MERG Report 2001-1

# Research of Low Permeability Cover Performance at the Arctic Gold and Silver Mine Site, Carcross, Yukon

By EBA Engineering Consultants Ltd.

July 2001

MERG is a cooperative working group made up of the Federal and Yukon Governments, Yukon First Nations, mining companies, and non-government organizations for the promotion of research into mining and environmental issues in Yukon.

MERG (Mining Environment Research Group) reports are available at Geoscience Information and Sales, Yukon Geological Survey, Department of Energy, Mines and Resources, Room 102, Elijah Smith Building, Whitehorse, Yukon.

Mailing Address:
102-300 Main Street
Whitehorse, Yukon Y1A 2B5
Phone (867) 667-5200
toll free within the Yukon
1-800-661-0408 ext. 5200
Fax (867) 667-5150
E-mail geosales@gov.yk.ca

The reports are also available electronically at the MERG Website:
http://www.emr.gov.yk.ca/mining/merg/

# RESEARCH OF LOW PERMEABILITY COVER PERFORMANCE ARCTIC GOLD AND SILVER MINE SITE CARCROSS, YUKON

**EBA File: 0201-00-14535**

**July 2001**

# RESEARCH OF LOW PERMEABILITY COVER PERFORMANCE ARCTIC GOLD AND SILVER MINE SITE CARCROSS, YUKON

Prepared by:

EBA ENGINEERING CONSULTANTS LTD.
Whitehorse, YT

Submitted to:

Department of Economic Development
Mining Environment Research Group
Yukon Government
Whitehorse, Yukon

Project No. 0201-00-14535

July 2001

# TABLE OF CONTENTS

## LIST OF FIGURES (included as links)



## LIST OF FIGURES (included within)



## LIST OF TABLES (included within)



## APPENDICES (not included in on-line version)

## EXECUTIVE SUMMARY

The production of acid rock drainage (ARD) from mine tailings is a significant environmental concern at various abandoned mine sites in Yukon. Leachate with low pH and high dissolved metals concentrations deriving from mine tailings impoundment areas can negatively impact various groundwater and surface water resources.

The presence of both *oxygen* and *water* is required for ARD to develop. Therefore, the removal of the oxygen source and the water source from the mine tailings through the use of a low permeability cover (which acts as an oxygen/infiltration barrier) will halt ARD production. This is the basis of the design and recent reclamation (1998-99) of the Arctic Gold and Silver (AGS) Tailings Site in Carcross, Yukon that EBA has been involved with in association with PWGSC.

The use of a low permeability cover to reduce ARD such as that used at the AGS site is one of the first such reclamation applications in Yukon, however, there are up to 40 abandoned mine sites in Yukon that have been evaluated by INAC which may require future remediation. The goal for this project was to collect information relating to the performance of the cover at AGS to gain further information regarding this reclamation technique, so that it could potentially be applied to future reclamation projects in Yukon.

Three reports pertaining to the use of this type of tailings reclamation in Yukon were studied, and their results are summarized herein. The results of these studies were used to design a suitable field program for the AGS site. Following the literature review a field program and monitoring system was designed.

Initial field observations, and monitoring equipment installations were conducted by EBA in September, 2000 and consisted of:

- concentrations of oxygen gases within the tailings to evaluate the extent of $O_2$ migration into the tailings and hence the oxidation of the iron-sulfide minerals.

- moisture conditions within the low permeability cover and near surface tailings to evaluate infiltration conditions.
- temperature profiles within and below the cover, tailings, and native material.
- average thickness of low permeability cover material

This project was designed such that the on going monitoring was conducted by the Carcross Tagish First Nation (CTFN) in association with INAC. There was a training session during the first monitoring event to instruct the CTFN technician, and, EBA provided a Field Manual for use by the CTFN that outlined the field procedures (included as Appendix A of the final report). The CTFN representative provided the field data obtained during two subsequent monitoring events to EBA for evaluation and interpretation.

The observations from this field program serve as an excellent supplement to the Summary Report for Artic Gold and Silver Tailings Site Remediation (EBA, 2001), as a verification of as-built conditions of the cover system. Results of this study have confirmed the cover thickness, and low conductivity properties of the clayey silt cover. This investigation has also provided valuable preliminary data to evaluate the performance of the low permeability cover system. Observations from this field-program indicate that there is preliminary evidence that the low permeability cover at AGS is functioning effectively as a moisture and oxygen barrier. This preliminary information is optimistic for the use of this type of system for future reclamation at other mine sites throughout Yukon. However, limited data, and data variability has restricted the effectiveness of identifying and interpreting definitive trends at such an early stage.

The following work could be conducted at the AGS site to further this study, and the assessment of ARD conditions:

- Ongoing oxygen monitoring (2 or 3 events per year) for 3 years to get sufficient data set to make more definitive conclusions
- Ongoing temperature monitoring (2 or 3 events per year in conjunction with oxygen monitoring)
- Ongoing moisture content monitoring (2 events per year in conjunction with oxygen monitoring)

- Groundwater chemistry to compare with baseline (every 2 years for long term)

## 1.0 INTRODUCTION

There are up to 40 abandoned mine sites in Yukon that have been evaluated by INAC which may require future remediation. The use of a low permeability cover to reduce ARD such as that used at the AGS site is one of the first such reclamation applications in Yukon.

Although INAC may be completing some future performance monitoring at the AGS site, this will consist of activities necessary to satisfy federal and legal requirements, and will likely be focused on groundwater and surface water quality. Therefore, the impetus for this study has been to further the understanding of the intrinsic properties and the effectiveness of the low permeability cover reclamation technique to restrict moisture and oxygen contact with mine tailings. This study has been conducted with funding from MERG and INAC and in partnership with the Carcross Tagish First Nation. It is hoped that the results of this study can further the understanding of mine reclamation in Yukon.

The project entailed the following sequence of tasks as describe in our proposal:

- Literature Review and Research
- Design of Monitoring System
- Implementation of Monitoring System
- Evaluation and Reporting

These tasks have been completed, and are the subject of this report. A brief public presentation summarizing the results of this investigation will be given at Carcross during the spring of 2001.

The production of ARD from mine tailings is a significant environmental concern at various abandoned mine sites in Yukon. ARD is the product formed by the atmospheric oxidation (i.e. by water, oxygen and carbon dioxide) of the relatively common iron-sulphide minerals pyrite ($FeS_2$), pyrrhotite ($Fe_{n-1}S_n$), and chalcopyrite ($CuFeS_2$) in mine tailings. Leachate with low pH (from the increase in sulfuric acid, an end product of ARD) and high dissolved metals concentrations deriving from mine tailings impoundment areas can negatively impact various groundwater and surface water resources.

In addition to these iron-sulphides, the presence of both oxygen and water is required for ARD to develop. Current research has shown that the oxidation of pyritic waste rock and the subsequent generation of ARD is controlled to a large extent by the availability and transport of oxygen and water to the sites. Therefore, the removal of the oxygen source and the water source from the mine tailings through the use of a low permeability cover (which acts as an oxygen/infiltration barrier) will halt ARD production. This was the basis of the design and recent reclamation (1998-99) of the Arctic Gold and Silver (AGS) Tailings Site in Carcross, Yukon that EBA has been involved with in association with Public Works and Government Services Canada (PWGSC). The project sponsor for the AGS reclamation was Indian and Northern Affairs Canada (INAC).

## 2.0 BACKGROUND AND SITE CONDITIONS

The Arctic Gold and Silver Tailings site (AGS site), also known as the Arctic Caribou Tailings site, is located approximately 4 km south of the Village of Carcross, Yukon (See Figure 1). It was the location of a 180 tonnes per day ore concentrating operation during the late 1960’s. Ore from underground workings several kilometres from to the site was processed in the mill with gold and silver concentrate being the final product.

The mining operation was not viable and all operations at the tailings site ceased in September 1969. During operations, the waste stream from the milling operation included tailings and process water, both of which were discharged into a roughly trapezoidal 1.8 hectare tailings impoundment at the location shown on Figure 2. It is estimated that up to 47 000 tonnes of ore was processed during the mining operation and up to 27 000 $m^3$ of tailings were discharged into the tailings impoundment. In addition to the discharge of tailings into the impoundment, it was evident that some tailings were spilled from the mill and from the tailings impoundment leaving two channels on the site with the remnants of spilled tailings. Some of the spilled tailings were also found to have reached the unnamed lake located 80 m west of the impoundment. Over the years since abandonment of the site, tailings have also been blown from the impoundment creating a plume of wind blown tailings to the north east of the impoundment.

In the period since the mine became inactive, the site has become classified as an orphaned site and it was sporadically monitored for environmental performance by various federal agencies.

Starting in 1993, the AGS site was screened as part of the Arctic Environmental Strategy – Action on Waste program. This screening suggested that further evaluations were necessary to identify the environmental and physical risks associated with the site and to develop suitable restoration activities to mitigate such risks should they exist.

Detailed evaluation of the AGS site followed between 1997 and 1999. The detailed studies were completed under the direction of the Environmental Services Directorate of Public Works and Government Services Canada (PWGSC) using funding provided by the Department of Indian Affairs and Northern Develop (DIAND).

Environmental Services in turn retained the services of EBA Engineering Consultants Ltd. (EBA) and Steffen Robertson & Kirsten Consulting Engineers (SRK) to complete site specific environmental and geotechnical evaluations, and to review risk levels and potential remediation alternatives. The activities of EBA and SRK were reported to Environmental Services by SRK in the February 1999 report entitled: "Final Report - Assessment of Remedial Measures for Arctic Gold & Silver Tailings Site". During the drilling investigation completed within the tailings impoundment by EBA, it was observed that the tailings thickness ranged from 1.4 to 2.5 m. The tailings consisted of two layers distinguished by the extent of oxidation (as evidenced by the characteristic rust colour associated with the ferric hydroxide presence in the tailings). The thickness of the oxidized tailings appeared to vary from 0.8 m to 1.7 m. The geochemical properties of the tailings are discussed in a PWGSC March 1998 report entitled Phase III ESA of the Arctic Gold & Silver Mill and Tailings Empoundment. Table 2.1 provides a summary of geochemical information from that report. In brief, the tailings are strongly acidic and contain very high levels of total and soluble arsenic.

**TABLE 2.1: Tailings Geochemical Properties (from PWGSC, 1998)**

| Parameter | Range | Average |
|---|---|---|
| Acid Base Accounting | | |
| Paste pH | 1.8 to 3.5 | 2.6 |
| AP (kg$CaCO_3$/t) | 0.63 to 92 | 20 |
| NP (kg$CaCO_3$/t) | -23 to -2.5 | -12 |
| NNP (kg$CaCO_3$/t) | -107 to -3.1 | -33 |
| | | |
| Solids Metals[1] | | |
| Al(%) | 0.09 to 0.41 | 0.22 |
| As (ppm) | 3193 to > 10,000 | 6712 |
| Cu (ppm) | 29 to 1266 | 164 |
| Fe (%) | 1.1 to 5.73 | 2.8 |
| Pb (ppm) | 590 to 4222 | 1730 |
| Ag (ppm) | 25 to > 200 | 82 |
| Zn (ppm) | 33 to 643 | 183 |
| | | |
| Soluble Metals[2] | | |
| Al (mg/L) | 3.1 to 99 | 33 |
| As (mg/L) | 0.3 to 50 | 17 |
| Cu (mg/L) | 0.34 to 6.4 | 3.4 |
| Fe (mg/L) | 6.5 to 287 | 136 |
| Pb (mg/L) | <0.05 to 3.7 | 1.4 |
| Ag (mg/L) | 0.03 to 0.2 | 0.12 |
| Zn (mg/L) | 0.36 to 13 | 5.6 |

1. From ICP Analyses
2. From leach extraction testing

The recommendations of the SRK report were that the environmental and physical risks at the site would be most economically addressed by completing a "consolidate and cover" operation. A consolidate and cover operation would require that all ore and tailings exterior to the impoundment be consolidated within the impoundment and that the impoundment be upgraded and covered.

Based on this recommendation, the overall remediation plan for the site was developed by Environmental Services and presented within specification documents issued in the spring and fall of 1999, and in the spring and summer of 2000. Remediation activities at the site were contracted by PWGSC to the Carcross Tagish Development Corporation (CTDC) in July 1999. Remediation activities at the site were conducted by CTDC between July 1999 and September 2000.

Reclamation work during the summer of 1999 under the supervision of EBA generally consisted of the following:

- leveling and grading of the existing tailings
- placement of between 0.5 m and 0.6 m of native sand and gravel (with some cobbles) over the tailings
- covering of the tailings with a final 0.3 m thick layer of clayey silt.

A well-graded sand till berm exists around the perimeter of the tailings impoundment. This material was put in place when the tailings pond was active, and remains in place following reclamation work. Further details regarding the site reclamation are detailed in a contract report prepared for Public Works and Government Services Canada by EBA in March 2001; Summary Report Arctic Gold and Silver Tailings Site Remediation.

The low hydraulic conductivity cover of clayey silt underlain by the sand and gravel above the tailings forms a composite cover system. This type of cover inhibits the flux of oxygen into the tailings impoundment using the capillary barrier concept, which occurs when a fine grained material is placed over a coarser one. The difference in unsaturated hydraulic characteristics of the two adjacent materials is designed to favour a high degree of saturation in the top, fine material layer and, in turn, reduce the oxygen flux to the lower layer since the saturated porous media acts as an oxygen barrier. The coarser bottom gravel was designed to drain to residual saturation (minimum water content at high suction), which prevents significant moisture drainage from the clayey silt.

## 3.0 LITERATURE REVIEW

The first phase of the MERG AGS study was to perform a literature review of relevant documents and reports that relate to the use of low permeability covers over mine tailings as a reclamation technique. This section provides the findings from three documents reviewed for the MERG AGS study. Throughout the course of the study, other relevant research papers were reviewed on a more cursory level, and are not summarized within this section but are referenced within this report. The section below provides a summary of` the purpose and methods employed for each study or paper, as well as the relevant results that pertain to the present study.

### 3.1 SRK Report on Faro Mine Tailings Abandonment Plan Development Program

*Faro Mine Tailings, Tailings Abandonment Plan Development Program, January 1997*

**Purpose:**

The purpose was to prepare an abandonment plan which provides adequate protection to the environment and long term maintenance. The report provides a work plan for the implementation of a test plot program to test various closure design alternatives. The results of the test plot program would generate the necessary data to provide a basic design of the abandonment plan.

### 3.1.1 Results:

The results of the work plan included specific design details for the proposed test plot layout and data analysis methods. Relevant notes related to the design of the monitoring system at the AGS site are included below:

- Section 1.3.1 contemplates alternate control technologies for the abatement of ARD, and states that control technologies may be directed at the control of sulfides, water, oxygen, temperature, or bacteria. Of these, SRK reports that the bacteria *Thiobacillus ferrooxidans* were not present at any significant depth into the Faro Mine Tailings (SRK, 1986) and therefore, that biological activity would not be a major cause of acid production. The control of ARD by sulphide removal or chemical stabilization was not practical due to the requirement that the tailings would have to be reprocessed. The control of water available for chemical reactions was not practical since there was groundwater base leaching occurring at the Site and there were no low permeability soils available in the vicinity of the mine to create a cover. Control of oxygen was considered to be the best control methodology. Oxygen entry from the base was considered low since dissolved oxygen levels in groundwater were relatively low. Control measures would be required to limit oxygen entry through the tailings surface and therefore, several design protypes were considered in the test plots to evaluate various alternatives. The test plot with 0.6 m of till soil over the tailings (as a low hydraulic conductivity soil cover) best reflects the cover design employed at the AGS Site. It was recognized that a low permeability cover would also control the physical migration of the acid leachate deriving from the tailings. Therefore, the performance of the cover to reduce the volumetric flux through the tailings and hence the production of and vertical migration of acidic leachate is an important aspect of the design.

- Section 1.5 presents the test plot program objectives, of the various test plots. The layout of the test plots and the instrumentation was designed to determine the seasonal and time rate of change of:
  - Quality and quantity of seepage water draining from the test cells during the 3 year test period
  - Quality of the interstitial pore fluid vertically along the trial cell
  - Temperature profile
  - Oxygen concentration profile
  - Moisture profile
  - Rate of infiltration

- Although the test plot design is not described in detail herein, the reader is referred to the SRK, 1987 for this information. Of particular note, the test plots were designed with horizontal sampling tubes that were installed prior to the placement of 'new tailings'. The use of horizontal sampling tubes was intended to eliminate the need for vertical sampling and to reduce the potential of creating a vertical preferential seepage or oxygen diffusion pathways through the cover. [Note: Since the AGS study will not include the preparation of test plots with the placement of new tailings, but rather the monitoring of the performance of the existing field scale cover, a similar horizontal test apparatus was not considered practical.]

- Sections 1.6 and 2.3 describe the objectives of the water quality and solids characterization program. The methods described for oxygen profiling in this section are of particular interest to the AGS study. In the Faro study, tailings oxygen concentration profile sampling was conducted by collecting samples from the lysimeters and water samplers. Oxygen concentration testing was done in the field using a portable oxygen gas analyzer, following the method described in Feenstra et al, 1983 at Elliot Lake, Ontario.

- Sections 2.4 and 3.0 outline the instrumentation installations and test plot sampling methods and testing. The testing program was designed to measure temperature profile, pore pressure profile, moisture profile, oxygen concentration profile, pore fluid quality, and meteorological information. The parameters measured in the SRK study which are relevant to the current AGS study are:

    - Temperature profile was measured with the use of ground temperature cables placed at 0.3 m intervals along the tailings profile. As well, ambient temperatures were measured.
    - Infiltration and seepage was measured by recording precipitation and evaporation (daily), total infiltration and seepage (total volume of drainage from the sand under the drain in each cell), moisture content/density profile (on a bi-weekly basis using a nuclear probe).
    - Oxygen concentration profiles were measured at the locations of the lysimeters/water samples on each occasion when water samples were collected. A Neutronics Model 910 oxygen gas analyzer was used for this purpose, pumping at a rate of 100 mL/min until a stable oxygen reading was achieved.

Pore water quality, solids sampling, and surface runoff quality sampling details are not described, since such extensive testing was not within the scope of the less detailed AGS study. More detailed information of the frequency and test methods are provided in the SRK, 1987 report.

## 3.2 SRK Report on the Tailings Covers Test Facility at Faro:

*Faro Tailings Abandonment Plan Development Program, 1989 Progress Report on the Tailings Covers Test Facility*, April 1990

### 3.2.1 Purpose:

The purpose of the report was to present a status report of various data collected at the tailings covers test facility between 1987 and 1989. There were no as-built drawings or information provided, although Figure 1-2 illustrates the vertical profiles for each of these test plots. [Note: of the 6 different plots, 'test pit #5' which consists of 0.5 m of till cover over 2 m of tailings is most similar to the AGS tailings cover]

### 3.2.2 Method:

The following summarizes the methods of data collection:

- Ground temperature cables and piezometers instruments were measured monthly in July, September, October and November, 1989.
- Water samples were collected in July and October, 1989 from air/water samplers, lysimeters, and pit bottom drains.
- Temperature, pH, redox potential, conductivity, and dissolved oxygen were measured on unfiltered sample water. Alkalinity and acidity were measured immediately in the field by titration to limit the effects of iron oxidation and hydrogen ion generation.
- Water samples were filtered and 2 samples from each air/water sampler and lysimeter were collected in plastic 250 mL containers. Cation analysis samples were acidified to <pH1 using HCL. Non-acidified anion samples were also prepared.
- Tailings (solids) samples were taken in October, 1989 from the uppermost of the horizontal PVC sampling tubes from test pits 2,3,5, and 6 (extraction from 1 and 4 not successful). The samples were analysed for metals, total sulfur, sulfate, and suphide sulphur. Acid-base accounting was also used.
- Oxygen and carbon dioxide concentrations in the unsaturated zone of the test tailings were measured using a portable $O_2/CO_2$ gas analyzer in October, 1989 and February, 1990.

### 3.2.3 Results and Discussion:

The results of the 1989 monitoring event were described in this report. As well, the results of the 1987 and 1988 monitoring events were presented for comparison. The relevant discussion from the report is summarized below:

- From the results of the temperature measurements, it was noted that there was a reduction in tailings temperature during the summer months as a result of the covers placed in the plots (as compared to no cover). It was suggested that this would reduce acid generation since lower temperatures would reduce the biological growth of *T.Ferrooxidans*, thereby reducing the rate of bacterial oxidation.
- The results of pH tests of the pore water indicate that the rate of pH depression in the near surface tailings of these test pits is less than the rate in the control pit (no cover) tailings, indicating either a reduced rate of infiltration, or acid generation, or both. The pH measurements at depth in the six test pits indicated that the rate of infiltration front advance into the tailings with covers is slower than in the tailings without covers.
- Oxygen profiles of each test pit were provided. In the unsaturated zone of the tailings, the depletion of oxygen with depth is in part a function of two processes: the oxidation rate of sulphides; and the rate of oxygen diffusion into the tailings. Oxygen diffusion is in turn dependent on temperature and the permeability of the tailings. Barometric pumping is responsible for convective transport of oxygen into the tailings. The measurements in the pre-1975 tailings where test pit seven was located (not a constructed test plot as with the other six) indicated that oxygen concentrations ranged from 20.7% at the surface to 19.7% at a depth of 1.8 m. This was reported as a small reduction in oxygen and it was suggested that oxidation is not limited by oxygen availability. In the test pits of the test facility, the oxygen profiles did not indicate concentration depletion patterns with depth. Oxygen concentrations in the test pits ranged from 19.6% to 20.3%.

### 3.2.4 Conclusions:

The following conclusions were drawn from the results of the study:

- The chemical results were considered encouraging due to the low rates of acid generation in all test pits, with concentrations of select chemical parameters diverging from those found in the control test pit.
- Results indicate that changes can be detected in the rates of pore water flushing or rates of acidification in the tailings of individual test pits.

- It was recognized that the low rates of oxidation and the data variability created a problem in identifying and interpreting trends at such an early stage.
- Various recommendations were made respecting the type and frequency of measurements that were suggested for the final (1990) monitoring event.

## 3.3 Nicholson Critical Evaluation of ARD Modelling

*Critical Evaluation of Acid Mine Drainage Modelling, August, 1993*

### 3.3.1 Purpose:

The purpose of the study was to complete a critical evaluation of the test plot program and tailings modelling that was prepared by SRK Consultants Ltd. of Curragh's Down Valley tailings system. Specifically, the objective was to review several potential issues related to the SRK report, including the quality of the data, the metal mobility in the subsurface, the tailings cover test facility, the modelling assessment, and the limits of oxidation and confidence in predicted values.

### 3.3.2 Method:

The methodology included reviewing the water, solids, and gas analyses presented in the report, the results of the test-plot experiment, and the model results for predicting zinc concentrations in Rose Creek.

### 3.3.3 Results:

The results are summarized according to the key potential issues that guided the critical review exercise and that are relevant to the current study:

- The data quality was considered to be of good quality, and the protocols described in the test plot reports also suggest that data collection is correct and the quality of the data was good. An exception to this was the data respecting oxygen concentrations with depth in the test plots. The authors interpret that all data except that for TP7 appeared to be contaminated by atmospheric oxygen.

Suggestions for improved oxygen measurements were provided in a subsequent section.

- The review results for the test cover test facility generally indicate that it was an elaborate test facility designed to collect data related to sulphide mineral oxidation in tailings. The reviewers agree that the data indicate that the composite cover test pits (TP1 and TP4) reduce oxidation rates compared to the control, till covered, and organic covered test pits. The reviewers plotted the maximum observed concentrations of sulphate and iron in the top 0.5 m of the tailings against time. In these plots, it was observed that the concentrations of sulphate and iron have increased steadily over the 49-month period for all plots . However, it was noted that the largest increase in concentrations were with the control plot and organic covered plot and the smallest increases were observed with the composite covered and the till covered plots. This analysis indicates that the oxidation rates are still rising and that maximum rates have not been attained.

- There were suggested modifications to the cover test program to improve the maintenance and data collection. First, the test plots should be drained to bring water levels as low as practically possible, to better reflect the primarily unsaturated conditions of the tailings at the Faro property. Secondly, oxygen concentrations should be monitored in the test plots by inserting gas sampling tubes in a similar manner to that used on the old tailings (TP7). Permanent tubes could be installed vertically from the surface at reasonable cost so that gas samples could be collected and analyzed. Permanent tubes pushed or pounded into the tailings would minimize the potential for downward leakage of oxygen along the samplers. The original plan for horizontal installation of gas samplers through to the access tanks disregard the fact that oxygen can diffuse as easily in the horizontal direction as in the vertical direction. A simpler analytical method was recommended using inexpensive oxygen sensors so that instrument problems could be avoided. The samplers could be installed at 0.1 m intervals over the first metre with 0.5 m spacing below 1 m. It was also recommended to determine the degree of water saturation at narrow intervals within 1 m of the surface, using simple volumetric samples collected over a selected depth range. It was recommended that mass balance calculations of both sulphate and iron be conducted for the shallow zone of the tailings to provide more quantitative estimates of oxidation rates, if the residence time of water for the sampling intervals is considered. These calculations could be made with concentration data and estimates of net infiltration at the site. Finally, it was suggested that some data was not useful, and was not necessary to collect, including dissolved oxygen (DO), acid-base accounting, and solids data. The DO measurements were considered unreliable due to large sampling errors. Acid-base accounting and solids data are gross numbers with natural variations that probably mask any short term temporal changes.

There was extensive analysis of the modelling work conducted by SRK. However, this is not described herein, as it does not relate directly to the proposed monitoring program at the AGS site.

# 4.0 FIELD MONITORING SYSTEM DESIGN AND SAMPLING METHODOLOGY

## 4.1 Design Background

Following the literature review a field program and monitoring system was designed to gather empirical data with respect to the performance of the low permeability cover material as an infiltration and oxygen barrier to reduce acid generation in mine tailings at AGS. As discussed earlier, the oxidation of iron pyrite (this term is used to collectively refer to all disulphide minerals) requires oxygen and water. The generally accepted initial reaction for this process is shown below:

$$2\ FeS_2 + 7\ O_2 + 2\ H_20 \text{ ----}\rightarrow 2\ Fe_2^{+} + 4\ SO_4 + 4\ H$$

This reaction is exothermic and thus generates heat as well as acid. Therefore, even without a quantitative knowledge of the gas and heat transport properties of the tailings pond, measurements of the oxygen, moisture and temperature profiles can be interpreted to provide insight into the oxidation and, hence, potential of a tailings pond to produce acid rock drainage.

The main objective of the field program was to collect preliminary data regarding the performance of the low permeability cover at AGS to act as an oxygen and moisture barrier. Secondary objectives were to:

- Design and install monitoring equipment (soil gas probes, and ground temperature cables) to supplement further monitoring of the Arctic Gold and Silver Site in the future.
- Provide the CTFN with the knowledge to carry on further monitoring at the site should it be considered worthwhile.

The monitoring program was designed by EBA based on the information obtained from the literature review and with the technical support of Dr. Carl Mendoza of the University of Alberta, and Scott Hannam of Aurora Laboratory Services Environmental Ltd. (ALS) (formerly ASL) in Vancouver. The monitoring program was designed to evaluate the following:

- concentrations of oxygen gases within the tailings and cover
- moisture conditions within the low permeability cover and near surface tailings
- temperature profiles within and below the cover, tailings and underlying native material.
- average thickness of low permeability cover material
- groundwater conditions using existing monitoring wells at the Site
- Microbial enumeration was not conducted within this program.

## 4.2 Logistics of Field Program

The monitoring system design, installation, and initial field monitoring activities were carried out by EBA. The project was designed such that the on going monitoring would be conducted by the Carcross Tagish First Nation (CTFN) in association with INAC. There was a training session during the first monitoring event to instruct the CTFN technician, Frank James, in the use of on-site equipment to measure groundwater levels, soil vapour oxygen concentrations, and field sampling for groundwater quality. As well, EBA prepared a Field Manual for use by the CTFN, which outlined the field procedures for the monitoring as part of the field program. The field manual is included as Appendix A of the final report. Following the first monitoring event, subsequent monitoring events were conducted by Frank James of the CTFN who provided field data to EBA for evaluation.

### 4.3 Oxygen Monitoring Within Cover and Tailings

The objective of oxygen monitoring within the cover and tailings was to measure the oxygen profile within the low permeability cover and tailings to evaluate the effectiveness of the cover as a barrier to oxygen flux from the atmosphere into the tailings impoundment. The presence of oxygen in soil is known to be affected by three main factors: consumption (by redox and/or biochemical reactions), gaseous diffusion, and advection. Consumption by microorganisms, particularly *T.Ferrooxidans*, will result in the lowering of oxygen concentration within the tailings. The metabolic processes of bacteria in concert with the pyrite oxidation will further increase the rate of oxygen consumption. The conversion of ferrous to ferric iron in the overall pyrite reaction sequence has been described as the “rate determining step”, and this conversion can be greatly accelerated by Thiobacillis ferroxidans. Oxygen concentrations are reintroduced and increased by the processes of advection and diffusion through the barrier. Oxygen transport rates through diffusion are controlled by the diffusion coefficient, which is dependant on the porosity and moisture content of the cover. Another mode of oxygen flux to consider is convective and barometric pumping through the bottom and sides of the impoundment. However, this was not considered to be a major issue at AGS due to the nature of the impoundment construction since it was expected that the relatively low conductivity berms around the impoundment would limit oxygen flux through the sides of the impoundment.

### 4.3.1 Background

The key points pertaining to the monitoring of oxygen levels in soil gases that were identified through the literature review are the following:

- SRK reported high oxygen levels in soils below the cover material (at Faro Tailings), however, Nicholson reports that the horizontal tubing system that was used by SRK had resulted in erroneous data due to contamination from atmospheric oxygen.
- Nicholson recommended that permanent vertical tubes be pushed or pounded in the cover and tailings to minimize the potential for downward leakage of oxygen along the sample tubes.
- Nicholson recommends the use of oxygen sensors to evaluate oxygen levels in future monitoring programs.

Composite covers such as the one used at AGS have been shown at other sites to achieve oxidation rate reductions in the order of 100 to 1000 times over exposed tailings (Nicholson and Tibble, 1996).

During the design process for oxygen monitoring, EBA consulted specialists in soil gas sampling, Scott Hannam of ALS, and Dr. Mendoza of University of Alberta. The following are the key points obtained from these conversations.

- Scott Hannam recommended that high-density polyethylene (HDPE) tubing be used as oxygen can permeate through Teflon tubing, and thus cause contamination by atmospheric oxygen.
- Scott Hannam recommended using low flow rates for purging and sampling of the wells to ensure that short-circuiting of atmospheric oxygen along the tubing from the surface to the probe tip does not occur.
- Dr. Mendoza recommended the use of the Luer Loc™ valve system with multiple ports for sampling

### 4.3.2 Design Methodology

Based on the results of the literature review, and consultation with Dr. Mendoza and Mr. Hannam, the soil gas probe design (SGP) was finalized. The SGPs consist of a screened stainless steel tip with a high-density polyethylene (HDPE) tube that exits at the surface and is completed with a Luer Loc™ (multiple port) valve for soil gas sampling (See Figure 2).

These vertical SGPs were installed by EBA within the reclaimed tailings pond at two locations; one at the center of each of the north and south halves of the impoundment that is separated by a drainage channel (See Figure 1). SGPs were installed with a hollow tube hilti-hammer system to advance the screened tip and high-density polyethylene (HDPE) tube vertically into the ground with minimum annulus to limit short circuiting of atmospheric oxygen down the annulus (See Photograph 1). At each location, probe tips and tubes were advanced to the following layers: one into the low conductivity cover, one in the coarse ramp material (capillary barrier), and two at progressively deeper depths within the tailings. A hydrated bentonite seal was placed from 0 to 0.3 m below grade to ensure a vapour seal around the annulus of each tube (See Photograph 2). As well, a polyethylene sheet was placed along ground surface to further inhibit short-circuiting of atmospheric oxygen into the SGPs (See Photograph 3). The polyethylene sheet was then covered with some of the clayey silt cover material.

### 4.3.3 Sampling Methodology

Oxygen sampling from the SGPs was carried out during three sampling events. Samples were collected with a field instrument that measures the oxygen percentage in gas. A Minigas® 3 portable oxygen rented from EnviroRentals was used for this program. The Minigas® monitors oxygen within the range of 0 to 35% by volume with a 0.1% resolution. A careful sequence of events was followed during the sample collection. The sampling protocol is summarized in detail within the Field Manual in Appendix A of the final report. The general sampling sequence is outlined below:

- Removed 1L of gas with SKC air sampling pump (200 mL/ minute) from each SGP to purge the well.
- Closed the Luer Loc™ to ensure that atmospheric oxygen cannot enter SGP tubing

- Conditioned the well for 5 minutes
- Pass soil gas through sampler with hand pump at low flow rate
- Continue pumping at 30 second intervals until oxygen concentrations reach minimum or stabilize

As a quality assurance measure, gas bomb samples were collected for laboratory analysis to verify field readings with the Minigas® portable gas analyzer. Three gas bomb duplicate samples were collected during the first sampling event, and two gas bomb samples during the final sampling event. This was done following a recommendation by Mr. Scott Hannam of ALS. Mr. Hannam cautioned that portable oxygen analysers sometimes indicate elevated oxygen readings due to interference affects from moisture. The gas bomb samples were collected following the procedure outlined in the Field Manual of Appendix A; a collection method recommended by Mr. Hannam.

## 4.4 Physical Properties

It has been illustrated that the transport of oxygen through tailings covers was shown to be mainly by molecular diffusion resulting from concentration gradients established between the atmosphere and soil void spaces (MEND Report 2.21.1, 1992). The rate of oxygen diffusion is dependent on moisture content, grain size, and other physical properties such as flow path length (cover thickness) and porosity.

The ability of a cover material to restrict water flow is dependant primarily on hydraulic conductivity.

The field program was designed to collect information regarding the physical properties of the cover material as they relate to observed oxygen concentrations and water conditions within the tailings impoundment. The methodologies for determining these physical properties are outlined in the following sections.

### 4.4.1 Moisture Content

Moisture content affects oxygen transport in several ways. The first effect of moisture content on oxygen diffusion is the increase in aqueous film thickness around the individual particles of the mixture. The second effect is a matrix effect whereby as moisture content increases, capillary action fills the small pores with water, which increases the distance oxygen must diffuse through the water. If a fine-grained cover is to be effective as an impermeable barrier to oxygen movement then it must be able to retain moisture. Retention of moisture results in a more effective oxygen barrier in fine-grained covers, because the water occupies void spaces that otherwise would act as oxygen diffusion conduits. When looking at moisture retention, it is important to illustrate the moisture content profile in the cover and relate this to the ratio of field capacity to retain moisture.

Two shallow test pits were hand dug and soil samples were collected from regular intervals within the three distinct zones (cover material, granular ramp material and tailings). Of these samples, four were selected for moisture content testing as per the American Society for Testing and Materials (ASTM) standard test method 2216. One sample was chosen for determination of capillary-moisture properties following the method laid out in ASTM D3125.

### 4.4.2 Grain Size

The grain size of the cover material is important as it relates to the ability of the cover to transmit water and air. Smaller grainsizes generally have lower conductivities. A particle size analysis was conducted on two samples from the borrow source that was used as cover material for the impoundment. Based on the results of two grainsize curves from a previous investigation (EBA, 1999), the cover material consisted of primarily Silt (65 and 72%) and Clay (29 and 21%), with trace Sand (6 and 7%).

### 4.4.3 Hydraulic Conductivity

Hydraulic conductivity (K) may be used as a measure of the ability of the fractured or porous media to transmit water. Soils with a relatively small amount of void space such as silt or clay tend to have low hydraulic conductivity, thus inhibiting the flow of water. Gravels and clean sands would have a high hydraulic conductivity on account of the relatively large void spaces they contain. A parameter that is often associated with hydraulic conductivity is intrinsic permeability (k). The important distinction between these two terms is that K takes into account the porous medium and the fluid units while intrinsic permeability is only related to the medium. In ARD situations, the existence of gas and water in a multiphase flow system makes the use of a fluid free conductance parameter (ie. Permeability) attractive. Evaluating the permeability of the material comprising the cover is important in judging the performance of the cover as a barrier to the flow of infiltration water. The other important parameter related to groundwater flow is porosity. Porosity is the volume of voids divided by the total unit volume of the soil matrix. Collectively, hydraulic conductivity and porosity are the key parameters in the Darcy equation for groundwater flow.

The Guelph Permeameter Test is a field test of saturated hydraulic conductivity of low k soils. Water is supplied at constant head above a set of stainless steel rings that have been carefully driven into the material to be tested (See Photograph 4). During the field test on September 17$^{th}$, 2000, the rate of water infiltration into the low conductivity material over a known area was monitored over time. Two Guelph Permeameter tests were performed at the site, one at the center of the north half and the other at the center of the south half of the low permeability cover.

### 4.4.4 Cover Thickness

The thickness of the impermeable cover material was determined using a permafrost probe on September 6$^{th}$, 2000. This probe consisted of a 5 mm diameter steel rod with a pointed tip that can be used to measure the thickness of a surficial soil layer, in this case, the clayey silt cover. The method lent itself well to its application in this project, because the cover material and the granular ramp material underlining the cover have significantly different grain size properties. Thus, the two layers could be easily distinguished from each other when the apparatus was manually pushed into the ground.

## 4.5 Microbial Activity

Microorganisms are often integrally involved in the chemical alteration of minerals. Minerals, or intermediate products of their decomposition, may be directly or indirectly necessary to their metabolism. Microorganisms participate through a number of different modes, as follows:

a) the dissolution of sulphide minerals under acidic conditions (ARD),
b) the precipitation of minerals under anaerobic conditions,
c) catalysis of naturally occurring redox reactions, such as pyrite oxidation
d) the adsorption of metals by bacteria or algae, and,
e) the formation and destruction of organometallic complexes.

Micro organisms may be directly involved in cell metabolic processes where minerals are available as soluble trace elements, serve as specific oxidizing substrates, or are electron donors/acceptors in oxidation-reduction reactions.

In the case of *T.Ferroxidans*, these bacteria are known to accelerate the generation of ARD from pyritic and pyrrhotitic rocks under suitable conditions by using sulphur and sulphides for energy production as part of their metabolic processes. Bacteria tend to catalyze the most energetically favourable reaction or a reaction where the change in free energy from the oxidized to the reduced species is the greatest, which is true for ferrous oxidation. *T.Ferroxidans* have been shown to increase the iron conversion reaction rate by a factor of hundreds to as much as one million times. The by-product of the metabolic process is sulphuric acid ($H_2SO_4$).

Unfortunately budget constraints did not allow for an actual microbial enumeration of *T.Ferroxidans* within this current program.

## 4.6 Ground Temperature

The significance of temperature within the impoundment for the purposes of this investigation was twofold. Firstly, given that ARD is an exothermic (heat generating) reaction, knowledge of ground temperatures within the tailings lends valuable information as to whether ARD may be occurring at that location. Secondly, ground temperature has a marked influence on the rate of biological activity such as *T.Ferrooxidans*. The biochemical reactions that cause ARD are slowed down at lower temperatures (MEND Report 1.62.2, 1998).

Past studies have indicated that impermeable barriers such as the one at the Arctic Gold and Silver Site moderate the ground temperature, thus keeping the tailings cooler in the summer when the biochemical reactions causing AMD are most likely to occur. This is desirable, as reduced temperature should lead to reduced microbial activity and thus limit the potential for ARD generation.

Temperature profiling and monitoring was accomplished by installing a solid PVC pipe into a test pit within the impoundment. Within the PVC pipe, a string of thermistor beads (ground temperature cable) was installed into a glycol solution that was used to fill the cavity between the cable and the PVC. The bottom of the ground temperature cable was installed to a depth of approximately 1.8 m below ground surface with one thermistor bead above surface to measure air temperature.

# 5.0 FIELD PROGRAM RESULTS AND DISCUSSION

## 5.1 Oxygen Monitoring

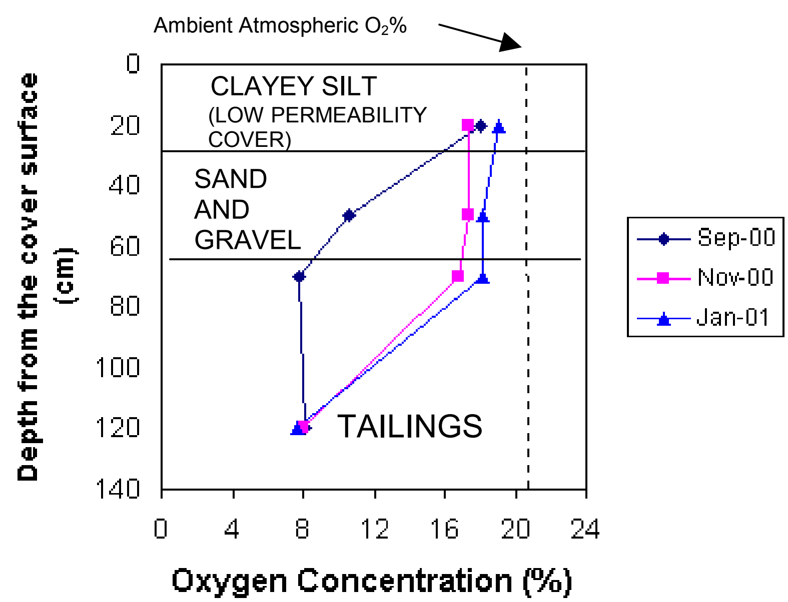
Observed oxygen readings for the multi level SGPs at SGP 1 measured with the Minigas® during the three field monitoring events are shown in table 5.1.1.

**Table 5.1.1: Oxygen Monitoring Results from SGP 1**

| Depth (cm) | Stabilized $O_2$ Reading % $O_2$ (09/19/00) | Stabilized $O_2$ Reading % $O_2$ (11/09/00) | Stabilized $O_2$ Reading % $O_2$ (01/14/01) | Average $O_2$ Reading % $O_2$ |
|---|---|---|---|---|
| 20.0 | 18.0 | 17.4 | 19.0 | 18.1 |
| 50.0 | 10.6 | 17.4 | 18.4 | 15.5 |
| 70.0 | 7.8 | 16.8 | 18.1 | 14.2 |
| 120.0 | 8.1 | 8.0 | 7.7 | 7.9 |

A graphical representation of the oxygen% monitoring data collected from SGP 1 is shown below in Figure 5.1.1. Note that ambient atmospheric oxygen concentration is 20.9 %, and has been indicated on the Figure.

**Figure 5.1.1: Oxygen Profiles for SGP 1**



The trends that can be observed based on the oxygen profile graph are the following:

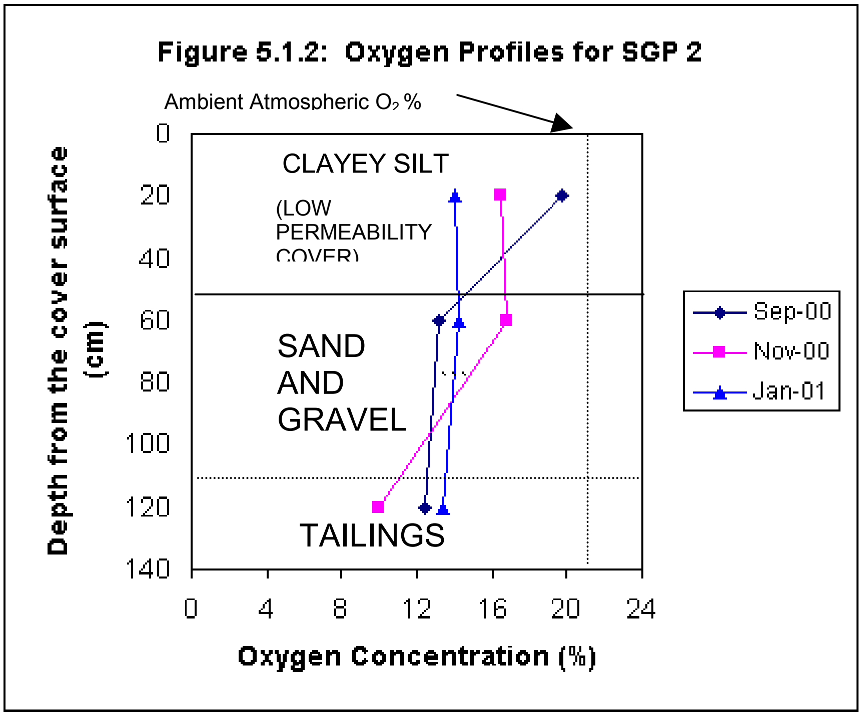
- During each monitoring event, there is less oxygen by % volume within the cover material than in ambient air. The clayey silt cover material had approximately 18% by volume of oxygen at a depth of 20 cm. This suggests that there is some limitation of oxygen flux between the atmosphere, and the tailings.
- During each monitoring event, there was a significant reduction in oxygen levels between the cover material and the tailings. The oxygen levels within the tailings were consistently at 8% by volume.
- Although there is consistency of oxygen levels with the clayey silt, and tailings over the three monitoring events, there is a temporal variability in oxygen levels within the sand and gravel and upper tailings. This could be explained by factors such as groundwater table fluctuations, seasonal frost variations, temperature effects on *T.Ferooxidan* activity, and barometric pumping, which would affect the oxygen concentrations in the sand and gravel due to the higher porosity within this layer.

Observed oxygen readings for the multi level SGPs at SGP 2 measured with the Minigas® during the three field monitoring events are shown below in table 5.1.2.

**Table 5.1.2: Oxygen Monitoring Results for SGP 2**

| Depth (cm) | Lowest $O_2$ Reading % $O_2$ (09/19/00) | Lowest $O_2$ Reading % $O_2$ (11/09/00) | Lowest $O_2$ Reading % $O_2$ (01/14/01) | Average $O_2$ Reading %$O_2$ |
|---|---|---|---|---|
| 20.0 | 19.7 | 16.5 | 14.0 | 16.7 |
| 60.0 | 13.2 | 16.8 | 14.2 | 14.7 |
| 120.0 | 12.4 | 10.0 | 13.4 | 11.9 |
| 150.0 | Plugged | Plugged | Plugged | N/A |

A graphical representation of the oxygen concentration data collected from SGP 2 is shown below in Figure 5.1.2.




The trends that can be observed based on the oxygen profile graph are the following:

- There were some temporal variations in the oxygen levels observed within the low permeability cover material at 20 cm below grade over the monitoring period. Oxygen concentrations ranged from 13 % to 19 % by volume, however they were consistently below the ambient oxygen concentrations (20.9%) suggesting that the cover material was limiting the flux of ambient air into the tailings impoundment.

- There is a noticeable reduction in $0_2$ concentrations between the clayey silt and the tailings, during the two warmer monitoring events, yet there appears to be no significant reduction in $0_2$ during the January event. This could possibly be explained by the temperature effects on *T.Ferroxidan* activity and a subsequent reduction in the rate of sulphide oxidation and hence oxygen demand.

At both SGP locations, it has been observed that there is a notable oxygen reduction with depth into the tailings. This suggests that there is some oxidation occurring within the tailings, or that decomposition of the organic silts and peats that underlie the tailings is consuming oxygen. Given that higher concentrations of oxygen exist within the sand and gravel unit above the tailings, there is a concentration gradient between these two units, which would result in the driving force for diffusion. For a typical pyritic mine waste dump, the mass of oxygen required to oxidize all the pyritic material is about a thousand times greater than the oxygen initially available in the pore space of the pile (MEND Report 1.22.1a, 1993). Thus for complete oxidation of pyritic wastes, oxygen needs to flow from the surface of the wastes to oxidation sites within the wastes. The impermeable cover system is designed to restrict this oxygen flux leading to a low oxidation rate and hence a low rate of generation of contaminants within the wastes. Whatever the mechanism of the lower levels of available oxygen within the tailings at depth, it would be valuable to observe a decrease in oxygen levels within the AGS tailings over time, as this would indicate that oxygen flux through the cover system is limiting the amount of oxygen available for pyrite oxidation within the tailings.

### 5.1.1 Gas Bomb Air Sample Results

Gas Bomb Laboratory results are included in Appendix C of the final report, and are tabulated below in table 5.1.1.1. A comparison of the Minigas® field readings with the gas bomb analytical results shows that the gas bomb samples had consistently higher oxygen concentrations than the corresponding field readings.

**Table 5.1.1.1: Gas Bomb Analytical Results Compared with Field Readings**

| Sample Name | Depth Below Ground Surface (cm) | Field Readings with Minigas® $O_2$ % | Gas Bomb Laboratory Analysis $O_2$% | Difference $0_2$ % | Relative Percent Difference % |
|---|---|---|---|---|---|
| SGP 1 @ 0.2 | 20 | 18 | 19.7 | -1.7 | -9 |
| SGP 1 @ 1.2 | 120 | 8.1 | 15.6 | -7.5 | -63 |
| SGP 2 @ 1.2 | 120 | 12.4 | 17.8 | -5.4 | -36 |
| SGP 1 @ 1.2 | 120 | 7.7 | 16.7 | -9.0 | -74 |
| SGP 2 @ 1.2 | 120 | 13.4 | 18.4 | -5.0 | -31 |

Relative percent differences between the analytical results and the field results range from 9% to 74%. According to Mr. Hannam, we should expect the opposite effect; that the moisture effects would cause elevated results in the field measurements. For this reason, and because the Minigas® had been calibrated before each use, and showed accurate ambient $0_2$ concentrations in the field, the field measurements are assumed to be accurate, while the lab results are erroneous. The differences between the two modes of sampling were discussed with ALS. Possible explanations for the unexpectedly high oxygen concentrations in analytical results are as follows:

- While collecting the gas bomb sample (1L), a vacuum is created in the gas bomb, and then allowed to fill from the SGP. The suction created from the evacuation of the SGP causes a relatively large volume of gas to be removed from the SGP in a very short period and may result in some short circuiting of atmospheric air through the annulus of the SGP, and into the sample.
- A second explanation is that during air transport to the laboratory, the gas bomb samples were subjected to changes in pressure from altitude, resulting in seepage of air through the seal of the bomb, and subsequent contamination of the sample by atmospheric oxygen.

## 5.2 Physical Properties

### 5.2.1 Cover Thickness

The cover thicknesses obtained following the methodology in Section 4.3.4 are indicated on Figure 1 at the 12 locations that were probed. The cover thickness ranged from 0.22 m to 0.45 m with an average thickness of 0.35 m. The average cover thickness indicates that the as built cover thickness exceeds the specified thickness of 0.30 m and that at 8 locations out of 12 the cover thickness equalled or exceeded the design thickness of 0.3 m. Capillary moisture relationships as indicated in Section 5.2.2 illustrate that a cover material of 0.2 m in thickness or greater would be effective as an oxygen flux barrier. Thicknesses at each of the 12 locations exceed 0.2 m.

5.2.2 Moisture Contents

Moisture content is the ratio of the mass of water to the mass of solids in the soil. Samples from each of the hand dug testpits were transported to the EBA laboratory in Whitehorse where the moisture contents were determined by weighing a sample of the soil, and then drying the sample in an oven at a temperature of 105 °C, and then reweighing the sample. Moisture contents for samples obtained from the testpits are calculated in tables 5.2.1 and 5.2.2 below, and represented graphically on Figures 5.2.1 and 5.2.2.

**Table 5.2.1**
**Moisture Contents for Test Pit 1**

| Depth (m) | Weight of Wet Soil (g) | Weight of Dry Soil (g) | Moisture Content % |
|---|---|---|---|
| 0.10 | 231.4 | 188.3 | 22.9 |
| 0.20 | 195.3 | 154.6 | 26.3 |
| 0.30 | 193.1 | 164.3 | 17.5 |
| 0.40 | 221.7 | 198.9 | 11.5 |
| 0.60 | 173.9 | 160.6 | 8.3 |
| 0.75 | 187.4 | 170.6 | 9.8 |

Figure 5.2.1: Moisture Profile for Test Pit 1

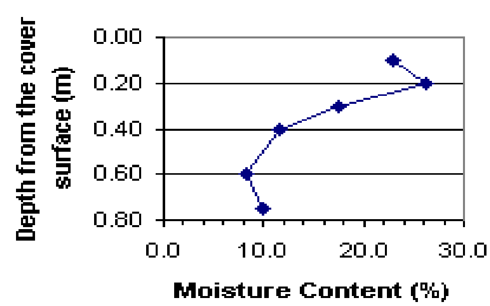
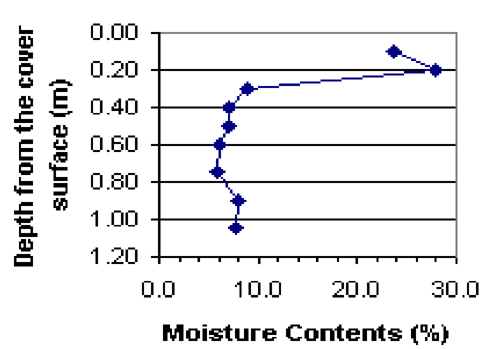



**Table 5.2.2**
**Moisture Contents for Test Pit 2**

| Depth (m) | Weight of Wet Soil (g) | Weight of Dry Soil (g) | Moisture Content % |
|---|---|---|---|
| 0.10 | 238.5 | 192.9 | 23.6 |
| 0.20 | 229.7 | 179.7 | 27.8 |
| 0.30 | 250.8 | 230.5 | 8.8 |
| 0.40 | 248.4 | 232.1 | 7.0 |
| 0.50 | 243.4 | 227.4 | 7.0 |
| 0.60 | 243.4 | 229.4 | 6.1 |
| 0.75 | 243.8 | 230.2 | 5.9 |
| 0.90 | 233.6 | 216.4 | 7.9 |
| 1.05 | 240.0 | 222.7 | 7.8 |

Figure 5.2.2: Moisture Profile for Test Pit 2

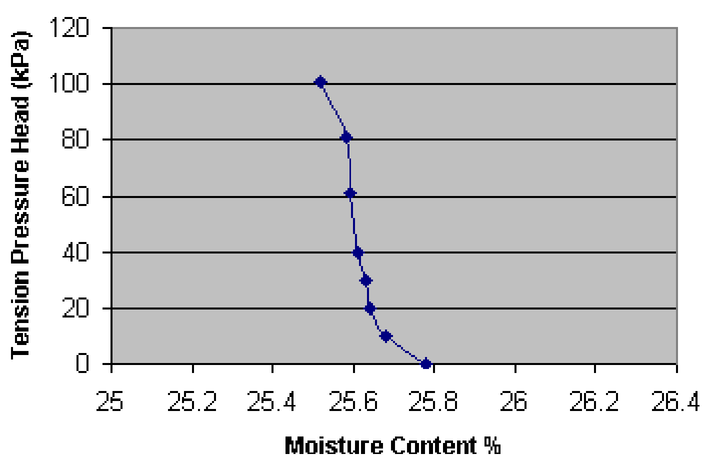


As can be observed from the tables and graphs presented above, the results of moisture content testing for each of the samples were very similar. The moisture contents started at approximately 23% at 0.10 cm and increased to approximately 27 % (full saturation) at 0.20 m within the cover material. Within the sand and gravel till below the cover, the moisture contents continued to decrease slowly. The hand-dug testpit at TP1 had refusal within the sand and gravel till on a cobble, and hence was not advanced into the tailings. TP 2, however was advanced into the tailings, where the moisture content increased slightly. Based on the moisture content results, it appears that the cover material is working effectively to limit moisture migration into the tailings impoundment.

### 5.2.3 Capillary Moisture Relationship

A sample collected from 0.1 to 0.2 m within the clayey silt cover material at TP 2 was retained for a long-term test for capillary-moisture relationships for fine textured soils by pressure membrane apparatus. This testing was completed at EBA's geotechnical laboratory in Edmonton, AB (per ASTM Standard D 3152) between December 2000, and March 2001.

FIGURE 5.2.2.1: Capillary-Moisture Relationship
DRYING CURVE



The significance of the capillary-moisture relationship as shown on Figure 5.2.2.1 is that the clayey silt cover material at 0.1 to 0.2 m below the surface of the cover did not exert a negative tension pressure head suggesting that at a moisture content of 25.8%, or 95% saturation, there is no matrix suction pressure. This means that the soil is at field capacity (fully saturated given the field conditions), and would drain if further moisture were added. This suggests that in an unsaturated environment, the maximum saturation of this material is 95% leaving 5% void space for air to occupy. Note that in Section 5.2.2 the moisture contents for samples obtained from 0.1 m at each of the testpit locations had moisture contents in the order of 26% at 0.2 m suggesting there is no matrix suction at this depth. Samples from 0.1 m at each of these locations have moisture contents below 25.8% and thus would be exerting negative matrix suction. Some of the moisture from this zone within the cover has likely been drawn out by capillary rise to the surface and subsequent evapouration. This illustrates that a protective cover less than 0.1 m in thickness would not be effective to retard oxygen diffusion. Analogously, thicknesses of silty clay greater than 0.1 m when wetted to field capacity would further decrease the amount of oxygen diffusion through the cover.

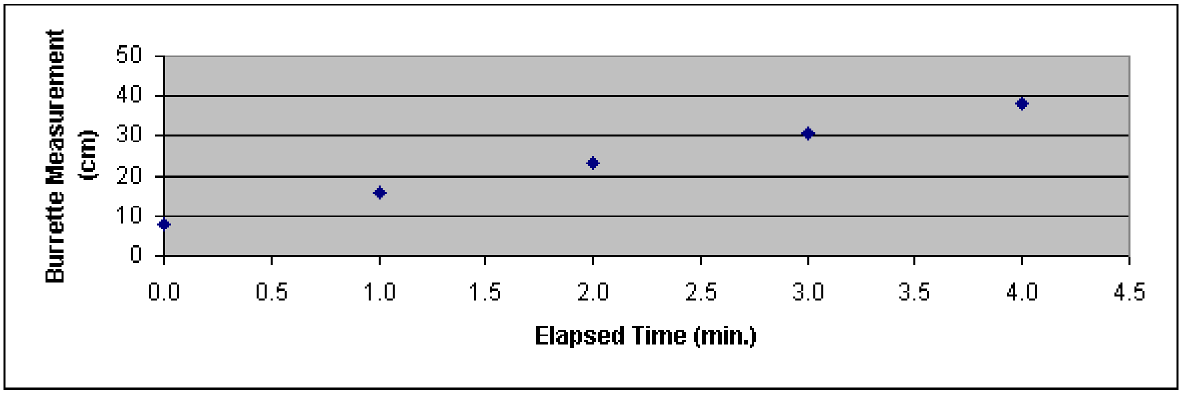
### 5.2.4 Hydraulic Conductivity

The tabulated data, and corresponding graphs and calculations for the data collected during the Guelph Permeameter tests at GP1 and GP2 (See Figure 1) are shown below.

**Table 5.2.4.1: Guelph Permeameter Testing for GP 1**

| Time | Elapsed Time (min.) | Measurement Time (s) | Burette Measurement (cm) | Measured Difference (cm) | Flow Rate (cm/s) |
|---|---|---|---|---|---|
| 9/5/00 12:55 | 0 | | 8.00 | | |
| 9/5/00 12:56 | 1 | 60 | 16.00 | 8.00 | 0.13333 |
| 9/5/00 12:57 | 2 | 60 | 23.50 | 7.50 | 0.12500 |
| 9/5/00 12:58 | 3 | 60 | 30.80 | 7.30 | 0.12167 |
| 9/5/00 12:59 | 4 | 60 | 38.20 | 7.40 | 0.12333 |

**Figure 5.2.4.1: Graph showing Guelph Permeameter Results for GP1**




**Hydraulic Conductivity Calculation for GP 1**

**Kfs=(Ç*G*A*R1)/(a((Ç*H1)+1)+(G*Ç*3.14156*(a^2)))**

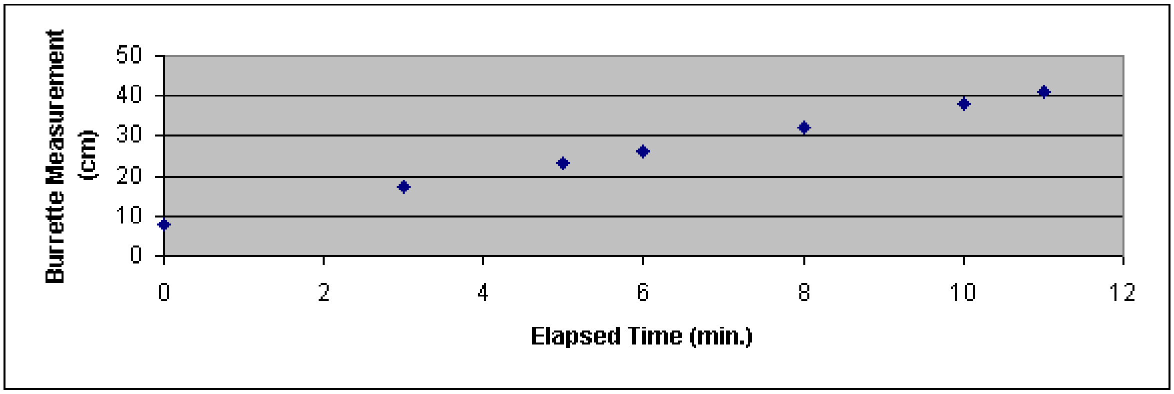
**Values:**

| | |
|---|---|
| Ç= Soil Texture/Structure Factor ($cm^{-1}$)= | 0.0100 |
| G = Dimensionless Shape Factor = 0.316(d/a)+0.184 = | 0.3736 |
| A = Cross Sectional Area of Reservoir (Burrette) ($cm^2$) = | 0.3850 |
| R1 = Steady rate of Water level fall in the reservoir (cm/s) = | **0.1250** |
| a = Inside radius of infiltration surface (cm) = | 10.0000 |
| H1 = Steady Pressure Head on the infiltration surface (cm) = | **27.0000** |
| d = Depth of penetration of cutting ring into soil (cm) = | **6.0000** |
| **Kfs = Field Saturated Hydraulic Conductivity (cm/s) =** | **1.30E-05** |

**Table 5.2.4.2: Guelph Permeameter Testing for GP 2**

| Time | Elapsed Time (min) | Measurement Time (s) | Burrette Measurement (cm) | Measured Difference (cm) | Flow Rate (cm/s) |
|---|---|---|---|---|---|
| 9/6/00 8:25 | 0 | | 8.00 | | |
| 9/6/00 8:28 | 3 | 180 | 17.50 | 9.50 | 0.05278 |
| 9/6/00 8:30 | 5 | 120 | 23.20 | 5.70 | 0.04750 |
| 9/6/00 8:31 | 6 | 60 | 26.20 | 3.00 | 0.05000 |
| 9/6/00 8:33 | 8 | 120 | 32.00 | 5.80 | 0.04833 |
| 9/6/00 8:35 | 10 | 120 | 38.20 | 6.20 | 0.05167 |
| 9/6/00 8:36 | 11 | 60 | 41.00 | 2.80 | 0.04667 |

**Figure 5.2.4.2: Guelph Permeameter Data for GP 2**




**Hydraulic Conductivity Calculation for GP 2**

**Kfs=(Ç*G*A*R1)/(a((Ç*H1)+1)+(G*Ç*3.14156*(a^2)))**

| | | |
|---|---|---|
| **Values:** | Ç= Soil Texture/Structure Factor ($cm^{-1}$)= | 0.0100 |
| | G = Dimensionless Shape Factor = 0.316(d/a)+0.184 = | 0.3736 |
| | A = Cross Sectional Area of Reservoir (Burrette) ($cm^2$) = | 0.3850 |
| | R1 = Steady rate of Water level fall in the reservoir (cm/s) = | **0.0500** |
| | a = Inside radius of infiltration surface (cm) = | 10.0000 |
| | H1 = Steady Pressure Head on the infiltration surface (cm) = | **27.0000** |
| | d = Depth of penetration of cutting ring into soil (cm) = | **6.0000** |
| | **Kfs = Field Saturated Hydraulic Conductivity (cm/s) =** | **5.18E-06** |

The Permeameter test for the cover material at GP1, at the center of the north section of the tailings impoundment yielded a hydraulic conductivity of $1.3 \times 10^{-7}$ m/s; this result is consistent with those values of hydraulic conductivity observed for silt (Freeze and Cherry 1979, pp 29). The second permeameter test at GP2 which is located at the center of the south section of the tailings impoundment, yielded a hydraulic conductivity in the order of $5 \times 10^{-8}$ m/s. This is consistent with fine silt (Freeze and Cherry, 1979, pp 29).

The permeameter tests confirmed that the material used for the cover on the mine tailings was a low permeability cover through which water would flow at a relatively slow rate.

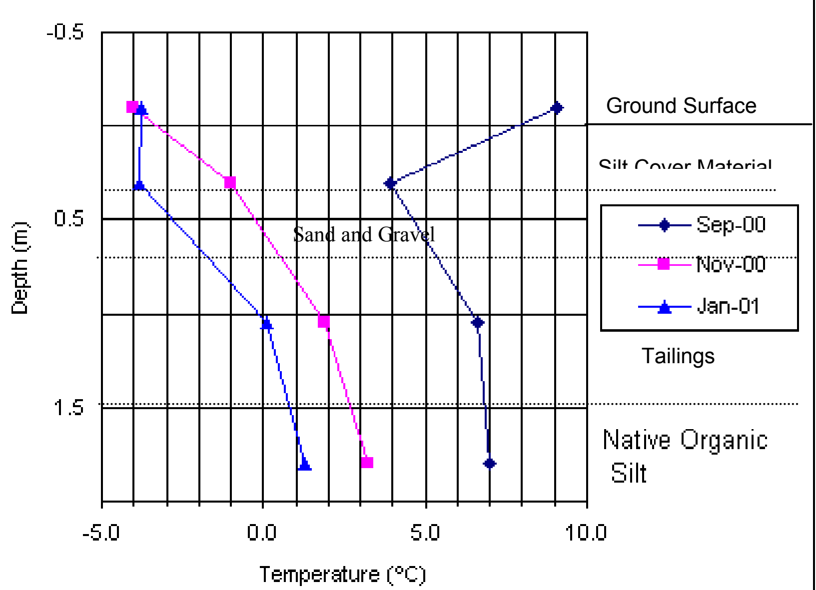
## 5.3 Ground Temperature

Ground temperatures were obtained by measuring the resistance at each of the beads on the ground temperature cable for each of the monitoring events. The thermistor string was placed such that Bead #1 was located above grade and provides an ambient air temperature. Bead #2 is positioned within the cover material, while Bead #3 is within the tailings, and Bead#4 in the native organic silt that underlies the tailings. Ground temperature readings for the 3 monitoring events are shown below in Table 5.3.1, and represented graphically in table 5.4.1:

**Table 5.3.1: Ground temperature cables Readings**

| Bead # | Depth (m) | Temp. (ºC) 09/19/00 | Temp. (ºC) 11/09/00 | Temp. (ºC) 01/14/01 |
|---|---|---|---|---|
| 1 | +0.10 | 9.08 | -4.01 | -3.79 |
| 2 | -0.30 | 3.92 | -0.98 | -3.83 |
| 3 | -1.05 | 6.63 | 1.91 | 0.08 |
| 4 | -1.80 | 6.98 | 3.26 | 1.24 |

**Figure 5.4.1: Temperature Profile**



The following key observations are illustrated in Figure 5.4.1:

- The range of temperatures observed during each of the monitoring events did not fluctuate as much as did the ambient atmospheric temperatures, which suggests that the cover material has a moderating effect on the ground temperature within the tailings, resulting in cooler ground temperatures (in summer and fall) and hence less biological activity. This is consistent with the result reported by SRK for the tailings cover test facility at Faro.
- The tailings temperatures are very similar but always slightly colder than the underlying organic silt. Should ARD be occurring at this location, it would be expected that the temperature at 1.05 m within the tailings would be elevated with respect to that at 1.8 m within the underlying silt, due to the exothermic nature of pyritic redox reactions.
- The temperature within the tailings at 1.05 m below grade does not drop below 0°C and reaches a maximum of 7°C in September (It is expected to be slightly higher during the summer months). A linear interpolation of this graph suggests that ground frost extended to the surface of the tailings during the November monitoring event, and to approximately 1.0 m at the time of the January monitoring event.
- It should also be noted that the winter of 2001/2001 was exceptionally warm when compared to Yukon normals. This has resulted in warmer than normal ground temperatures.

## 6.0 CONCLUSIONS AND RECOMMENDATIONS

The observations from this field program serve as an excellent supplement to the Summary Report for Arctic Gold and Silver Tailings Site Remediation (EBA, 2001), as a verification of as-built conditions of the cover system. Results of this study have confirmed the cover thickness, and low conductivity properties of the clayey silt cover. This investigation has also provided valuable preliminary data to evaluate the performance of the low permeability cover system.

Observations from this field-program, indicate that there is preliminary evidence that the low permeability cover at AGS is functioning effectively as a moisture and oxygen barrier. This preliminary information is optimistic for the use of this type of system for future reclamation at other mine sites throughout Yukon. However, long term observations of temperature and oxygen concentrations within the cover and tailings, and groundwater quality from below the tailings would be valuable to further the knowledge of the effectiveness of this type of system to inhibit ARD production. Limited data, and data variability has restricted the effectiveness of identifying and interpreting definitive trends at such an early stage. Thus, it would be valuable to continue monitoring observe oxygen levels within the tailings to observe whether there is a continued reduction within the tailings over time. A continued reduction over time would indicate that oxygen flux through the cover system is limiting the amount of oxygen available for pyrite oxidation within the tailings.

The following work could be conducted at the AGS site to further this study, and the assessment of ARD conditions:

- Ongoing oxygen monitoring (2 or 3 events per year) for 3 years to get sufficient data set to make more definitive conclusions
- Ongoing temperature monitoring (2 or 3 events per year in conjunction with oxygen monitoring)
- Ongoing moisture content monitoring (2 events per year in conjunction with oxygen monitoring)
- Groundwater Chemistry to compare with Baseline values (every 2 years for long term)

Based on the results of this investigation, it appears that the collection of gas bomb oxygen samples is not effective, and further oxygen monitoring should be conducted with the Mini Gas potable oxygen monitor.

Frank James, the CTFN representative was trained to collect SGP oxygen samples and ground temperature cables readings. Should further monitoring work at the site proceed; Frank James or another CTFN representative could carry out this fieldwork under the supervision of EBA. Some of the more specialized fieldwork that has been recommended groundwater chemistry should be conducted by EBA directly.

## 7.0 ACKNOWLEDGEMENTS

This project was a collaborative effort involving the expertise of persons both in the private and public sector. EBA would like to acknowledge the contribution of the various people that aided in both the field program and the preparation of this report.

The project was initiated by Michael Billowits, P.Eng., formerly of EBA, and now working with Public Works and Government Services Canada (PWGSC) in Hull, Quebec as the Manager of Contaminated Sites in the Environmental Services Branch. He managed the project until his departure from EBA in September 2000. Given the PWGSC involvement in this project Mr. Billowits was also able to review this report. Mark Palmer, currently the regional manager of environmental services for PWGSC, conducted a review of this report on behalf of Indian and Northern Affairs Canada.

Technical advisement in the preparation of the field program was provided by Dr. Carl Mendoza and Scott Hannam. Dr. Carl Mendoza is a professor with University of Alberta, with expertise in soil gas sampling, and vapour transport within the subsurface. Scott Hannam, a senior scientist with Aurora Laboratory Services Environmental, aided in the selection of appropriate equipment for the field program.

EBA would also like to acknowledge the contributions of Frank James of the Carcross Tagish First Nation in the gathering of field data for this project, and Kirn Dhillon of EBA for his assistance in the preparation of this report.

## 8.0 CLOSURE

EBA Engineering Consultants Ltd. has appreciated the opportunity to be involved in this research project for the Mining Environmental Research Group and to work with our partners in this project; INAC, CTFN, U of A, and PWGSC. If you have any questions or concerns regarding any of the information presented, please contact the undersigned.

Respectfully submitted,

Prepared by:

Ryan M. Martin, MSc.(Eng.), P.Eng
Project Engineer, Environmental
*(Direct Line: (867) 668-2071, ext. 31)*
*(e-mail: rmartin@eba.ca)*

Reviewed by:

J. Richard Trimble, M.Sc. (Eng.), P.Eng
Project Director, Yukon Region
(Direct Line: (867) 668-2071, ext. 22)
(email: rtrimble@eba.ca)

RMM/ksd

**References**

EBA Engineering Consultants Ltd. 1999. Soil Investigation Program for AGS Capping Material km 50.7 Tagish Road, Carcross unpublished report for Carcross Tagish Development Corporation. June.

EBA Engineering Consultants Ltd. 2001. Summary Report Arctic Gold and Silver Tailings Site Remediation Near Carcross Yukon unpublished report for Public Works and Government Services Canada. March.

Freeze, R. Allen, and John A. Cherry. 1979 . Goundwater . Englewood Cliffs, New Jersey: Prentice Hall

Nicholson, R.V., and J.M. Scharer. 1993. Critical Evaluation of Acid Mine Drainage Modeling, 1986-1991 for Curragh, Down Valley Tailings, Faro, Yukon., Unpublished contract report prepared for Environmental Protection, Environment Canada. August: pp 65.

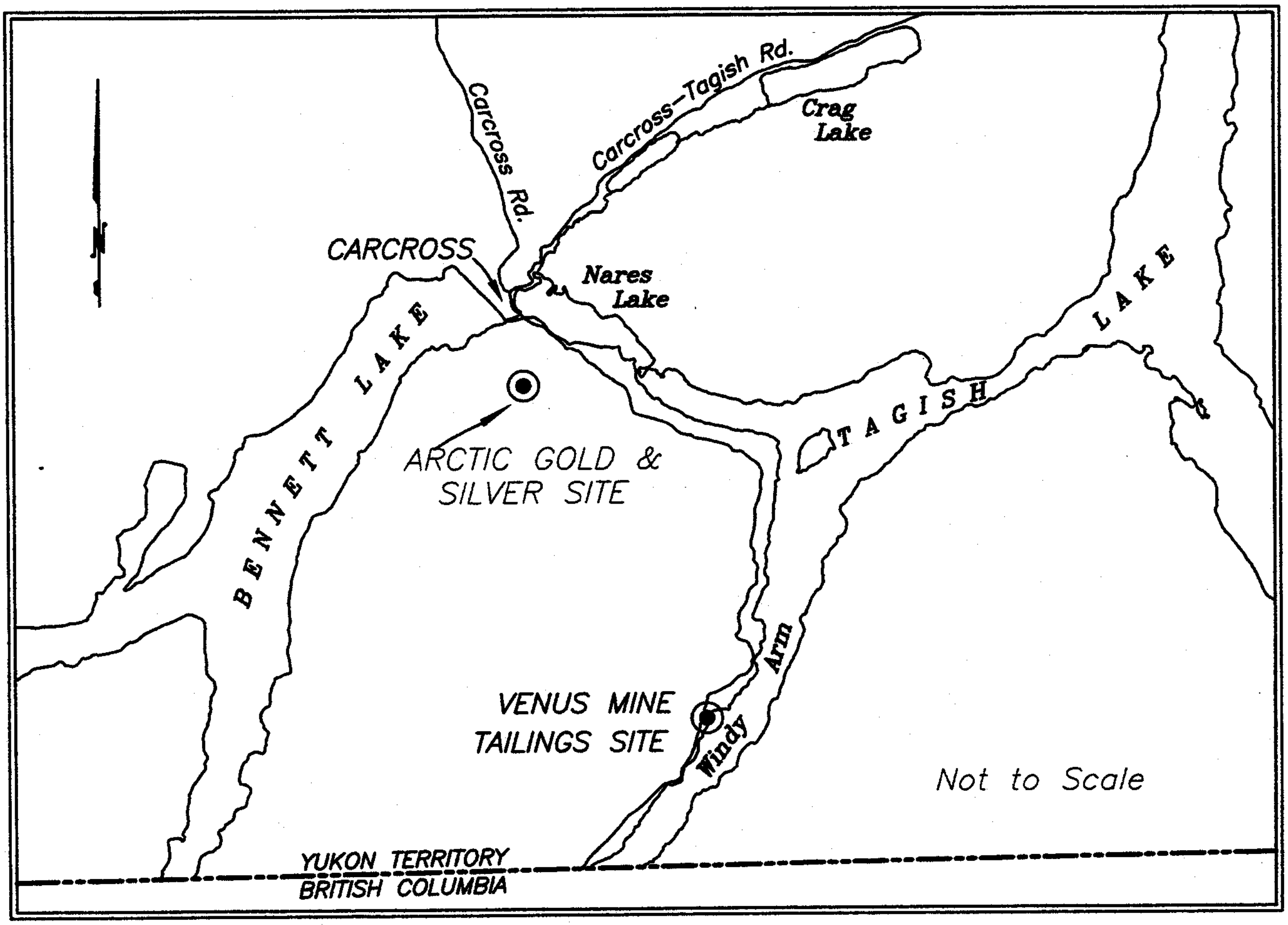
Nolan, Davis and Associates (N.B.) Limited. 1993. Field Procedures Manual, Gas Transfer Measurements, Waste Rock Piles, Heath Steele Mines, New Brunswick published report in Mine Environment Neutral Drainage (MEND) Program Report 1.22.1a. May.

Norwest Mine Services Ltd. 1998. Acid Mine Drainage Behaviour in Low Temperature Regimes-Thermal Properties of Tailings published report in MEND 1.62.2. July.

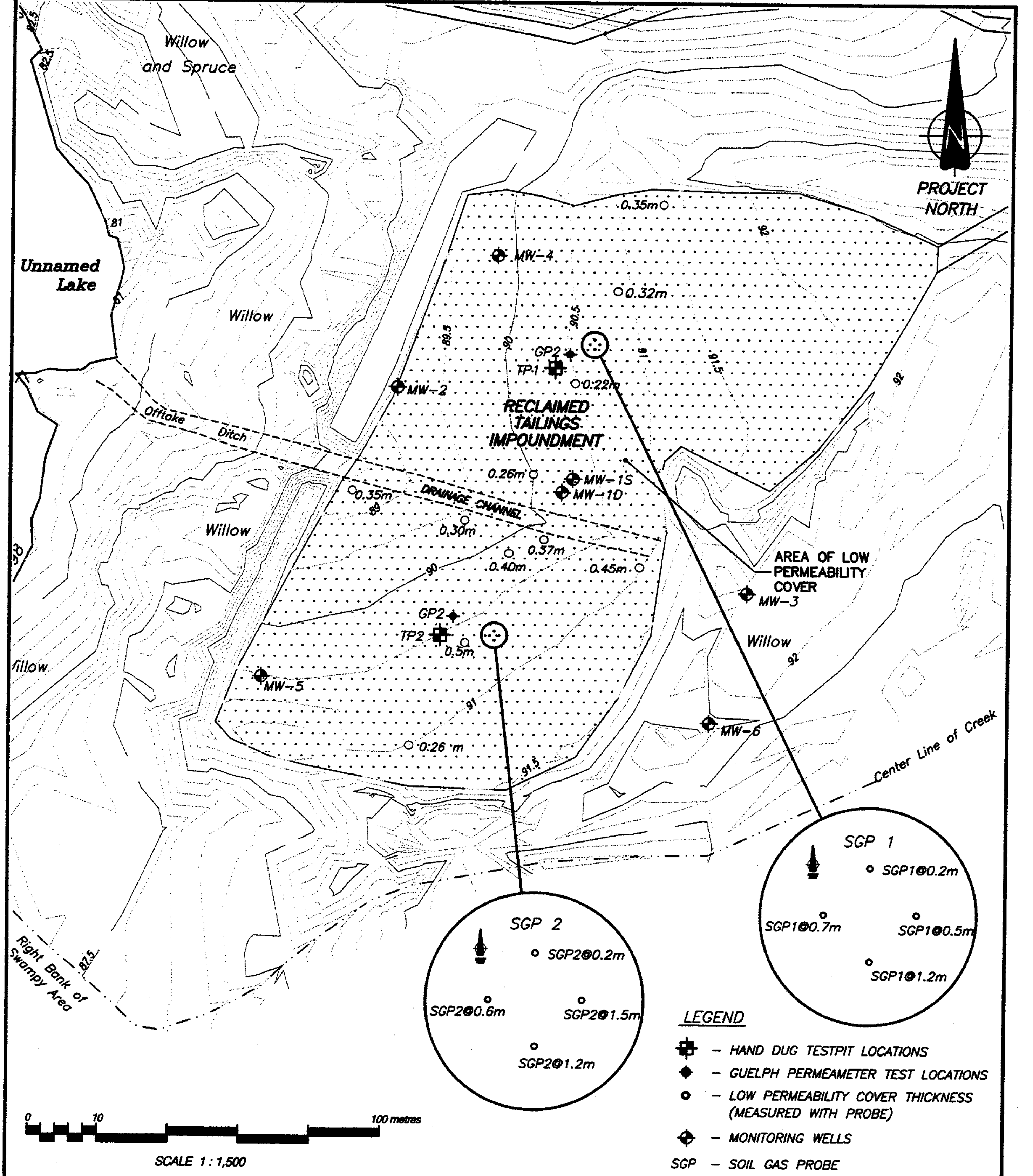
Steffen Robertson & Kirsten (B.C.) Inc. 1987. Faro Mine Tailings, Tailings Abandonment Plan Development Program, Unpublished contract report prepared for Curragh Resources. 117 Industrial Road, Whitehorse, Yukon, January: pp 45.

Steffen Robertson & Kirsten (B.C.) Inc. 1990. *Faro Tailings Abandonment Plan Development Program, 1989 Progress Report on the Tailings Covers Test Facility,* Unpublished contract report prepared for Curragh Resources Inc. 117 Industrial Road, Whitehorse, Yukon, Report 60620, April: pp 55.

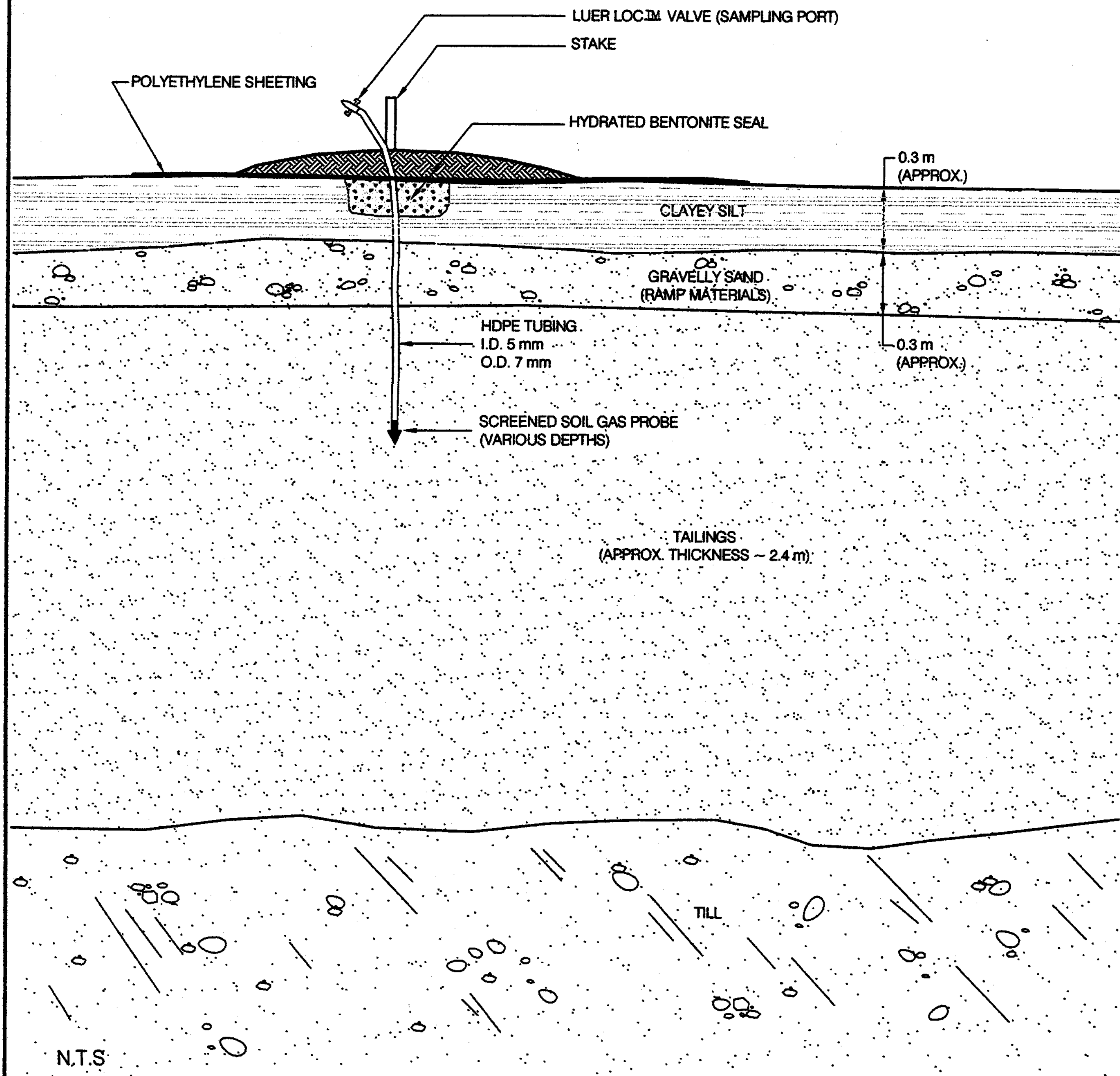
University of Waterloo. 1992. Development of Laboratory Methodologies for Evaluating the Effectiveness of Reactive Tailings Covers published report in MEND 2.2.1.1. March.




| EBA Engineering Consultants Ltd. | | | PROJECT: EVALUATION OF LOW PERMEABILITY COVER ARCTIC GOLD & SILVER TAILINGS POND - CARCROSS, YT. | |
|---|---|---|---|---|
| CLIENT: MERG/DIAND | | | TITLE: SITE LOCATION | |
| DATE JULY, 2001 | DWN. RMM | CHKD. RMM | FILE NO. 0201-00-14535 | DRWG. FIGURE 1 |




| EBA Engineering Consultants Ltd. | PROJECT: EVALUATION OF LOW PERMEABILITY COVER ARCTIC GOLD & SILVER TAILINGS POND - CARCROSS, YT. |
|---|---|
| CLIENT: MERG/DIAND | TITLE: SITE PLAN SHOWING SAMPLING LOCATIONS |
| DATE: JULY, 2001 — DWN.: JSB — CHKD.: RMM | FILE NO.: 0201-00-14535 — DRWG.: FIGURE 2 |




| | | | |
|---|---|---|---|
| EBA Engineering Consultants Ltd. | | PROJECT: EVALUATION OF LOW PERMEABILITY COVER ARCTIC GOLD & SILVER TAILINGS POND - CARCROSS, YT. | |
| CLIENT: MERG/DIAND | | TITLE: SGP CONSTRUCTION DETAILS | |
| DATE: JULY, 2001 | DWN.: JSB | CHKD.: RMM | FILE NO.: 0201-00-14535 | DRWG.: FIGURE 3 |