EVALUATION OF MAN-MADE SUBAQUEOUS DISPOSAL OPTION AS A METHOD OF CONTROLLING OXIDATION OF SULFIDE MINERALS - SYNTHESIS REPORT

MEND Project 2.12.1a

This work was done on behalf of MEND and sponsored by Aur Resources Inc., Noranda Inc.,Teck Corporation, and le Ministère des Ressources naturelles du Québec and the Canada Centre for Mineral and Energy Technology (CANMET) through the CANADA/ Québec Mineral Development Agreement

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Prepared by
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EXECUTIVE SUMMARY

The Louvicourt project was multifaceted with contributions from industry, university, consulting and government organizations. These groups completed a broad range of studies and investigations. This provided the rare opportunity to assess and compare the effectiveness of different test procedures, equipment and predictive techniques.

Previous investigations funded through the MEND (Mine Environment Neutral Drainage) Program had determined that subaqueous disposal of acid generating tailings in natural lakes was an effective mitigation strategy for the prevention of acid generation. Similar benefits were also attributed to constructed tailings basins but little scientific demonstration of this technology was presented in the literature. The primary objectives of the Louvicourt project were to assess and demonstrate the effectiveness of shallow water covers in a man-made basin and determine the benefits of the placement of organic or inorganic barriers at the tailings/water cover interface. This demonstration would enhance the current state of knowledge with both site-specific design information for the closure of the full scale Louvicourt basin as well as generic design and predictive modelling information for application to other reactive tailings sites.

This report has been prepared to provide a summary of the key findings from these studies as well as to provide a synthesis of what this body of work has contributed to the understanding of water covers in man-made tailings basins.

The key findings from this work are:

- Shallow water covers in man-made basins are an effective means of controlling sulphide oxidation. Oxidation rates are reduced by at least 3 orders of magnitude as compared with unsaturated surface tailings deposits.
- The low rates of oxidation observed in the column and field cell studies result in metals release (notably Cd and Zn) to the overlying water cover. Measured metal fluxes would not likely result in metals levels in the effluent exceeding discharge standards.
- The measured depth of oxygen penetration into the tailings is typically less than 1 cm. Sampling and measurement of porewaters within such a very small zone is difficult and complicates the interpretation of the geochemistry within this layer.
- It is apparent that periphyton growth affects oxidation and the transport of oxygen into the tailings. Although the exact role and impact of vegetation is uncertain, other studies to date have shown no significant degradation of water cover quality as a result of plant growth.
- Barriers between the tailings and the water cover generally serve to limit the access of oxygen to the submerged tailings and act to reduce the diffusive flux of contaminants from the tailings porewater. From this study it is clear that barrier materials may be a significant source of dissolved contaminants and full characterization of these barrier materials must be included in the cover design process. Careful consideration must be given to the short-term impacts that these materials may have on water quality, and whether these impacts outweigh the longer-term benefits. From the Louvicourt column

studies, there was no short-term benefit to barriers at the tailings/water interface. Given the similar performance of the water cover option without barriers, there would be no basis at this time to suggest additional barriers would be warranted for the Louvicourt site.

SOMMAIRE 2.12.1a

Le projet Louvicourt était diversifié en raison des contributions de l'industrie, d'universités, de firmes d'experts-conseils et d'organisations gouvernementales. Ces groupes ont réalisé un large éventail d'études, ce qui a offert une rare occasion d'évaluer et de comparer l'efficacité de différents équipements, procédures d'essai et techniques de prévision.

Des études antérieures, financées par le Programme de neutralisation des eaux de drainage dans l'environnement minier (NEDEM), ont montré que la déposition subaquatique de résidus miniers acidogènes dans des lacs naturels constituait une stratégie efficace d'atténuation des risques de production d'acide. Les bassins artificiels de résidus miniers présenteraient des avantages similaires, mais il y a trop peu de documentation sur cette technologie pour le confirmer. Les principaux objectifs du projet Louvicourt étaient d'évaluer et de démontrer l'efficacité des couvertures aqueuses peu profondes dans un bassin artificiel, et de cerner les avantages des barrières de matières organiques ou inorganiques placées à l'interface des résidus et de la couverture aqueuse peu profonde. Une telle démonstration permettrait d'approfondir nos connaissances avec des données sur la conception propres au site pour la fermeture de l'ensemble du bassin de Louvicourt et des données génériques sur la conception et la modélisation prédictive applicables à d'autres sites de résidus réactifs.

Nous avons rédigé ce rapport afin de résumer les principales conclusions de ces études et de faire la synthèse des contributions de ce projet à l'avancement des connaissances en matière d'utilisation de couvertures aqueuses dans des bassins artificiels de résidus miniers.

Voici les principales conclusions du projet :

- Les couvertures aqueuses peu profondes placées dans des bassins artificiels constituent un moyen efficace pour réduire le taux d'oxydation des sulfures, par un facteur d'au moins trois ordres de grandeur par rapport aux taux observés pour des dépôts de résidus en surface non saturés.
- Les faibles taux d'oxydation observés lors d'études en colonne et en cellules de terrain entraînent le passage de métaux (notamment de Cd et de Zn) dans la couverture aqueuse sus-jacente. Les taux de diffusion mesurés des métaux n'occasionneraient probablement pas de concentrations de métaux supérieures aux normes dans les effluents.
- La mesure de la profondeur de pénétration de l'oxygène dans les résidus est habituellement inférieure à 1 cm. L'échantillonnage et l'analyse des eaux interstitielles dans cette très mince couche est difficile et complique l'interprétation de la géochimie dans cette dernière.
- Il est évident que la croissance du périphyton influe sur l'oxydation et l'apport d'oxygène dans les résidus. Le rôle et les effets exacts de la végétation demeurent incertains, mais des études antérieures ont montré que la croissance de végétaux n'entraîne pas une dégradation significative de la qualité de la couverture aqueuse.
- Les barrières entre les résidus et la couverture aqueuse servent habituellement à limiter la pénétration de l'oxygène dans les résidus submergés et à réduire la diffusion des contaminants présents dans l'eau interstitielle des résidus. D'après les résultats de cette étude, il est évident que les matériaux des barrières peuvent constituer une importante source de contaminants dissous. La caractérisation complète de ces matériaux doit donc

être intégrée dans le processus de conception de la couverture. On doit également porter une attention particulière aux effets à court terme de ces matériaux sur la qualité de l'eau et on doit établir si ces effets l'emportent sur les avantages à long terme. D'après les études en colonne menées à Louvicourt, les barrières à l'interface résidus/eau n'offrent pas d'avantage à court terme. Étant donné les résultats similaires pour la couverture aqueuse sans barrière, rien ne justifie en ce moment l'utilisation de barrières supplémentaires au site de la mine Louvicourt.

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1.0 INTRODUCTION

1.1 BACKGROUND

Previous investigations funded through the MEND (Mine Environment Neutral Drainage) Program had determined that subaqueous disposal of acid generating tailings in natural lakes was an effective mitigation strategy for the prevention of acid generation. Similar benefits were also attributed to constructed tailings basins but little scientific demonstration of this technology was presented in the literature. The primary objectives of the Louvicourt project were to assess and demonstrate the effectiveness of shallow water covers in a man-made basin and determine the benefits of the placement of organic or inorganic barriers at the tailings/water cover interface. This demonstration would enhance the current state of knowledge with both site-specific design information for the closure of the full scale Louvicourt basin as well as generic design and predictive modelling information for application to other reactive tailings sites.

The Louvicourt project was multifaceted with contributions from industry, university, consulting and government organizations. These groups completed a broad range of studies and investigations. This provided the rare opportunity to assess and compare the effectiveness of different test procedures, equipment and predictive techniques.

This report has been prepared to provide a summary of the key findings from these studies as well as to provide a synthesis of what this body of work has contributed to the understanding of water covers in man-made tailings basins.

1.2 THE LOUVICOURT PROJECT REPORTS

The following reports were prepared for the "Evaluation of Man-made Subaqueous Disposal Option as a Method of Controlling Oxidation of Sulphide Minerals" project. The successful completion of this work could not have been achieved without the ongoing contributions and cooperation of the staff and joint venture partners of the Louvicourt Mine.

MEND 2.12.1.a-Synthesis Report. This report by SENES Consultants Limited (SENES, July 2002) provides highlights of the Louvicourt project studies and an evaluation of the findings and lessons learned.

MEND 2.12.1.b-Background and General Description. This report by Golder Associés Ltée (Golder, July 2001) provides background information on the Louvicourt project, an overview of the component studies and a description of the field cell construction and instrumentation.

MEND 2.12.1c-Subaqueous Disposal of Reactive Mine Tailings, Louvicourt Mine Test Cells, Geochemical Sampling and Analysis. This report by the Institut National de la Recherche Scientifique (INRS-EAU, March 2001) describes the geochemical sampling methods used to monitor the field cells and provides a technical evaluation of cell performance.

MEND 2.12.1d-Reactivity Assessment and Subaqueous Oxidation Rate Modelling for Louvicourt Tailings. This report by the Noranda Technology Centre (Noranda, December 2000) presents the results of the tailings characterization program, static and dynamic ARD assessment, an interpretation of the data, and the presentation of predictive modelling results on the effectiveness of the shallow water cover in a full-scale application.

MEND 2.12.1e-Column Studies. This report by the Canada Centre for Mineral and Energy Technology (CANMET, December 2000) presents the results of flooded column studies with variable water depths and surface barriers.

The draft reports (MEND 2.12.1c,d,e) were peer reviewed by Dr. Tom Pederson who served as project advisor.

1.3 THE LOUVICOURT MINE

The Louvicourt Mine as shown on Figure 1 is located 20 km east of Val d'Or, Québec. The deposit is a massive sulphide ore with copper, zinc, silver and gold produced as flotation concentrates for sale. Tailings backfill is used extensively in the mine leaving 45 % of the original ore tonnage (~4300 tpd) for disposal in the flooded tailings impoundment located 8.5 km northwest of the mill (see Figure 2). The tailings management area provides 4.7 Mm^3 of capacity. The basin also includes a lime addition plant for pH control and a sedimentation basin for final polishing before effluent discharge to the Colombière River.

The Louvicourt project included the construction of two test cells adjacent to the tailings basin in 1996. As shown by the enclosed pictures, these cells are nearly rectangular, measuring about 20 m x 20 m, with 2 to 3 m of tailings and 0.3 m of water cover. The cells were filled with tailings from the Louvicourt mill.

1.4 TAILINGS CHARACTERISTICS

1.4.1 Mineralogy

In MEND 2.12.1d a mineralogical evaluation of the Louvicourt tailings is presented. A typical analysis is provided in Table 1.4.1 at the end of section 1.4.

Metal content of the surface tailings in Cells 1 and 2 are reported in MEND 2.12.1c and these results are summarized in Table 1.4.2 at the end of section 1.4.

The key observations from these samples are:

- Surface tailings in Cell 2 are relatively homogenous while those in Cell 1 are heterogeneous.
- Base metals levels (Cd, Cu, Pb, Zn) are greater in surface tailings samples from Cell 1 as compared with Cell 2. This is the result of a longer filling time for Cell 1 during a period when these metals levels in the tailings were higher.

1.4.2 ARD Characteristics

i) Static Tests

The MEND 2.12.1d report presented results of extended acid base accounting (ABA) testing of 5 samples of Louvicourt tailings. These samples contained total sulphur levels ranging from 15.21 to 24.55 % and net neutralization potential (NNP) ranging from –294 to -742 kg/t as $CaCO_3$ (i.e. the samples could theoretically produce from 294 to 742 kg acidity as $CaCO_3$/t of tailings if completely oxidized).

ii) Kinetic Tests

MEND 2.12.1d presented results from a series of humidity cell tests conducted over a period of 80 weeks. Key findings from this test work include:

- All samples oxidized rapidly. The rate of oxidation (acidity production) ranged from 864 to 2143 kg $CaCO_3$ eq/t/wk.
- The lag time to produce acid conditions averaged 1.2 years in the humidity cells. In the field, the projected the lag time could average about 4.5 years.

1.4.3 Physical Characteristics

The Louvicourt tailings are primarily silt to fine sand sized particles with 80 % of the particles with diameters of less than 45µm. The specific gravity of the solids is about 3.3 – 3.6 with a calculated in place density of about 1.7 t/m^3 at 50% porosity.

TABLE 1.4.1 Typical Mineralogy of Louvicourt Tailings

MINERAL	% by Mass
Quartz	34.7
Muscovite (K-feldspar, Na-plagioclase)	6.5
Chlorite (Clinochlore)	6.8
Magnesium Siderite	10.0
Ankerite	7.1
Rutile (ilmenite, goethite)	4.0
Pyrite	28.0
Pyrrhotite	0.6
Chalcopyrite	0.3
Sphalerite	0.6
Galena	0.01
Total	98.6

TABLE 1.4.2 Metals Content- Surface[1] Tailings Louvicourt Test Cells

	Core Number	Cadmium mg/kg	Copper mg/kg	Iron %	Manganese mg/kg	Nickel mg/kg	Lead mg/kg	Zinc mg/kg
Cell 1	1	35.5	1705	14.8	2546	13.9	541	9105
	2	21.8	1508	15.7	2638	15.2	479	4590
	3	20.5	1503	15.9	2762	14.8	497	4455
	4	14.9	1173	13.1	1987	13.8	356	2136
	5	23.1	1555	15.2	2571	18	482	4945
Cell 2	1	16.2	1102	14.9	2255	15.4	325	2525
	2	14.7	996	15.4	2332	9.8	239	1914
	3	14.9	1044	14.6	2345	7.5	257	2243
	4	13.8	1127	14.3	2416	6.5	229	1812
	5	16.0	993	15.4	2277	11.7	275	2313

Note 1-Samples from upper 0.5 cm

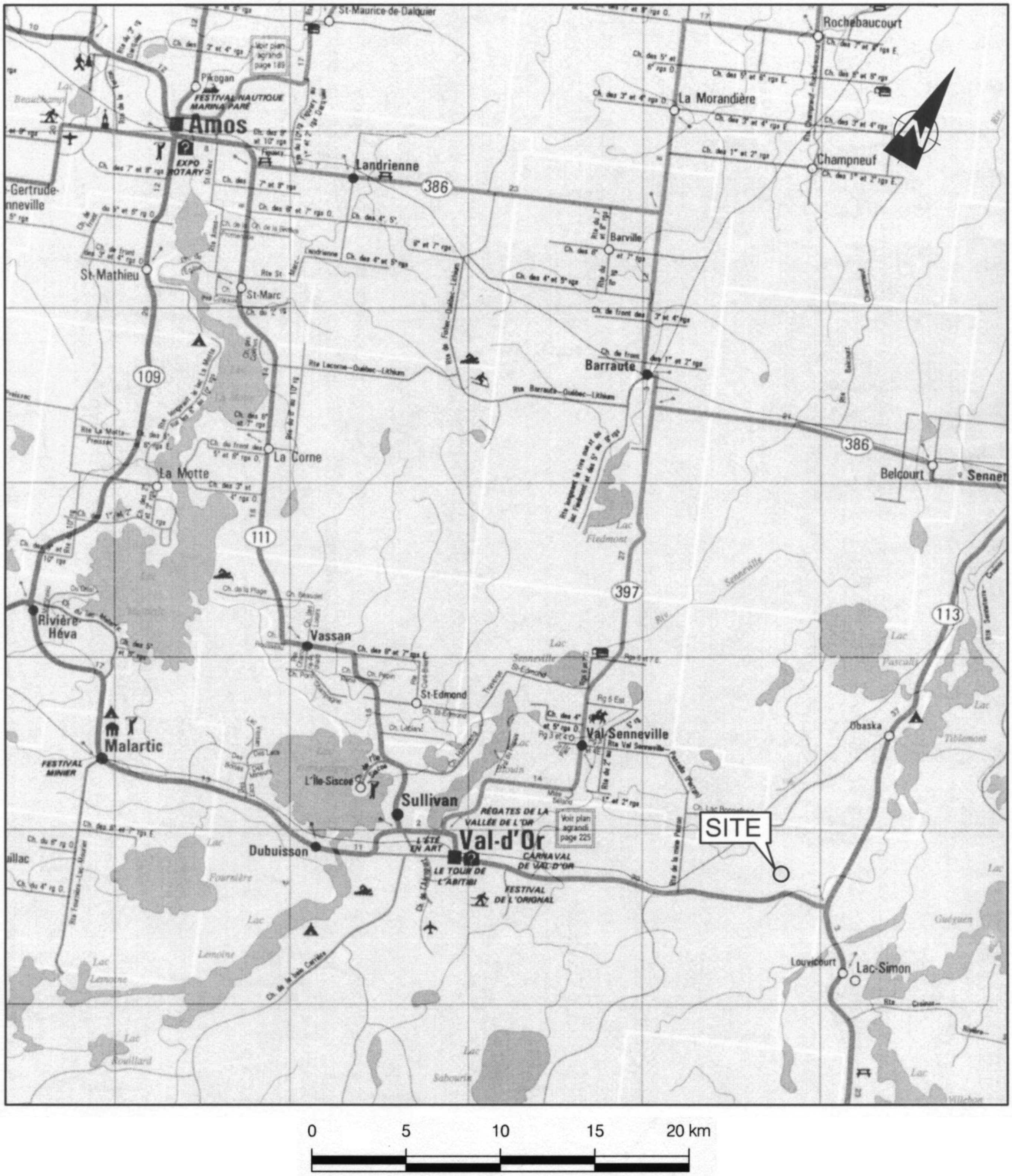
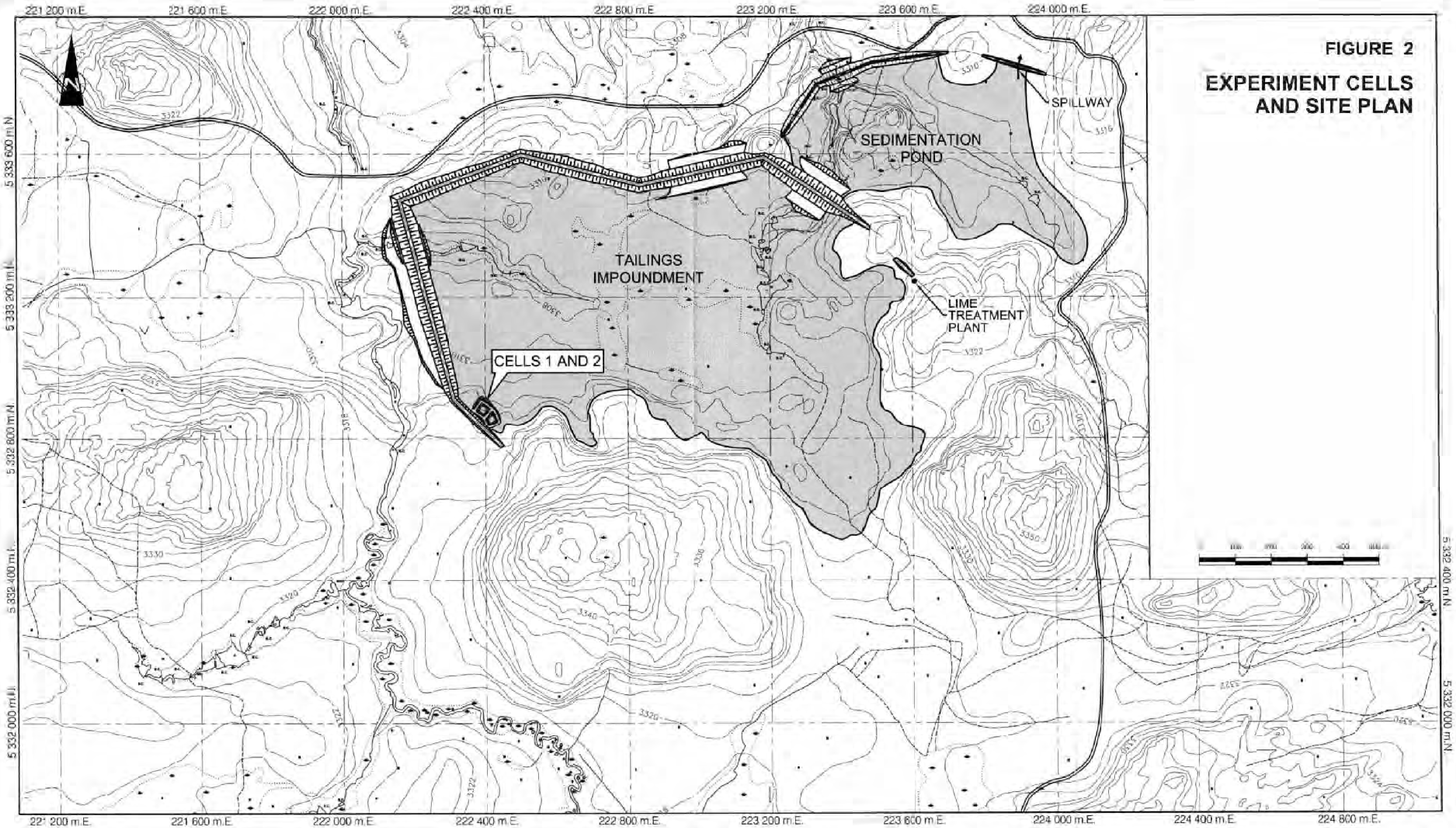


FIGURE 1

SITE LOCATION MAP

SOURCE: GOLDER ASSOCIATES, DWG No. 9502904, 2001



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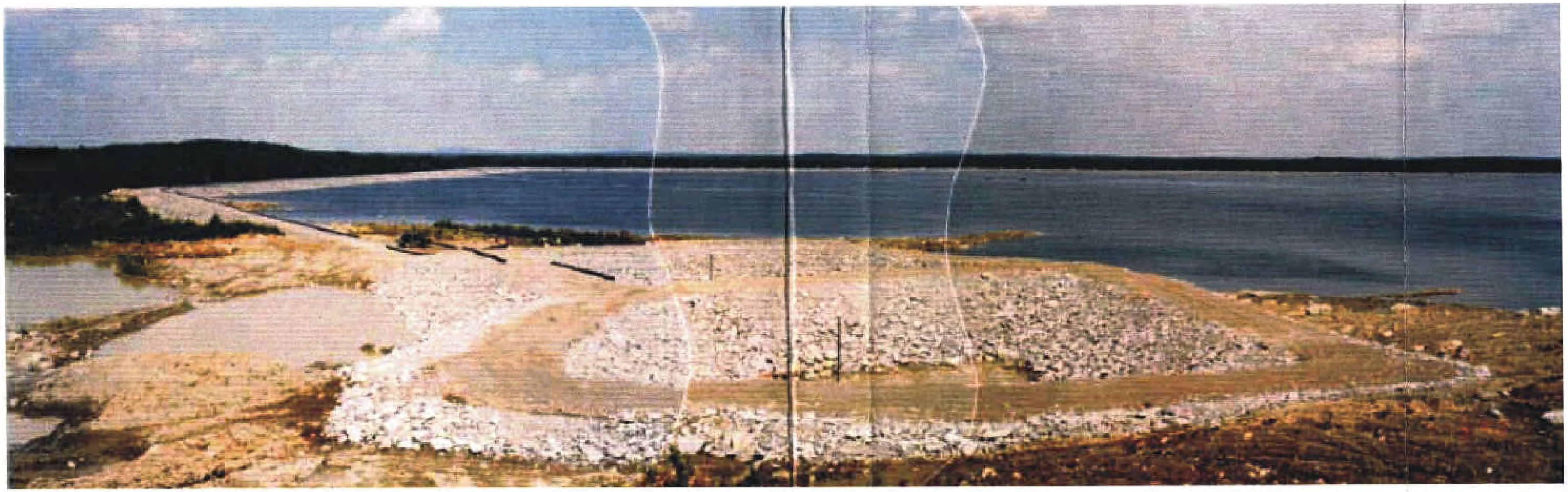

Picture #1: Cells with the tailings impoundment in the background.

Picture 2: Cell #1 before filling.

Picture 3: Cell # 2 before filling.

SOURCE: GOLDER ASSOCIATES, 2001

2.0 SUMMARY FINDINGS OF THE LOUVICOURT REPORTS

This section includes edited summaries of the 4 technical reports encompassing the results of the Louvicourt Project (MEND 2.12.1).

2.1 BACKGROUND AND GENERAL DESCRIPTION (GOLDER 2001, MEND 2.12.1B)

The "Background and General Description" report describes the construction of two test cells as part of a research program on the use of man-made shallow water cover, as a means of reducing oxidation of acid generating tailings.

The objectives of the field program were to:

1) Create a test facility within the tailings impoundment, which simulates as closely as possible the conditions that might exist following the closure of the Louvicourt tailings basin. In order for this facility to be representative of post-closure conditions, it had to be isolated from mill process water and replenished with natural water;
2) Instrument the test facility to collect the necessary hydrogeological and hydrological data for the study;
3) Collect and analyze representative samples of cover water, tailings solids, interstitial tailings porewater and groundwater to meet the overall study objectives previously provided; and
4) Complete suitable monitoring programs that will allow for the laboratory and field test programs to be related to actual future conditions in the closed-out tailings basin.

The field investigation included the design, construction and instrumentation of two test-cells, each measuring about 20 m x 20 m, in an area adjacent to the Louvicourt tailings pond. Some construction problems were encountered and required deviation from the proposed design. The presence of shallow bedrock and the proximity of the tailings pond resulted in a slight relocation of the cells and a raising of the cell floor levels. Cells were also slightly different in size and shape and ended up with sloped floors. Cells were filled with 2 to 3 m of tailings during the first three weeks of August 1996 and covered using a 0.3 m deep water cover.

During filling of the cells, large variations of the geochemical characteristics of the tailings were reported. This had a large impact on the reproducibility of in-situ testing between both cells. The comparative characteristics of the surface tailings in the two cells are therefore different and they are even different within each cell. Both test cells were provided with permanent instrumentation consisting of a sampling well/piezometer installation and a battery operated pH meter, water level and flow meter with continuous recorder at each cell overflow.

2.2 SUBAQUEOUS DISPOSAL OF REACTIVE MINE TAILINGS, LOUVICOURT MINE TEST CELLS, GEOCHEMICAL SAMPLING AND ANALYSIS (INRS-EAU 2001, MEND 2.12.1C)

The objective of this study was to assess the effectiveness of a shallow water cover in reducing the oxidation of sulphidic mine tailings and thus preventing the development of acidic drainage in the experimental field cells at the Louvicourt Mine. From 1996 to 1998, the chemistry of the interstitial water near the tailings/water interface was monitored using in-situ dialysis. The pH and dissolved oxygen (DO) profiles across the tailing-water interface were monitored using microelectrodes.

Penetration of DO into the tailings was limited to < 7 mm, even in the presence of DO produced by benthic periphyton. Anoxia in the tailings was further demonstrated by the appearance of dissolved sulphide species and elevated levels of Fe and Mn levels in porewater at depths of 1.5 cm below the interface. However, there was evidence of surface oxidation of the mine tailings at the mm scale (i.e., DO depletion, coupled with localized increased levels of hydrogen ions and sulphate).

Mobilization of Cd and Zn from this surface layer was indicated by the presence of sub-surface peaks in the concentrations of these two metals in the tailings interstitial water and by an increased proportion of labile fractions in the solid phase relative to the underlying tailings. In contrast, there was no evidence for mobilization of Cu from tailings.

Unlike previous reports, which suggested that submerged tailings were effectively inert, results from this study show some alteration of the surficial layer over time. The observed Cd and Zn releases from the submerged tailings are however very small. For a typical disposal operation (a 1 km x 1.5 km impoundment with an average depth of 1 m, calculations indicate that these releases would increase the overlying water Zn concentration by 3 ug/L and the Cd concentration by 0.04 ug/L. The Cd and Zn fluxes from the tailings to the overlying water would thus have only minor impacts on the overlying water quality.

2.3 REACTIVITY ASSESSMENT AND SUBAQUEOUS OXIDATION RATE MODELLING FOR LOUVICOURT TAILINGS (NORANDA 2000, MEND 2.12.1D)

This report documents the results of the Noranda research project completed by Noranda Technology Centre. The project was designed to evaluate the effectiveness of shallow water covers in the prevention of acid mine drainage from reactive sulphidic tailings, using Louvicourt Mine as the experimental site.

In this study, various Louvicourt tailings samples were characterized for grain size distribution, quantitative mineralogy, geochemical whole-rock composition, and extended acid-base accounting (ABA). Flow-through cell leach tests were used to investigate the influences of four parameters on metal releases by tailings under simulated submergence. Eight humidity cells containing duplicates of four samples were tested for eighty weeks to determine the rates of sulphide oxidation and acid neutralization. Pre- and post-humidity cell analyses were performed to complete geochemical and mineralogical mass balances and to validate the humidity cell data interpretation. Data generated from these laboratory tests were used to predict field acid generation for a hypothetical full-scale tailings basin. Mathematical modelling was used to evaluate the effects of four oxygen transport mechanisms on the degree of subaqueous sulphide oxidation.

ABA results indicate that the tailings are potentially net acid generating. A four-month in-plant monitoring campaign conducted in 1994-1995 showed a variation of sulphide content from 11 to 49%. The sulphides in the tailings are dominated by pyrite, with minor or trace phyrrhotite, sphalerite, and chalcopyrite. Carbonate mineral contents in the samples varied from nearly nil to as high as 24%. The main carbonate minerals are ankerite and siderite, both containing varying amounts of magnesium and manganese. The main silicate-based neutralizing mineral is chlorite (clinochlore).

Flow-through cell leach experiments with different leachant solutions using the Taguchi design approach suggest the following influence on metal releases: leachant Fe^{2+} concentration (strong) > leachant DO level (strong) > leachant pH (medium) > hydraulic gradient (weak). Presence of Fe^{2+} in the inflow increases metal releases likely through a one-time ion exchange process. High DO in the inflow promotes Zn releases through oxidation of sulphides whereas low DO facilitates the release of Mn. Lower pH favours metal releases probably because of higher solubility of hydroxides and carbonates of most metals. The tailings were found to contain sufficient buffering capacity to maintain the porewater pH nearly neutral. Mechanisms controlling metal releases include solubility control and dissolution rate control. Overall metal releases are low throughout the experiments except during the initial flush-out of accumulated soluble constituents.

The humidity cell results show that the Louvicourt tailings have relatively high oxidative reactivity. The oxidation rate of the eight tests ranged 864-2143 (average 1449) mg $CaCO_3$ eq/kg/week, and the NP consumption rate ranged 955-2238 (average 1500) mg $CaCO_3$ eq/kg/week. All samples are potentially net acid generating, with predicted humidity cell lag times ranging 0.56-2.5 (average 1.2) years. Predictions based on a hypothetical field exposure of the tailings without a water cover indicate that the lag time before acid generation is 4.5 years. For a worse-than-average case the lag time reduces to 2.6 years.

Sphalerite oxidation appeared to be accelerated by galvanic effects after the leachate pH dropped below about 3.0. Ankerite appeared to contribute fully to the total available NP. Siderite and clinochlore were less reactive and contributed less to the total available NP. Siderite dissolution seemed to be accelerated after onset of acid generation whereas clinochlore dissolution was relatively unaffected by acidification.

A new technique was employed to calculate the dissolution rates of individual neutralizing minerals and sulphide minerals from weekly leachate volume and chemical data. The validity of this technique appears to be acceptable judging from the independently measured mineralogical mass balances.

Due to the "non-ideal" design of the humidity cell tests, not all particles placed in the cells were accessible for oxidation and neutralization reactions. This was probably attributable to the formation of impermeable particle aggregates as a result of cementation and coating. Methods for correcting for the non-ideal conditions were proposed and demonstrated. It was found that, without agitation, on average only about 37% of the sample mass in the humidity cells was available for oxidation and neutralization reactions.

Four cases that may occur after reactive tailings are disposed of under a shallow, 0.3 m water cover were mathematically modelled using typical tailings properties and other site-specific conditions found at the Louvicourt Mine. The four cases are 1) stagnant water cover, 2) fully oxygenated and mixed water cover, 3) fully oxygenated and mixed water cover with downward infiltration, and 4) tailings resuspension. The stagnant water cover through which oxygen must diffuse across transports the least amount of oxygen to the submerged tailings, with the flux being on the order of 3 g O_2/m^2/year. Although this is the most desirable condition, to date field data collected in other studies indicated that it is highly questionable that this condition exists in reality, since winds that are almost always present in the field naturally cause mixing, circulation, wave action, and aeration in shallow water bodies. The three other cases are more likely scenarios and result in increased oxygen flux into the submerged tailings. Modelling results suggest that, compared with the base case of stagnant water cover, the mixing/oxygenation of the water cover and tailings resuspension each is capable of increasing the oxygen flux by one order of magnitude, whereas downward infiltration of fully-aerated water cover can enhance the oxygen flux by a factor of three.

The range of oxygen fluxes seen in the modelling results suggest that for most sites, a simple, well-maintained water cover alone without additional measures is sufficient to suppress oxidation of sulphides in reactive tailings while maintaining the discharge from the water cover during wet seasons in compliance. Nevertheless, for exceptional circumstances where this is not achievable, supplemental measures, such as physical, chemical, and biological barriers/oxygen interceptors, are available to further reduce the oxygen flux and enhance the effectiveness of the water cover.

2.4 Column Studies (CANMET 2000, MEND 2.12.1e)

Tailings samples collected over a period of a month by site personnel from the backfill circuit of the Louvicourt mill were shipped to CANMET with a layer of process water maintained over the tailings at all times. These were transferred in slurry and allowed to settle and form the bottom layer in four series of triplicate columns (0.3 m inner diameter), each simulating a different scenario of subaqueous tailings disposal. The column set up was as follows:

- Series 1: 0.3 m water directly overlying tailings
- Series 2: 0.3 m water overlying 0.3 m peat as an intermediate layer over the tailings

- Series 3: 0.3 m water overlying 0.3 m sand as an intermediate layer over the tailings
- Series 4: 1.0 m water directly overlying tailings

The column experiments were designed to evaluate the effectiveness of two water depths (0.3 m and 1.0 m) and two intermediate barriers (peat and sand) to prevent weathering of submerged tailings. Both the peat and sand used in the column studies were locally available material sampled by mine personnel from within the Louvicourt property. To facilitate replenishment of the water cover as needed during the study, the process water in each column was replaced by untreated Ottawa River water at start-up.

The column studies consisted of two major phases. Phase I, which lasted for 200 days, focused on oxygen diffusion and ionic fluxes under conditions of a circulated water cover. In the first 100 days, the water cover in each column was circulated but not aerated. In the second 100 days, aeration of the water cover was also included. Phase II, which lasted for 13 months, incorporated precipitation, runoff and drawdown events at rates comparable to those observed in the field. The impact on the chemistry of the water cover and porewater in each series of columns was investigated. Both Phases I and II commenced with a new batch of natural water as water cover such that only the porewater in each column retained remnant effects of the previous stage of testing.

The test results showed that water covers with and without the additional peat or sand layers were effective in reducing but not eliminating oxidation of tailings. However, the 1 m water cover performed somewhat better than the 0.3 m water cover. This was in large part the result of a greater reserve of alkalinity available in the 1 m water cover. A significant finding was that the barriers placed over the tailings may be significant sources of contamination. In the column studies, slight pH depression was observed in the overlying water in the peat and sand columns. The peat proved to be a source of acidity and dissolved metals (Al, Fe, Mn, and possibly Zn and Cu). Like the peat, sand also proved to be an initial source of metals (Fe, Mn and Zn). It is clear that careful characterization of barrier materials must be completed if these barriers are to be used in combination with water covers.

One weakness in the study was the measurement technique to monitor porewater quality near the tailings water interface. To better assess chemical gradients and the geochemistry near the interface, a much higher resolution sampling method would be required.

3.0 DISCUSSION OF THE FINDINGS

3.1 KEY FINDINGS

3.1.1 Depth of Oxidation

The depth of oxidation into the surface of the tailings was measured by monitoring dissolved oxygen levels. The MEND 2.12.1e measurement technique involved an in-line DO probe placed in samples obtained through bore needles with sampling pumps from ports located in the side of the columns. Samples were collected at 1, 3, 5 , 7, 9, 14, 19, etc. cm below the tailings or barrier surface. In the MEND 2.12.1c study microelectrodes were used to measure in-situ oxygen concentrations in the near surface tailings of the test cells.

The MEND 2.12.1e measurements suggest that oxygen is depleted in the upper few cm of the flooded tailings columns. In contrast, INRS-Eau in MEND 2.12.c found that oxygen was consumed in the upper few mm (< 7 mm) in the field test cells. In order to explain the differences between the field test and laboratory columns, microelectrode DO measurements were completed on the columns at CANMET and compared with the CANMET procedure. The microelectrode measurements indicated depletion of oxygen at 2 to 6 mm as in the field tests while the CANMET data in MEND 2.12.1e suggested low residual levels of oxygen at these depths. DO measurements with the microelectrodes also suggested that oxygen may have been introduced inadvertently while sampling the columns through the sampling ports, leading to a systematic artefact of perhaps +0.5 mg/L in the CANMET DO measurements. In contrast, CANMET also noted that reaction product concentrations (acidity and metals) peaked at 1 to 2 cm below surface, which could suggest that oxygen penetration was actually deeper than 1 cm. Another explanation could be that sampling from the numerous porewater sampling ports below the tailings surface caused a convective flow of oxygen and contaminants downward in the column thus explaining the presence of oxygen and the peak in reaction product concentrations below 1 cm in depth.

In either case, the depth of oxidation is very shallow ranging from a few mm to perhaps a few cm. INRS-Eau in MEND 2.12.1c note that in this respect, “the tailings are behaving like normal fine-grained lake sediment, where the oxic surface layer is normally < 1 cm in thickness”.

3.1.2 Oxidation Fluxes and Oxidation Rates

i) Oxygen fluxes (oxygen consumption)

Oxidation fluxes for flooded tailings were estimated based upon oxygen gradients in MEND 2.12.1c and 2.12.1e. Noranda in MEND 2.12.1d also predicted oxygen fluxes based upon first principle calculations.

From the column studies reported in MEND 2.12.1e, after 18 months of study, oxygen fluxes were similar for all tests and ranged from a low of 3.8 g $O_2/m^2/y$ to a high of 6.3 g $O_2/m^2/y$. INRS-Eau in MEND 2.12.1e estimated a consumption of 0.00324 $nmol/cm^2/s$ or 32.7 g $O_2/m^2/y$ based upon oxygen measurements in the field test cells. This low oxygen flux compares with the estimated high oxygen consumption of 6.5 $nmol/cm^2/s$ or 65,600 g $O_2/m^2/y$ as measured in the humidity cell tests. For the water-covered tests, the oxygen flux available to oxidize sulphide minerals has been reduced by 2,000 to 20,000 times that which was consumed in the unsaturated humidity cell tests.

ii) Oxidation/Acid Production Rates

Sulphide oxidation rates cannot be estimated unless all oxygen is assumed to be consumed in the oxidation of sulphide minerals (i.e. no other oxygen consumers). In humidity cell testing, one can estimate sulphide oxidation by monitoring the sulphate flux with time. Given the high levels of sulphate in porewater and diffusion of this inventory of sulphate into the water cover, oxidation rates must be estimated by other means for the column studies and test cells. For the column and field studies, the oxidation rates can be prorated on the basis of oxygen fluxes. From the humidity cell tests, Noranda calculated the acid production rates to range from about 510 mg $CaCO_3$/kg/wk before acid conditions to > 1000 mg $CaCO_3$/kg/wk after the onset of acid conditions. Prorating acid production with oxygen fluxes, the acid production rates under flooded conditions are 3 to 4 orders of magnitude lower in the field cells and column studies than in the unsaturated humidity cell tests.

3.1.3 ARD Prediction

The Louvicourt tailings have a high acid generation potential and experience high rates of oxidation if left exposed on surface in an unsaturated condition. From the column studies, field tests and model projects, acidic conditions would not be expected if tailings were flooded at water depths used in these studies.

3.1.4 Metals Leaching

Estimates of metal fluxes were completed in MEND 2.12.1e, MEND 2.12.1c and Li et al. (1997). For demonstration purposes only the results for zinc leaching are presented, as this is the most leachable metal. The results are summarized below.

i) Model Projections

Li et al. (1997) completed a conservative upper limit calculation for the flooded tailings basin. Using an average zinc concentration of 0.2 mg/L, an annual net outflow of 540,000 m^3 and a surface area of 960,000 m^2, the net zinc flux was calculated to be 0.11 $g/m^2/y$.

ii) Column Studies

MEND 2.12.1e reports cumulative fluxes at days 100 and 200 for Phase 1 and day 217 for Phase 2. The calculated fluxes were determined by dividing the cumulative fluxes by the number of days and surface area of the columns. These are reported in Table 3.1.1.

TABLE 3.1.1 Cumulative Zinc Fluxes from Flooded Columns ($g/m^2/y$)

	Series 1 0.3 m water cover	Series 4 1 m water cover
Phase 1 –Day 100	0.120	0
Phase 1 - Day 200	0.184	0.058
Phase 2 –Day 217	0.257	0.042

ii) Field Cells

In MEND 2.12.1c oxygen fluxes to the water column were calculated for Cell 2. The zinc flux was estimated at 1.5 x 10^{-7} nmol $Zn/cm^2/s$ or 0.003 g $Zn/m^2/y$. Estimated zinc fluxes were similar for Cell 1 (~ 2 x 10^{-7} nmol $Zn/cm^2/s$ or 0.004 g $Zn/m^2/y$) despite the higher surface tailings zinc content – although both the overlying water and the porewater zinc concentrations were higher in Cell 1, compared to Cell 2, the Zn concentration gradients were similar to those in Cell 2. These levels are substantially lower than estimated from the column studies.

When column and field cell tests are compared, it can be concluded that the zinc flux is similar but highly dependent upon the pH of the water cover. Regardless of the flux estimate used to predict future metals levels, the concentration of zinc in the water cover would remain below 0.5 mg/L (the Federal and Provincial monthly average discharge standard).

3.2 COMPLIANCE WITH PROJECT OBJECTIVES

3.2.1 Primary Objectives

The primary objectives for the project were to:

1) *Demonstrate the effectiveness of man-made water covers as a permanent means of preventing the oxidation of sulphide minerals and the consequent formation of acid rock drainage.*

All studies completed demonstrated the effectiveness of water covers as a means of controlling the oxidation of sulphide minerals but in all cases the authors project that oxidation of sulphide minerals did continue, albeit at very low rates. The measured and projected rates of oxidation and metals release would not cause significant degradation of the surface water cover. Rates of oxidation were less than those measured in humidity cells by 3 or more orders of magnitude.

2) *Establish whether there is a benefit to the placement of a thin organic or inorganic barrier on the surface of the flooded tailings*.

Studies completed by CANMET in MEND 2.12.1.e demonstrated that both inorganic and organic covers might have both positive and negative benefits. The local sand and peat barriers placed over the tailings were short-term sources of contamination. The peat proved to be a source of acidity and dissolved metals (Al, Fe, Mn, and possibly Zn and Cu). Like the peat, sand also proved to be an initial source of metals (Fe, Mn and Zn). MEND 2.12.1e measured reduced oxygen fluxes to the tailings surface with barriers and MEND 2.12.1d projected that barriers would reduce access of oxygen to the flooded tailings. From the CANMET work, there was no significant difference in the performance of the shallow water covered basins with or without a thin barrier.

3.2.2 Secondary Objectives

The secondary objectives were to:

1) *Obtain an in-depth understanding of the physical and chemical interactions within the deposited tailings using monitoring data from the solid phase and interstitial water, with emphasis on:*

a) Diffusion of oxygen from the water cover into the tailings
b) Interactions between the aqueous and solid phases (sorption, oxidation and dissolution)
c) Vertical advection of porewater flow

a) The field studies by MEND 2.12.1c using microelectrodes clearly show that oxygen penetration into the tailings only occurred in the near surface layer (~7mm). Column studies by CANMET (MEND 2.12.1e) measured deeper oxygen penetration using the CANMET in-line cells for D. O. measurement however, when columns were tested using the microelectrode, DO penetration was similar to that in the test cells. Oxygen fluxes were in all cases low especially as compared with rapid oxidation rates measured in humidity cell tests (see Table 3.2.1).

b) Interactions between the aqueous and solid phases are less clear. Near surface oxidation of sulphide minerals is apparent while metals mobility is low. INRS-Eau noted that the partitioning of metals such as zinc from refractory (sulphides) fractions to more labile fraction is occurring at the tailings water interface. Both MEND 2.12.1c and MEND 2.12.1e observed iron hydroxide precipitation at the tailings/water cover interface.

TABLE 3.2.1 Measured Oxygen Fluxes

Data Source	Oxygen Flux $g/m^2/y$	Comment
MEND 2.12.1e	3.8-6.3	Range of fluxes with and without barriers
MEND 2.12.1c	32.7	Calculated from MEND 2.12.1c flux of 0.00324 $nmol/cm^2/s$
MEND 2.12.2d	3.0- 34.2	Range of modelled fluxes for stagnant to fully aerated water cover
MEND 2.12.2d	65,600	Mean result from unsaturated humidity cell tests (6.5 $nmol/cm^2/s$)

c) The processes of diffusion and advection may result in vertical flux of constituents in porewater. All researchers calculated fluxes to the water cover. These fluxes were low in all studies.

2) Interpret the controls on the chemical behaviour of submerged tailings based upon solid-phase, porewater and water column geochemical data.

Although oxidation is proceeding in the near surface tailings, a significant factor controlling release to the water column is the alkalinity in the water cover. All reports surmise from the data that secondary precipitates are forming at the tailings/water cover interface, which is to some degree attenuating metals mobility. This may be due to both sorption on iron oxyhydroxides and direct precipitation. In MEND 2.12.2e, the column with the greatest alkalinity reserve in the water cover had the lowest metals fluxes.

3) Develop a predictive capacity to determine the future performance of a flooded tailings basin (Louvicourt) by correlating with laboratory and field test cell data.

The laboratory columns and field cells provided similar data. Differences in performance are largely attributed to testing and sampling methodology. Based upon the laboratory and column results and full-scale experience at other flooded tailings basins, it is reasonable to conclude that either laboratory or field-scale data provide adequate information to estimate the performance of man-made water covers for tailings basins. Areas of uncertainty would include the role of algae, aquatic plants, wind induced suspension of tailings, and the formation of natural sediment barriers etc., on the ultimate rates of oxidation and metals mobility from the tailings surface.

4) Assess model capability to predict the long-term performance of flooded tailings.

Both mechanistic and empirical models have been used to assess the performance of the flooded Louvicourt tailings basin. In MEND 2.12.1c and MEND 2.12.1e, measured data were used to estimate oxidation rates and metal fluxes which in turn can be applied to the Louvicourt full-scale application to assess long-term performance. Noranda in MEND 2.12.1d also undertook oxygen flux modelling to assess the potential rates of oxidation in the flooded Louvicourt basin. The projected oxygen fluxes are similar to those measured in MEND 2.12.1c and MEND 2.12.1e. Li et al. (1997) completed a worst case assessment of long-term zinc levels in the Louvicourt basin. For this very conservative assessment, Li assumed that the water cover was fully mixed during the ice-free period and that 2 mm of surface tailings were in suspension, that all oxidation was from sphalerite and that no metals attenuation/precipitation occurred. Even with these conservative assumptions, zinc levels were projected to remain below discharge limits.

Overall, it is concluded that predictive tools are available and support results from laboratory and field-scale tests.

5) Develop additional technology pertaining to mine closure.

The test program did provide additional and or new technology pertaining to mine closure. Key elements include:

- The use of microelectrodes for measurement of pH and oxygen at the mm level in subaqueous tailings can be used to support mine closure studies. This technology had been previously applied to monitor lake sediments.
- Demonstration that man-made water covers do effectively control but do not eliminate sulphide oxidation.
- Intermediate barriers over flooded tailings may have both positive and negative benefits. This study indicated that barriers were not required for surface water quality to meet effluent discharge standards.

3.3 Lessons Learned

3.3.1 Instrumentation Weaknesses

The MEND 2.12.1c and MEND 2.12.1e studies demonstrated that for Louvicourt tailings, upon flooding, the oxidation zone was limited to a surface zone of only a few mm in thickness. Given this narrow boundary layer, the use of in-situ dialysis and sampling ports in column were inadequate to fully characterize water chemistry within the oxidation zone. The microelectrodes were successful in measurement of pH and DO and without these data, interpretation of the results could have been different (would not have the capacity to detect the acidic peaks a few mm below surface and would not have measured DO depletion at < 7 mm).

3.3.2 Role of Periphyton Layer and Aquatic Plants

An interesting observation by INRS-Eau in MEND 2.12.1c was the role of the periphyton layer on pH and DO levels in the near surface zone of the tailings. After 2 years, the periphyton layer formed on the surface of the tailings, was affecting both pH and DO levels in the upper 3-4 mm of tailings. During the day, a subsurface DO peak and concomitant pH rise occurs which is absent during night time. INRS-Eau hypothesize that photosynthesis by the periphyton would explain the results. It is unclear whether this layer has a negative or positive benefit on acidity or metals flux from the surface.

Davé (1993, MEND 3.12.2) found similar results with aquatic plants in the Panel wetlands study completed at the Panel Mine in Elliot Lake, Ontario. Davé reported that oxidation was occurring in near surface root zones of the plants yet pH levels in the water cover were increasing during the summer months. Davé attributed this to sulphate reduction and photosynthesis of aquatic plants.

Although plants are playing a role in the near surface oxidation, the growth of periphyton and aquatic plants do not appear to have a negative effect on surface water quality. Vegetation does have the positive benefit of providing physical stabilization of the tailings and improving aquatic habitat. Future work on the effects of vegetation and its effect on oxygen/reduction at the water/tailings interface is warranted.

3.3.3 Benefits of Barriers

It is clear from the CANMET column studies in MEND 1.12.1e that careful characterization of barrier materials must be completed if these barriers are to be used in combination with water covers. While barriers generally serve to limit the access of oxygen the submerged tailings, barrier materials may be a source of dissolved contaminants as was the case with the local sand and peat used in the CANMET column studies. CANMET noted, “careful consideration must be given to the short-term impacts that these materials may have on water quality, and whether these impacts outweigh the longer-term benefits.” Noranda in MEND 2.12.1d stated “a simple, well-maintained water cover alone without additional measures is sufficient to suppress oxidation of sulphides in reactive tailings while maintaining the discharge from the water cover during wet seasons in compliance.”

3.3.4 Role of Alkalinity Balance in Cover Water

Investigations by MEND 2.12.1e and MEND 2.12.1c and modelling completed by Noranda in MEND 1.12.1d all indicate that oxidation of sulphide minerals continues under shallow water covers in man-made impoundments. Oxidation rates are very low but may be sufficient to cause a pH depression in surface waters under stagnant conditions where minimal alkalinity is supplied to the cover water. Although this is a possibility and should be considered in the design of a shallow water cover system, the field cells at Louvicourt with 0.3 m water cover have remained alkaline since construction.

3.3.5 Field Versus Laboratory Investigations

Most of the data collected in the laboratory column studies were not materially different than those obtained in the field cells. The laboratory studies have the advantage of being more flexible and suited to investigation of many factors (cover type, aeration, water depth, flow through effects etc.). The field cells provide a reality check in that they better approximate full-scale conditions. Although the results from the test programs may vary, the differences would not have materially affected the final design for the water cover had both laboratory and field investigations not been completed. The proof of the pudding will come once the performance of the full-scale basin with water cover can be monitored at the time of mine closure.

3.3.6 Heterogeneous Nature of Tailings

The field cell construction demonstrated the variability of tailings characteristics and the importance of experimental design. Because Cell 1 took longer to fill, the surface layer of tailings contained significantly higher levels of metals (notably zinc) making a direct comparison with Cell 2 (supposedly a duplicate experiment) difficult. The field project was going to investigate the effects of a peat layer however without a comparable control, this cover test was abandoned. In future, if cells are to be duplicated, it is essential that filling be conducted simultaneously and that tailings remain saturated with water during the entire placement.

3.3.7 The Effect of Water Cover Depth

Although not a focus of the field study, water cover depth was assessed in the column studies. In the field cells, the 0.3 m water cover functioned well. One concern expressed was the potential for suspension of tailings during the field test program. In the absence of resuspension, CANMET in MEND 2.12.1e determined that the 0.3 m water cover versus 1.0 m water cover did not impact on oxygen flux. The only significant difference was the inventory of alkalinity present in the cover water. As long as the alkalinity available was similar, it is likely that the performance of the water cover would not be materially different.

The potential effects of tailings suspension on oxygen consumption (i.e. oxidation rates) of the tailings was modelled in MEND 1.12.1d. It was determined that complete aeration of the water cover would produce similar oxidation rates (and thus potential acid generation and metals leaching) as would be encountered if 2 mm of tailings was continuously retained in suspension. Given that the surface layer in the field cells remained fully aerated (i.e. no DO depression with depth) and that suspension would only occur intermittently, based upon this work, one would hypothesize that tailings suspension would not materially increase oxidation rates. In the field cells, INRS-Eau in MEND 2.12.1c measured an oxygen consumption of 32.7 g $O_2/m^2/y$. This compares well with the Noranda estimate of 34.2 g $O_2/m^2/y$ for the aerated water cover.

Assuming tailings were suspended for 5% of the time, the impact on oxygen consumption would be an increase of perhaps 2 g $O_2/m^2/y$. This level is unlikely to be material to the overall rate of tailings oxidation and metals leaching.

4.0 CONCLUSIONS AND RECOMMENDATIONS

4.1 CONCLUSIONS

Based upon the synthesis of the Louvicourt project studies, the following conclusions are drawn.

1) Shallow water covers in man-made basins are an effective means of controlling sulphide oxidation. Oxidation rates are reduced by at least 3 orders of magnitude as compared with unsaturated surface tailings deposits.

2) The low rates of oxidation observed in the column and field cell studies result in metals release (notably Cd and Zn) to the overlying water cover. Measured metal fluxes would not likely result in metals levels in the effluent exceeding discharge standards.

3) The measured depth of oxygen penetration into the tailings is typically less than 1 cm. Sampling and measurement of porewaters within such a very small zone is difficult and complicates the interpretation of the geochemistry within this layer.

4) It is apparent that periphyton growth affects oxidation and the transport of oxygen into the tailings. Although the exact role and impact of vegetation is uncertain, other studies to date have shown no significant degradation of water cover quality as a result of plant growth.

5) Barriers between the tailings and the water cover generally serve to limit the access of oxygen to the submerged tailings and act to reduce the diffusive flux of contaminants from the tailings porewater. From this study it is clear that barrier materials may be a significant source of dissolved contaminants and full characterization of these barrier materials must be included in the cover design process. Careful consideration must be given to the short-term impacts that these materials may have on water quality, and whether these impacts outweigh the longer-term benefits. From the Louvicourt column studies, there was no short-term benefit to barriers the tailings/water interface. Given the similar performance of the water cover option without barriers, there would be no basis at this time to suggest additional barriers would be warranted for the Louvicourt site.

4.2 RECOMMENDATIONS

1) Further research into the role of aquatic vegetation on the performance of water covers is warranted.

2) Further monitoring of the test cells would assist in assessing the longer term performance of shallow water covers.

5.0 REFERENCES

Blanchette, Kwong, Y. T. J., M. C., Davé, N. K., and Tisch, B., 2000. Column Studies. Canada Centre for Metals and Mineral and Energy Technology Mineral Sciences Laboratories (CANMET MMSL), (MEND 2.12.1e), December.

Davé, N. K., 1993. Panel Wetlands-A Case History of Partially Submerged Pyritic Uranium Tailings Under Water. Centre for Mineral and Energy Technology Mineral Sciences Laboratory (CANMET MSL) divisional report MSL 93-32(CR), (MEND 3.12.2), February.

Golder Associés Ltée, 2001. Background and General Description. (MEND 2.12.1.b), July.

INRS-Eau, 2001. Subaqueous Disposal of Reactive Mine Tailings, Louvicourt Mine Test Cells, Geochemical Sampling and Analysis, Report No. 547, (MEND 1.12.1c), February.

Li, M. and St-Arnaud, L., 2000. Reactivity Assessment and Subaqueous Oxidation Rate Modelling for Louvicourt Tailings. Noranda Technology Centre, (MEND 2.12.1d), December.

Li., M. G., Aubé, B, and St-Arnaud, L., 1997. Considerations in the Use of Shallow Water Covers for Decommissioning Reactive Tailings. Noranda Technology Centre, Presented at the Fourth International Conference on Acid rock Drainage, May.

Pedersen Thomas F., 2000. The Louvicourt Mine-Tailings Assessment Project: Review of Experimental and Field-Based Research, report to MEND, December.