THE VERIFICATION OF MODELLED PORE WATER MOVEMENT WITHIN THICKENED TAILINGS USING TRACERS AT THE FALCONBRIDGE LIMITED KIDD METALLURGICAL DIVISION TIMMINS, ONTARIO

MEND PROJECT 2.23.2c

This work was completed on behalf of MEND and sponsored by
Falconbridge Limited as well as
Ontario Ministry of Northern Development and Mines
Canada Centre for Mineral and Energy Technology (CANMET)
Through the CANADA/Northern Ontario Development Agreement
(NODA)

May 2000

FINAL REPORT

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EXECUTIVE SUMMARY

The Falconbridge Limited, Kidd Metallurgical Division undertook a study which involved the injection of two tracer compounds into thickened tailings in 1992, and downstream pore water sampling and analyses in 1993 and 1996. The key objective was to verify the predicted movement of the pore water.

The research program was developed based on extensive knowledge of the site which included the results of two MEND studies completed at the site. The actual pore water sampling and analysis program presented a number of challenges. The greatest challenge was in collecting representative samples of pore water. The program was modified on a number of occasions to meet these challenges. The findings of the study were developed after expert review of the tracer monitoring database. A key finding is that the measured pore water velocities tend to support the present understanding of the pore water movement. The measured average horizontal velocity of the pore water is approaching the maximum predicted horizontal velocity of 70 $cm \cdot yr^{-1}$. Pore water flow is indicated to be predominantly downgradient and follows the tailings slope as previously modelled. The greatest velocities are in the horizontal direction, with the average downward velocity ranging from 8 to 16% of the average horizontal velocity.

The Falconbridge Limited, Kidd Metallurgical Division was the first to adopt the thickened tailings disposal system conceived by Dr. Eli I. Robinsky. Thickened tailings disposal has successfully been practiced at the site since 1973. The thickened tailings are deposed in a 1200 ha tailings management area (TMA) which contains in the order of 105 Mt of tailings. The thickened tailings as disposed form a flat-sloped tailings mound, also referred to as the Robinsky cone.

The Kidd TMA is one of the most extensively studied tailings impoundments in the world. Much of this research has been focussed on determining the properties and characteristics of the thickened sulphide tailings. The MEND project described in this report represents the third component of a three-part study of the Kidd TMA (2.23.2c). The previous two MEND studies examined the hydrologic and hydrogeologic properties of the TMA (2.23.2ab) and its geochemical, hydrogeological and hydrological characteristics (2.23.2d). The previous MEND studies demonstrated that:

- The thickened tailings are non-segregating and form a homogenous deposit.
- The thickened tailings exhibit a very high level of saturation with the capillary fringe extending upwards to near the surface.
- Sulphide oxidation is limited to exposed and unsaturated tailings in the near surface zone.

- The elevated central area of the TMA serves as the pore water recharge area, receiving infiltration due to precipitation and tailings discharge.
- Pore water movement is radially downslope from the central elevated area to the flat-lying peripheral areas of the TMA. Pore water movement predominantly follows the tailings slope with downward movement impeded by the underlying saturated conditions and the low hydraulic conductivity of the tailings and natural clay base.

The present study involved the use of tracers to verify the predicted movement of pore water within the thickened tailings. Horizontal pore water velocities, representative of rates of salt transport due to advection, had been estimated in MEND 2.23.2ab to range from a minimum of 0.1 $cm \cdot yr^{-1}$ to a maximum of 70 $cm \cdot yr^{-1}$.

Three tracer injection and monitoring sites were chosen to provide tracer monitoring data in different areas of the tailings mound. The sites were situated along the southern slope of the TMA with the topmost station located on the apex of the tailings mound where the slope is steepest. Potassium bromide and potassium iodide tracers were injected in the tailings in the fall of 1992. The movement of the tracers was sampled using mini-piezometers in June 1993. Collecting samples of pore water from shallow (e.g. $\leq$ 0.5 m deep) mini-piezometers using filter paper presented a challenge. A sampling methodology that included the addition of ~20 mL of deionized water to shallow piezometers prior to sampling was used in September 1993. The revised method was not considered optional because of uncertainties regarding the concentrations of tracers in samplers. In response, the pore water sampling and analysis program was revisited and revised for the second time to include:

- The collection of tailings cores using an aluminum tube.
- The extraction of pore water from the tailings core samples.

In October 1996, the above method proved useful in sampling unsaturated tailings, but was found unsuitable for the sampling of saturated tailings. An attempt was then made to sample the tailings using a power auger - this method was acceptable for unsaturated tailings but was problematic in the saturated tailings.

Pore water samples were promptly analyzed for the presence of the tracers. The tracer monitoring database was later assessed by Barbour and Bews (1998). In summary,

- The June 1993 monitoring data indicated that the pore water horizontal velocity range from 80 to 112 $cm \cdot yr^{-1}$. These results should not be heavily relied upon given concerns associated with the initial high density of the tracer solutions and diffusion effects. These concerns are expected to diminish with time and as the tracer plume expands.

- The October 1996 monitoring data are likely subject to the effects referred to above but to a lesser extent. The October 1996 data indicate that the average pore water horizontal velocity is in the range of 67 to 74 $cm \cdot yr^{-1}$ and as such is approaching the predicted maximum horizontal velocity of 70 $cm \cdot yr^{-1}$.

SOMMAIRE

La Kidd Metallurgical Division de Falconbridge Limitée a réalisé une étude qui a consisté à injecter deux composés traceurs dans des résidus épaissis en 1992 ainsi que des échantillonnages et des analyses de l'eau interstitielle en aval en 1993 et 1996. L'objectif principal était de vérifier le mouvement prévu de l'eau interstitielle.

Pour l'élaboration du programme de recherche, on s'est basé sur les vastes connaissances que l'on possédait sur le site, notamment sur les résultats de deux études NEDEM. Le programme d'échantillonnage et d'analyse de l'eau interstitielle a comporté un certain nombre de défis. Le plus grand a été de prélever des échantillons représentatifs de l'eau interstitielle. On a, à cette fin, modifié à quelques reprises le programme. Les conclusions ont été tirées après une analyse par des experts de la base de données sur le suivi des traceurs. Selon l'une des conclusions principales, les vitesses de l'eau interstitielle appuient les connaissances actuelles sur le mouvement de l'eau interstitielle. La vitesse horizontale moyenne de l'eau interstitielle telle que mesurée se rapproche de la vitesse horizontale maximale prévue de 70 $cm \cdot an^{-1}$. L'eau interstitielle s'écoule surtout vers l'aval et suit la pente des résidus comme l'indiquait le modèle. Les vitesses les plus élevées sont horizontales, la vitesse descendante moyenne se situant entre 8 et 16 % de la vitesse horizontale moyenne.

La Kidd Metallurgical Division de Falconbridge Limitée a été la première à adopter la méthode d'entreposage par épaississement des résidus conçue par Eli I. Robinsky (Ph. D.). Cette méthode a été utilisée avec succès depuis 1973. Les résidus épaissis sont déposés dans un parc à résidus de 1 200 ha qui contient dans l'ordre de 105 Mt de résidus. Les résidus épaissis forment un monticule à sommet conique, aussi appelé le cône Robinsky.

Le parc à résidus Kidd est l'un des plus étudiés dans le monde. La grande partie de cette recherche a consisté à déterminer les propriétés et les caractéristiques des résidus de sulfures épaissis. Le projet NEDEM décrit dans le présent rapport est la troisième composante d'une étude à trois volets du parc à résidus Kidd (2.23.2c). Les deux études précédentes du NEDEM portaient sur les propriétés hydrologiques et hydrogéologiques du parc à résidus (2.23.2ab) et sur ses caractéristiques géochimiques, hydrogéologiques et hydrologiques (2.23.2d). Les études antérieures du NEDEM ont mis en lumière les faits suivants :

- Les résidus épaissis ne produisent pas de ségrégation des sédiments et forment donc un dépôt homogène.
- Les résidus épaissis sont très saturés, la frange capillaire remontant près de la surface.
- L'oxydation des sulfures se limite aux résidus exposés et non saturés dans la zone quasi superficielle.

- La partie centrale élevée du monticule sert de zone d'alimentation en eau interstitielle dans laquelle s'infiltrent les précipitations et l'eau des résidus.
- Le mouvement de l'eau interstitielle est radiale vers le bas de la pente entre le centre élevé et les zones périphériques plates du parc. L'eau interstitielle s'écoule en suivant la pente du monticule et la descente n'est entravée que par la saturation des résidus sous-jacents et la faible conductivité hydraulique des résidus et la base argileuse naturelle.

Dans la présente étude, on utilise des traceurs pour vérifier le mouvement prévu de l'eau interstitielle dans les résidus épaissis. Les vitesses horizontales de l'eau interstitielle, représentatives du transport par advection du sel, varient, selon NEDEM 2.23.2ab, entre un minium de 0,1 $cm \cdot an^{-1}$ et un maximum de 70 $cm \cdot an^{-1}$.

On a choisi trois sites pour l'injection des traceurs et leur suivi dans différentes zones du monticule. Les sites étaient situés le long de la pente sud du parc à résidus, le site le plus haut se trouvant sur le sommet du monticule, là où la pente est la plus abrupte. Au cours de l'automne de 1992, on a injecté deux traceurs : du bromure de potassium et de l'iodure de potassium. En juin 1993, on a déterminé le mouvement en utilisant des minipiézomètres. Le prélèvement des échantillons des minipiézomètres peu profonds (p. ex. $\leq$ 0,5 m de profondeur) avec du papier filtre a exigé un processus complexe. En Septembre 1993, on ajoutait pour ce faire ~20 mL d'eau désionisée dans les piézomètres. À cause d'incertitudes relatives aux concentrations des traceurs dans les échantillons, il a fallu réviser la méthode. Le programme d'échantillonnage et d'analyse de l'eau interstitielle a donc été examiné et modifié pour la deuxième fois de façon à inclure les exigences suivantes :

- Le prélèvement de carottes de résidus avec un tube en aluminium.
- L'extraction de l'eau interstitielle des carottes de résidus.

En octobre 1996, la méthode ci-dessus s'est avérée utile pour échantillonner des résidus non saturés, mais pas pour échantillonner des résidus saturés. On a d'abord tenté d'utiliser un tarière électrique – méthode qui s'est avérée acceptable pour les résidus non saturés mais problématique pour les résidus saturés.

On a dès lors analysé les échantillons d'eau interstitielle pour y déceler la présence des traceurs. La base de données sur le suivi des traceurs a ensuite été évaluée par Barbour et Bews (1998). En voici un résumé :

- Les données de suivi de juin 1993 indiquaient que la vitesse horizontale de l'eau interstitielle variait entre 80 et 112 $cm \cdot an^{-1}$. Il ne faudrait pas faire reposer ces résultats sur des considérations liées à la masse volumique élevée initiale des solutions traceuses et des effets de la diffusion. Le poids de ces considérations devrait s'atténuer avec le temps et à mesure que le panache des traceurs prend de l'expansion.

- Les données de suivi d'octobre 1996 devraient dépendre des effets mentionnés ci-dessus, mais dans une moindre mesure. Les données d'octobre 1996 indiquent que la vitesse horizontale moyenne de l'eau interstitielle varie entre 67 et 74 $cm \cdot an^{-1}$ et qu'elles sont donc proches de la vitesse horizontale maximale prévue de 70 $cm \cdot an^{-1}$.

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1.0 INTRODUCTION

This report presents the results of a study which involved the use of tracers to verify the predicted movement of pore water within thickened tailings deposited in the tailings management area (TMA) at the Falconbridge Limited, Kidd Metallurgical Division in Timmins, Ontario. The tracer study represents the third component of a three-part study of the Kidd tailings under MEND 2.23.2 where MEND 2.23.2ab has assessed hydraulic properties, and MEND 2.23.2d has assessed geochemistry.

The objective of MEND 2.23.2ab was to measure the hydraulic properties of the thickened tailings and to analyse their long-term impacts to the environment. The field program included measurements of moisture content, hydraulic head, water table elevation, hydraulic conductivity, precipitation, pan evaporation and evaporation. Pore water was sampled and analysed for major metal and ion concentrations. The results inferred the presence of a significant capillary fringe above the water table. The analysis of pore water indicated that sulphide oxidation is occurring. However, low pore water velocities and near-surface saturated conditions will ensure that contaminants released to the environment will remain at low rates.

MEND 2.23.2d reviewed the hydrogeological flow system, the geochemical interactions and the influence of discharging pore water on run off quality during storm events. The study revealed four distinct geochemical zones:

(1) A bottom zone with high alkalinity and low dissolved metals.

(2) A zone above the bottom; displaying high alkalinity with characteristics similar to mill discharge water.

(3) A zone above the previous layer where jarosite dissolution has affected the pore water quality.

(4) The surface layer which exhibits oxidation to a depth of approximately 0.5 m.

Al and Blowes (1995a), also reported as MEND 2.23.2d, determined that the elevated central area of the Kidd tailings mound is a tailings pore water recharge area where precipitation infiltrates and moves downward to replace pore water that has migrated from the area. Recharge rates vary from a maximum near the apex of the mound and decline outward to limits of the TMA. The dominant pore water flow direction is radially downward from the top central area of the mound to discharge in the flat peripheral areas of the TMA.

Of specific interest to the present tracer study are predictions of the maximum, average and minimum pore water velocities within the tailings as determined by St-Arnaud and Woyshner (1992) (also reported as MEND 2.23.2ab) and shown in Table 1.1.

Table 1.1

ESTIMATES OF HORIZONTAL PORE WATER VELOCITIES REPRESENTATIVE OF RATES OF SALT TRANSPORT DUE TO ADVECTION

Value	Horizontal Velocity ($cm \cdot yr^{-1}$)
Minimum	0.1
Average	7
Maximum	70

Source: (St-Arnaud and Woyshner, 1992) (MEND 2.23.2ab).

The present tracer study involved the injection of potassium iodide and potassium bromide tracers at three locations along the thickened tailings slope. The migration of the tailings pore water and tracers was then monitored through sampling and analysis - the procedures for which were modified on several occasions during the study to overcome difficulties both in sampling and analysis. The monitoring data was subsequently assessed by Barbour and Bews (1998) and the results compared to the predicted pore water velocities.

Thickened tailings can be generally defined as tailings that are discharged at greater than 50% solids and disposed in a cone-shaped mound that has a surface slope of 2 to 6%. Thickened tailings create a very high level of saturation with the capillary fringe extending near surface. At the Kidd TMA, the thickened tailings are discharged to form a gently sloped tailings mound, also referred to as a tailings cone, which covers an area of approximately of 1200 ha and contains in the order of 105 million tonnes of sulphide tailings.

Thickened tailings form a homogeneous mass with a low hydraulic conductivity and a high moisture content. Robinsky (1990, 1999) and Robinsky et al. (1991) report that the thickening of tailings at the Kidd Metallurgical Division eliminates tailings particle segregation and has produced a homogeneous tailings deposit. The high air entry values (e.g. in the order of 5 to 6 m) exhibited by the thickened tailings assist in controlling acid generation. The water table is at surface of the tailings on the flatter lower slopes of the tailings mound, and about 5 to 6 m below the tailings surface at the apex of the mound. Strong capillary suction causes the vadose zone to rise considerably above the water table and in the process sufficiently saturates the tailings pore spaces and as a result reduces atmospheric oxygen flux to the sulphide solids. As an example, in areas of the TMA where the water table is 2.5 to 3.5 m below the tailings surface, the vadose zone extends to near surface. As such, sulphide oxidation is limited to the near-surface, unsaturated thickened tailings layer. MEND 2.23.2d demonstrates that sulphide oxidation is limited to within the upper 0.5 m layer of unsaturated tailings with the sulphide oxidation by-products transported through tailings pore water movement. MEND 2.23.2ab and

2.23.2d studies confirm that the thickened tailings disposal system is beneficial with respect to controlling acidic drainage.

The hydrological component of the study undertaken by Al and Blowes (1995a) provided estimates of the amount of low quality tailings pore water that contributes to TMA run off during storm events. Based on a chemical hydrograph separation of storm run off contained in the drainage flow from the TMA, and upstream of the treatment process, the tailings pore water comprises between 0 and 23.5% of the surface flow. The maximum measured pore water contribution to run off (23.5%) occurred during a moderate intensity, long-duration rainfall event. Long-duration rainfall events which cause the water table to rise throughout the TMA represent the greatest potential for contributing low quality pore water to the drainage flows to the TMA effluent treatment process. Given that the tailings are saturated to near surface, a minor water input can produce a rapid rise in the water table in thickened tailings.

MEND 2.17.1 reviewed the use of an elevated water table within tailings as a method to control and reduce acidic drainage. The use of 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. One means of maintaining elevated water table conditions within tailings is to use thickened tailings disposal.

2.0 THEORY

This section reviews theories related to:

1. Acidic drainage generation and control.
2. Capillary rise in thickened tailings.
3. Thickened tailings disposal.
4. Interstitial pore water flow.
5. The use of tracers.

2.1 ACIDIC DRAINAGE GENERATION AND CONTROL

Acidic drainage is produced as a result of the oxidation of sulphide minerals in the presence of water or humidity, and under conditions where the acidity produced is not buffered. The overall oxidation process leading to the generation of acidic drainage based on the oxidation of pyrite (FeS_2) can be described by the following equations (Singer and Stumm, 1970).

$$FeS_2 + 7/2\ O_2 + H_2O \rightarrow Fe^{2+} + 2SO^{2-}_4 + 2H^+ \quad (2.1)$$

$$Fe^{2+} + 1/4\ O_2 + H^+ \rightarrow Fe^{3+} + 1/2\ H_2O \quad (2.2)$$

$$FeS_2 + 14\ Fe^{3+} + 8\ H_2O \rightarrow 15\ Fe^{2+} + 2SO^{2-}_4 + 16H^+ \quad (2.3)$$

$$Fe^{3+} + 3\ H_2O \rightarrow Fe(OH)_3\ (solid) + 3H^+ \quad (2.4)$$

The oxidation of Fe^{2+} as indicated in equation (2.2) can be catalyzed through the bacterial action of *Thiobacillius ferrooxidans* and *Thiobacillus thioooxidans*. These microorganisms depend on dissolved CO_2 as a source of carbon, and require oxygen, nitrogen and phosphorous for chemosynthesis and growth (MEND 2.11.1a).

Acid generation process by-products include dissolved metals, sulphate and free acidity. These contaminants can be transported through pore water movement to groundwater or surface waters. At tailings areas where sulphide oxidation occurs, a potential concern relates to the movement of contaminated pore water and the discharge of contaminants to receiving surface waters and ground water resources. The degree to which emerging tailings pore water may effect the quality of surface waters depends upon site-specific conditions. At some sites, acidic pore water is neutralized by available excess alkalinity contained within the tailings mass either at the reaction sites or along the tailings pore water flow path. At other sites where pore water acidity is not sufficiently buffered, metal leaching may occur within the tailings along the pore water flow path.

2.2 Capillary Rise in Thickened Tailings

A typical groundwater profile found in soils including conventional, unthickened 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 capillary pressure 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 capillary pressure and consequently the higher the capillary rise above the water table.

Tailings are crushed rock particles - a waste by-product 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 µm (200 mesh) in size. During conventional tailings placement, beach type deposits are formed as the particles are hydraulically separated by grain size, density, and shape. In contrast, thickened tailings do not segregate but remain homogeneous when placed.

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. An elevated water table in reactive tailings reduces the total thickness of unsaturated tailings exposed to oxygen as the elevated water table and its capillary zone act as a diffusion barrier to atmospheric oxygen. From experimental data in tailings, which can be generalized to other porous media, a useful expression for the effective diffusion coefficient (D_e) as a function of the degree of saturation is as follows (Elberling et al., 1993):

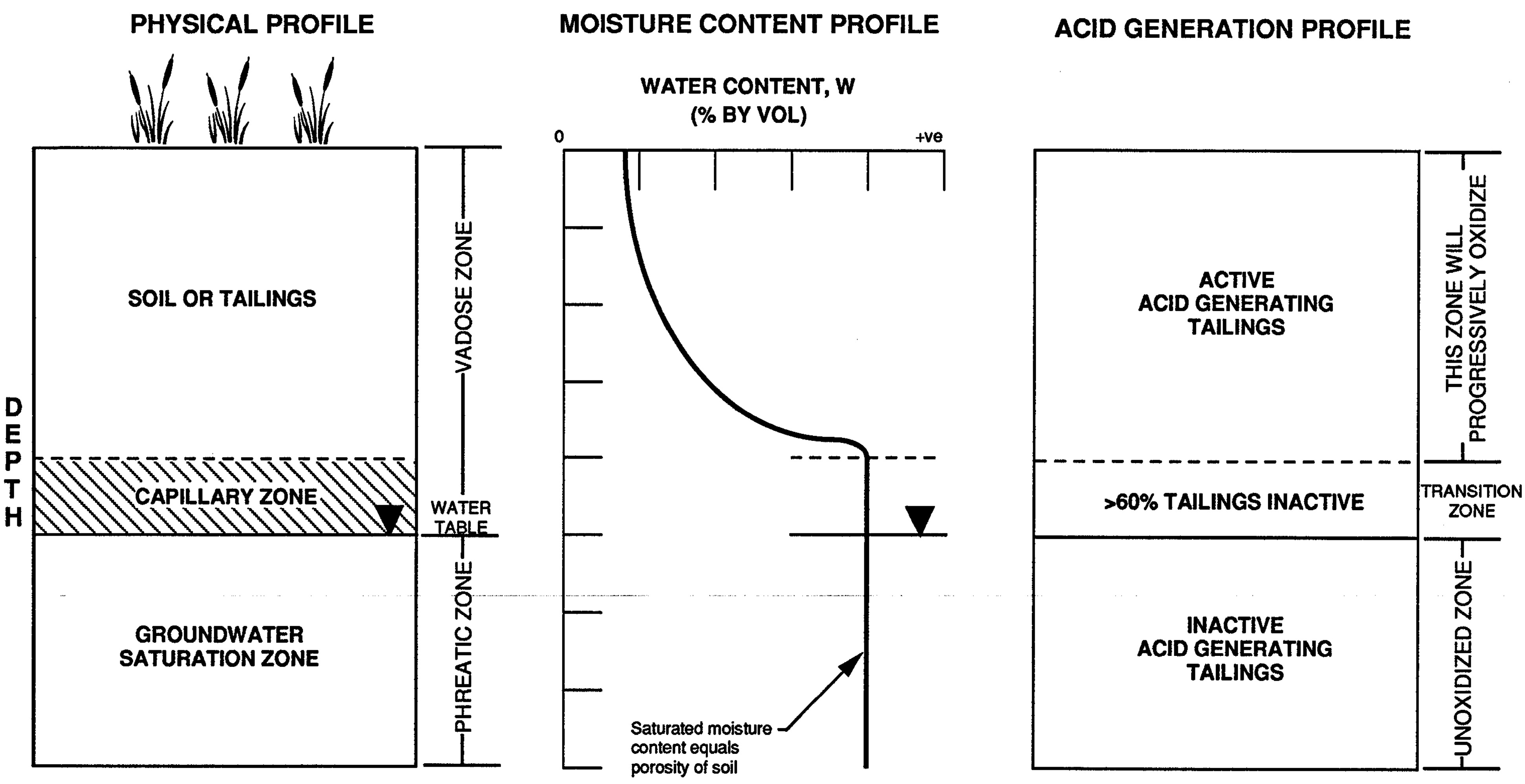
$$D_e = D_a t (1 - S)^a + \frac{D_w t S}{H} \qquad (2.5)$$

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)

FIGURE 2.1

GROUNDWATER PROFILES



SOURCE: FIGURE 2.1 MEND 2.17.1

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 $\tau = 0.032$ and $\alpha = 3.92$. The effective diffusion coefficient with field samples varied from 5.64×10^{-7} m^2 s^{-1} to 1.66×10^{-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 2.5 and the fitted parameter values determined above ($\alpha = 3.92$) 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 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}).

MEND 2.22.2B showed that the effective oxygen diffusion coefficient of partly saturated tailings becomes practically equal to that of water when the saturation ratio (S_R) reaches about 90%. At this value of S_R, the gaseous phase is discontinuous and oxygen transport is controlled by diffusion, with solubilization, through water filled pore spaces. Aachib et al. (1994) report that a degree of saturation of 90% in a porous material produces a layer that has about the same effective oxygen diffusion coefficient as water.

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.
2) A shallow water table can lead to the discharge of near surface tailings pore water to surface run off 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). Item 2 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). This phenomenon is of interest as contaminated pore water may impact run off quality during rainfall events.

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 (Figure 2.1). 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, 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.

2.3 THICKENED TAILINGS DISPOSAL (TTD)

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, 1999), and Robinsky et al. (1991) and Barbour et al. (1993), tailings disposal by the thickened, sloped, discharge scheme provides the following advantages over the 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.
- A homogeneous non-segregated 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. Thickening promotes the development of a thick capillary fringe and the near-saturation of surface tailings.

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 sulphide 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. A key objective of the closure plan for the Kidd Metallurgical Division TMA is to inhibit acidic drainage generation. The closure strategy for the TMA involves the placement of thickened acid-buffering gold mine tailings as a cover over the thickened Kidd tailings. The capillary zone would rise more frequently into the cover, and the gold tailings surface would be vegetated (Falconbridge, 1997). Other closure strategies to maintain saturation or limit oxygen diffusion are being considered.

2.4 Interstitial Pore Water Flow

Hydrogeological theories on interstitial flow (e.g. groundwater direction and flows including pore water flow in tailings) are well established and can be applied to assess the migration of pore water transported contaminants in thickened tailings. Geochemical equilibrium models can be used in concert with this information to predict the future pore water quality, the rate of release and the impact (if any) on receiving water quality. Al and Blowes (1995ab) and MEND 2.23.2d applied these techniques to:

- <u>Model pore water flow</u>. Hydraulic head measurements suggest that pore water flow within the Kidd thickened tailings is from the centre of the tailings impoundment, outward to the perimeter, with pore water discharge occurring in the flat-lying peripheral areas of the TMA. Observations support the theory that capillary action can maintain a considerable saturated zone above the thickened tailings water table.

- <u>Assess the tailings pore water quality at the Kidd TMA</u>. Sulphide oxidation in near-surface unsaturated thickened tailings generates low pH conditions in the pore water and increases the concentrations of Al, Cd, Co, Cr, Cu and Ni, and further increases the concentrations of Mg, Mn, Fe, Zn, Pb, As and SO_4. Oxidation reactions in the near-surface, unsaturated tailings are initially buffered. Sulphide oxidation modelling to estimate the long-term effects of sulphide oxidation (using an uncovered tailings surface scenario) showed that future sulphide oxidation would be greatly limited by the high degrees of saturation present in the tailings mass.

2.5 THE USE OF TRACERS

Tracer substances are used to track the movement of surface and ground waters. There are two general classes of tracers: the first is a tracer that is a natural constituent of the water and can be used to distinguish the water through the analysis of samples; the second is a tracer substance that is specifically introduced into the water of interest to make the water distinguishable when analyzed.

In general, a suitable tracer for tailings pore water is one that can be introduced into an environment where:

- The selected tracer substance was not previously present at a detectable level. This must be verified prior to the introduction of a tracer.
- The tracer will remain conservative and mobile - it will be chemically stable and not react or combine with other constituents including the pore water and tailings solids.
- The tracer can be readily analysed in samples of solids or water, and detectable when present at low concentrations.
- The tracer is safe to handle and use.
- The tracer is economic to purchase, apply, and identify through analytical testing using established procedures.

The tracers used in the tracer study (e.g. potassium bromide and potassium iodide) met the above requirements.

In concept, the use of a tracer in a tailings impoundment involves: 1) introducing the tracer to the tailings pore water at specified locations, 2) pore water or tailings solids sampling at downstream locations and depths of interest, 3) the analyses of samples, and 4) data assessment. While straightforward in concept, the actual use of a tracer can be challenging.

3.0 THICKENED TAILINGS DISPOSAL AT THE KIDD TAILINGS MANAGEMENT AREA (TMA)

The Kidd Metallurgical Division was the first metallurgical complex to use the thickened tailings disposal (TTD) system. The TTD system at Kidd has been progressively improved to its present status where tailings are thickened in an Outokumpu high-rate thickener, to in excess of 60% solids and then discharged from an elevated spigot position to form a cone-shaped mound. As the approach was developed by Dr. E.I. Robinsky (1975, 1978, 1999), the tailings mound is also known as the Robinsky cone. The slope of the mound has been demonstrated to be a function of the percentage solids, and at Kidd is in the range of 3% near the apex of the mound and 1.5% overall. Photograph 3.1 provides an aerial view of the TMA.

The Kidd Metallurgical Division concentrator presently produces in the order of 6,000 t/day of tailings. The thickened tailings are discharged from a central, elevated position in the 1200 ha TMA. A plan view of the TMA is provided in Figure 3.1.

3.1 TECHNICAL STUDIES

There is considerable information on the hydrologic characteristics of the thickened tailings disposal method at Kidd Creek. 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) (MEND 2.23.2ab) and Al and Blowes (1995ab) (MEND 2.23.2d).

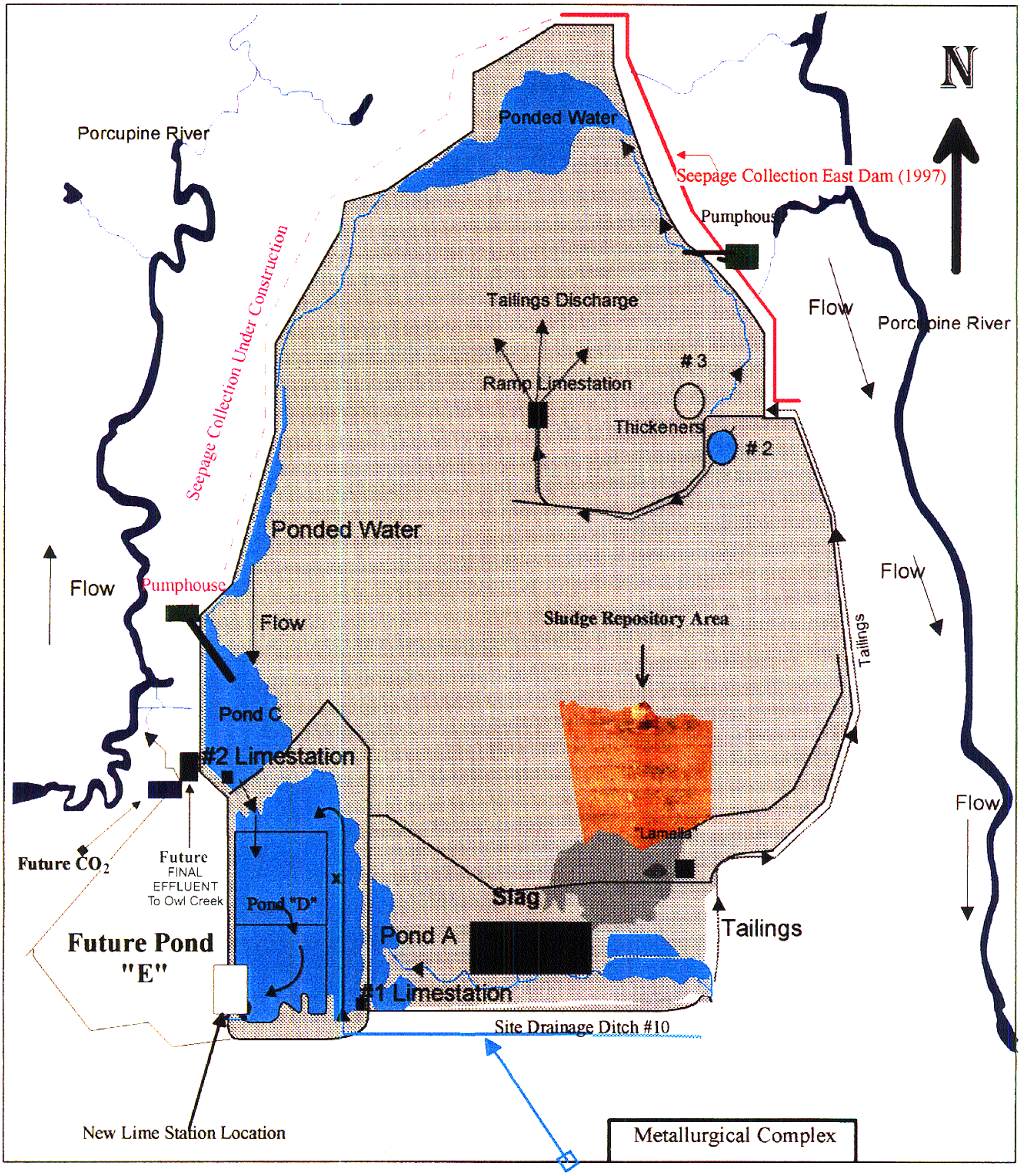
The sulphide tailings are potentially acid-generating, and sulphide oxidation occurs in near-surface, exposed tailings, and along shrinkage cracks.

The mineralogy of the tailings varies locally but is homogeneous on a large scale. Table 3.1 provides the results of a mineralogical analysis of the tailings. These results are typical, with the exception of the jarositic value which fluctuates between 0 and about 5% depending upon the sampling location within the tailings impoundment. Key sulphide minerals within the tailings as determined by Jambor et al. (1993) are: pyrite (10 to 25 Wt%); pyrrhotite (1 to 2 Wt%); sphalerite, chalcopyrite, and galena (combined 1 to 2 Wt%).

PHOTO 3.1 - AERIAL VIEW OF TMA (LOOKING SOUTH)

FIGURE 3.1

GENERAL PLAN OF THE TMA



SOURCE: FIGURE 4.1, FALCONBRIDGE (1997)

Table 3.1
MINERALOGICAL ANALYSIS OF THE KIDD TAILINGS [(1)]

MINERALOGY	Wt%
Quartz	48.7
Chlorite	21.4
Pyrite	12.5
Siderite (and iron oxides)	4.9
Muscovite	3.3
Dolomite	3.1
Natrojarosite	1.5
Pyrrhotite	1.4
Albite	0.8
Amphibole	0.5
Gypsum	0.5
Chalcopyrite	0.5
Sphalerite	0.3
Cassiterite	0.3
Stilpnomelane	>0.5
TOTAL	99.6

Note: (1) Source: Table 1, Appendix V, Al and Blowes (1995a).

A mineralogical examination of the Kidd tailings by Lakefield Research (1994) indicated that:

- In excess of 85% of the pyrite solids are liberated, and typically range in size from 20 to 70 µm.
- About 60% of the pyrrhotite solids are liberated, and range in size from 20 to 80 µm.
- In excess of 75% of the sphalerite solids are liberated, and range in size from 14 to 30 µm.
- About 60% of the chalcopyrite particles are liberated, and range in size between 10 to 79 µm.

The thickened tailings slurry has a low water content (approximately 30% by weight) during discharge and the mineral grain size distribution remains unsegregated after placement. The lack of segregation creates a relatively homogeneous tailings that has characteristics that are favourable for high moisture retention above the water table (high capillary tension). The high moisture retention above the water table, has implications for lower oxidation rates in the tailings.

Under the auspices of the MEND program, St-Arnaud and Woyshner (1993) completed an extensive technical study of the Kidd TMA (also reported as MEND 2.23.2ab) in which 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, the height of the capillary zone 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:

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

(2) Dewatering during a drought year is expected to have little impact on the long-term saturation of the tailings. However during these periods, oxidation is promoted deeper in the 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 was 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 rate 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 x 10^{-9} to 1 x 10^{-6} $m \cdot s^{-1}$ with in excess of 70% of the measured values in the limited range of 1 to 5 x 10^{-8} $m \cdot s^{-1}$. The water table elevation across the site varied seasonally at the apex of the pile and more moderately near the base of the cone. The hydraulic head profile across the tailings slope is shown in Figure 3.2. 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.

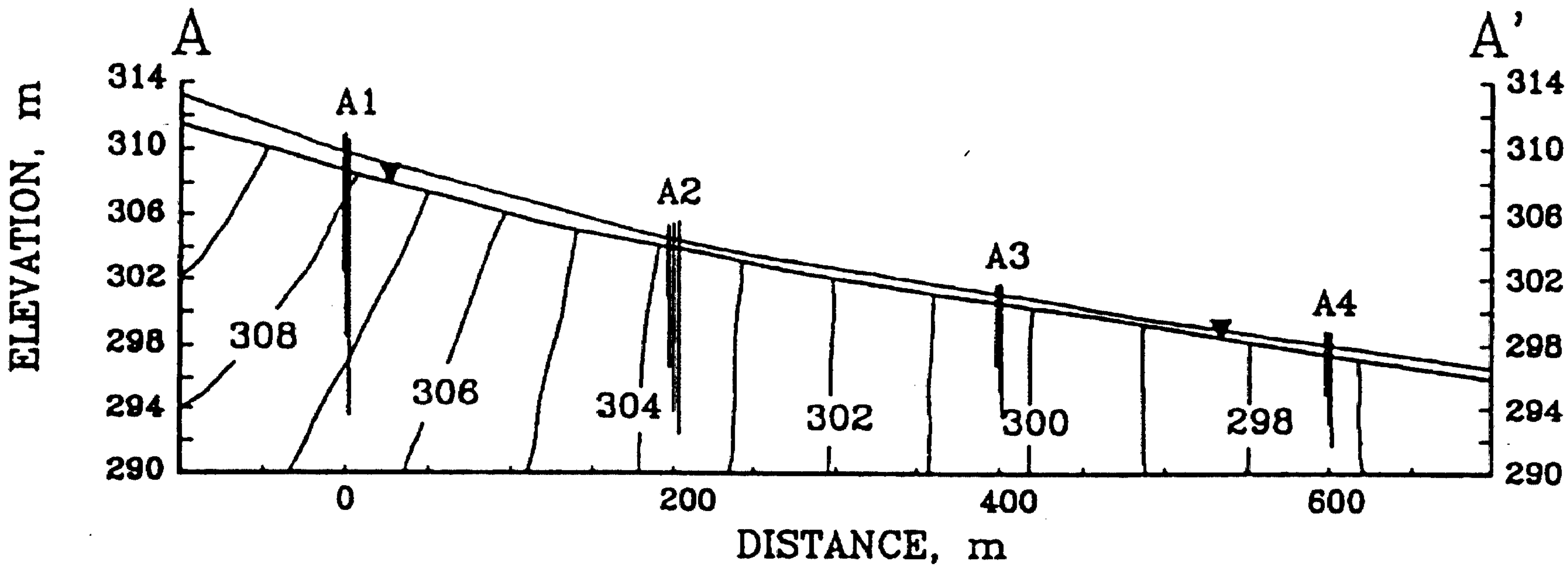
The depth to the water table within the tailings has been shown to vary across the TMA, with seasonal effects. Along the flanks of the tailings mound, the depth to the water table fluctuates from about 2 m in the winter months to about 4 m in the summer. In the flat peripheral area along the base of the mound, the depth to the tailings water table is typically quite close to (e.g. within about 15 cm of) the tailings surface. Al and Blowes (1995) determined that recharge rates over the tailings basin are at a maximum near the tailings apex, and decline radially towards the perimeter dykes. The dominant pore water flow direction is radially outward from the apex to the flat-lying peripheral area, with some downward pore water flow. Robinsky (1990) indicated that because of the moisture retention characteristics and capillary suction that allow nearly saturated conditions to be maintained near the surface of the tailings, acid production is greatly reduced.

Research carried out by Al and Blowes (1995a) included the installation of piezometers within the tailings area, and the collection and analysis of tailings solids and pore water. As part of their investigations, they assessed the quality of pore water in the near-surface layer of tailings where the tailings had been exposed for some time, and sulphide oxidation had occurred. They determined that within the near-surface oxidizing zone, concentrations of SO_4, Mg, Mn, Zn, and Pb were elevated. Detectable concentrations of metals such as Al, Cu, Cd, Co, Ni, and Cr were found to be present only in the oxidizing zone. Tailings pore water samples were also obtained from saturated tailings located below the tailings water table and at the base of the tailings. It was determined that a shallow to intermediate zone had been affected by past jarositic waste disposal and that there was an underlying deep zone where tailings pore water quality was similar to mill discharge water.

The TMA is underlain by a 3 to 20 m thick layer of clay which rests on till over bedrock. The migration of contaminated pore water to the ground water regime is significantly inhibited by thick underlying clay sediments. The tailings area is encompassed by low-head containment dykes and drainage from the tailings area is collected and lime-treated. Effluent treatment is required as a result of the oxidation of the near-surface, unsaturated tailings.

FIGURE 3.2

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



SOURCE: FIGURE 4.5.2 MEND 2.17.1, AFTER WOYSHNER AND ST-ARNAUD (1994)

3.2 WATER BALANCE

The water balance for the Kidd Creek tailings impoundment include average annual values of precipitation (P) of 860 mm, run off (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 $cm.yr^{-1}$ 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 tailings reveals an air entry value (AEV) of approximately 6 m of water (or 60 kPa) as shown in Figure 3.3. 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.

Figure 3.4 shows surface drainage within and from the TMA. The tailings transport water, run off, and seepage are intercepted and diverted to Ponds A and C, and treated at lime stations 1 and 2 respectively. Treated waters flow from the lime stations to Pond D (a sludge settling/polishing pond). Run off from a section of the Metallurgical Site and mine water from the Kinross underground gold mine flow along Ditch 10 and mix with treated flows in Pond D. Treatment sludge is dredged from Pond D and disposed within a designated area in the south end of the TMA.

The flowrate to Pond D varies considerably, and has ranged from a low in the range of 1,000 m^3/day in summer to in excess of 300,000 m^3/day during the spring freshet. The average daily flow of water to Pond D is in the order of 70,000 m^3/day, of which approximately 30,000 m^3/day is recycled to the metallurgical process, with the balance discharged to the lower section of Owl Creek and hence to the Porcupine River. Water inputs to the tailings basin are summarized in Table 3.2.

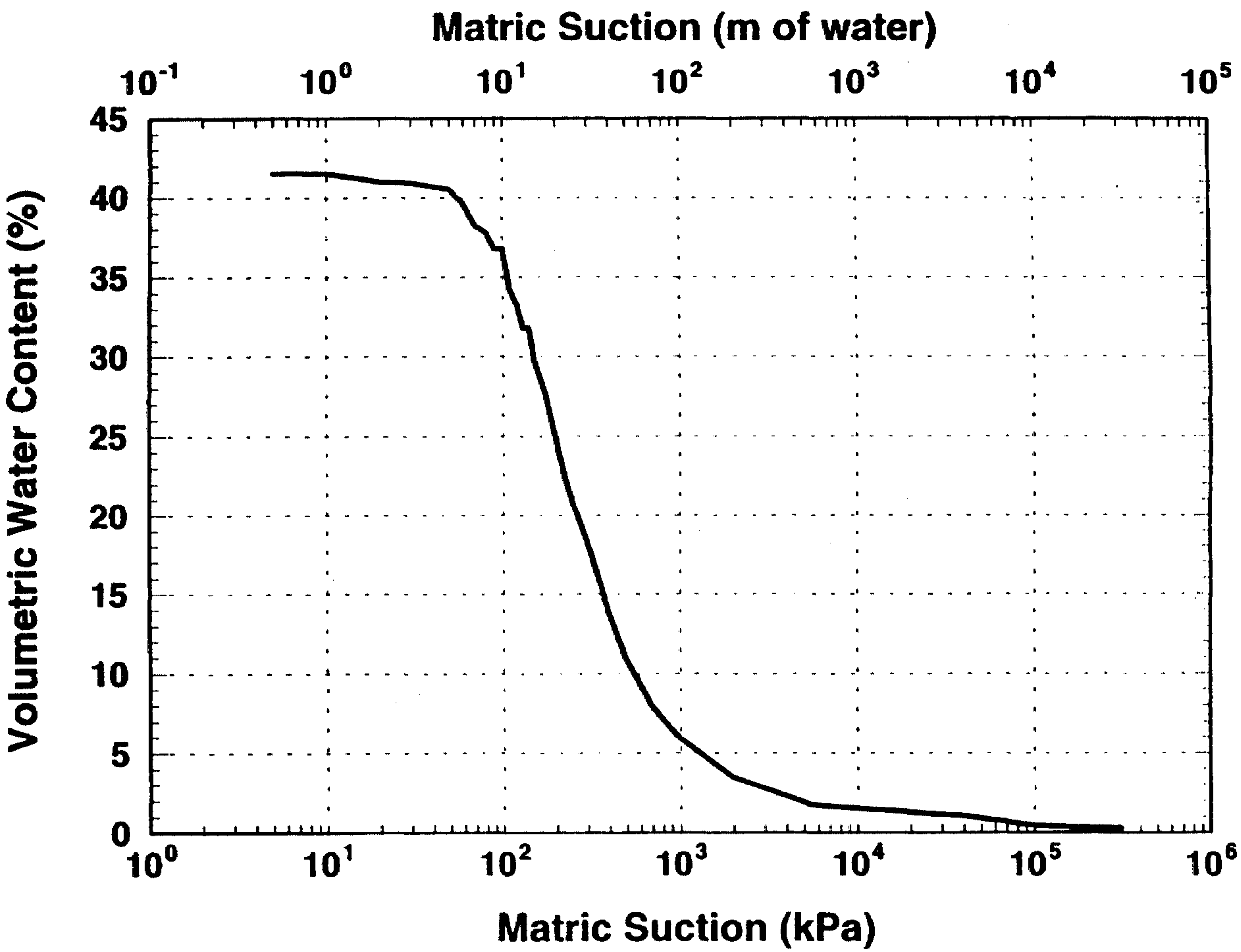
Table 3.2
WATER INPUTS TO THE TMA(1)

Source	Average Daily Flowrate	Percentage of Total
Tailings Thickener Overflow	37,500 m^3/day	54%
Tailings Thickener Underflow	12,000 m^3/day	17%
Net Precipitation	13,000 m^3/day	19%
Ditch 10	6,400 m^3/day	10%
Total	68,900 m^3/day	100%

Note:(1) Table based upon a review of 1990 average monthly flow data; a water balance for the tailings basin prepared by Woyshner and St-Arnaud (1994); and 1995 average monthly flow data.

FIGURE 3.3

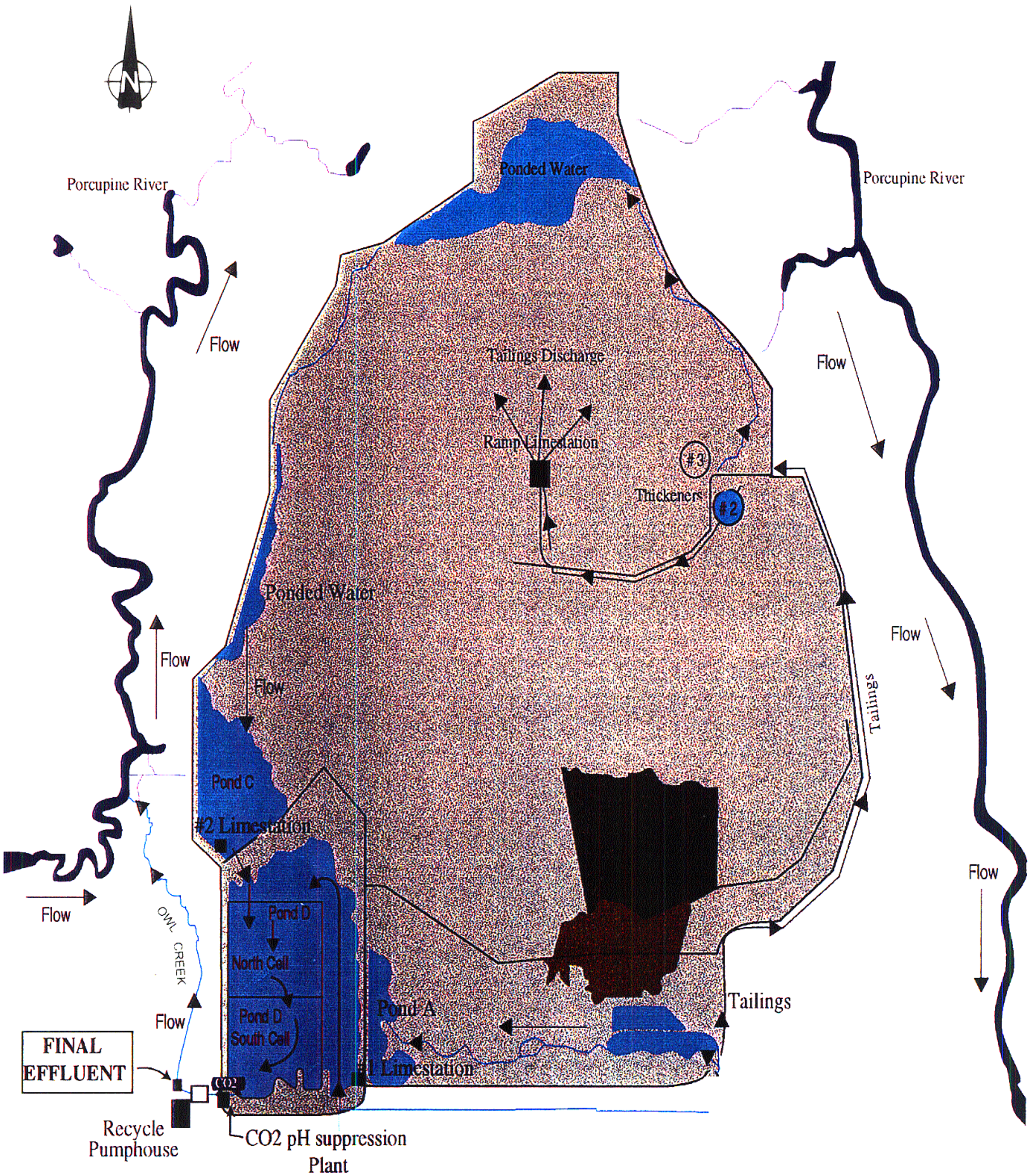
DRAINAGE CURVE OF THE KIDD CREEK TAILINGS



SOURCE: FIGURE 5 MEND 2.23.2ab, AFTER YANG et al (1992)

FIGURE 3.4

KIDD CREEK METALLURGICAL SITE THICKENED TAILINGS BASIN



SOURCE: FIGURE 4.5.1, MEND 2.17.1

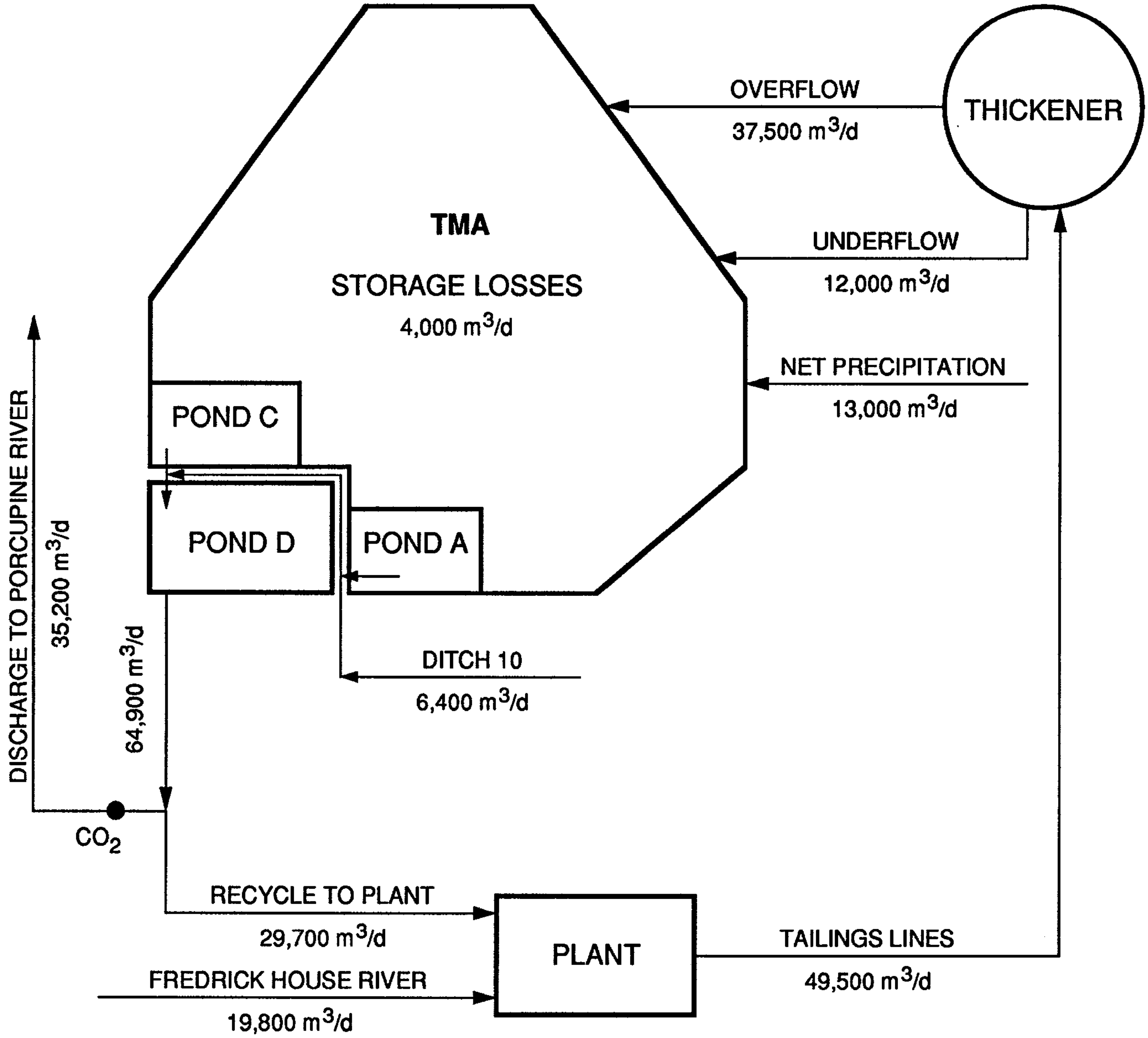
Table 3.2 includes net precipitation, and accounts for losses due to evaporation and infiltration. Other water losses within the basin are, for practical purposes, limited to water retained in tailings pore spaces. These other losses total about 4,000 m^3/day (seepage is intercepted and returned to the basin). The water balance for the TMA is shown schematically in Figure 3.5.

Drainage from the TMA is treated using a conventional lime treatment process. Slaked lime is added to the flows from Ponds A and C at lime stations 1 and 2 respectively, and the treatment sludge settles in Pond D. The pH of the final effluent from Pond D is maintained within a range of 6.0 to 9.5 using CO_2.

Under MEND 2.23.2ab, St-Arnaud and Woyshner (1993) determined that pore water in the saturated zone tends to move downward near the centre of the tailings mound and laterally along the tailings slope. The suction condition and the low hydraulic conductivities of the tailings retard the downward seepage of water through the tailings.

FIGURE 3.5

SCHEMATIC PLAN SHOWING WATER BALANCE FOR THE TMA



NOTE:

1. ALL FLOWS SHOWN ON THIS FIGURE ARE AVERAGE FLOW RATES PER DAY.
2. RECYCLE TO PLANT HAS MORE RECENTLY AVERAGED APPROXIMATELY 42,000 m^3/d

SOURCE: FIGURE 4.3.2, FALCONBRIDGE (1997)

4.0 METHODOLOGY

4.1 GENERAL

The tracer study was undertaken with the objective of verifying predictions that pore water migration was predominantly radially and downstope from the apex of the tailings mound towards its boundaries, and that the horizontal pore water velocities were in the range of those predicted by St-Arnaud and Woyshner (1992).

4.2 PRE-PLANNING AND PHYSICAL SET-UP

Pre-planning involved:

- The selection of the tracers and confirmation of their suitability for the Kidd site.
- The selection of the tracer injection and monitoring sites including the relative locations of the tracer injection pipes and the monitoring mini-piezometers.
- The development of a tracer sampling and testing program.

Prior to the start of the field program in 1992, analyses of tailings solids and pore water samples were used to confirm that the tracer compounds (potassium bromide and potassium iodide) were not already present in detectable concentrations, and that the tracers would remain conservative (e.g. unreactive and mobile) in the tailings pore water environment.

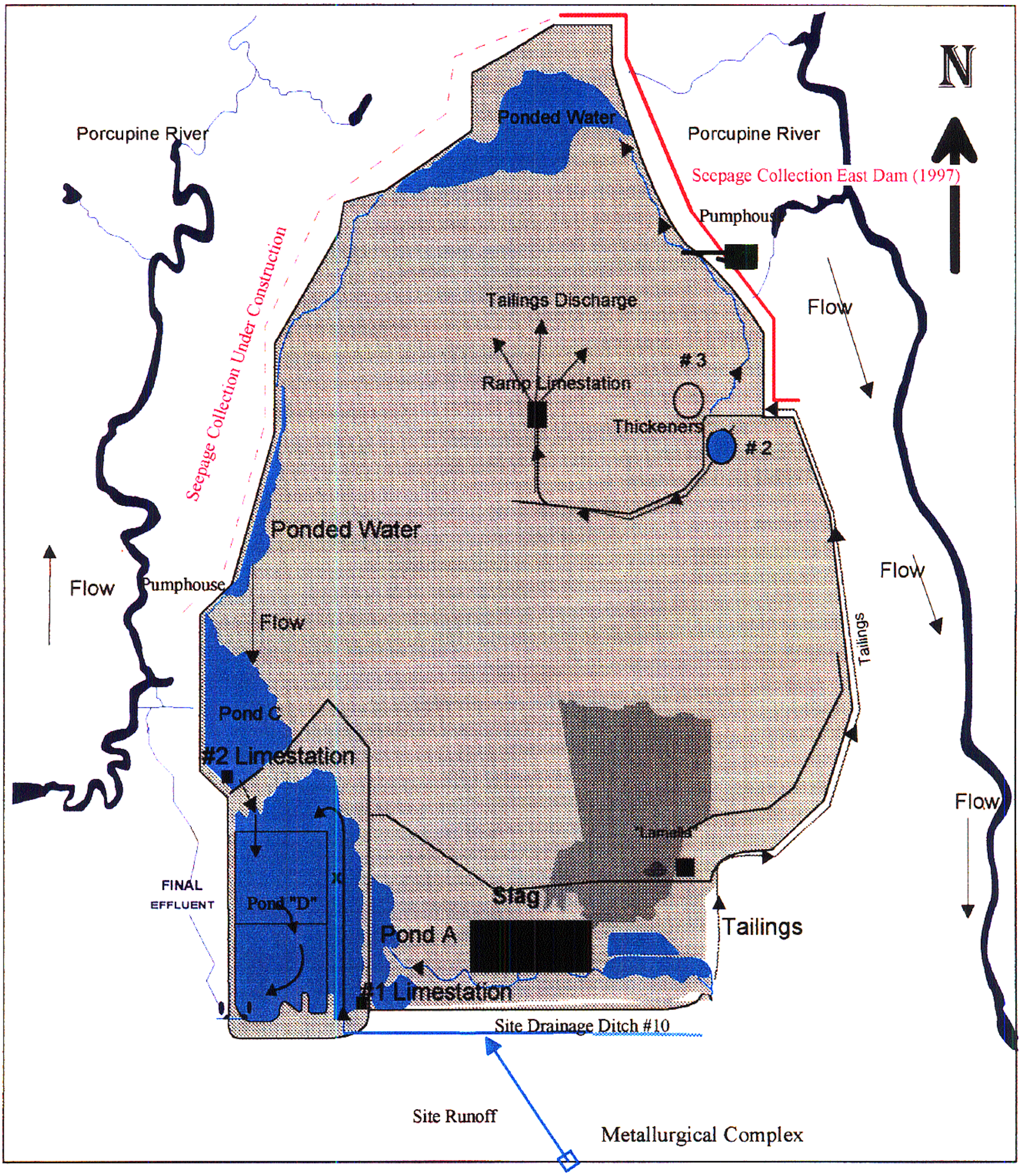
Three tracer injection and monitoring sites were selected to provide tracer monitoring data in different areas of the tailings mound. The sites were situated along the southern slope of the TMA with the topmost station located on the apex of the tailings mound where the slope is steepest (Figure 4.1).

Each of the tracer monitoring sites included three tracer monitoring set-ups comprised of four tracer injection pipes and 15 downstream piezometers for pore water sampling. The layout for a typical test site, as well as the depths of the piezometers, are shown in Figure 4.2. Each site included a total of 45 mini-piezometers.

The tracer injection pipes, or seed tubes, are located up-slope of the monitoring mini-piezometers, and consist of 4 cm (1.5 in) diameter PVC pipe. The seed tubes were installed so that the tracer solution would be introduced into the tailings pore spaces at depths of 0.3 to 0.8 m. The mini-piezometers (consisting of 10 mm diameter, flexible polyethylene tubing with removable protective caps at surface) were installed downgradient of the seed tubes. As shown

FIGURE 4.1

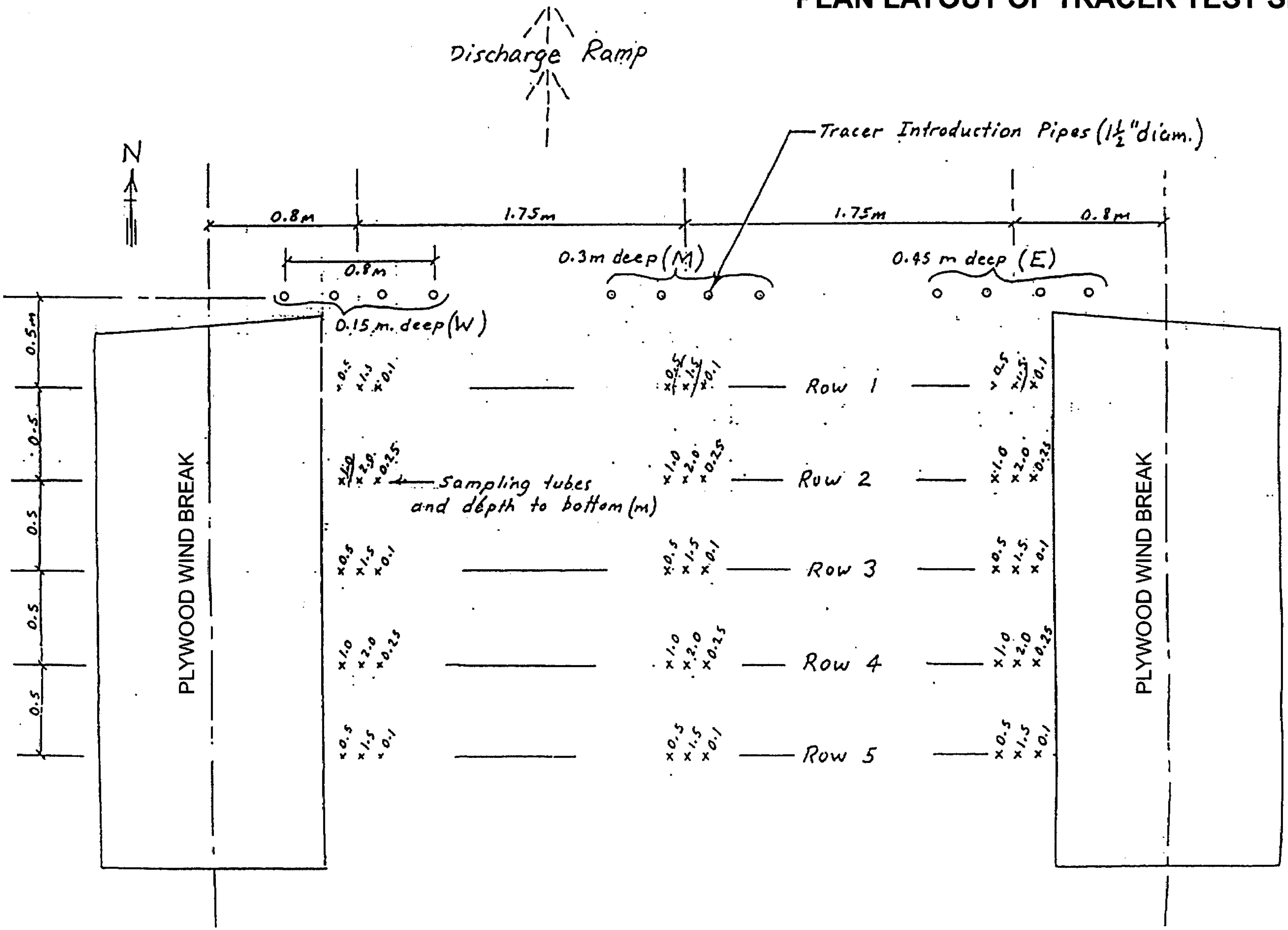
TAILINGS BASIN AND POLISHING POND
FALCONBRIDGE LIMITED KIDD METALLURGICAL DIVISION



SOURCE: FIGURE 4.3.1, FALCONBRIDGE (1997)

FIGURE 4.2

PLAN LAYOUT OF TRACER TEST SITE



SOURCE: ROBINSKY (1992)

in Figure 4.2, the depths of the mini-piezometers was varied to provide opportunities to sample pore water at depths that varied from 0.1 to 2.0 m.

The 2 m depth limit was selected based on previous investigations which indicated that pore water velocities would be greater in the horizontal direction in comparison to the vertical direction. A depth of 2 m would provide an adequate sampling range given the horizontal extent of the tracer monitoring sites.

The tracers were introduced in the fall of 1992 with potassium bromide introduced at the edges of the test plot (in the east and west seed tube sets) and potassium iodide introduced in the central seed tubes. The initial sampling program was developed based on the premise that the tailings were saturated to near-surface and that moisture containing iodide or bromide tracer ions could be sampled and the tracers identified through analytical testing. The sampling program was subsequently modified over the course of the study as described in the following subsections.

4.3 INITIAL PORE WATER SAMPLING

The mini-piezometers were initially sampled in June 1993, at which time the sampling procedure involved the use of an absorbant material as follows:

- An absorbant material (cellulose filter paper, 7.5 cm diameter circle) was tightly rolled and folded to snugly fit into a clean 10 mm diameter, polyethylene tube (Photograph 4.1). The protective cap (a rubber stopper) was removed from the top of the mini-piezometer to allow sampling.
- The polyethylene tube was lowered into a selected mini-piezometer where a sample of the pore water was collected in the filter paper through absorption and capillary action. The procedure required that the polyethylene tubes be left in place for a period of 1 to 2 minutes, except in cases where the filter paper became saturated immediately. Care was taken to avoid dislodging the filter from the polyethene tube when sampling. Experience showed that it is difficult to saturate filter papers when sampling piezometers having depths of 0.5 m or less.
- Once retrieved, a saturated filter paper was placed in a labelled plastic bag. The mini-piezometer was recapped. The pore water saturated filter paper samples were taken to the analytical laboratory at the Kidd Metallurgical Division complex. The section of polyethylene tubing used to hold the filter paper for the sampling of one mini-piezometer was discarded and removed from the sampling site. A new, clean length of polyethylene tubing was used for the sampling of each piezometer.
- In the laboratory, the filter papers were subjected to a quick leach using a known volume of deionized water for a period of approximately five minutes. The leaching

Photograph 4.1

7.5 cm FILTER MEDIA INSERTED IN SAMPLE TUBE time was kept short, as longer leaching times were found to result in high nitrate solutions in the leachate solutions. Nitrate leached from the filter media matrix was found to interfere with tracer analyses. A 10 µL sample of the leachate solution was then analyzed using a Dionex 2000 Ion Chromatograph equipped with an AG3, AS3 separator column and a conductivity detector. To reduce the effects of other ions, particularly sulphate and nitrate, the leachate samples were diluted 2x and 10x for bromide and iodide analysis respectively. The detection limit used for the diluted sample was 0.25 µg/mL or 0.5 to 2.5 mg/L for an undiluted sample.

The above procedure was later modified based on the experience gained from the June 1993 sampling.

4.4 September 1993 Sampling

The procedure used in September 1993 included the addition of approximately 20 mL of deionized water to mini-piezometers with a depth of 0.5 m or less. The water was allowed to stand in the piezometers for two to five minutes before the piezometer was sampled using rolled filter paper as described previously.

The revised procedure was successful in allowing saturated filter papers to be extracted from the shallow mini-piezometers. The method was not optimal because the concentration of the tracer in the sample presented an area of uncertainty. Additionally, it was conceivable that dilution could occur to a point where the concentration of the tracer in the sample would be lowered to a level that would be undetectable in the analyses. In response to this issue, the sampling and analysis program was revisited and the sampling and analyses program was consequently revised for the second time.

4.5 October 1996 Sampling

The revised sampling program was based on the collection and analysis of tailings core samples, and included an analytical procedure for the analysis of the cores. The samples used to develop the analytical procedure were obtained from the northern most sampling site, and specifically 1 m from the seed tubes. A tailings core was collected using an aluminum tube (Photograph 4.2), and the core was then dissected into three - 20 cm lengths and one - 25 cm length where the latter represented the bottom of the extracted core. The dissected core was logged and taken to the laboratory for ion chromatography analysis, where:

- The tailings samples were weighed, dried and leached in 1 L of hot deionized water for 15 minutes. After settling, a portion of the leachate was decanted for analysis.

Photograph 4.2

INITIAL CORING SETUP

- The leachate samples were diluted 2x and 10x for bromide and iodide analyses respectively to reduce interference by other ions. A 10 µL sample volume was used in the analysis. The detection limit for undiluted leachate samples was 0.25 µg/L.

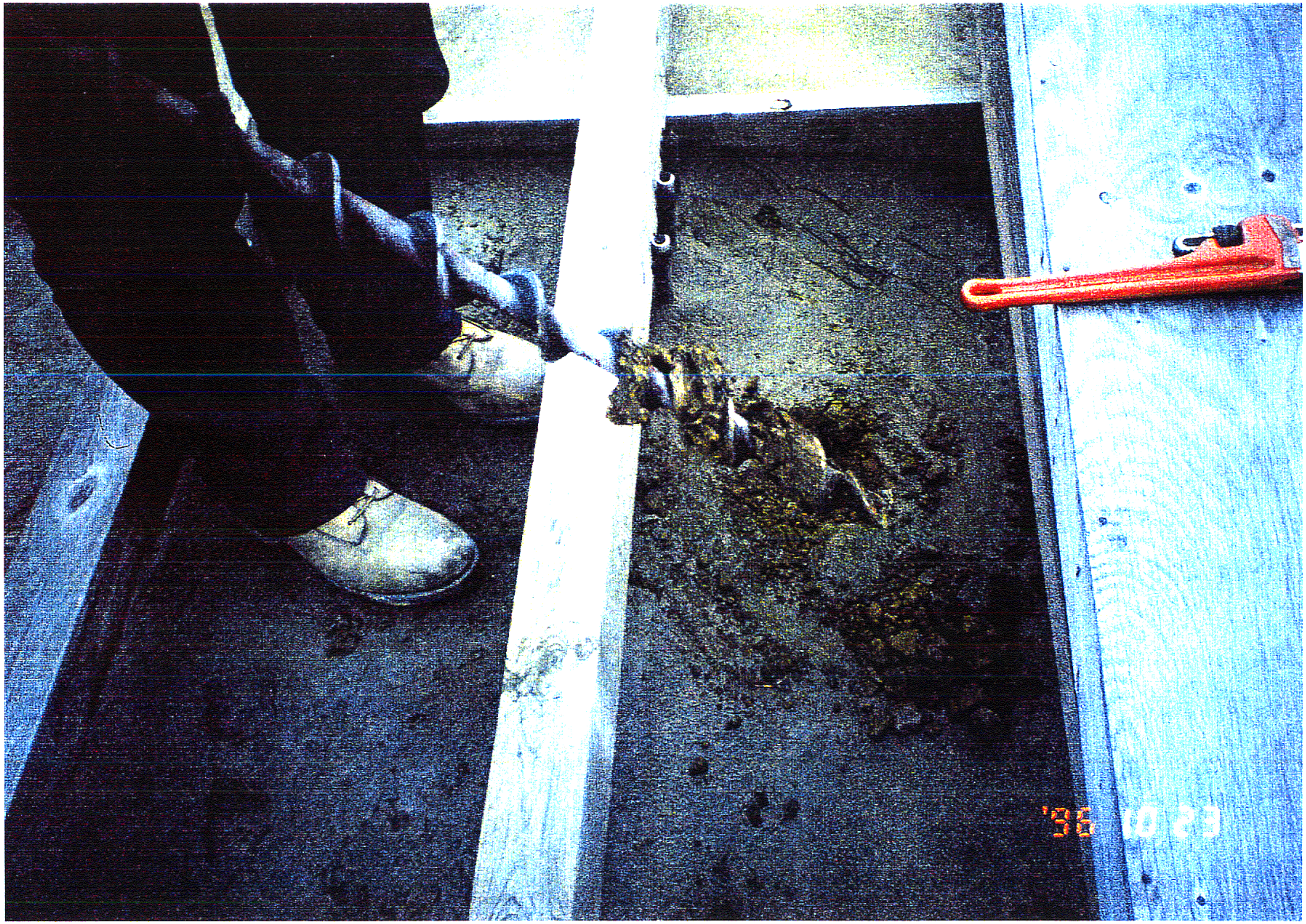
The results of the analyses were encouraging, and this method was adapted for use in analyzing the tailings cores collected in October 1996. Capped tubes (5 cm (2 in.) diameter, 1.5 m (5 ft.) long) were driven into the tailings (Photograph 4.2) using a sledge hammer. The bottom end of each tube had a spring-loaded trap device to ensure that the tailings remained in the tube during extraction from the hole. The topmost 60 to 90 cm of tailings were successfully sampled using this method. However, at greater depths where the tailings were near or at saturation, the thickened tailings could not be sampled using the tubes. Specifically, the tube would not penetrate into the saturated tailings.

An auger was then tested as a means of sampling the saturated tailings (Photograph 4.3). The power auger unit was mounted on a trailer that was pulled using an all terrain vehicle. The power auger was found to be effective to depths of 1 m. This technique was applied to collect 48 tailings samples within a 1 m depth at locations where the tracer plume front was estimated to have migrated. The auger procedure involved:

- Spotting the hole and augering 30 cm. The auger was then raised, and the sample carefully removed, bagged and tagged. The auger was then cleaned.

- The procedure was repeated for the next 30 cm of hole depth.

An attempt was made to use the power auger at depths of greater than 1 m. The auger was not suitable for this application as it was difficult to extract from saturated tailings.



Photograph 4.3

CORING WITH AUGER
SETUP OCTOBER, 1996

5.0 OVERVIEW AND CONCLUSIONS

This section provides an overview of the present state of knowledge about pore water movement in the Kidd thickened tailings management area (TMA), and reviews the results of the tracer study with respect to the modelled pore water flow direction and velocities. Conclusions are presented respecting the use of tracers to track pore water movement in thickened tailings.

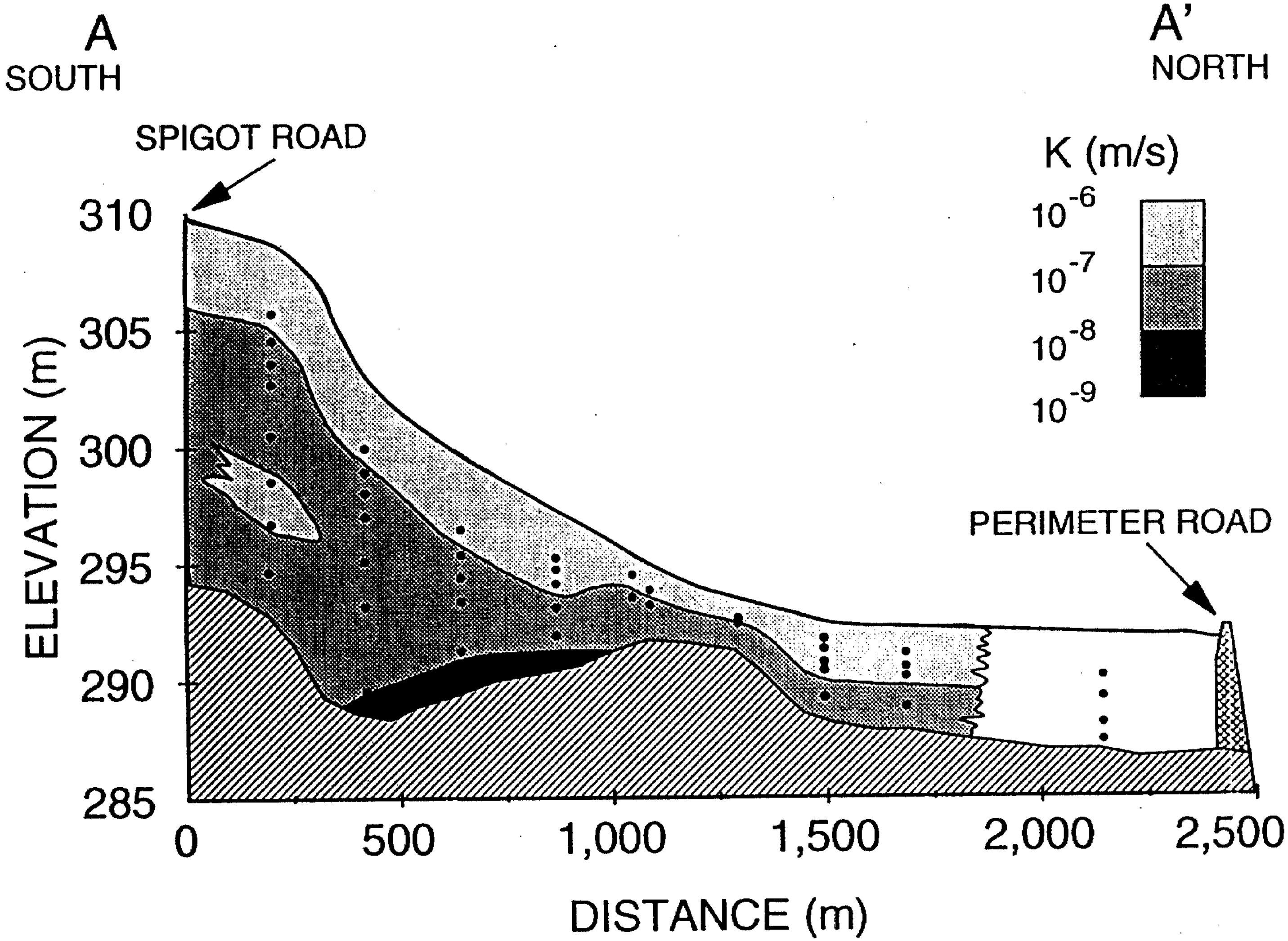
5.1 OVERVIEW - PORE WATER MOVEMENT

As a result of numerous site-specific studies, the Kidd TMA is well characterized in terms of its hydrogeological, hydrological, chemical and physical characteristics. The state of knowledge regarding the movement of pore water within the thickened tailings mound is summarized below:

- The elevated central area of the TMA serves as a pore water recharge area, receiving infiltration from precipitation as well as from ongoing tailings disposal. Pore water flow within the tailings is dominated by recharge from infiltration in the central, elevated area of the TMA. Elevated water table conditions are predicted to be naturally maintained after closure.
- The pore water movement is radially downslope from the central elevated area to the flat-lying peripheral areas of the TMA. Al and Blowes (1995a), also reported in MEND 2.23.2d, that based on measurements of hydraulic head:
    1. The gradients are downward near the apex of the tailings mound.
    2. The gradients are lateral and slightly downwards along the mound slopes.
    3. The gradients are upward in the flat-lying peripheral areas of the mound. The pore water discharge occurs as exfiltration except during storm events when the water table may temporarily rise to the tailings surface. Water loss due to evaporation is sufficient to normally maintain the water table below much of the tailings surface in this area.
- Pore water movement predominantly follows the tailings slope. Downward pore water movement is impeded by the low hydraulic conductivity (K) of the tailings. Al and Blowes (1995a) report that the narrow distribution of hydraulic conductivity (e.g. between 10^{-8} to 10^{-6} $m{\cdot}s^{-1}$) displayed by the tailings is a reflection of the relatively uniform grain-size distribution of the tailings. They obtained the lowest K values from tailings samples collected at depth. The decrease in K values with depth may be due to tailings consolidation - the spatial distribution of hydraulic conductivity along a section of the tailings mound is shown in Figure 5.1. The highest pore water velocities occur in the area of the mound apex and in the tailings

FIGURE 5.1

CROSS-SECTION OF THE TAILINGS SHOWING THE SPATIAL DISTRIBUTION OF HYDRAULIC CONDUCTIVITY



NOTE:
1. BLACK DOTS REPRESENT PIEZOMETER LOCATIONS
2. VERTICAL EXAGGERATION = 55x

SOURCE: FIGURE 5.2 MEND 2.23.2d, AL AND BLOWES (1995a) nearest the surface where the hydraulic conductivity is 1 to 2 orders of magnitude higher than in deeper tailings.

- In several areas of the TMA, the near-surface zone of tailings contains shrinkage cracks formed as a result of the drying of fresh tailings. These fractures create a surficial zone of high effective hydraulic conductivity that can increase the discharge rate of pore water to the tailings surface and hence to tailings area run off during precipitation events.
- A high level of saturation is attained above the tailings water table as a result of thickening. The thickened tailings maintain a high degree of saturation to near surface even when the water table and vadose zone fluctuate in response to short-term wetting and drying events.

Al and Blowes (1995a) report that the maximum pore water velocity (calculated to be 50 $cm{\cdot}yr^{-1}$) occurs near the apex of the tailings mound. This estimate is consistent with independent measurements of pore water velocity using solute tracers that are a by-product of the dissolution of natrojarosite co-disposed with the tailings. Al and Blowes (1995a) estimated the vertical pore water velocity in the tailings based on the difference between the depth of natrojarosite occurrence and the depth of a zone containing natrojarosite dissolution by-products and dividing by the co-disposal time period. The maximum vertical pore water velocity was determined to be approximately 70 $cm{\cdot}yr^{-1}$ near the tailings spigot as shown in Figure 5.2. The figure additionally indicates that the vertical pore water velocity approaches zero at about 1 km from the centre of the tailings mound. This is consistent with the findings of Al and Blowes (1995a) where, based on flow-modelling, pore water discharges to surface beyond a 900 m radius from the mound centre. Estimates of the maximum, average and minimum rates of salt transport due to advection within the thickened tailings are reproduced in Table 5.1. This range of estimates was to be verified through the use of tracers.

Table 5.1

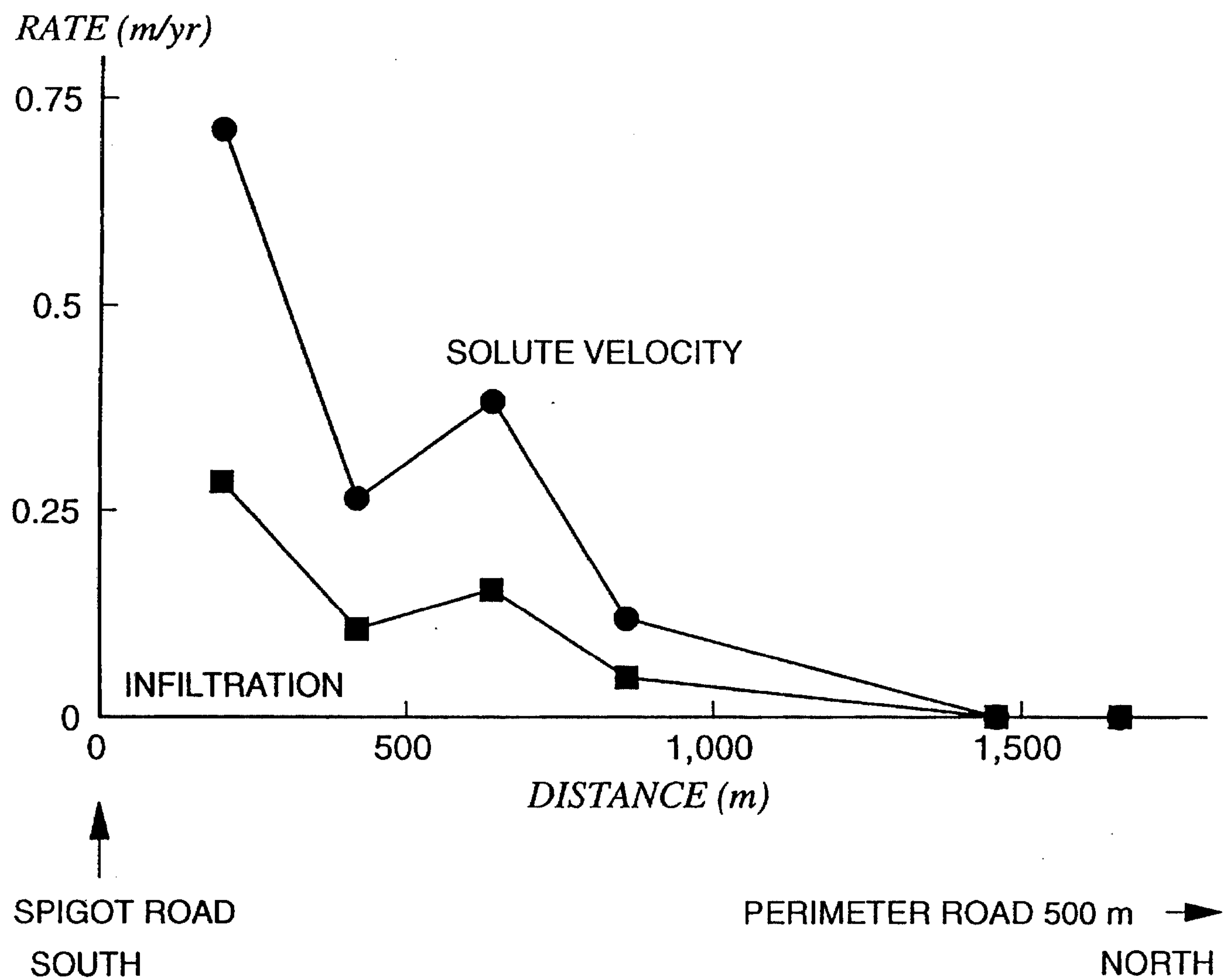
ESTIMATES OF HORIZONTAL PORE WATER VELOCITIES

Value	K (cm/s)	Horizontal Gradient (I_x)	Porosity (n)	Horizontal Velocity ($cm{\cdot}yr^{-1}$)
Minimum	1.8×10^{-6}	0.001	0.5	0.1
Average	10^{-5}	0.01	0.45	7
Maximum	4.4×10^{-5}	0.02	0.4	70

Source: St-Arnaud and Woyshner (1992).

FIGURE 5.2

VERTICAL PORE-WATER VELOCITIES AND INFILTRATION FLUXES CALCULATED FROM DISPLACEMENT OF Na DOWNWIND FROM THE MAXIMUM DEPTH THAT NATROJAROSITE HAS BEEN DETECTED



SOURCE: FIGURE 5.8 MEND 2.23.2d, AL AND BLOWES (1995a)

5.2 OVERVIEW - TRACER STUDY PROCEDURES AND RESULTS

The tracer study was developed on the knowledge base described in Section 5.1 and undertaken on a technical basis. Three tracer injection and monitoring sites (referred to as the North, Central and South sites) were situated in locations of interest with the North site located in the pore water recharge area, and the Central and South sites strategically located along the slope of the tailings mound over a slope distance of approximately 1000 m. The monitoring sites were designed to allow tracer monitoring to be completed over a fixed area to depths of 0.1 to 2.0 m.

Each tracer monitoring site had three sets of tracer injection tubes (West, Middle, and East seed tubes) and tracer monitoring mini-piezometers. Two tracers were introduced in the fall of 1992. Potassium iodide tracer was injected in the Middle seed tubes, and potassium bromide tracer was introduced in the East and West seed tubes. The suitability of the tracers for use in the study had been confirmed prior to their introduction.

The mini-piezometers were first sampled in June 1993. The sampling proved to be challenging when there was insufficient moisture to saturate the filter paper used to collect pore water. The procedure was modified to include the addition of a specified quantity of deionized water to selected shallow mini-piezometers to allow the filter papers to be saturated. Although the modified technique proved successful in allowing pore water samples to be collected, the researchers discontinued this practice due to a concern about the representativeness of the samples, in favour of the collection of tailings cores and the in-laboratory extraction of pore water. A procedure was developed to extract the pore water samples from the cores, and analyse for the presence of the tracers.

The tracer monitoring database was subsequently reviewed by Barbour and Bews (1998). For reference, Barbour and Bew's review comments, which include a discussion of the assumptions used in interpreting the tracer monitoring data, are presented in Appendix A. Key sections of the review are reiterated below.

Tracer Velocities:

The average horizontal (V_x) and vertical (V_y) tracer velocities are listed in Table 5.2.

Table 5.2
SUMMARY OF TRACER VELOCITIES (cm·yr^{-1})

Sampling Date	North Site	Centre Site	South Site	North Site	Centre Site	South Site
	Horizontal Velocity (V_x)			Vertical Velocity (V_y)		
June 1993	80	100	112	88	145	91
October 1996	67	74	72	11	6	8

Source: Table 1. Barbour and Bews (1998).

Barbour and Bews (1998) noted that the June 1993 sampling data should not be heavily relied upon given the difficulties that were encountered in interpreting the monitoring results with regards to:

- The effects associated with the introduction of the tracers and the resultant localized, high initial density of the tracer solution in the tailings.
- Diffusion effects would tend to indicate high initial pore water velocities. The effect of high initial tracer solution density could have, by itself, accounted for the high initial average vertical rate of pore water movement measured in June 1993.

Based on a previous pore water velocity estimate of 50 $cm \cdot yr^{-1}$, the tracers would be expected to migrate about 40 cm horizontally over nine months after their introduction. In such a scenario, it could be expected that the tracer would be not well dispersed after nine months. In addition, tailings fractures could allow tracers to migrate preferentially. This supports the concern expressed by Barbour and Bews with respect to not relying on the June 1993 tracer monitoring data.

The October 1996 data are likely also subject to the above concerns, however, the effects are likely to diminish with time as the tracer plume expands, given that:

- The high initial tracer solution concentrations will be diluted.
- The initial high rates of diffusion transport will diminish.

Barbour and Bews noted that the October 1996 data suggested that the measured rates of pore water movement have decreased significantly since 1993. This could be due in large part to the expansion of the tracer plume. In 1996, the measured horizontal velocities were greater than the vertical velocities. In addition, the 1996 measured horizontal velocities are approaching those estimated by St-Arnaud and Woyshner in 1992 (Table 5.1).

Pore Water Flow:

A key objective of the tracer study was to verify the rate of advective transport within the tailings at three different slope locations, and to define the potential for the upward migration of dissolved salts to the surface as a result of evaporation and capillary movement. Barbour and Bews (1998) noted that the results seem to support the present understanding of the flow system, where the flow is predominantly parallel to the slope surface with the surface slope controlling the hydraulic gradients.

Tracers were detected in some near-surface samples (e.g. 15 to 30 cm depth) but were absent at other near surface sampling locations. The tracer plume did not migrate to the upper tailings surface.

Lessons Learned:

The following suggestions were developed taking into account the experience of the researchers in carrying out the tracer study and the assessment of the database and comments received from Barbour and Bews.

1. Tracer injection points in tailings should be located distant from one another to avoid possible flowpath interceptions and subsequent difficulties in interpreting the tracer monitoring data. This would avoid problems in interpretation should tracer from one seed tube preferentially migrate to the downstream monitoring location of another seed tube.
2. Within the constraints of an operating tailings impoundment, and given the physical characteristics of tailings and the possible slow migration of tracers in thickened tailings, consideration should be given to:
   - Undertaking a tracer study over a longer time frame.
   - Carrying out additional pore water sampling to specifically identify the furthest horizontal and vertical extent of the tracer plume movement. This would assist in the evaluation of the tracer monitoring data base.

5.3 CONCLUSIONS

The tracer study presented a number of challenges to the researchers and predominantly in sampling and the interpretation of the tracer monitoring data. Barbour and Bews (1998) assessed the monitoring data and were able to develop a number of comments as described previously in this section. The following conclusions are based on the review undertaken by Barbour and Bews.

1. The results of the tracer study seem to support the present understanding of the pore water flow system within the thickened tailings. The current rates of transport suggest a hydraulic conductivity in the tailings area of somewhat greater than 1×10^{-5} $cm \cdot s^{-1}$ with a porosity of around 0.4.
2. Based on October 1996 tracer monitoring data, the average horizontal velocity of the tailings pore water is approaching the maximum horizontal velocity of 70 $cm \cdot yr^{-1}$ predicted by St-Arnaud and Woyshner (1992).

3. The greatest velocities are in the horizontal direction. The average downward velocity ranges from 8 to 16% of the average horizontal velocity.

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APPENDIX A

REVIEW OF TRACER TEST RESULTS

BY

BARBOUR AND BEWS (1998)

May 20, 1998

VIA COURIER

Mr. Bernie Swarbrick
Falconbridge Ltd. - Kidd Creek Division
P.O. Bag 2002
Timmins, ON
P4N7K1

Dear Bernie:

Re: Review of Tracer Test Results

The latest set of test results for the field tracer tests, initiated in the fall of 1992, have been compiled and reduced. Enclosed with this letter are the following summaries of this data reduction exercise as compiled by my research engineer, Brenda Bews.

- Memo -'Assumptions/Notes Regarding Tracer Study Plots and Velocity Calcs.'
- Table - Summary of Test Results from June 93, Sept 93, October 96
- 3-D block diagrams of test results from the North, Centre and South Sites
- 2-D diagrams of the test results from the North (NW,NM,NE), Centre (CW,CM,CE) and South (SW,SM,SE) sites

Estimates of the maximum, average and minimum rates of salt transport by advection within the tailings mass had been provided previously by Noranda Technology Centre ("Hydrologic Evaluation of the Thickened Tailings Disposal System at Kidd Creek Division, Falconbridge Ltd." by St.-Arnaud and Woyshner, April 1992). Table 1, shown below, illustrates the basis for these estimates.

Table 1 - NTC Estimates of Horizontal Velocities

	K (cm/s)	Horizontal Gradient (i_x)	Porosity (n)	Horizontal Velocity (cm/y)
Average:	1e-05	0.01	0.45	7
Minimum:	1.8e-06	.001	.5	0.1
Maximum:	4.4e-05	.02	.4	70

The average rates of movement of the tracer, as measured in samples taken either in June 1993 or October 1996, are summarized in the table shown below. These rates of movement are based on the assumptions laid out in the attached memo. The rates are calculated in the horizontal or downslope direction (v_x), the vertical direction (v_y) and in the cross-slope direction (v_z). The cross-slope rates were calculated from the appearance of Iodine (initially placed in the center position, M) in sample locations on either side of the centre line (E or W). Sampling was also undertaken in September 1993; however, only 3 tracer samples were detected, consequently these results are not summarized here.

The initial set of sampling undertaken in 1993 indicated that the tracer had moved very rapidly in all three directions. In the letter we wrote to Dr. Eli Robinsky on March 04, 1994, we indicated that these high rates of movement should not be relied on too heavily given the difficulties in interpreting the results. In particular, the impact of tracer injection, the high initial density of the tracer solution, and the effects of diffusion would tend to produce rather high velocities. For example, the effect of initial solution density alone could be shown to account for the high vertical (v_y) rates of movement.

Table 2 - Summary of Tracer Travel Rates (cm/yr.)

Sample Date:	North Site:		Center Site:		South Site:	
	v_x	v_y	v_x	v_y	v_x	v_y
June 1993	80	88	100	145	112	91
October 1996	67	11	74	6	72	8

The initial interpretation of the preliminary data is supported by the current set of test data. This current set of test data will still suffer from some of these original concerns; however, with time, the impact of these difficulties will diminish. High initial solution concentrations will dilute, densities will decrease, and high rates of transport by diffusion will diminish as the plume continues to expand. In fact, we see that the rates of transport have decreased substantially. The greatest velocities are now those in the horizontal (or downslope) direction, v_x, and approaching the maximum velocities predicted by NTC. The vertical velocities have slowed quite substantially and seem to indicate only a small downward movement of the tracer. The cross-slope velocities have also decreased.

The key objective of the tracer test was to determine the rate of advective transport within the tailings at three different slope locations, and to define the potential for upgrade migration of dissolved salts to the tailings surface as a result of evaporation and capillary movement.

These results seem to support the current understanding of the flow system. The flow is predominately parallel to the surface slope, with the surface slope controlling the hydraulic gradients. The current rates of transport would suggest a hydraulic conductivity in the tailings area of somewhat greater than 1×10^{-05} cm/s with a porosity of around 0.4. It is important to note; however, that the full tracer plume was not sampled. In many cases, only the edge of the plume seems to have been detected. The actual position of the plume could encompass a region closer and deeper to the initial tracer injections, although in some locations, such as Centre West (CW), it is possible that the plume extends farther from the source.

It is encouraging that the plume has not migrated to the upper tailings surface. In a couple of instances (CM and SW), tracer was detected in the top sampling point (15 to 30 cm deep); however, in other instances (SM, CW, NW), tracer was not detected in the most shallow sampling points.

It would be useful to 'walk-out' the entire plume at one or two locations. The farthest and deepest extent of the plume would then be known with some confidence. This would provide verification to the interpretations made to date and would also allow some transport modelling to be initiated which would include molecular diffusion and mechanical dispersion of the tracer within the tailings. The initial recommendation for a radioactive tracer which could have been profiled by indirect measurement would of expedited this type of plume definition.

Memorandum

Date: May 4, 1998

To: Professor Barbour

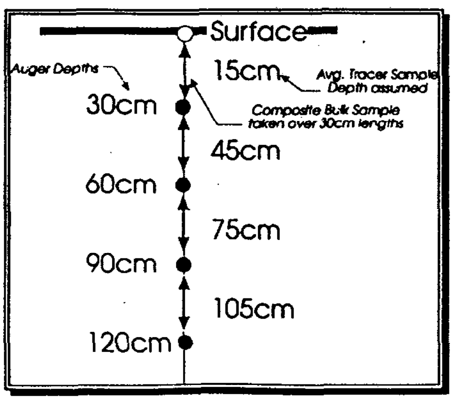
From: Brenda E. Bews, Research Engineer

RE: ***Assumptions/notes regarding Kidd Crk. Tracer Study Plots and Velocity calculations***

Attached is the spreadsheet used to calculate velocities as well as the 3-d and 2-d tracer plots.

A number of assumptions were made during the calculation of velocities and general plot tracing for the Kidd Creek Tracer study. They are as follows:

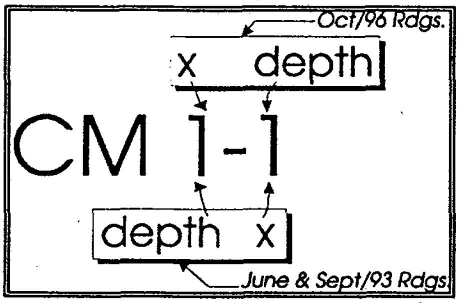
- Assumed tracers were installed on the first day of the months given: Sept.1 and Oct.1/92. All velocities are calculated with respect to these tracer installation dates.
- For the Sept./93 rdgs., the 16th day of the month was assumed because there was no date on the data itself. The date used was obtained from Dr. Robinsky's 2-d tracer diagrams. It is not known where Dr. Robinsky obtained this date from but because of a lack of information and for estimation purposes, this date was used.
- For the June/93 data, for the South (S) and Centre (C) sites, June 30 was used, while for the North (N) site, June 21 was used - both of these dates were taken from the data itself.
- For the Oct./96 rdgs., Oct.21 was assumed correct because this date was written in pen on the data received from B. Swarbrick in his letter dated Feb. 13/98.
- For the Oct/96 rdgs., depths were assumed as average values because of the way samples were taken (See Feb.13/98 letter from B. Swarbrick to Dr. Barbour):



- Simply because no samples were taken at the East sites in Oct./96 does not necessarily mean that no tracer exists at those sites. B. Swarbrick, in his Feb.13/98 letter, said that no samples were taken at any E sites because of time and weather constraints, as well as problems with the motorized auger unit.

- Furthermore, samples were not taken at any great depth in the Oct/96 set. They were only obtained from a maximum depth of 1.05m; whereas, the previous rdgs. taken in June and Sept/93 went to depths of 2m. Therefore, again, just because measurements were not taken at greater depths does not necessarily mean that there would not have been any tracer detected there (or that the plume may not have migrated even further to the West (W) or East (E)). It is understood, however, that because of time/weather/money constraints, measurements can not be taken everywhere and it can be considered a partial success in that some tracer was detected at most sites and times and that there is an approximate idea of where the plume is with time. It has been assumed by looking at where the readings were taken that the locations were selected based on Dr. Barbour's suggestion that the plume dropped at first because of density effects and then went forward as the tracer was diluted.

- The reading sequence of the Oct/96 samples (Feb.13/98 fax from B. Swarbrick) is opposite to the June and Sept/93 samples (June 29/92 Robinsky report). This difference should be checked to ensure that one is not mistaken. For the purpose of this analysis, however, it was assumed that both configurations were correct for the dates specified:



- Some tracers strayed from the injection sites, ex) Bromine (Br) appeared in an Iodine (I) site and vice versa.

- Velocity in the z direction, Vz was calculated for Iodine only when it migrated to the E or W because with Iodine, it is possible to know the origin of the tracer since there is only one Middle site, M, where it was injected. When migrated Bromine is detected at an M site, however, it cannot be determined whether the tracer originated in the E or W. No Vz calculations therefore, were completed for Bromine.

- Vx and Vy were calculated for both Br and I appearing at any one site. Velocities were not just calculated for the tracer injected at that particular site.

- 'Average' velocities consider both Br and I, i.e., 'average' means general movement of ALL tracers at the N, C and S sites, not just the tracer injected at any particular site.

- Note that if there were samples taken but no tracer detected at a site, that site was not accounted for in the calculation of Vavg., ex) Sept/93: Cavg considered CE only. The total was not divided by 3 which would have considered the idea that a measurement was taken but no tracer was detected at CM and CW.

- In reviewing the velocity calculations made in Dr. Barbour's March 4/94 fax/courier to Dr. Robinsky, it can be seen that the velocities were calculated for the maximum extent in the x and y direction of ANY tracer detected at the site, not just the tracer injected. In addition, information on dates and type of tracer were taken from Dr. Robinsky's 2-d tracer plots, not from the original data forms, i.e., all Dr. Robinsky's assumptions were inadvertently used.

- The 3-d plots show the movement of tracers in the z, x and y direction for the North, Centre and South sites.

- The 2-d plots show where samples were and were not taken as well as the tracers detected. This allows for some limited interpretation as to where there may or may not have been tracers detected if measurements had been taken.

BEB for Barbour - April 28/98
Kidd Crk. Tracer Study (Falconbridge)

Note:

1. All calc'd v's are with respect to the start times (when tracer was installed - Sept. or Oct./92)
2. Note that the Points for June and Sept/93 measurements are shown as (Depth, X) BUT Points taken for Oct./96 measurements are shown as (X, Depth)
3. Red values mean that the velocities are calc'd using a tracer not from that site (I.e., if considering site M (Iodine), a Bromine rdg. means it has has strayed from E or W)
4. For Vz, where the tracer has crossed over locations, +ve=East, -ve=West (Done for Iodine only).
5. For Oct.21/96 rdgs., the point ref. is from 2.5m (x distance) from where the last set of tracer tubes were.

Installed:

W: depth=0.15, Bromine
M: depth=0.3m, Iodine
E: depth=0.45m, Bromine
North Site - assume installed Sept.1/92
Central Site - assume installed Sept.1/92
South Site - assume installed Oct.1/92

For June and Sept/93 Rdgs.:

#	Depth(m)	X Dist.(m)
1	0.1	0.5
2	0.25	1
3	0.5	1.5
4	1	2
5	1.5	2.5
6	2	

For Oct./96 Rdgs.:

#	Depth(m)	X Dist.(m)
1	0.15	2.8
2	0.45	3.1
3	0.75	3.4
4	1.05	

('X Dist.' means dist. from original Tracer Addition Tubes)

These 2 Columns Considers Both Br&I

June21 or 30/93:

SITE	Point Ref. Given	Tracer Detected	X Dist. (m)	Depth (m) Measured	Depth (m) Installed	Y Dist. (m)	Z Dist. (m)	Date Installed	Date Measured	Time (days)	Vx (cm/yr)	Vy (cm/yr)	Vz(Iodine) (cm/yr)	Vx(avg.) (cm/yr)	Vy(avg.) (cm/yr)
NE (Bromine)	3,1	Br	0.5	0.5	0.45	0.05		1-Sep-92	21-Jun-93	293	62.29	6.23		80.08	88.09
	5,1	Br	0.5	1.5	0.45	1.05		1-Sep-92	21-Jun-93	293	62.29	130.80			
NM (Iodine)	5,1	I	0.5	1.5	0.3	1.2		1-Sep-92	21-Jun-93	293	62.29	149.49			
NW (Bromine)	2,2	Br	1	0.25	0.15	0.1		1-Sep-92	21-Jun-93	293	124.57	12.46			
	3,1	Br	0.5	0.5	0.15	0.35		1-Sep-92	21-Jun-93	293	62.29	43.60			
	4,2	Br	1	1	0.15	0.85		1-Sep-92	21-Jun-93	293	124.57	105.89			
	5,1	Br	0.5	1.5	0.15	1.35		1-Sep-92	21-Jun-93	293	62.29	168.17			
CE (Bromine)	6,2	I	1	2	0.45	1.55	1.75	1-Sep-92	30-Jun-93	302	120.86	187.33	211.51	100.72	145.03
CM (Iodine)	5,1	I	0.5	1.5	0.3	1.2		1-Sep-92	30-Jun-93	302	60.43	145.03			
CW(Bromine)	4,2	Br	1	1	0.15	0.85		1-Sep-92	30-Jun-93	302	120.86	102.73			
SE (Bromine)	3,1	Br, I	0.5	0.5	0.45	0.05	1.75	1-Oct-92	30-Jun-93	272	67.10	6.71	234.83	111.83	90.58
	4,2	I	1	1	0.45	0.55	1.75	1-Oct-92	30-Jun-93	272	134.19	73.81	234.83		
SM (Iodine)	3,1	I	0.5	0.5	0.3	0.2		1-Oct-92	30-Jun-93	272	67.10	26.84			
	4,2	I	1	1	0.3	0.7		1-Oct-92	30-Jun-93	272	134.19	93.93			
	6,2	I	1	2	0.3	1.7		1-Oct-92	30-Jun-93	272	134.19	228.13			
SW (Bromine)	4,2	Br	1	1	0.15	0.85		1-Oct-92	30-Jun-93	272	134.19	114.06			

Sept.16/93

SITE	Point Ref. Given	Tracer Detected	X Dist. (m)	Depth (m) Measured	Depth (m) Installed	Y Dist. (m)	Z Dist. (m)	Date Installed	Date Measured	Time (days)	Vx (cm/yr)	Vy (cm/yr)	Vz(Iodine) (cm/yr)	Vx(avg.) (cm/yr)	Vy(avg.) (cm/yr)
NE (Bromine)	*NONE DETECTED in any samples taken at this site*													96.05	67.24
NM (Iodine)	4,2	Br	1	1	0.3	0.7		1-Sep-92	16-Sep-93	380	96.05	67.24			
NW (Bromine)	*NONE DETECTED in any samples taken at this site*														
CE (Bromine)	2,2	Br	1	0.25	0.45	-0.2		1-Sep-92	16-Sep-93	380	96.05	-19.21		96.05	-19.21
CM (Iodine)	*NONE DETECTED in any samples taken at this site*														
CW(Bromine)	*NONE DETECTED in any samples taken at this site*														
SE (Bromine)	*NONE DETECTED in any samples taken at this site*													156.43	-5.21
SM (Iodine)	*NONE DETECTED in any samples taken at this site*														
SW (Bromine)	1,3	I	1.5	0.1	0.15	-0.05	-1.75	1-Oct-92	16-Sep-93	350	156.43	-5.21	-182.50		

Oct.21/96

SITE	Point Ref. Given	Tracer Detected	X Dist. (m)	Depth (m) Measured	Depth (m) Installed	Y Dist. (m)	Z Dist. (m)	Date Installed	Date Measured	Time (days)	Vx (cm/yr)	Vy (cm/yr)	Vz(Iodine) (cm/yr)	Vx(avg.) (cm/yr)	Vy(avg.) (cm/yr)
NE (Bromine)	NO MEASUREMENTS TAKEN IN ANY OF THE EAST SITES													67.64	10.87
NM (Iodine)	*NONE DETECTED in any samples taken at this site*														
NW (Bromine)	1,2	I	2.8	0.45	0.15	0.3	-1.75	1-Sep-92	21-Oct-96	1511	67.64	7.25	-42.27		
	1,3	I	2.8	0.75	0.15	0.6	-1.75	1-Sep-92	21-Oct-96	1511	67.64	14.49	-42.27		
CE (Bromine)	NO MEASUREMENTS TAKEN IN ANY OF THE EAST SITES													73.85	6.21
CM (Iodine)	1,2	I	2.8	0.45	0.3	0.15		1-Sep-92	21-Oct-96	1511	67.64	3.62			
	1,3	Br	2.8	0.75	0.3	0.45		1-Sep-92	21-Oct-96	1511	67.64	10.87			
	2,1	Br	3.1	0.15	0.3	-0.15		1-Sep-92	21-Oct-96	1511	74.88	-3.62			
	2,2	Br	3.1	0.45	0.3	0.15		1-Sep-92	21-Oct-96	1511	74.88	3.62			
	2,3	Br	3.1	0.75	0.3	0.45		1-Sep-92	21-Oct-96	1511	74.88	10.87			
	3,3	I	3.4	0.75	0.3	0.45		1-Sep-92	21-Oct-96	1511	82.13	10.87			
CW(Bromine)	2,2	Br	3.1	0.45	0.15	0.3		1-Sep-92	21-Oct-96	1511	74.88	7.25			
SE (Bromine)	NO MEASUREMENTS TAKEN IN ANY OF THE EAST SITES													71.96	8.13
SM (Iodine)	1,3	I	2.8	0.75	0.3	0.45		1-Oct-92	21-Oct-96	1481	69.01	11.09			
SW (Bromine)	1,1	Br, I	2.8	0.15	0.15	0	-1.75	1-Oct-92	21-Oct-96	1481	69.01	0.00	-43.13		
	1,2	Br	2.8	0.45	0.15	0.3		1-Oct-92	21-Oct-96	1481	69.01	7.39			
	1,3	Br, I	2.8	0.75	0.15	0.6	-1.75	1-Oct-92	21-Oct-96	1481	69.01	14.79	-43.13		
	3,2	I	3.4	0.45	0.15	0.3	-1.75	1-Oct-92	21-Oct-96	1481	83.79	7.39	-43.13		

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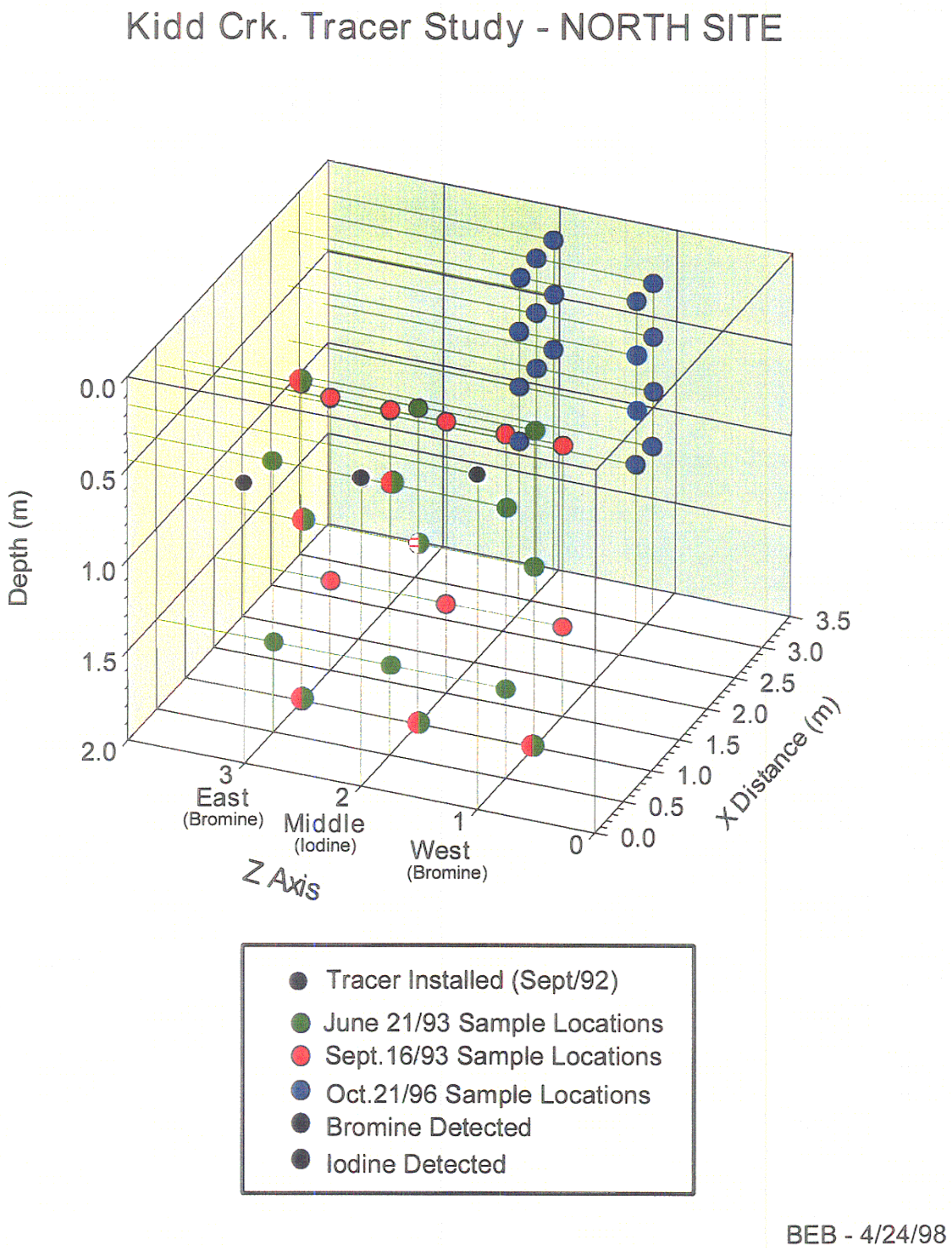
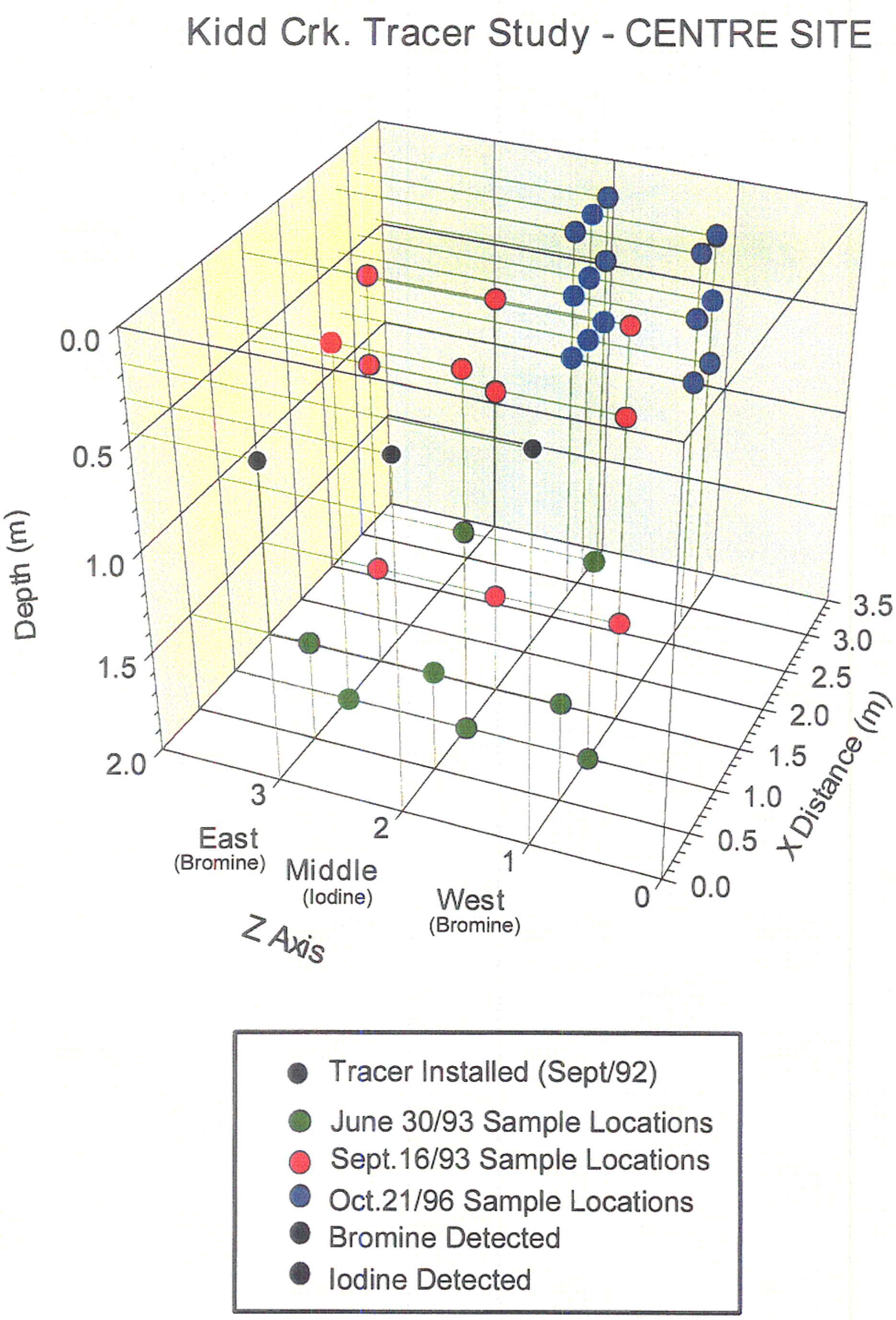


Welcome Screen | Search | Report List



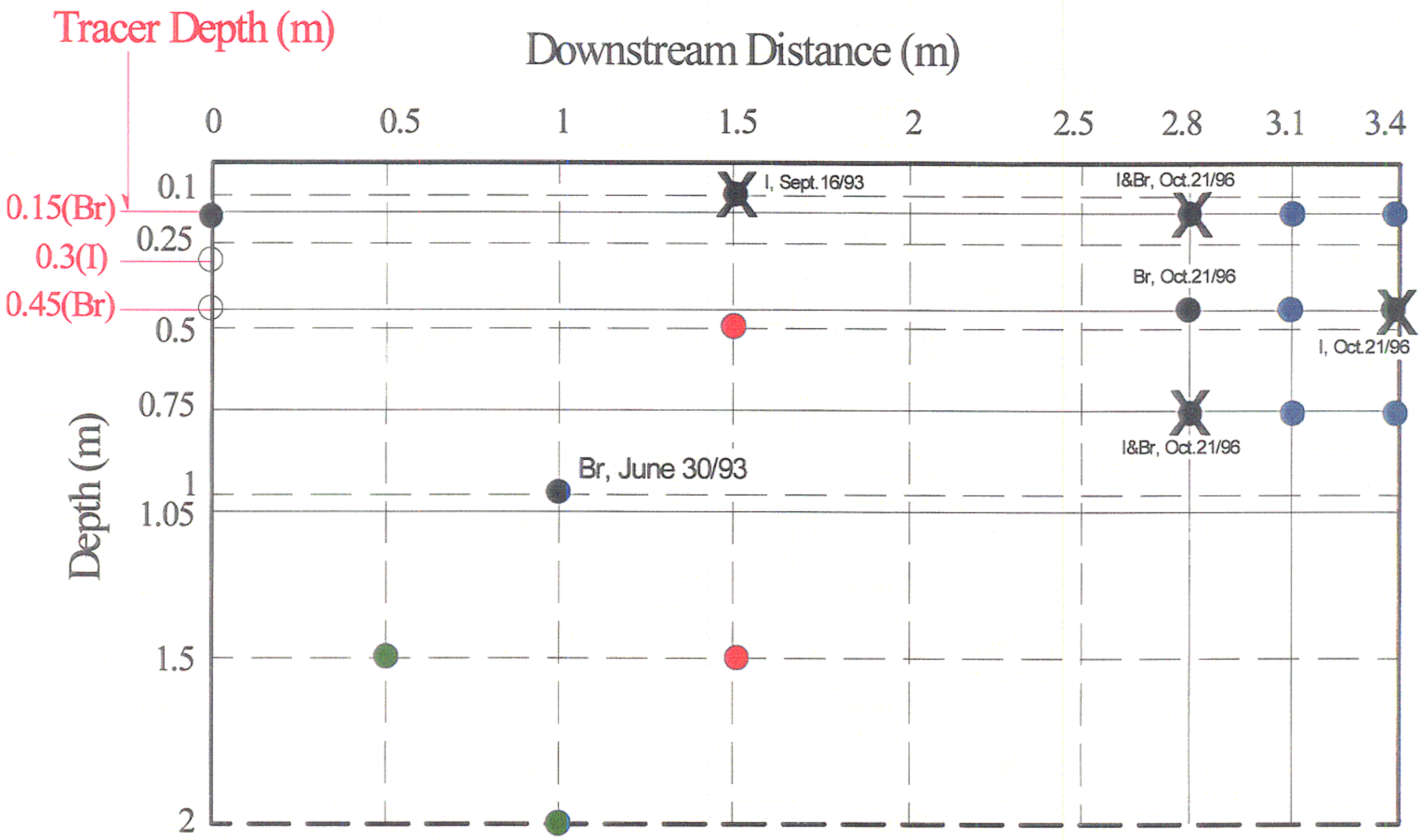
BEB - 4/24/98

Note:

1. W: depth = 0.15m, Potassium Bromide
   M: depth = 0.3m, Potassium Iodide
   E: depth = 0.45m, Potassium Bromide
2. Tracer Installed:
   North Site = Sept./92
   Central Site = Sept./92
   South Site = Oct./92

Site Location	SW
Tracer Depth	0.15m (Bromine)
Tracer Installed	Oct. 1/92
1st Rdg.	June 30/93
2nd Rdg.	Sept. 16/93
3rd. Rdg.	Oct. 21/96

Tailings Tracer Study at Kidd Creek



KEY:

- - - - - = earlier rdgs. (Sept./93, June/93)

______ = Oct./96 rdgs. (avg. depths)

● = Tracer Detected

X = Tracer from another site detected

● (green) = Measurements taken but no tracer detected (June/93)

● (red) = Measurements taken but no tracer detected (Sept/93)

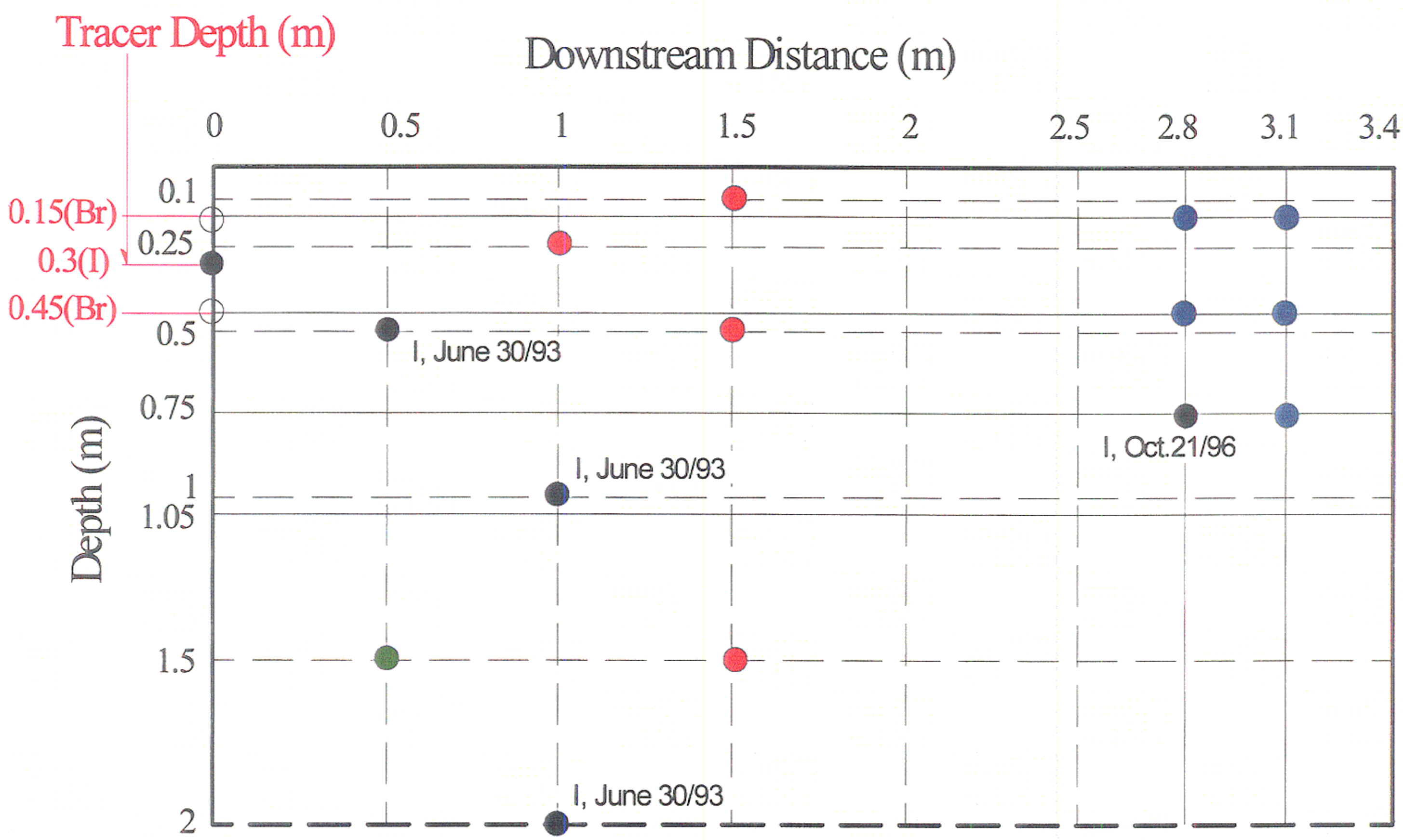
● (blue) = Measurements taken but no tracer detected (Oct/96)

Note:

1. W: depth = 0.15m, Potassium Bromide
   M: depth = 0.3m, Potassium Iodide
   E: depth = 0.45m, Potassium Bromide
2. Tracer Installed:
   North Site = Sept./92
   Central Site = Sept./92
   South Site = Oct./92

Site Location	SM
Tracer Depth	0.30 (Iodine)
Tracer Installed	Oct. 1/92
1st Rdg.	June 30/93
2nd Rdg.	Sept. 16/93
3rd. Rdg.	Oct. 21/96

Tailings Tracer Study at Kidd Creek



KEY:

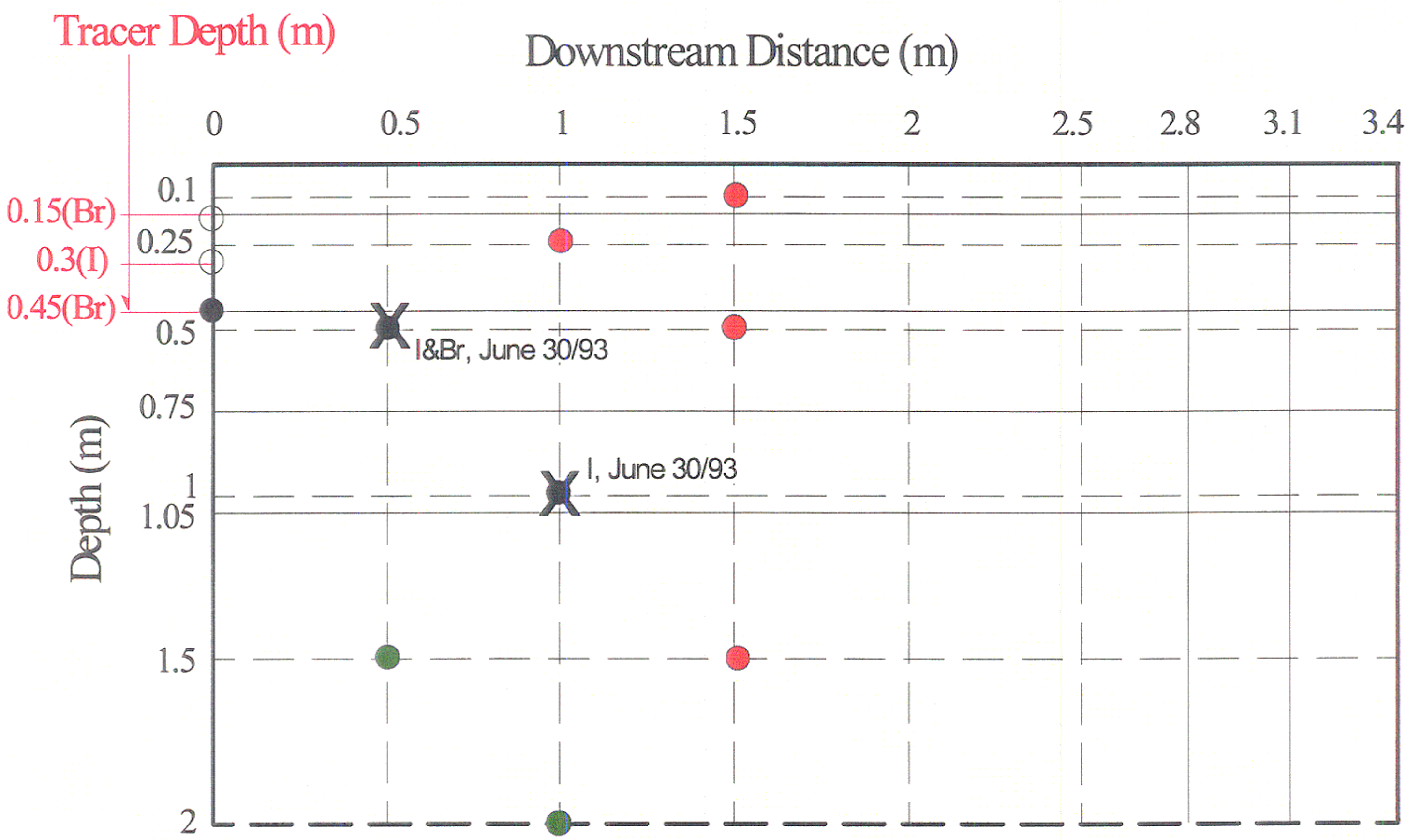
- - - - - = earlier rdgs. (Sept./93, June/93)
_____ = Oct./96 rdgs. (avg. depths)
● = Tracer Detected
X = Tracer from another site detected
● = Measurements taken but no tracer detected (June/93)
● = Measurements taken but no tracer detected (Sept/93)
● = Measurements taken but no tracer detected (Oct/96)

Note:

1. W: depth = 0.15m, Potassium Bromide
   M: depth = 0.3m, Potassium Iodide
   E: depth = 0.45m, Potassium Bromide
2. Tracer Installed:
   North Site = Sept./92
   Central Site = Sept./92
   South Site = Oct./92

Site Location	SE
Tracer Depth	0.45m (Bromine)
Tracer Installed	Oct. 1/92
1st Rdg.	June 30/93
2nd Rdg.	Sept. 16/93
3rd. Rdg.	None

Tailings Tracer Study at Kidd Creek



KEY:

- - - - - = earlier rdgs. (Sept./93, June/93)

______ = Oct./96 rdgs. (avg. depths)

● = Tracer Detected

X = Tracer from another site detected

● = Measurements taken but no tracer detected (June/93)

● = Measurements taken but no tracer detected (Sept/93)

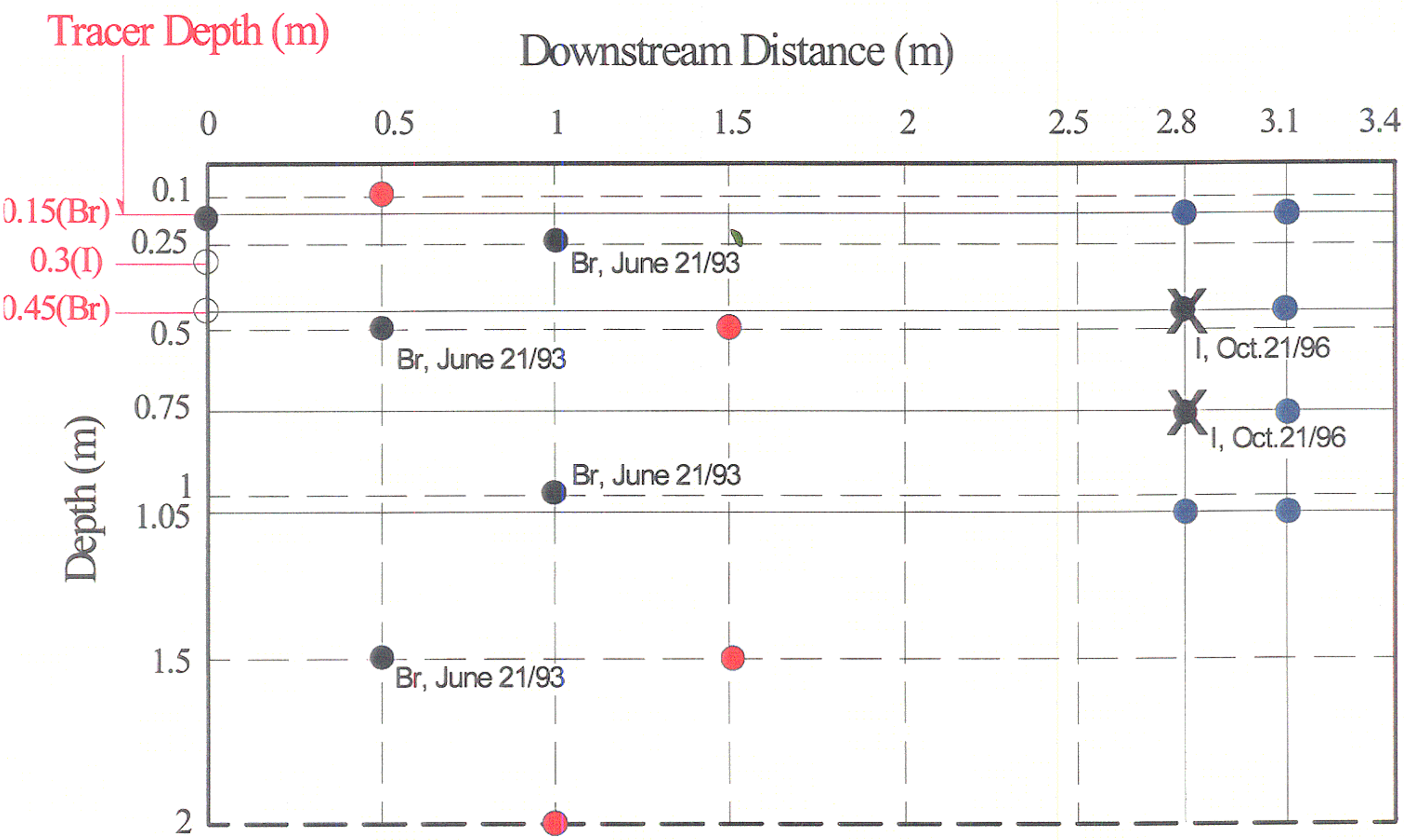
● = Measurements taken but no tracer detected (Oct/96)

Note:

1. W: depth = 0.15m, Potassium Bromide
   M: depth = 0.3m, Potassium Iodide
   E: depth = 0.45m, Potassium Bromide
2. Tracer Installed:
   North Site = Sept./92
   Central Site = Sept./92
   South Site = Oct./92

Site Location: NW
Tracer Depth: 0.15m (Bromine)
Tracer Installed: Sept. 1/92
1st Rdg.: June 21/93
2nd Rdg.: Sept. 16/93
3rd. Rdg.: Oct. 21/96

Tailings Tracer Study at Kidd Creek



KEY:

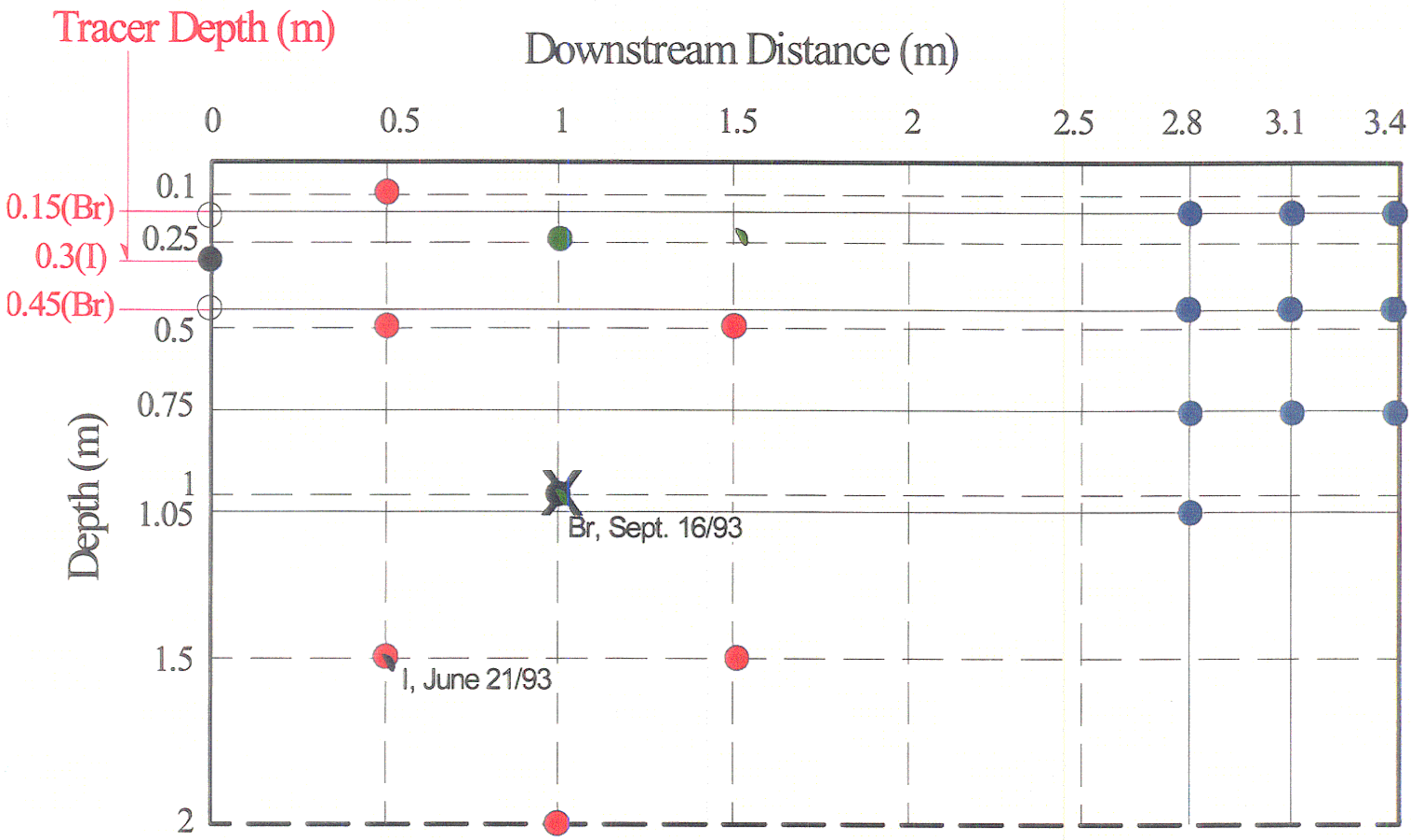
- - - - - = earlier rdgs. (Sept./93, June/93)
_____ = Oct./96 rdgs. (avg. depths)
● = Tracer Detected
X = Tracer from another site detected
● = Measurements taken but no tracer detected (June/93)
● = Measurements taken but no tracer detected (Sept/93)
● = Measurements taken but no tracer detected (Oct/96)

Note:

1. W: depth = 0.15m, Potassium Bromide
   M: depth = 0.3m, Potassium Iodide
   E: depth = 0.45m, Potassium Bromide
2. Tracer Installed:
   North Site = Sept./92
   Central Site = Sept./92
   South Site = Oct./92

Site Location	NM
Tracer Depth	0.3m (Iodine)
Tracer Installed	Sept. 1/92
1st Rdg.	June 21/93
2nd Rdg.	Sept. 16/93
3rd. Rdg.	Oct. 21/96

Tailings Tracer Study at Kidd Creek



KEY:

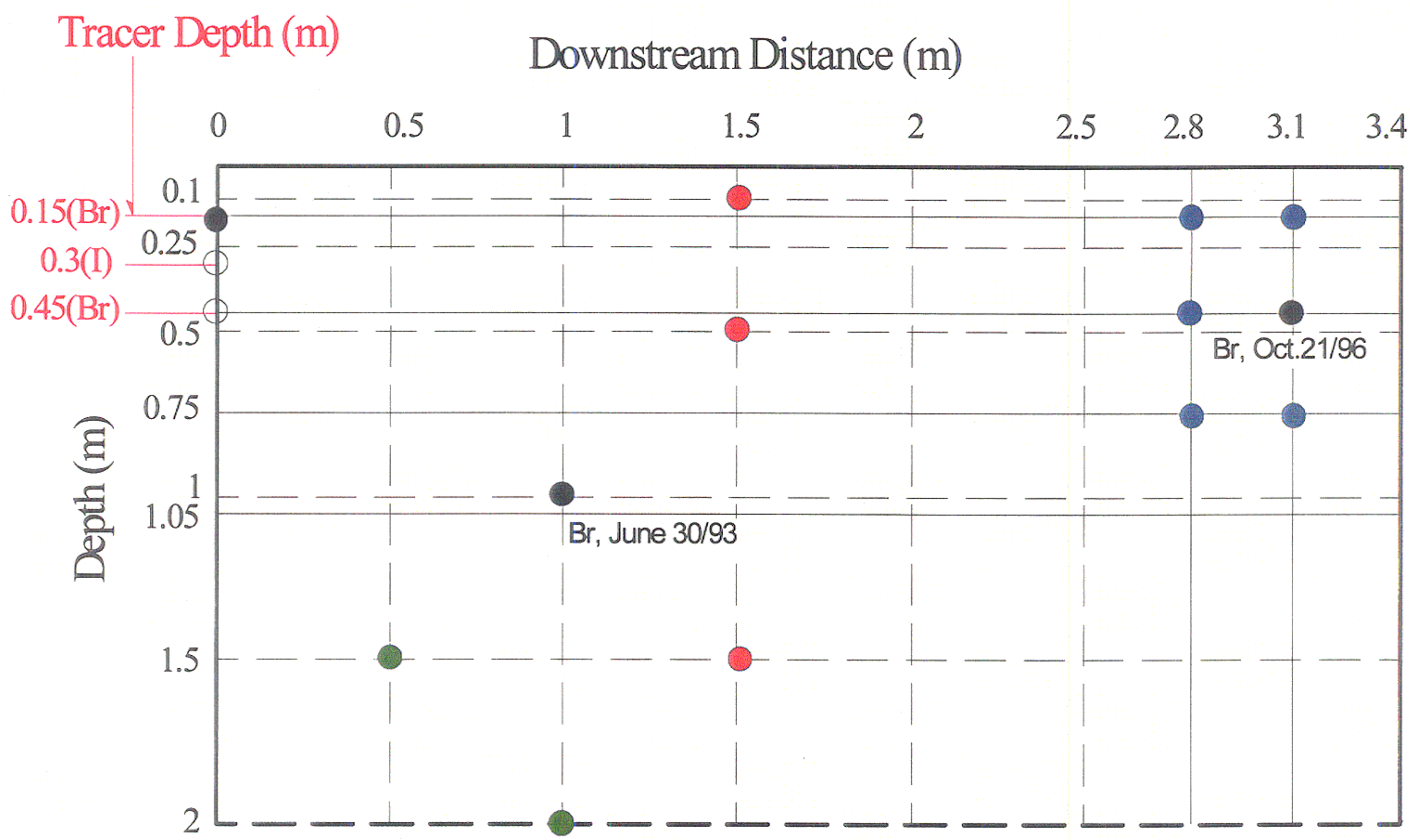
- - - - - = earlier rdgs. (Sept./93, June/93)
______ = Oct./96 rdgs. (avg. depths)
● = Tracer Detected
X = Tracer from another site detected
● = Measurements taken but no tracer detected (June/93)
● = Measurements taken but no tracer detected (Sept/93)
● = Measurements taken but no tracer detected (Oct/96)

Note:

1. W: depth = 0.15m, Potassium Bromide
   M: depth = 0.3m, Potassium Iodide
   E: depth = 0.45m, Potassium Bromide
2. Tracer Installed:
   North Site = Sept./92
   Central Site = Sept./92
   South Site = Oct./92

Site Location: CW
Tracer Depth: 0.15m (Bromine)
Tracer Installed: Sept1/92
1st Rdg.: June 30/93
2nd Rdg.: Sept. 16/93
3rd. Rdg.: Oct. 21/96

Tailings Tracer Study at Kidd Creek



KEY:

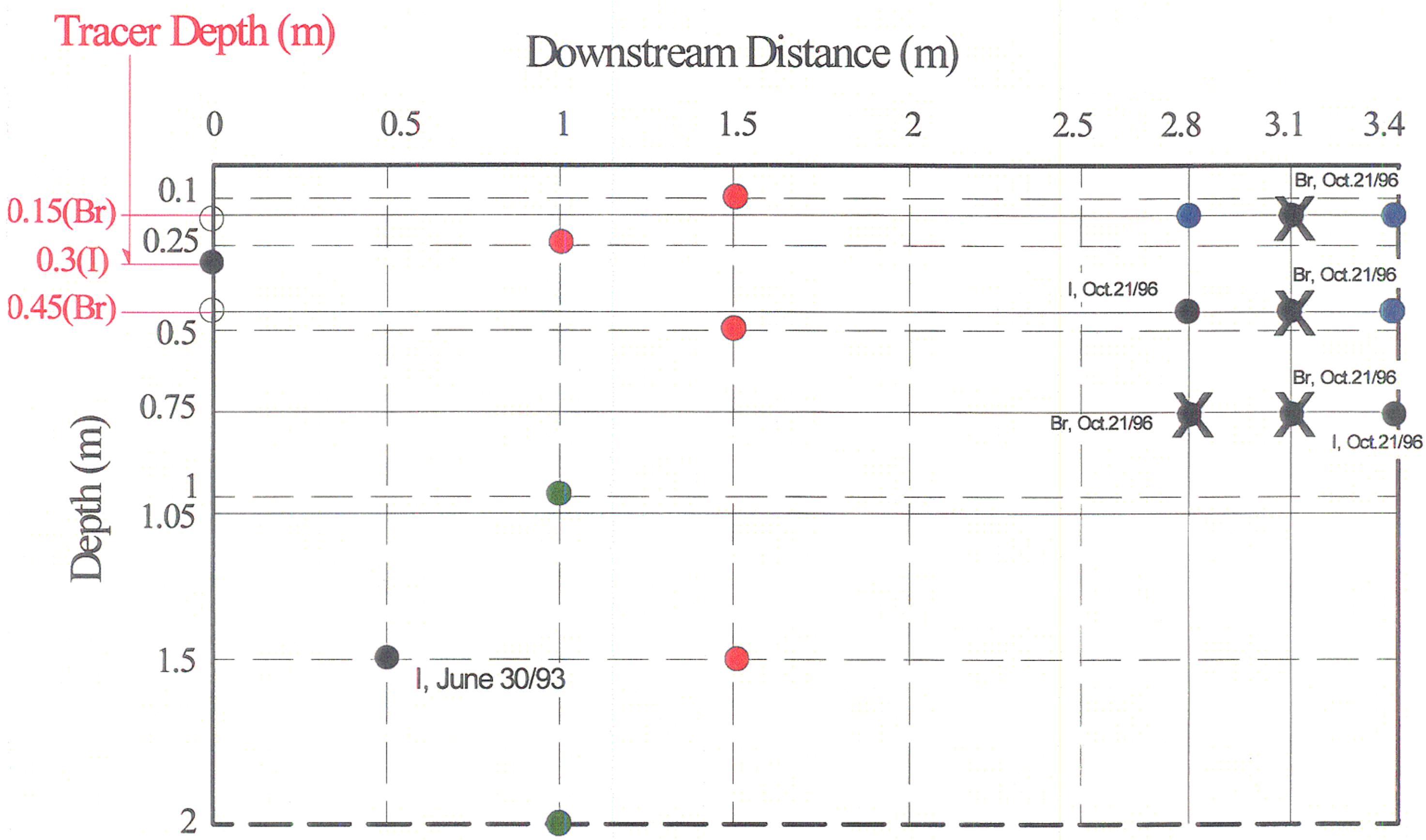
- - - - - = earlier rdgs. (Sept./93, June/93)
_____ = Oct./96 rdgs. (avg. depths)
● = Tracer Detected
X = Tracer from another site detected
● = Measurements taken but no tracer detected (June/93)
● = Measurements taken but no tracer detected (Sept/93)
● = Measurements taken but no tracer detected (Oct/96)

Note:

1. W: depth = 0.15m, Potassium Bromide
   M: depth = 0.3m, Potassium Iodide
   E: depth = 0.45m, Potassium Bromide
2. Tracer Installed:
   North Site = Sept./92
   Central Site = Sept./92
   South Site = Oct./92

Site Location	CM
Tracer Depth	0.30m (Iodine)
Tracer Installed	Sept. 1/92
1st Rdg.	June 30/93
2nd Rdg.	Sept.16/93
3rd. Rdg.	Oct. 21/96

Tailings Tracer Study at Kidd Creek



KEY:

- - - - - = earlier rdgs. (Sept./93, June/93)
_____ = Oct./96 rdgs. (avg. depths)
● = Tracer Detected
X = Tracer from another site detected
● = Measurements taken but no tracer detected (June/93)
● = Measurements taken but no tracer detected (Sept/93)
● = Measurements taken but no tracer detected (Oct/96)

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Note:

1. W: depth = 0.15m, Potassium Bromide
   M: depth = 0.3m, Potassium Iodide
   E: depth = 0.45m, Potassium Bromide
2. Tracer Installed:
   North Site = Sept./92
   Central Site = Sept./92
   South Site = Oct./92

Site Location CE

Tracer Depth 0.45m (Bromine)

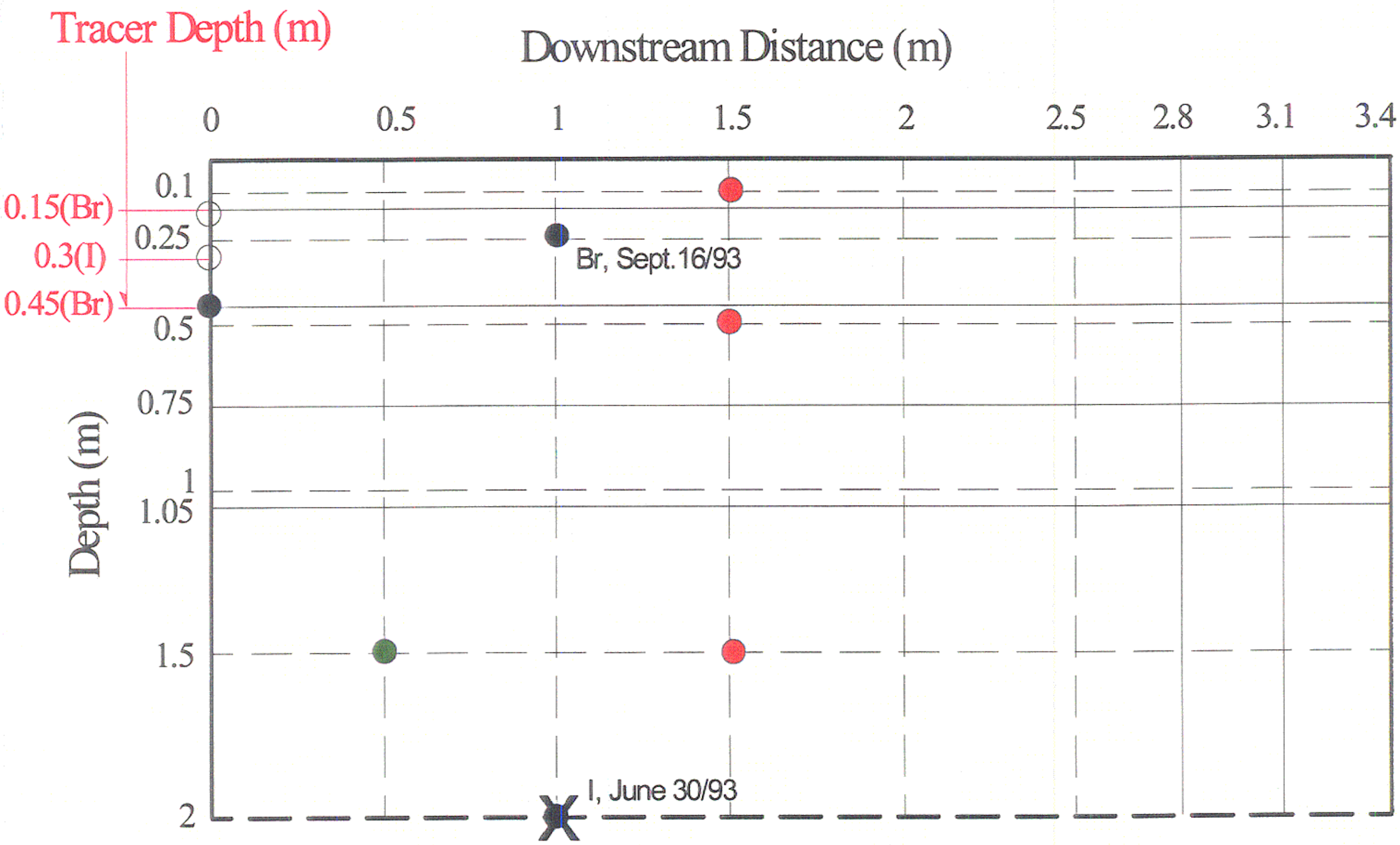
Tracer Installed Sept. 1/92

1st Rdg. June 30/93

2nd Rdg. Sept. 16/93

3rd. Rdg. None

Tailings Tracer Study at Kidd Creek



KEY:

- - - - - = earlier rdgs. (Sept./93, June/93)

_____ = Oct./96 rdgs. (avg. depths)

● = Tracer Detected

X = Tracer from another site detected

● = Measurements taken but no tracer detected (June/93)

● = Measurements taken but no tracer detected (Sept/93)

● = Measurements taken but no tracer detected (Oct/96)

June / Sept 1993 Tracer Results

North Site

	Bromine	Iodine
W 3-1	Y	N
W 5-1	Y	N
W 2-2	Y	N
W 4-2	Y	N
W 6-2	N	N
W 5-3	N	N
W 3-3	N	N
W 1-3	N	N
E 3-1	Y	N
E 5-1	Y	N
E 2-2	N	N
E 4-2	N	N
E 6-2	N	N
E 5-3	N	N
E 3-3	N	N
E 1-3	N	N
M 3-1	N	N
M 5-1	N	Y
M 2-2	N	N
M 4-2	Y	Y
M 6-2	N	N
M 5-3	N	N
M 3-3	N	N
M 1-3	N	N

Central Site

	Bromine	Iodine
E 5-1	N	N
E 6-2	N	Y
E 2-2	Y	N
E 5-3	N	N
E 3-3	N	N
E 1-3	N	N
E 2-1	N	N
E 3-1	N	N
E 1-1	N	N
M 5-1	N	Y
M 4-2	N	N
M 6-2	N	N
M 5-3	N	N
M 3-3	N	N
M1-3	N	N
M 2-1	N	N
M 3-1	N	N
W 5-1	N	N
W 4-2	Y	N
W 6-2	N	N
W 5-3	N	N
W 3-3	N	N
W 1-3	N	N

South Site

	Bromine	Iodine
W 3-1	N	N
W 5-1	N	N
W 2-2	N	N
W 4-2	Y	N
W 6-2	N	N
W 5-3	N	N
W 3-3	N	N
W 1-3	Y	Y
E 3-1	Y	Y
E 5-1	N	N
E 2-2	N	N
E 4-2	N	Y
E 6-2	N	N
E 5-3	N	N
E 3-3	N	N
E 1-3	N	N
M 3-1	N	Y
M 5-1	N	N
M 2-2	N	N
M 4-2	N	Y
M 6-2	N	Y
M 5-3	N	N
M 3-3	N	N
M 1-3	N	N

* some sample tubes were dry and sample was not obtained (mainly sample tubes < 1m in depth)

Aug 95 / Oct 96 Tracer Results

North Site

	Bromine	Iodine
M 1-1	N	N
M 1-2	N	N
M 1-3	N	N
M 1-4	N	N
M 2-1	N	N
M 2-2	N	N
M 2-3	N	N
M 3-1	N	N
M 3-2	N	N
M 3-3	N	N
W 1-1	N	N
W 1-2	N	Y
W 1-3	N	Y
W 2-1	N	N
W 2-2	N	N
W 2-3	N	N

Central Site

	Bromine	Iodine
M 1-1	N	N
M 1-2	N	Y
M 1-3	Y	N
M 2-1	Y	N
M 2-2	Y	N
M 2-3	Y	N
M 3-1	N	N
M 3-2	N	N
M 3-3	N	Y
W 1-1	N	N
W 1-2	N	N
W 1-3	N	N
W 2-1	N	N
W 2-2	Y	N
W 2-3	N	N

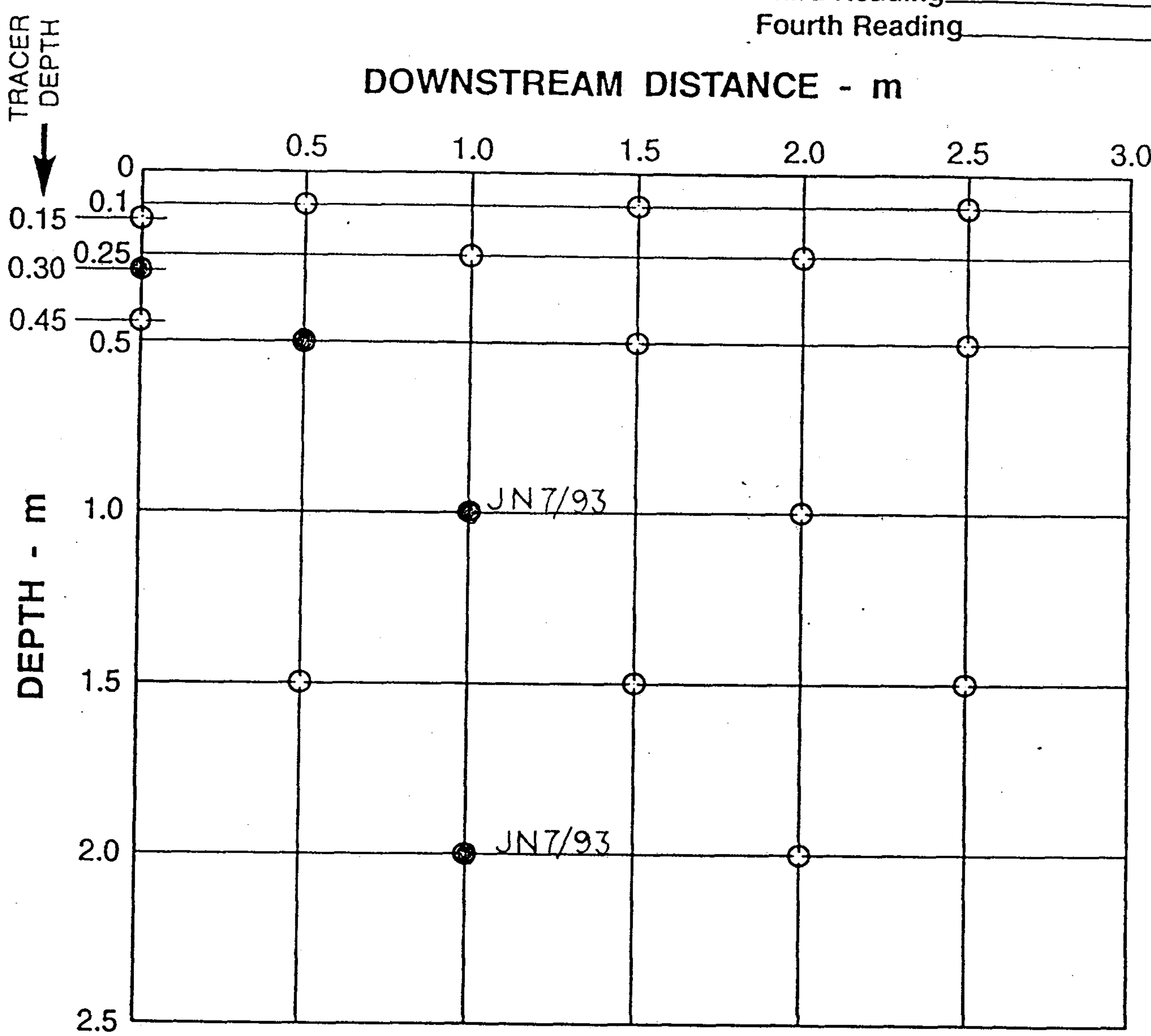
South Site

	Bromine	Iodine
M 1-1	N	N
M 1-2	N	N
M 1-3	N	Y
M 2-1	N	N
M 2-2	N	N
M 2-3	N	N
M 3-1	N	N
M 3-2	N	N
M 3-3	N	N
W 1-1	Y	Y
W 1-2	Y	N
W 1-3	Y	N
W 2-1	N	N
W 2-2	N	N
W 2-3	N	N
W 3-1	N	N
W 3-2	N	Y
W 3-3	N	N

*** Note: Labeling scheme differs from original as they are core samples**

TAILINGS TRACER STUDY

Site Location [illegible]
Tracer Depth 0.30M
First Reading JUN 7/93
Second Reading SEP. 16/93
Third Reading
Fourth Reading



	TRACER INSTALLED	DISTANCE FROM DISCHARGE
North Site	SEPT 92	
Central Site	SEPT 92	
South Site	OCT 92	

REMARKS:

TAILINGS TRACER STUDY

Site Location

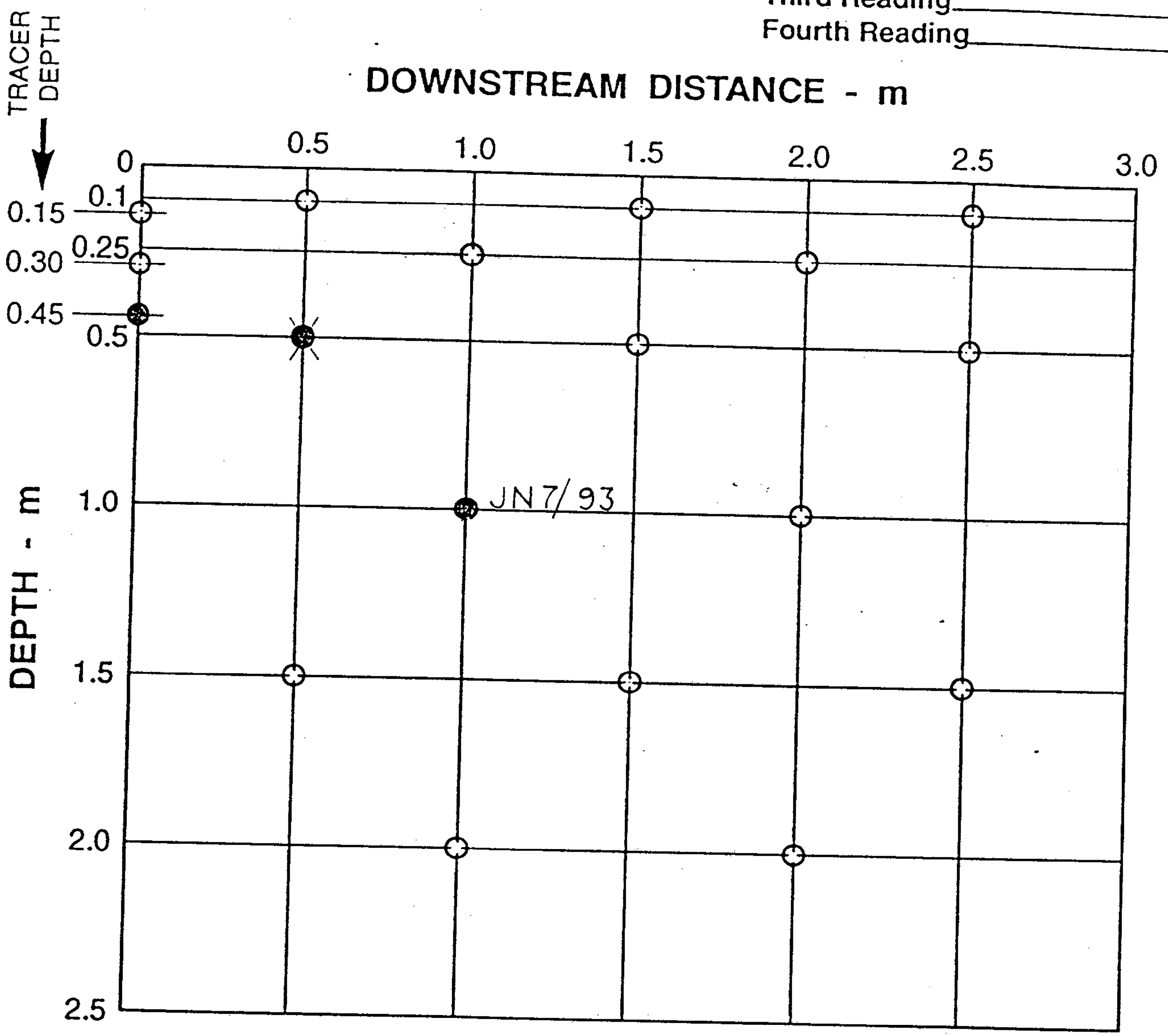
Tracer Depth 0.45M

First Reading JUN 7/93

Second Reading SEP. 16/93

Third Reading

Fourth Reading



X IODIDE + BROMIDE

	TRACER INSTALLED	DISTANCE FROM DISCHARGE
North Site	SEPT 92	
Central Site	SEPT 92	
South Site	OCT 92	

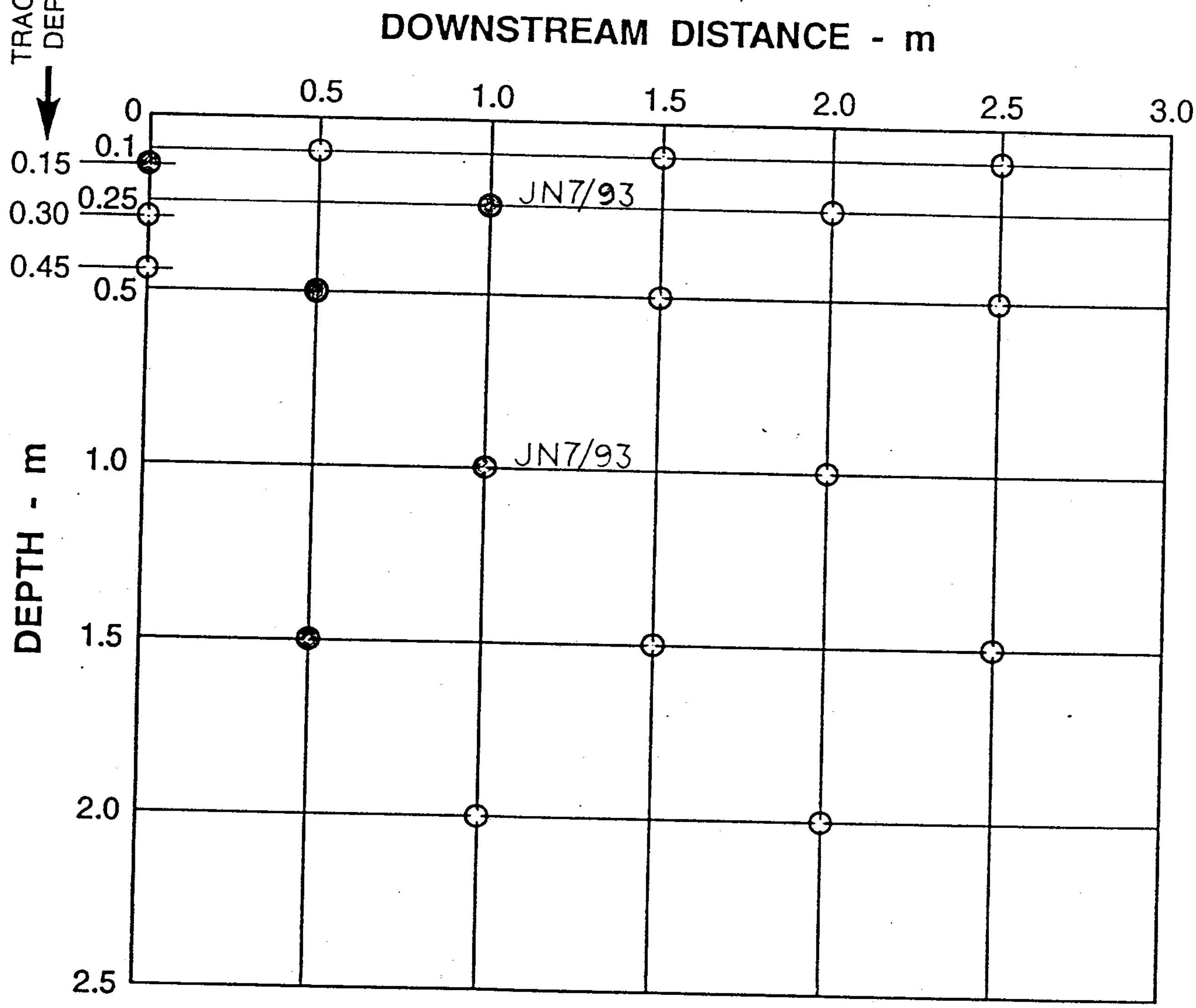
REMARKS:

FALCONBRIDGE LTD., KIDD CREEK DIVISION

E.I. ROBINSKY ASSOC. LTD., TORONTO, ONTARIO

TAILINGS TRACER STUDY

Site Location INVV
Tracer Depth 0.15 M
First Reading JUN 7/93
Second Reading SEP. 16/93
Third Reading
Fourth Reading

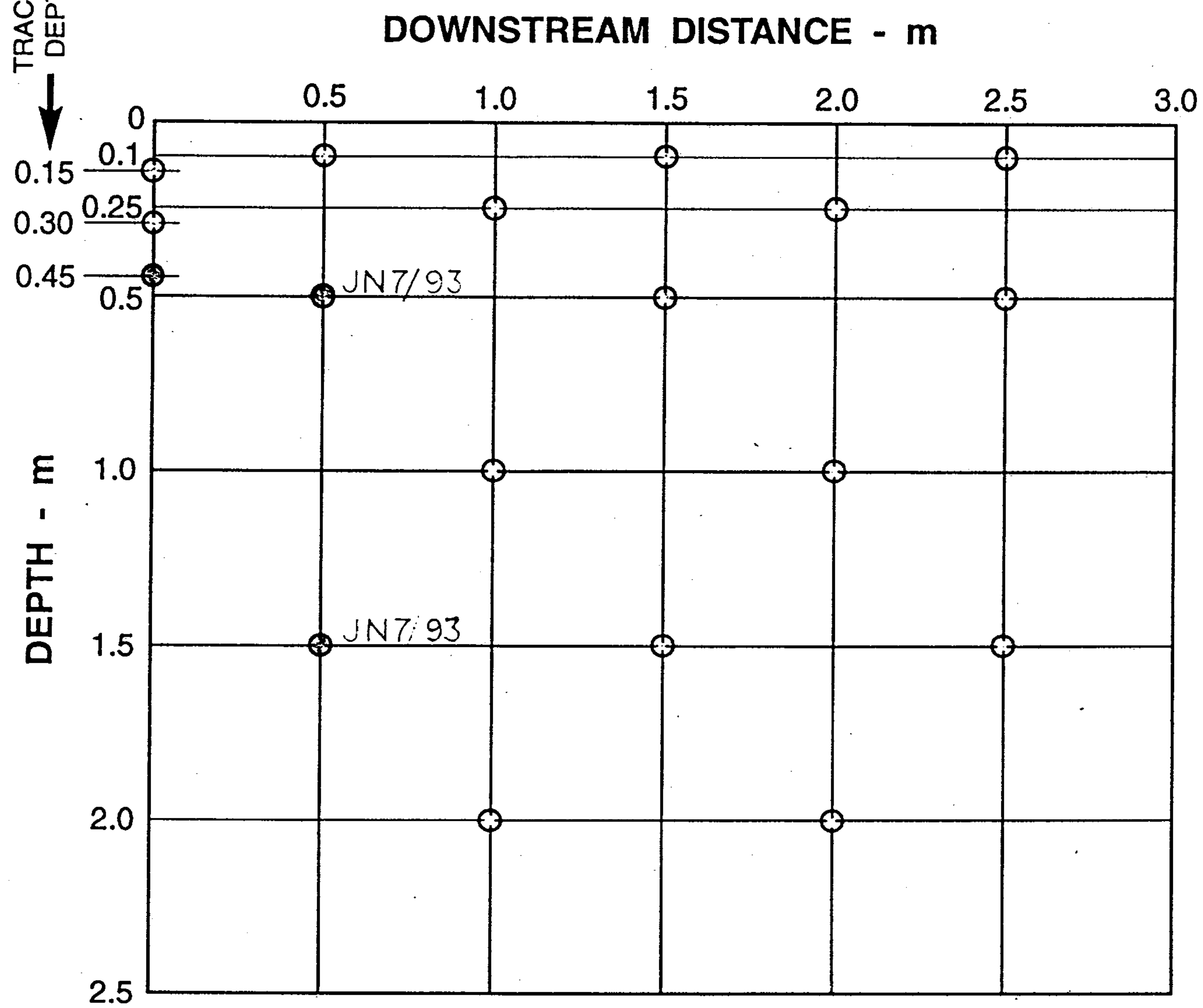


	TRACER INSTALLED	DISTANCE FROM DISCHARGE
North Site	SEPT 92	
Central Site	SEPT 92	
South Site	OCT 92	

REMARKS:

TAILINGS TRACER STUDY

Tracer Depth 0.45 M
First Reading JUN 7/93
Second Reading SEP. 16/93
Third Reading
Fourth Reading

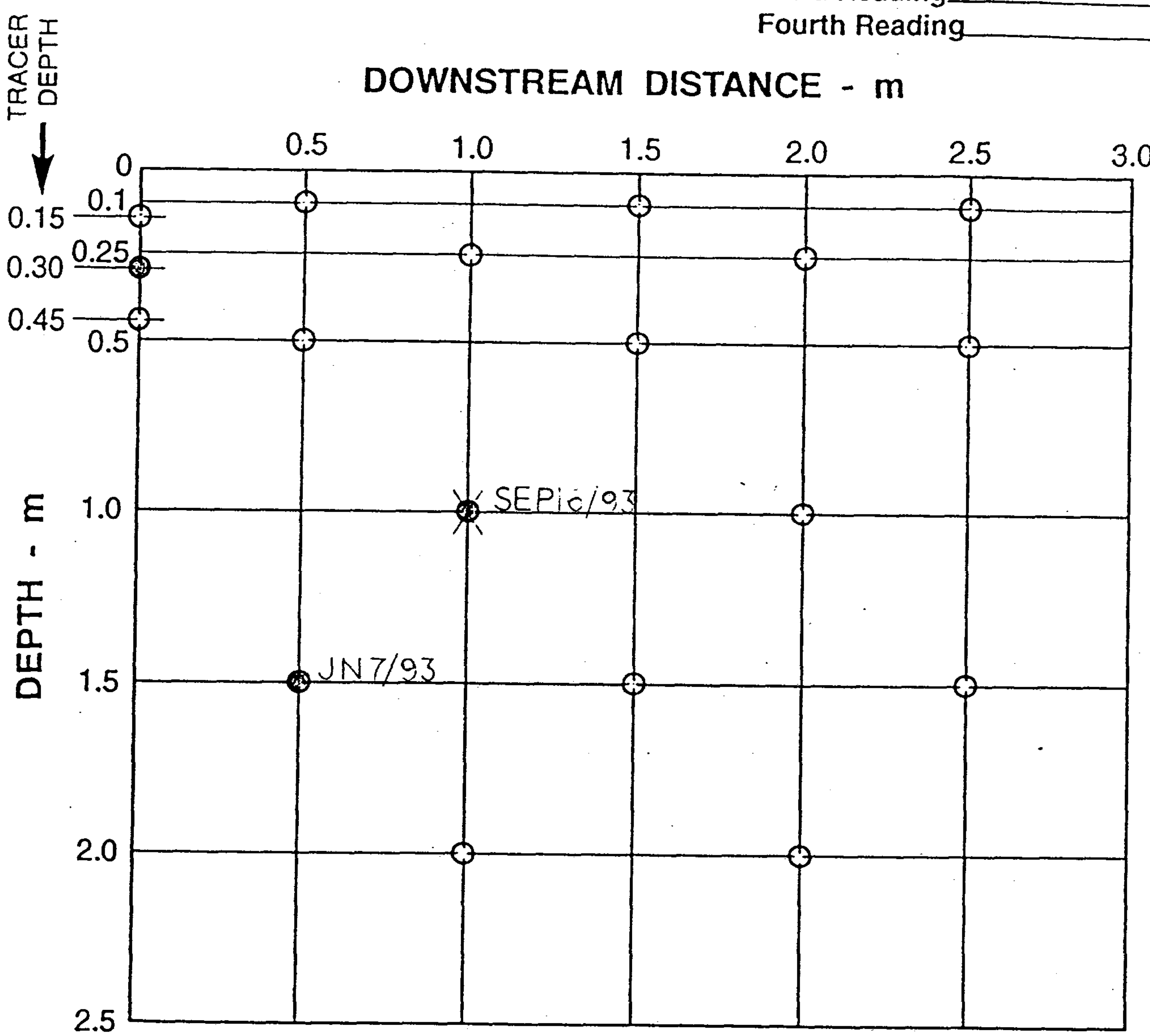


	TRACER INSTALLED	DISTANCE FROM DISCHARGE
North Site	SEPT 92	
Central Site	SEPT 92	
South Site	OCT 92	

REMARKS:

TAILINGS TRACER STUDY

Site Location [illegible]
Tracer Depth 0.30M
First Reading JUN 7/93
Second Reading SEP. 16/93
Third Reading
Fourth Reading



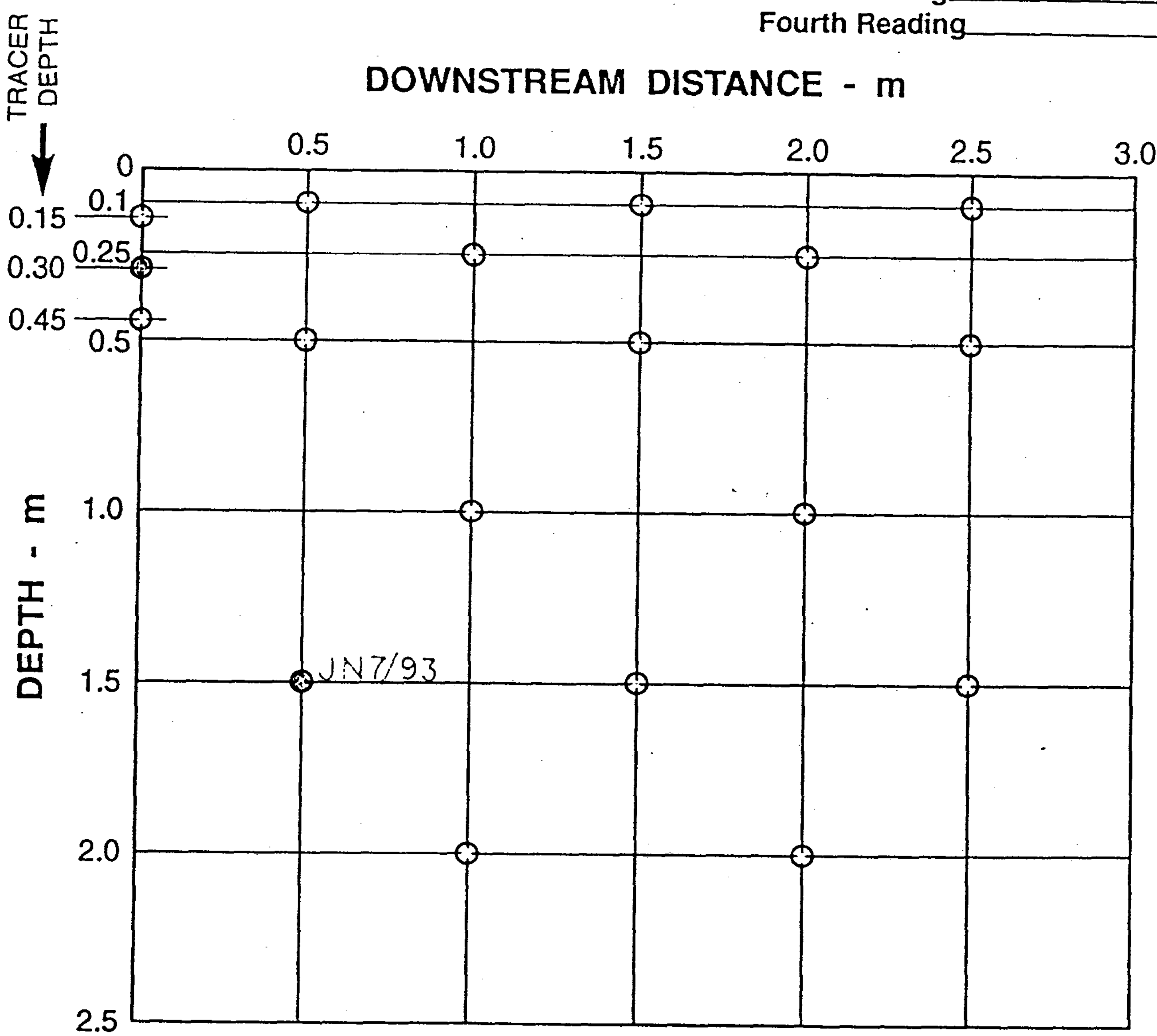
X BROMIDE

	TRACER INSTALLED	DISTANCE FROM DISCHARGE
North Site	SEPT 92	
Central Site	SEPT 92	
South Site	OCT 92	

REMARKS:

Site Location [illegible]
Tracer Depth 0.30M
First Reading JUN 7/93
Second Reading SEP. 16/93
Third Reading
Fourth Reading

TAILINGS TRACER STUDY



	TRACER INSTALLED	DISTANCE FROM DISCHARGE
North Site	SEPT 92	
Central Site	SEPT 92	
South Site	OCT 92	

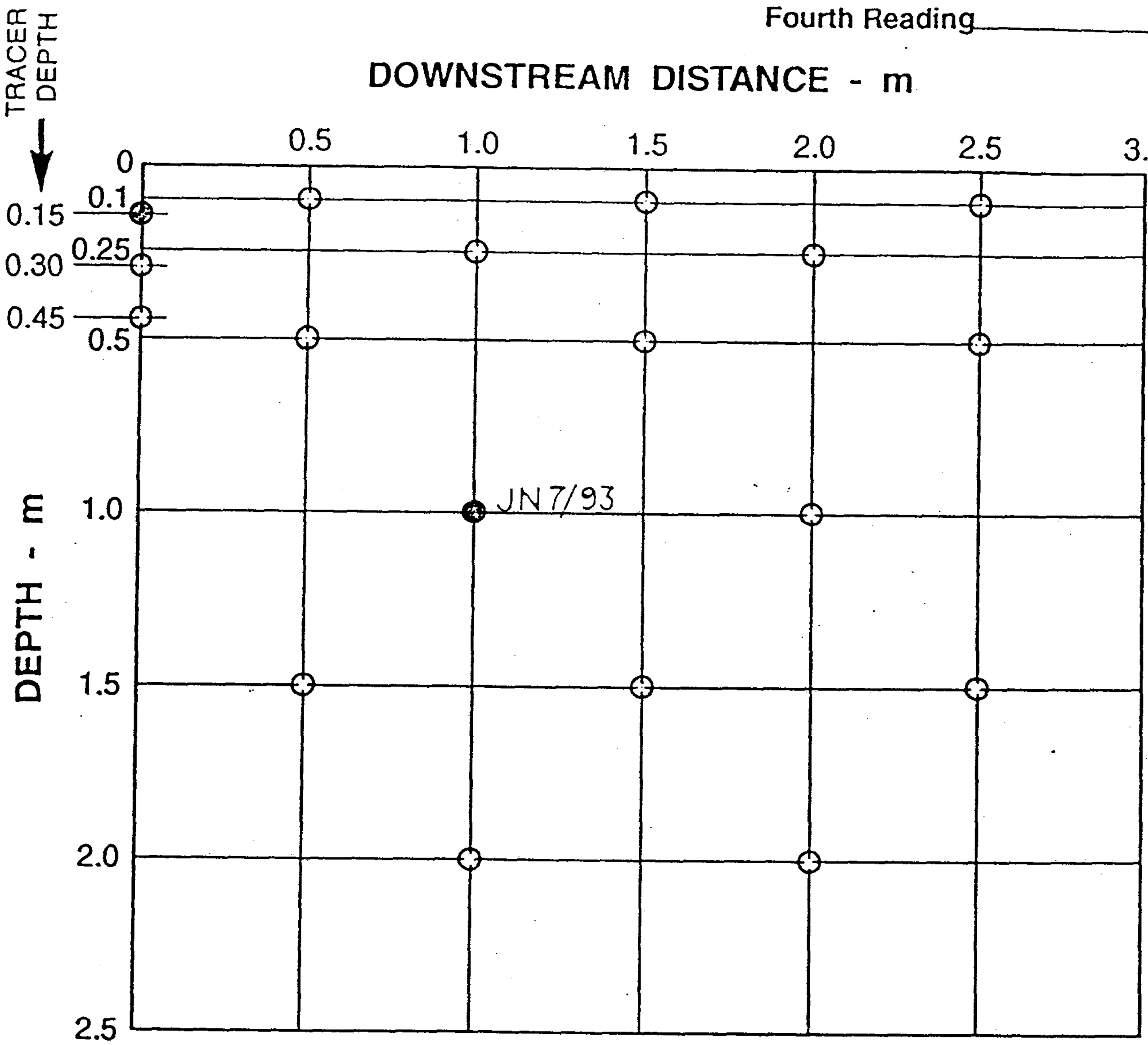
REMARKS:

FALCONBRIDGE LTD., KIDD CREEK DIVISION

E.I. ROBINSKY ASSOC. LTD., TORONTO, ONTARIO

TAILINGS TRACER STUDY

Site Location CW
Tracer Depth 0.15M
First Reading JUN 7/93
Second Reading SEP. 16/93
Third Reading
Fourth Reading



	TRACER INSTALLED	DISTANCE FROM DISCHARGE
North Site	SEPT 92	
Central Site	SEPT 92	
South Site	OCT 92	

REMARKS:

TAILINGS TRACER STUDY

Site Location

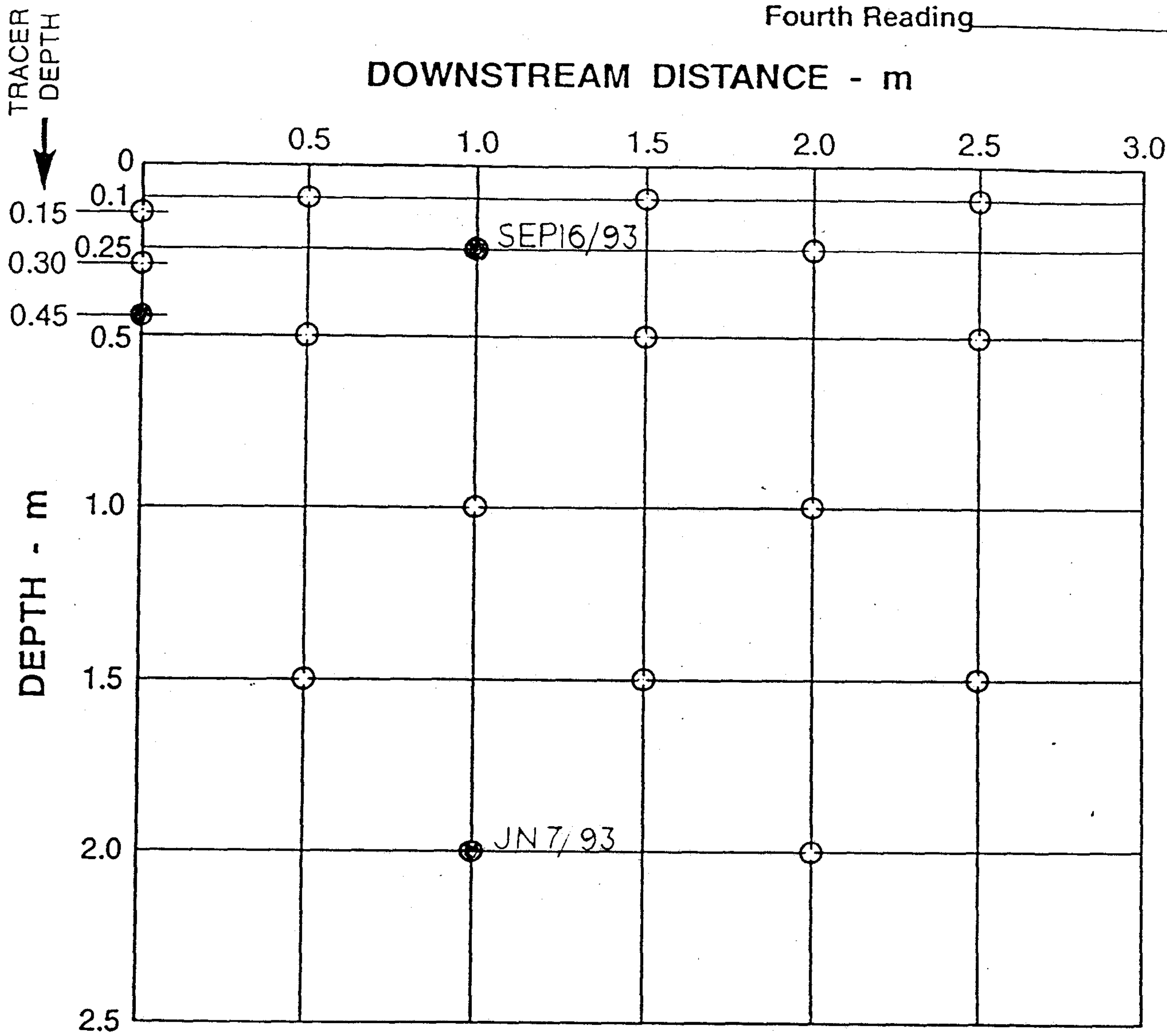
Tracer Depth 0.45M

First Reading JUN 7/93

Second Reading SEP. 16/93

Third Reading

Fourth Reading

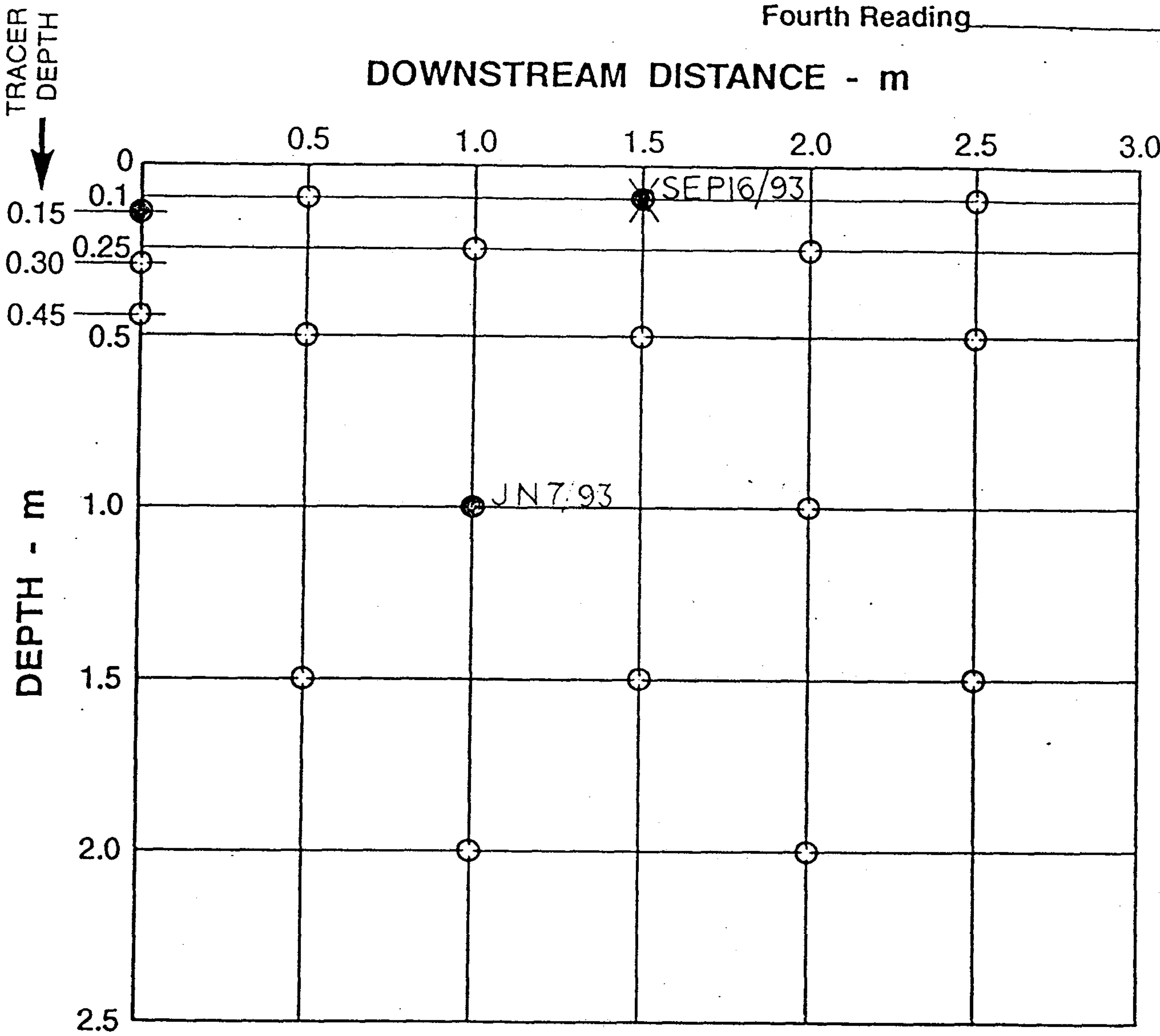


	TRACER INSTALLED	DISTANCE FROM DISCHARGE
North Site	SEPT 92	
Central Site	SEPT 92	
South Site	OCT 92	

REMARKS:

TAILINGS TRACER STUDY

Site Location ____
Tracer Depth 0.15 M
First Reading JUN 7/93
Second Reading SEP 16/93
Third Reading ____
Fourth Reading ____



X IODIDE

	TRACER INSTALLED	DISTANCE FROM DISCHARGE
North Site	SEPT 92	
Central Site	SEPT 92	
South Site	OCT 92	

REMARKS:

E. I. ROBINSKY ASSOCIATES LTD.
CONSULTING ENGINEERS

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Toronto, Ontario, Canada M4J 5B7

Telephone: (416) 469-4291
Fax: (416) 469-4319

June 29, 1992
Project 92-589

STUDY OF CHEMICAL TRACER MOVEMENT BENEATH TAILINGS SURFACE

(Environment - D. Bordin)

CODE FOR DESIGNATING TEST SAMPLES

The Code described hereunder shall be used to define each observation/sampling tube (and each sample) taken from each of three test sites. All test sites are on the south side of the original Central Discharge Ramp at increasing distance from the Ramp.

For Example:-

Test site designation (N,C,S)
Designation of group-of-4 tracer introduction pipes (W,M,E)
S - M - 5 - 3
Row No. of the 1/2" sampling tubes counted downhill from group of tracer pipes
No. of grooved rings near top of sampling tube

"Test site designation (N,C,S)"

N = Northernmost Test Site (Nearest to Discharge Ramp)

C = Central Test Site

S = Southernmost Test Site (Farthest from Discharge Ramp)

"Designation of group-of-4 tracer introduction pipes (W,M,E)"

Designation

W = Westernmost group (left-hand group when looking at discharge ramp) is at depth of 0.15 m. Single groove at top of pipe. Tracer is Potassium Bromide.

M = Middle group is at depth of 0.30 m. Two grooves at top of pipe. Tracer is Potassium Iodide.

E = Easternmost group (right-hand group when looking at discharge ramp) is at depth of 0.45 m. Three grooves at top of pipe. Tracer is Potassium Bromide.

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"No. of grooved rings near top of sampling tube"

Each tube has a number of grooved rings cut into it near the top. The number of grooves represents the depth to the bottom of the tube from the tailings surface.

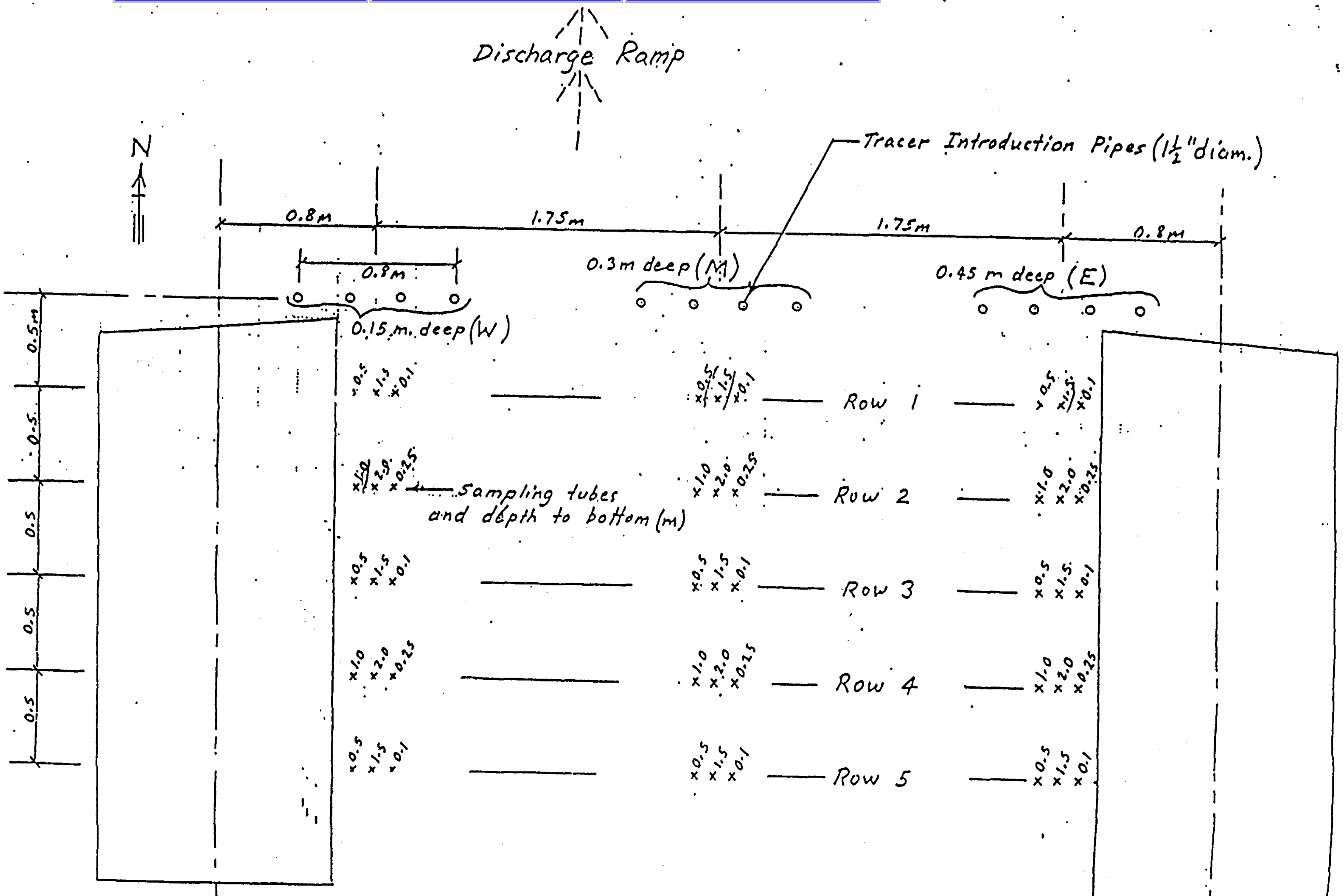
No. of Grooves	Depth
1	0.10 m
2	0.25 m
3	0.50 m
4	1.0 m
5	1.5 m
6	2.0 m

"Row No. of the 1/2" sampling tubes counted downhill from group of tracer pipes"

The rows of the 1/2" sampling tubes are at the following distances from the tracer pipes:-

Row No.	Distance from tracer introduction pipes
1	0.5 m
2	1.0 m
3	1.5 m
4	2.0 m
5	2.5 m

NOTE: Sample of field record sheet is attached.



LAYOUT OF TEST SITE

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