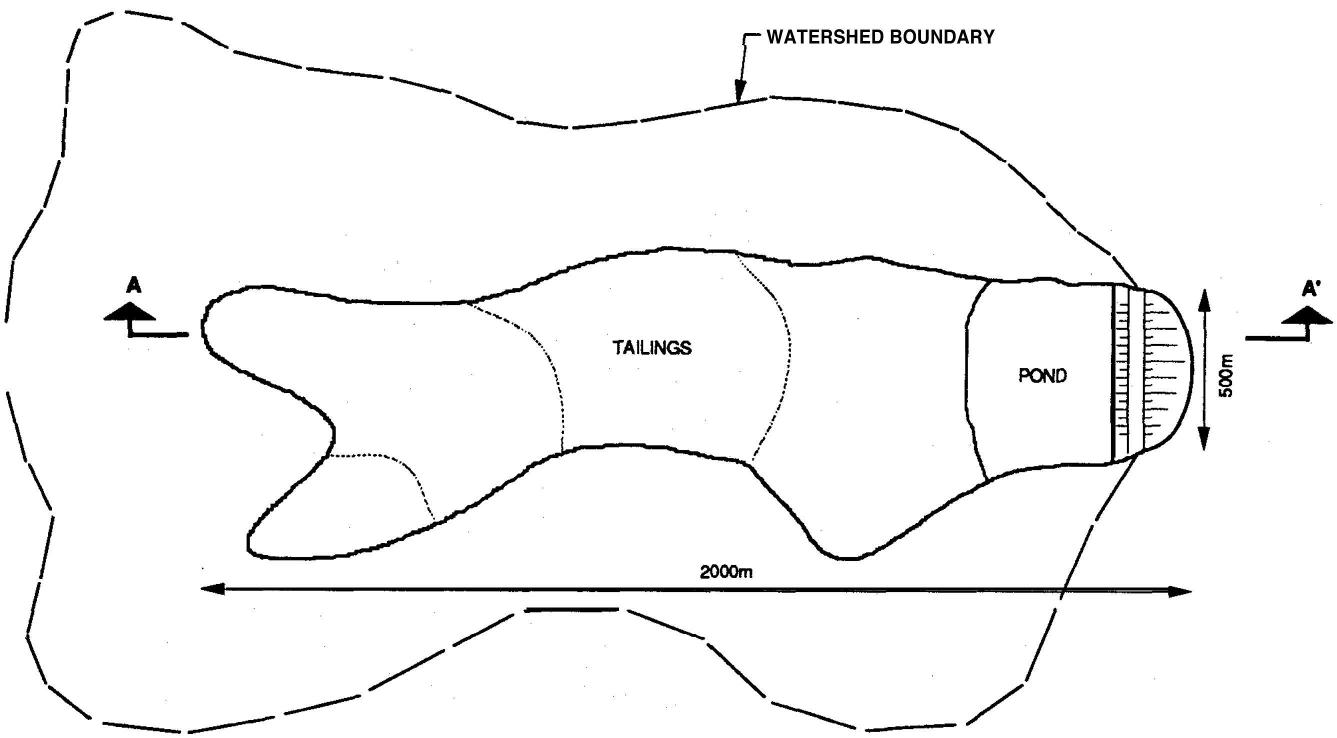
SECTION B-B

KEY FACTS:

1. **PERMEABILITY** - SHELLS 10^{-4} m/s, SLIMES 10^{-5} m/s, TILL 10^{-6} m/s
2. STORAGE VOLUME 10.5×10^{6} m^3, AVERAGE DEPTH 10m
3. TAILINGS SURFACE AREA 1.04 km^2, WATERSHED 1.5 km^2
4. WATER BALANCE - NET PRECIPITATION 0.375m x1.5 x $10^6 m^3$ = 562,500 m^3
   - NET INFILTRATION = 0.2m = 300,000 m^3
   - RUNOFF ~ 262,500 m^3/a
5. UNSATURATED TAILINGS ~ 25% = 3,938,000 t
6. NAPP = 512,000t ACIDITY (ASSUME 50% RELEASE DURING FIRST 100 YEARS, ACID PRODUCTION ~ 2,560 t/a)

FIGURE 5.1.2

TYPICAL VALLEY DAM WITH PERVIOUS FOUNDATION



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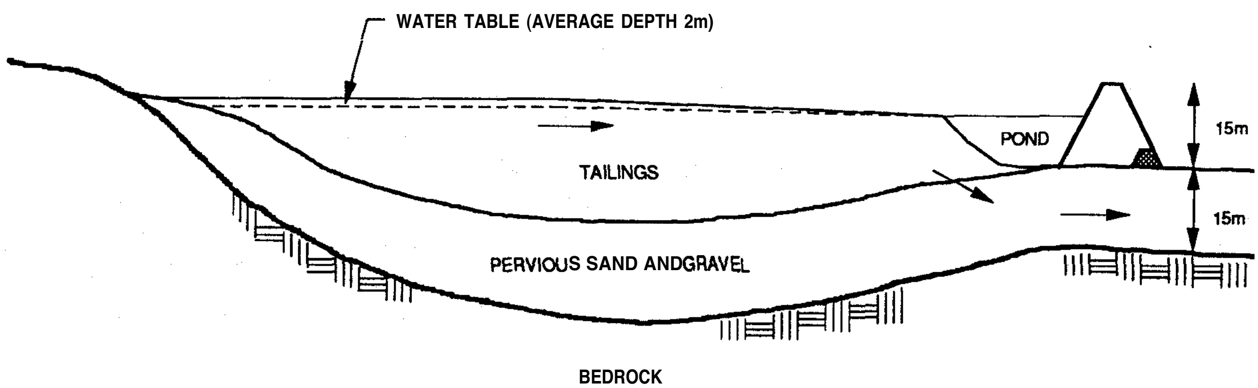


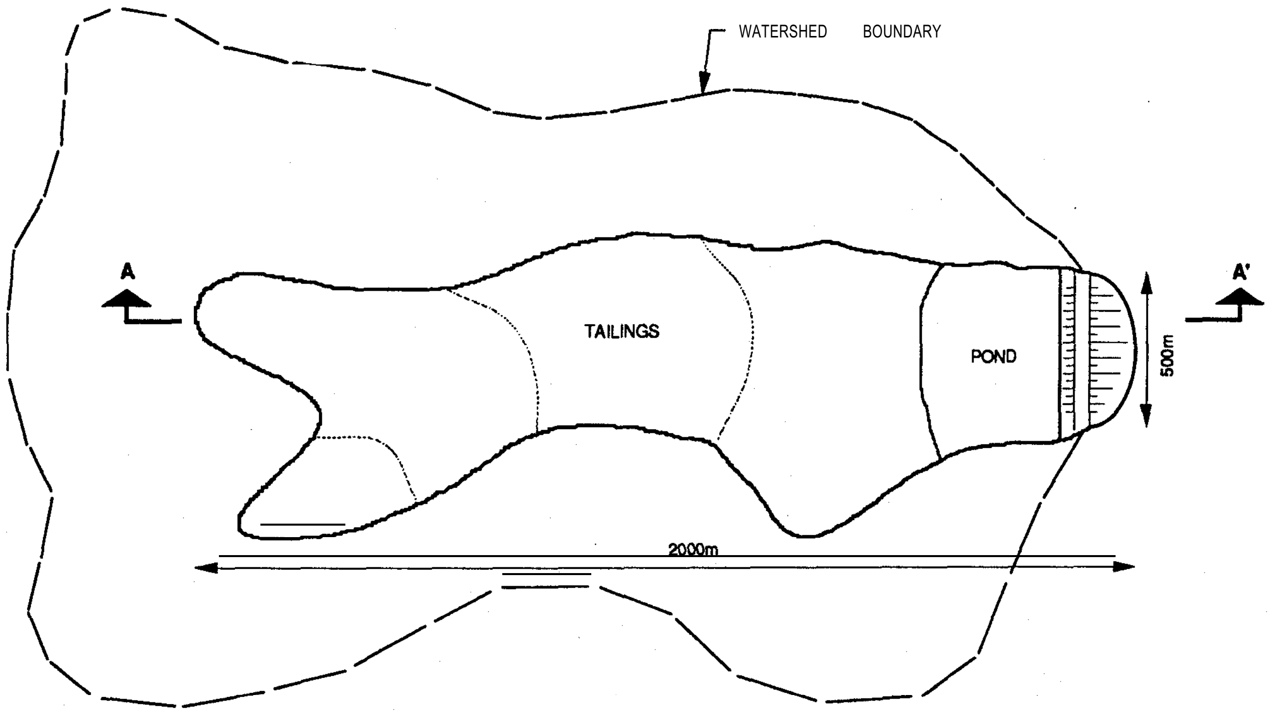
SECTION A-A

KEY FACTS:

1. **PERMEABILITY** - DAM 10^{-6} m/s, FOUNDATION 10^{-3} m/s, TAILINGS 2×10^{-5} m/s
2. STORAGE VOLUME 10.5×10^{6} m^3, AVERAGE DEPTH 10m
3. TAILINGS SURFACE AREA 1.04 km^2, WATERSHED 1.5 km^2
4. WATER BALANCE - NET PRECIPITATION 0.375m x $2.0 \times 10^{6} m^3$ = 750,000 m^3/a
   - SEEPAGE / INFILTRATION = 0.2m x $1.05 \times 10^{6} m^2$ = 210,000 m^3/a
   - RUNOFF ~540,000 m^3/a
5. UNSATURATED TAILINGS ~ 2m AVERAGE = 3,150,000 t
6. NAPP = 410,OOOt ACIDITY (ASSUME 50% RELEASE DURING FIRST 100 YEARS, ACID PRODUCTION ~ 2,050 t/a)

FIGURE 5.1.3

TYPICAL VALLEY DAM WITH IMPERVIOUS DAM AND FOUNDATION



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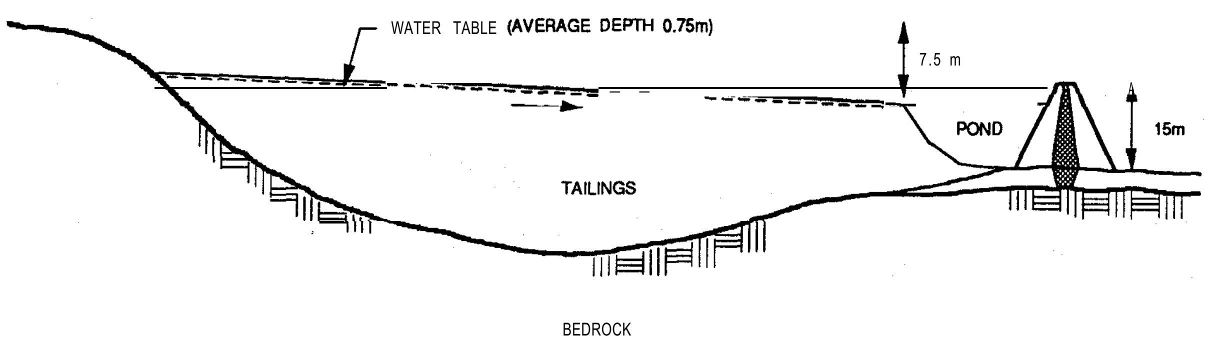


SECTION A-A'

KEY FACTS:

1. PERMEABILITY - DAM 10^{-6} m/s, FOUNDATION 10^{-6} m/s, TAILINGS 2×10^{-5} m/s
2. STORAGE VOLUME 10.5×10^{6} m^3, AVERAGE DEPTH 10m
3. TAILINGS SURFACE AREA 1.04 km^2, WATERSHED 1.5 km^2
4. WATER BALANCE
   - NET PRECIPITATION 0.375m x 2.0×10^{6} m^3 = 750,000 m^3/a
   - NET SEEPAGE ~ 20,000 m^3/a
   - RUNOFF ~ 730,000 m^3/a
5. UNSATURATED TAILINGS ~ 0.75 m AVERAGE = 1,181,000 t
8. NAPP = 153,562t ACIDITY (ASSUME 100% RELEASE DURING FIRST 100 YEARS, ACID PRODUCTION ~ 1,535 t/a)

From an acid generation perspective, the major differences in the options are:

- the raised stack option has the lowest average water table and, therefore, the highest Net Acid Producing Potential (NAPP); and

- the actual rate of acid production does not greatly change among the options as the available surface area for oxidation is similar (each option has a tailings surface area of 1.04 km^2). The major difference is the time over which oxidation occurs - it is greatest for the raised stack option.

The following sections address the estimated order of magnitude costs for development, operation and closure of the basins with and without the use of an elevated water table.

5.2 APPLICATION FOR A HYPOTHETICAL RAISED STACK

Refer to Figure 5.1.1.

Raised stacks are inexpensive to build and are typically constructed using spigotted tailings. Although costs can vary tremendously, a well-operated stack can likely be developed for somewhere in the range of \$0.25/t. This includes allowances for starter dykes, pipelines, and labour to relocate spigots, etc. The total development cost in this example would be in the range of \$4,000,000.

Closure options include:

1) collect and treat with vegetation;
2) application of an engineered cap (dry barrier); and
3) alternative developments using elevated water table concepts.

5.2.1 Collect and Treat

The collect and treat option would manage an average of 300,000 m^3/a of seepage and 263,000 m^3/a of runoff. The costs for closure would include costs for seepage collection and treatment, an effluent treatment plant, vegetation of the tailings and system operations and maintenance. The following costs have been estimated:

a) Capital Costs:

!	seepage collection systems (allowance)	\$ 150,000
!	HDS treatment plant direct costs (from Figure 6.2, SENES, 1994)	\$1,800,000
	- indirect costs	\$1,000,000
!	vegetate reactive tailings 105 ha x \$10,000/ha of tailings	\$1,050,000
	TOTAL CAPITAL COST	\$4,000,000

b) Operating Costs:
(pro-rated from Tables 7.2.1 and 7.2.2, SENES, 1994)

! treatment system operating cost	\$500,000/a
! sludge disposal to basin	\$ 50,000/a
! routine care and maintenance (allowance)	\$ 50,000/a
TOTAL OPERATING COST	\$600,000/a

Net Present Value (NPV) @ 3% discount \$20,000,000

c) Total Closure Cost:

Total capital plus operating costs for closure is approximately \$24,000,000, or about six times the development cost for the basin.

Discussion

This exercise indicates that closure cost is by far the most significant cost for the tailings basin. The cost of treating the effluent represents 83% of the estimated closure operation cost. The total cost of development and closure (using collection and treatment) is about \$28,000,000 or \$1.78/t.

5.2.2 Engineered Cap

A dry cover could be applied to avoid long term treatment. Cover costs would be site- specific but could range anywhere from \$10/m^2 to perhaps \$40/m^2, resulting in an overall cost of between \$10,000,000 and \$40,000,000 (plus treatment costs that could be incurred over an interim period of time) or 2.5 to 10 times the development cost.

5.2.3 Elevated Water Table Applications

For the raised stack option there are several elevated water table concepts that could be considered. These include modifications of the development plan to raise the water table or changes to the closure plan to modify the location of the water table.

If using a stack, operationally there is little that could be achieved in controlling the location of the water table. However, the development of the stack would be modified if thickened tailings were used. If the stack was already in operation, consideration could be given to revising the deposition plan to elevate the water table. Perhaps the most appropriate method would place a thickened tailings cap over top of the spigotted tailing as shown in Figure 5.2.1.

The benefits of this approach would be modest as the thickened tailings would be exposed to oxidation and the external dam shells, which contain the bulk of the available reactive tailings, would remain exposed. The costs to construct the thickener and operate the system could be offset by reduced closure costs but no net benefit is likely.

Other potential closure options for raising the water table include:

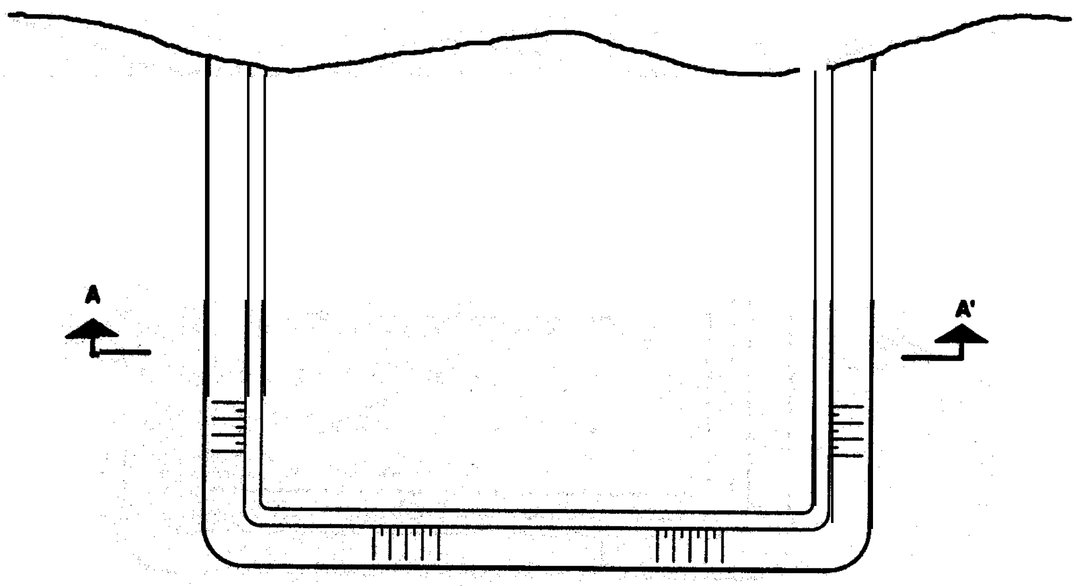
1) construction of cut-off walls at the dykes to reduce horizontal seepage; and
2) placement of a pervious cover to increase infiltration into the stack.

If the objective was to create a passive closure plan, a combination of both options would likely be required.

As shown in Figure 5.2.2, a slurry wall could be constructed along the length of existing dams. Given simple construction with no boulders or bedrock cut-off and a slurry wall area of about 34,700 m^2, the wall could be constructed for \$160/m^2 equivalent to a total cost of \$5,550,000. This would reduce seepage by about 75% from 300,000 to 75,000 m^3/a. This would result in a major increase in the water table elevation, likely to within 1 m of surface. The application of a coarse cover to reduce evaporation and promote infiltration would further raise the water table

FIGURE 5.2.2

SLURRY WALLS AND PERVIOUS COVER



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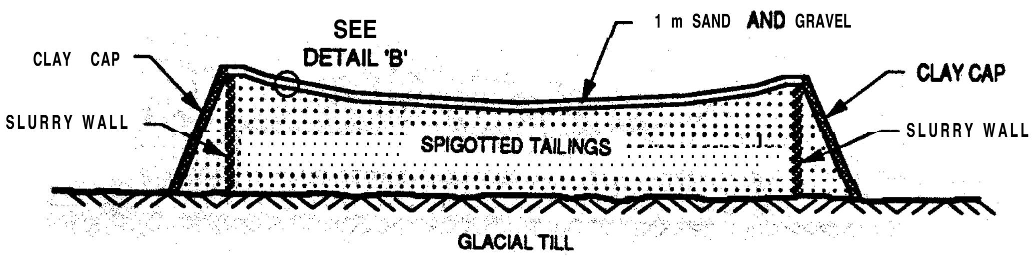
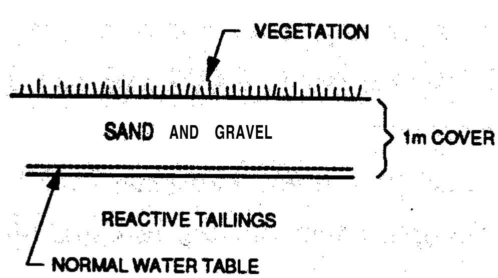


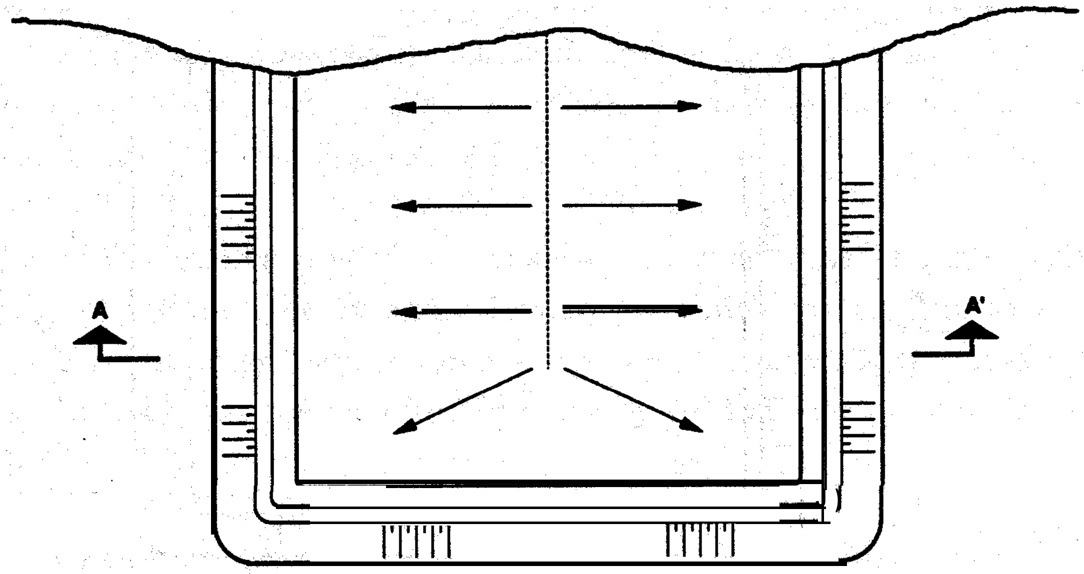
SECTION A-A'



DETAIL B

FIGURE 5.2.1

THICKENED TAILINGS CAP



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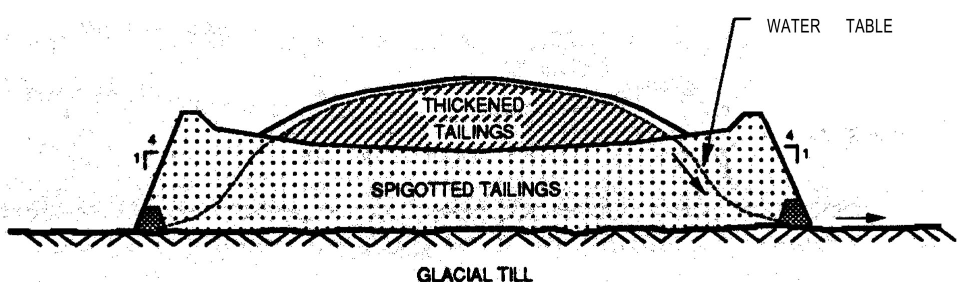
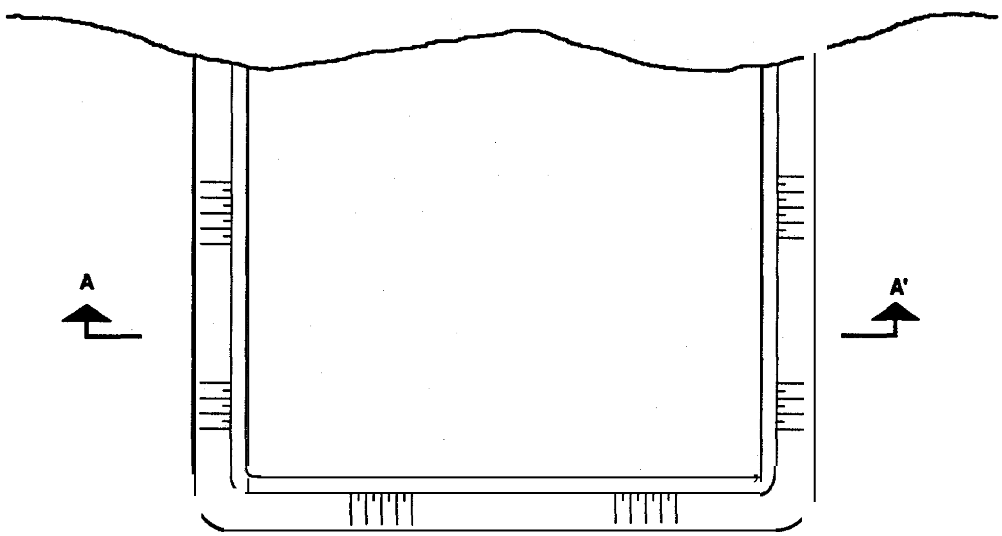


SECTION A-A

FIGURE 5.2.2

SLURRY WALLS AND PREVIOUS COVER



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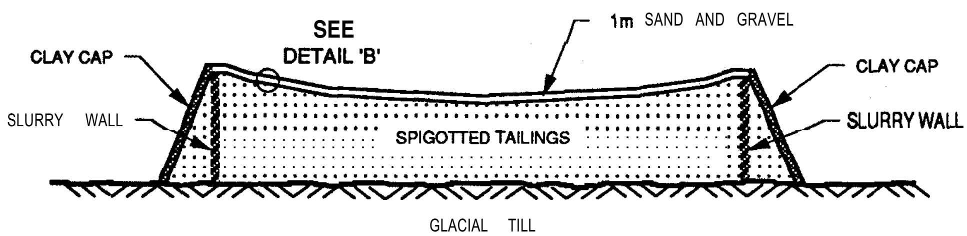
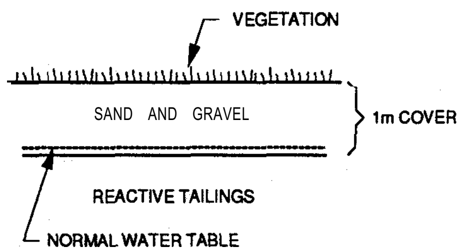


SECTION A-A



DETAIL B

elevation to perhaps an average of 0.5 m below the tailings surface. The tailings remaining available for oxidation would be limited to the upper 0.5 m of tailings and the external dam shells. If 1 m of cover was applied, the reactive tailings in the basin could remain saturated with perhaps no treatment necessary. Under this condition, the external shells could be clay capped, thus controlling infiltration, oxidation and seepage from the dewatered shells.

Costs associated with this option (Figure 5.2.2) are:

a) Capital Costs:

! slurry walls	\$ 5,550,000
! 1 m thick sand and gravel cover at \$7/m^3	\$ 7,000,000
! clay cap cover on exposed dam shells (\$15/m^2 x 3000 m x 48 m)	\$ 2,160,000
! vegetate clay cap and sand cover (105 ha x \$5,000/ha of cover)	\$ 525,000
TOTAL CAPITAL COST	\$15,235,000

b) Operating Costs:

Operating costs (routine care and maintenance) would be \$50,000/a equivalent to a NPV of \$1,670,000.

c) Total Closure Cost:

The closure cost is approximately \$16,900,000. The total cost of basin development and closure is \$20,900,000.

Discussion

Raising the water table by using slurry walls and a pervious cover could be a cost effective closure strategy. The total cost for development and closure based on this strategy was estimated to be about \$21,000,000 versus \$28,000,000 for long term collection and treatment. The conclusion is that the upfront capital investment required for use of a slurry wall and pervious cover will be greater but the NPV of costs for the elevated water table concept can be cost competitive with other closure options.

5.3 APPLICATION FOR A VALLEY DAM - PERVIOUS FOUNDATIONS

Refer to Figure 5.1.2.

Valley dams are commonly constructed to contain base metal tailings. Historically many dams were constructed on pervious foundations. Although these structures contain the tailings, seepage into the underlying soils can lower the water table substantially.

The development cost for valley dams is highly variable but costs in the order of $0.50/t are typical. The total development cost of a typical tailings basin (Figure 5.1.2) developed using this approach would be about $8,000,000.

Closure options for such a basin include:

1) collect and treat with vegetation;
2) application of an engineered cap (dry cover); and
3) use of elevated water table concepts

5.3.1 Collect and Treat

As shown on Figure 5.1.2, the collect and treat option would manage about 210,000 m^3/a of seepage and 540,000 m^3/a of runoff for a total flow of 750,000 m^3/a. Closure costs would include costs for a seepage collection system, an effluent treatment plant, vegetation of the tailings, and systems operations and maintenance.

Estimated costs are:

a) Capital Cost:

! seepage collection station	- allowance	$ 100,000
! HDS treatment plant	- direct costs	$1,800,000

- indirect costs $1,000,000

! vegetation 105 ha - reactive tailings @$10,000/ha of tailings $1,050,000

TOTAL CAPITAL COST ~$4,000,000

b) Operating Costs:

(pro-rated from Table 7.2.1 and 7.2.2, SENES, 1994)

! treatment system operation cost	$ 450,000/a
! sludge disposal to basin	$ 40,000/a
! routine care and maintenance (allowance)	$ 50,000/a
TOTAL OPERATING COSTS	$540,000/a

NPV @ 3% discount rate $18,000,000

c) Total Closure Cost:

Total capital and operating cost is $22,000,000 or about three times the cost for basin development.

Discussion

As with the raised stack, closure costs are more significant than the total development costs. Total development and closure costs are estimated to be $30,000,000 or about $1.90/t of tailings.

5.3.2 Engineered Cap

Options that could be considered for an engineered cap/dry cover include:

! an organic cover as an oxygen barrier (e.g. woodchips);

! a perched saturated layer as an oxygen barrier; and

! an engineered infiltration barrier (synthetic liner or clay seal).

As noted previously the cost would likely be in the range of \$10 to \$40/m^2 or total \$10,000,000 to \$40,000,000 - representing about one to five times the development cost for the basin.

5.3.3 <u>Elevated Water Table Applications</u>

Potential concepts for the raising of the water table elevation and the development of a passive closure solution include:

1) use of a surface cover: (i.e. infiltration layer, depyritized tailings layer, and simple soil cover);
2) use of thickened tailings;
3) construction of a slurry wall and an infiltration layer; and
4) dam raising, and construction of a slurry wall and infiltration layer.

5.3.3.1 Surface Cover

1) Infiltration Layer

The objective of applying a cover is to raise the water table elevation. Given that the water table needs to be raised 2 m, an infiltration layer by itself is unlikely to be sufficient as only an additional 0.2 to 0.3 m/a of precipitation could infiltrate. With the increased head on the pervious aquifer and lateral drainage (e.g. runoff to the pond), the water table would rise but may not be sustained, especially during drought conditions. For example, during a dry summer (say 3 months in duration) the water table could be lowered by 10 to 20 cm if the seepage rate was equivalent to 0.25 m/a over the surface area of the basin. Areas of fine tailings would retain near saturated conditions but areas containing coarse tailings would dewater and be exposed to oxidation.

For this assessment, it has been assumed that a 0.3 m layer of sand and gravel is applied to raise the water table to within 0.5 m of the tailings surface. The slimes are effectively saturated and the uppermost 0.5 m layer of coarse tailings remain exposed. With the fluctuating water table, perhaps 50% of this material would oxidize over the next 100 years producing only 260 t/a of acidity (about 12% of the acidity that would have been generated without the use of a cover). At this level the average acidity in the discharge would be 350 mg/L and could be treated without a sophisticated plant. Sludge production would be minor.

Estimated costs for use of an infiltration layer and effluent treatment are:

a) Capital Costs:

! infiltration layer 0.3 m thick sand cover @ $7/m^3	$2,205,000
! seepage collection station	$ 100,000
! simple lime addition/settling pond system, allowance	$1,000,000
! vegetation of 105 ha of sand and gravel @ $5,000/ha of cover	$ 525,000
TOTAL CAPITAL COST	$3,830,000

b) Operating Costs:
(Appendix C, SENES, 1994)

! treatment system operation	~$200,000/a
! sludge disposal	$ 5,000/a
! routine care and maintenance	$ 50,000/a
TOTAL OPERATING COST	$255,000/a

NPV Operating cost at 3% discount $8,500,000

c) Total Closure Cost:

The total closure cost would be $12,330,000 or about $10,000,000 less than the collect and treat option without elevation of the water table.

2) Depyritized Layer

A second option would be the installation of a pyrite removal circuit and the application of about 2.5 m of desulphurized tailings to the surface. Under these conditions, the upper layer would be non-acid generating and reactive tailings would be below the water table and no treatment plant would be necessary. The estimated costs are:

a) Capital Cost:

! pyrite removal circuit ($1,000/t installed capacity)	$3,000,000
! vegetate non-reactive tailings 105 ha @ $5,000/ha of depyritized cover	$ 525,000
TOTAL CAPITAL COST	$3,525,000

There is a possibility that existing mill circuits could produce a non-acid generating tailings with minimal need for additional flotation circuit capacity.

b) Operating Costs:

The operating costs cover the operation of the flotation circuit and disposal of the sulphide concentrate. Assuming 5% sulphur and a 25% concentrate, 20% of the tailings would be concentrate. These materials could be disposed of within the tailings pond below the final water table.

To create a 2.5 m cover, 5,000,000 t of tailings would need to be processed. The cost would be in the range of $1/t for a total cost of $5,000,000. An additional cost of $1,000,000 is assumed for disposal of the concentrate. The operating costs include: $6,000,000 for operation of flotation circuit; and $50,000/a for passive care and maintenance.

At a NPV of 3% discount for the care and maintenance costs, the total NPV of the operating cost would be $7,670,000.

c) Total Closure Cost:

Capital and operating costs would total approximately $11,200,000 as compared with $22,000,000 for the simple collect and treat option without use of an elevated water table.

3) Soil Cover

If the operating facility cannot support a flotation plant (i.e. inadequate time, unacceptable conditions, etc.) a simple soil cover could, in some circumstances, be applied to elevate the water table above the tailings. This would require a soil cover depth of about 2.5 m plus vegetation; however, no treatment should be necessary.

The estimated costs are:

a) Capital Costs:

! 2.5 m soil cover at $10/m^3	$26,250,000
vegetation 105 ha @ 5,000/ha of cover	$ 525,000
	$26,775,000

b) Operating Costs:

! passive care and maintenance at $50,000/a.

NPV Operating Costs	$1,670,000

c) Total Closure Cost:

The total cost for a soil cover would be about $28,500,000 or $6,500,000 more than the collect and treat option.

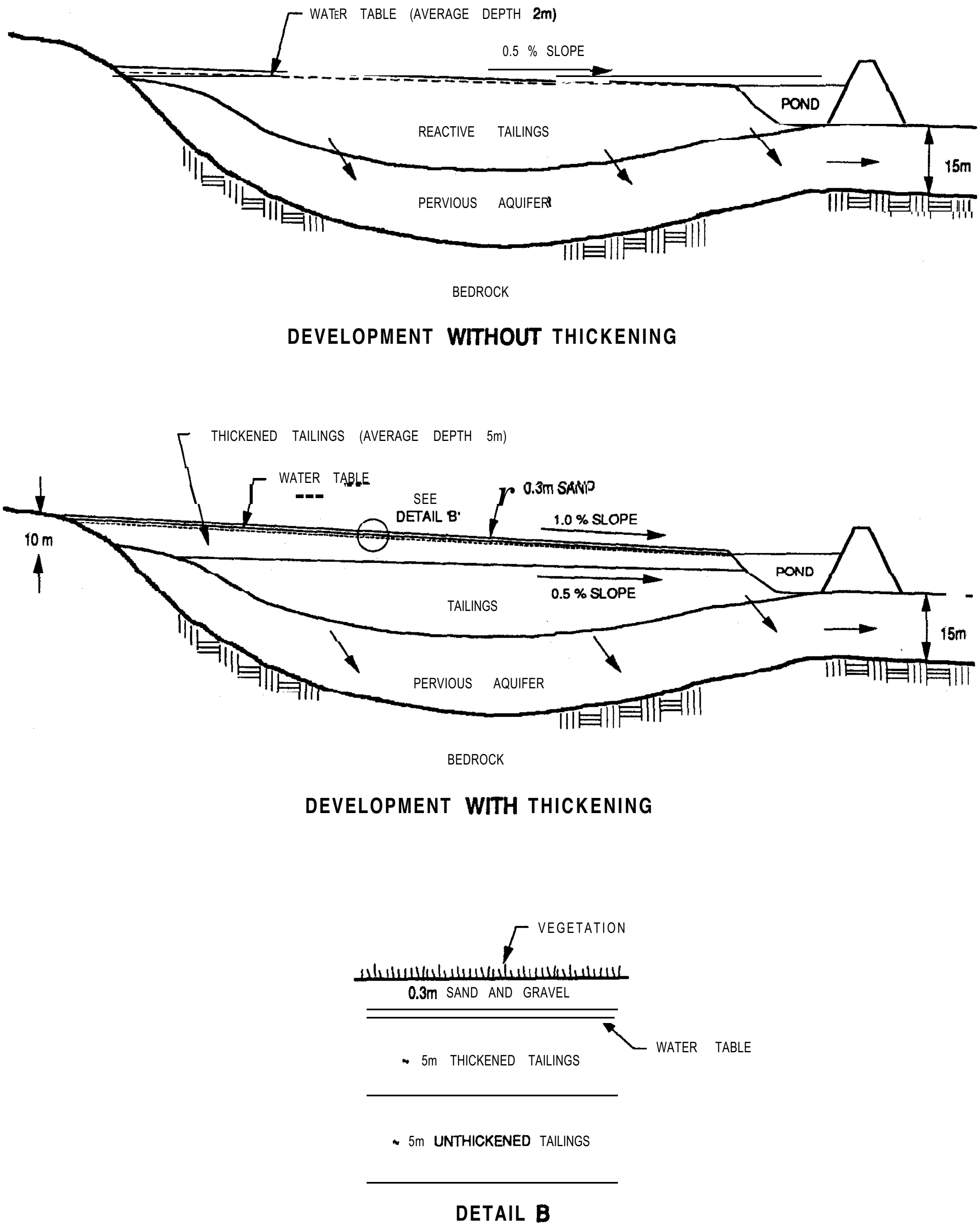
5.3.3.2 Thickened Tailings

Refer to Figure 5.3.1.

Thickened tailings could be applied over the upper layer of tailings to promote both a raised water table and near saturated conditions as shown in Figure 5.3.1. The surface thickened layer would vary in thickness from about 0.5 m near the pond to 10 m at the spigot end.

FIGURE 5.3.1

THICKENED TAILINGS - VALLEY DAM



After thickened tailings placement, an infiltration/evaporative barrier would be applied to the surface to ensure that the tailings remain saturated.

The major costs for the thickened tailings would be the capital cost of the thickener installation and the annual maintenance and pumping costs. It was assumed that the thickener and pumps could be installed for about $1,000,000 and that the increased costs for maintenance would average about $0.15/t or about $160,000/a.

The estimated costs are:

a) Capital Costs:

! thickener and pumps		$1,000,000
! 0.3 m thick sand and gravel cover @$7/$m^3$		$2,205,000
! vegetation of 105 ha of sand @ $5,000/ha		$ 525,000
TOTAL CAPITAL COST		$3,730,000

b) Operating Costs:

! thickened tailings operation		
~ 7.5 years @ $160,000/a	$1,200,000	
! passive care and maintenance @ $ 50,000/a		
NPV Care and Maintenance @ 3% discount	$1,670,000	
TOTAL OPERATING COST		$2,870,000

i) Total Closure Cost:

The total cost for using thickened tailings and an infiltration/evaporative barrier is $6,600,000, or about $15,000,000 less than the collect and treat option.

FIGURE 5.3.2

SLURRY WALL WITH INFILTRATION LAYER - VALLEY DAM

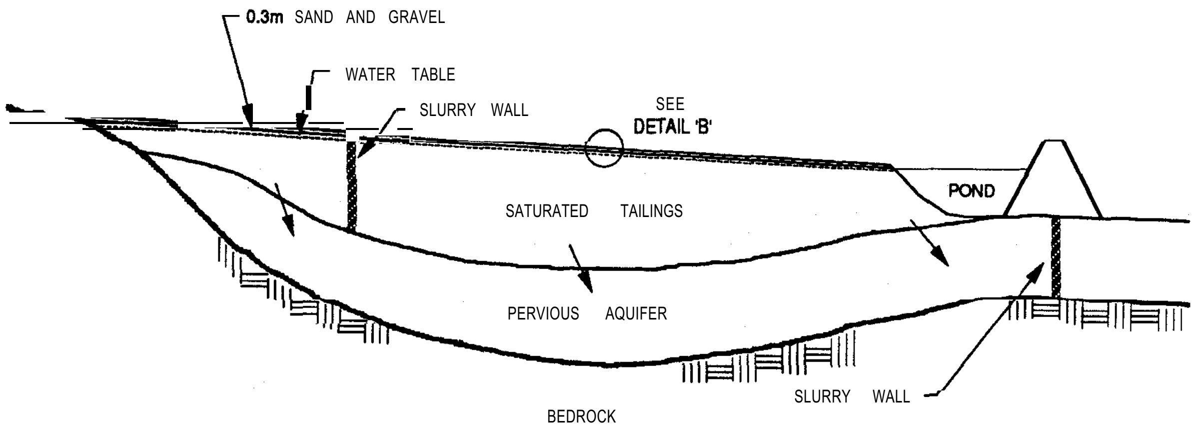
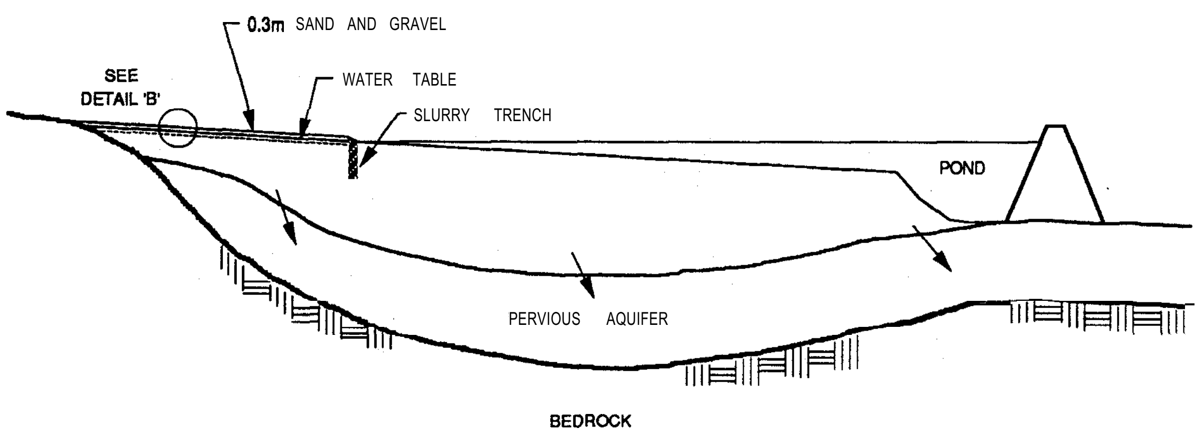
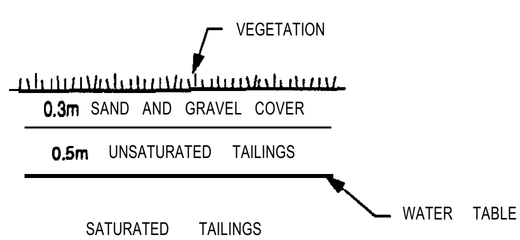


FIGURE 5.3.3

SLURRY TRENCH WITH INFILTRATION LAYER - RAISED VALLEY DAM





DETAIL B

5.3.3.3 Slurry Wall with Infiltration Layer

Refer to Figure 5.3.2.

A slurry wall could reduce seepage losses from 210,000 m^3/a to less than 20,000 m^3/a (100 Igpm to <10 Igpm). Under these conditions, the water table could rise to within 1 m of surface.

As the basin contains segregated tailings, the upper zones of the beach will be coarse and much better drained. The application of a shallow infiltration layer will raise the water table and reduce evaporation loss from the tailings but it is unlikely to fully raise the water table in the coarse tailings. In this zone it is proposed to construct a slurry wall to reduce the horizontal seepage flows. This effectively dams off the horizontal flow, leaving only vertical drainage. This wall is assumed to be 5 m deep over a 500 m length. Although some exposure of reactive tailings could occur upgradient of the slurry wall, the pathway for seepage would be limited to vertical migration. Given that the tailings have an NP of about 25 kg/t, if only the upper 0.5 m was exposed to oxidation, there would be adequate NP in the tailings to consume the produced acidity.

The estimated costs for this option are:

i) Capital Costs:

! slurry wall at dam 15 m x 500 m x $230/$m^2$	$1,730,000
! slurry wall on coarse tailings beach	
= 2,500 m^2 x $102/$m^2$(~$10/ft^2)	$ 257,000
! infiltration/evaporation layer	
0.3 m x 105 ha x $7/$m^3$	$2,205,000
! vegetation of 105 ha @ $5,000/ha of cover	$ 525,000
TOTAL CAPITAL COST	$4,717,000

ii) Operating Costs:

- ! passive care and maintenance at $50,000/a.

TOTAL OPERATING COST NPV @ 3% discount $1,670,000

iii) Total Closure Cost:

Total cost for slurry walls and an infiltration/evaporation layer would be about $6,400,000, or about $16,000,000 less than the collect and treat option.

5.3.3.4 Dam Raising

The dam can be raised to elevate the water table and flood a portion of the tailings. Raising would normally be considered in combination with a cut-off wall. The option is shown conceptually in Figure 5.3.3.

Because the basin has a net runoff of 562,000 m^3/a, it is possible to raise the dam to flood the tailings. A 5 m raising of the dam would flood about 50% of the exposed tailings. Under this condition, the water table in the exposed coarse tailings beach near the spigot point would still be depressed by about 1 to 2 metres. This could be elevated by constructing a shallow slurry trench and an evaporation layer and causing infiltration water to be discharged as seepage.

By raising the water level in the pond by 5 m, the head on the aquifer will increase on average by about 10 to 15%. However, the net runoff over the area would still be more than 500,000 m^3/a; therefore, the slurry wall under the dam may not be necessary to control seepage losses.

For this application, the estimated costs are:

i) Capital Costs:

- ! raise dam over 500 m length from 15 m to 20 m

- requires an average 200,000 m^3 @ $15/$m^3$	$3,000,000
! shallow slurry trench in coarse tailings	$ 257,000
! shallow infiltration/evaporation layer over 60% of area at 0.3 m x $7/$m^3$	$1,323,000
! vegetation of 52.5 ha of sand at $5,000/ha	$ 263,000
TOTAL CAPITAL COST	$4,843,000

ii) Operating Costs:

! passive care and maintenance at $50,000/a.

TOTAL OPERATING COST NPV @ 3% discount	$1,670,000

iii) Total Closure Cost:

The total closure cost for this dam raising option would be about $6,500,000 or $16,000,000 less than the collect and treat option.

5.4 APPLICATION FOR A HYPOTHETICAL IMPERVIOUS VALLEY DAM

Refer to Figure 5.1.3.

The impervious valley dam option has a naturally elevated water table with minor rates of seepage. As such, the water table will be near surface over much of the basin and was assumed to be within 1 m of surface.

The application of the elevated water table concept is more readily achievable. The potential applications to create a passive closure are analogous to the valley dam on a pervious aquifer with reduced requirements for cover, seepage control, etc. The following review uses the previous example as a basis.

A typical, engineered valley dam tailings basin would cost in the range of $0.50 to $1.00/t. The major difference in cost for development between this option and the valley dam with the pervious foundation is the cost for the cut-off wall. This cost was estimated to be about $1,730,000 which would raise the development cost to about $9,700,000 or $0.60/t.

Applying the same concepts as used in the pervious foundation option, the estimated costs are as follows.

5.4.1 Collect and Treat

Annual flow requiring treatment is about 730,000 m^3/a. Seepage flows are small and would not be intercepted and treated. Annual acid production is 1,535 t/a.

a) Capital Costs:

! HDS treatment plant	- direct costs	$1,800,000
	- indirect costs	$1,000,000
! vegetation 105 ha x $10,000/ha of tailings		$1,050,000
TOTAL CAPITAL COST		~$4,000,000

b) Operating Costs:
(pro-rated from Table 7.2.1 and 7.2.2, SENES, 1994)

! treatment system operations	$ 400,000/a
! sludge disposal	$ 30,000/a
! routine care and maintenance	$ 50,000/a
Subtotal	$ 480,000/a

TOTAL OPERATING COST NPV at 3% discount $16,000,000

c) Total Closure Cost:

Total closure cost for the collection and treatment option is estimated to be approximately $20,000,000.

5.4.2 Engineered Cap

As for the valley dam underlain by a pervious zone, costs will range from $10,000,000 to $40,000,000.

5.4.3 Elevated Water Table Applications

5.4.3.1 Surface Cover

i) Infiltration Layer

An infiltration layer would be effective at elevating the water table and reducing evaporation losses from the tailings surface. A 0.3 m thick layer of sand and gravel would likely raise the water table to the point where slimes are saturated and some of the coarse tailings remain unsaturated. Runoff should be clean, leaving seepage through the tailings as the prime contaminant transport path. For a shallow oxidation of less than 0.5 m, acidity produced should be consumed by buffering minerals in the tailings resulting in no net acid production.

The total capital cost would be the cost for the 0.3 m thick sand cover plus vegetation at $2,730,000. Operating costs for passive care and maintenance at $50,000/a has a NPV of $1,670,000 giving a total cost of $4,400,000, equivalent to about 50% of the basin development cost.

ii) Depyritized Layer

A depyritized layer with an average thickness of 1 m could effectively raise the water table into the reactive tailings. The capital costs would be $3,525,000. Operating costs include $2,400,000 for operation of the flotation circuit plus $1,670,000 for passive care and maintenance. Total costs would be in the order of $7,600,000.

iii) Soil Cover

A 1 m thick soil cover could be used instead of depyritized tailings. Capital costs would be $11,025,000 and operating costs $1,670,000. Total cost would be $12,700,000 or about 1.7 times the cost of using depyritized tailings.

5.4.3.2 Thickened Tailings

Thickened tailings offer little advantage in this case as the water table is already near surface. As such, this option was not considered.

5.4.3.3 Slurry Wall with Infiltration Layer

The slurry wall provides no function and is not necessary for the impervious dam option.

5.4.3.4 Dam Raising

Dam raising may be an effective option. By raising the dam 5 m, all slimes would be flooded and the water table in the upper coarse tailings beach would rise to within 0.5 m of surface. To ensure the tailings remain near saturated, an infiltration layer would be applied over the coarse tailings and the fine tailings in the zone where the pond water level fluctuates.

The capital cost to implement this option is $4,586,000. The $1,670,000 NPV of the operating costs would increase the total cost to $6,200,000.

5.5 SUMMARY

Table 5.5.1 provides a summary of the costs for the three tailings basins using the described development and closure strategies. The highlights are:

1) costs for basin development increase as improved environmental controls are included in the design;

2) closure costs decline as improved designs are applied to basin development; and

3) elevated water table concepts can offer substantial cost savings. For the options considered, cost reductions ranged from 25% for the raised stack to more than 50% for valley dam options when compared with simple collection and treatment.

Table 5.5.1

NPV COST COMPARISON OF OPTIONS

Item	Raised Stack ($)	Valley Dam Pervious Foundation ($)	Valley Dam Impervious Foundation ($)
A) Basin Development Cost	4,000,000	8,000,000	9,700,000
B) Closure Concepts			
(1) Collect and Treat	24,000,000	22,000,000	20,000,000
(2) Engineered Cap	10,000,000 to 40,000,000	10,000,000 to 40,000,000	10,000,000 to 40,000,000
(3) Elevated WT Options			
! Surface			
- infiltration layer	N/A	12,330,000	4,400,000
- depyritized layer	N/A	11,200,000	7,600,000
- soil cover	N/A	28,500,000	12,700,000
! Thickened Tailings	N/A	6,600,000	N/A
! Slurry Wall	16,900,000	6,400,000	N/A
! Dam Raising	N/A	6,500,000	6,200,000
C) Total Cost with Collect and Treat (A+B(1))	28,000,000	30,000,000	29,700,000
	$1.78/t[A]	$1.90/t	$1.89/t
D) Total Cost for Least Cost Elevated WT (A+B(3))	20,900,000	14,400,000	14,100,000
	$1.33/t	$0.91/t	$0.90/t
Approximate Savings (C-D)	7,100,000	15,600,000	15,600,000
	$0.45/t	$0.99/t	$0.99/t

[A] 15,750,000 t of tailings.

6.0 DISCUSSION OF FINDINGS

6.1 CURRENT STATE OF KNOWLEDGE

At present:

1) A good understanding of the basic principles of acidic drainage generation has been attained; and

2) Potential methods of controlling and inhibiting acidic drainage can be assessed from many perspectives including modelled performance, long term care and maintenance requirements, and cost.

There are three basic approaches to creating an elevated water table within tailings:

1. Modifying the tailings water balance;
2. Enhancing water retention ability of the tailings; and
3. Constructing groundwater flow barriers.

The suitability of these conceptual approaches is highly dependent upon site-specific conditions.

Modifications of the water balance has only recently been proposed as a measure to raise the water table within tailings although water balances have been certainly been modified to create and/or sustain flooded tailings conditions.

For instance, the raising of the water table was recently proposed for the Stanrock Tailings basin in Elliot Lake, Ontario. In this case, impervious tailings containment structures would replace historic pervious spigotted sand dams to reduce seepage losses and thus allow the water table to rise. This approach is based on sound and proven engineering practice for the control of acid generation through the control of oxygen flux into the tailings mass. Information confirms that tailings with an elevated water table that approaches the surface behave in a similar manner to tailings that are under a water cover in so far as oxidation rates are minimized by the high level of saturation which reduces oxygen flux by several orders of magnitude. There are few examples where monitoring has demonstrated such a technique is effective.

The water retention capability of tailings can be enhanced through the use of thickened or paste tailings. Thickened tailings have been deposited at several tailings facilities and their use as a means of inhibiting acidic drainage over the long term (post decommissioning) is being investigated.

Data obtained as part of this study have indicated that thickened tailings have excellent physical properties which are suited to controlling acid generation with elevated water tables. Thickened tailings exhibit high air entry values and with strong capillary action can remain near saturated for several metres above the water table. Evaporative losses from the near surface zone may result in a reduction of moisture content which permits acid production to occur. However, this can be readily overcome by placement of shallow evaporative loss barriers. Barriers such as coarse sand will encourage infiltration and saturation of the near surface tailings while at the same time reducing evaporative losses.

Several sites have investigated the use of a soil cover to inhibit atmospheric oxygen diffusion to reactive thickened tailings. Collective research and practical experience to date suggests that a moisture retaining cover could be applied to inhibit acid generation, however, concerns respecting high cost and long term performance still need to be addressed. One possible technique that combines the dry cover and elevated water table concepts is the use of desulphurized (thickened) tailings to form an outer cap. For this application an elevated water table is established in the desulphurized tailings above the reactive tailings.

Developments in paste fill have indicated that this technology can also be used for disposal of tailings. Paste tailings offer increased percent solids and greater angles of repose as compared to thickened tailings. These aspects offer marginal benefits for substantially higher cost and as such paste tailings does not appear to be warranted for industry wide use. This does not, however, exclude the use of paste technology should it be required to meet site-specific and special needs.

The use of groundwater flow barriers constructed within tailings have been found to be attractive from both technical and cost perspectives. Remedial work at the Sturgeon Lake (Ignace, Ontario) tailings basin incorporated a slurry wall which subsequently led to a rise in the tailings water table of about two metres. This substantially reduces the inventory of reactive tailings available for oxidation and the long term treatment liability.

The two dimensional modelling studies conducted as part of this study are preliminary and only one *typical* tailings impoundment scenario was investigated. The use of a steady-state groundwater flow model to study the hydraulic response to specific actions to alter the water balance is never-the-less very informative and represents an important tool to complement field and laboratory studies. This concept should be further scrutinized through additional modelling (including three dimensional modelling) involving other tailings impoundment scenarios, and transient models to assess the time required to raise water levels to steady-state conditions.

Although industry has had some experience in using/proposing elevated water tables, technical data on the performance of the elevated water table concept is still being obtained. It is expected that a database will develop as sites continue to be studied/monitored.

6.2 BASIC ISSUES

The following two issues surfaced repeatedly during the preparation of this report.

1. The long term maintenance of an elevated water table; and
2. The long term performance of an elevated water table and the potential for

acid production from near surface reactive tailings.

In concept, the water balance of a tailings basin can be modified to raise the water table to a preferred elevation. In practice, the water table elevation can be expected to fluctuate. This fluctuation is largely dependent upon changes in water input. Hydrologic tools are generally available to assess water level fluctuations which can be substantial.

Ideally, a water table should be able to rise and fall within a normal range and still inhibit sulphide oxidation. This could be accomplished by raising the water table higher than necessary (e.g. into a cover) or by providing a contingency means of recharging the tailings basin (e.g. through the diversion of stored, ponded water).

If oxygen diffusion is not controlled, near surface reactive tailings may oxidize and result in acidic drainage. At a decommissioned site where insufficient buffering capacity is available, this undesired oxidation could lead to the implementation of control measures. Such measures are unattractive as they could be difficult and costly to implement, and necessitate perpetual monitoring and readiness. However, short term collection and treatment of runoff from the near surface zone of reactive tailings may be more economical than implementation of alternative control strategies.

6.3 KEY FINDINGS

The key findings of this study are:

1. Elevated water tables have only recently been considered as a measure to permanently control acidic drainage from reactive tailings. Their use is attractive from many perspectives. Net precipitation conditions found in many parts of the country make the concept well suited for use in Canada.

2. Thickened tailings intrinsically offer a high air entry value allowing tailings to remain near saturation even well above the water table. Experience at thickened tailings sites suggests that the surface layer of tailings will

dewater and oxidize once tailings deposition ceases if the surface is no longer recharged and protected from evaporative losses. Simple covers may be suitable for preventing dewatering and surface oxidation.

3. Not all tailings basins are suitable for elevated water table application. Site-specific conditions will dictate the suitability of the concept. Even where elevated water tables may not prevent acid release, their use could substantially reduce long term treatment liabilities.

4. The use of groundwater flow barriers within tailings is attractive. Technical and field study is required to further develop this concept and explore more cost effective methods of creating barriers.

5. A potential deficiency is a lack of scientific data related to long term monitoring and fluctuation of water tables and moisture content in tailings.

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