Peer Review of MEND Studies Conducted from 1990 to 1994 on Acidic Drainage at Mine Doyon South Waste Rock Dump

MEND Project 1.14.3-E

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November 1996

Peer Review of MEND Studies Conducted from 1990 to 1994 on Acidic Drainage at Mine Doyon South Waste Rock Dump

Cadillac, Quebec

Final Report

MEND Prediction Committee

PWGSC Contract No. 234RO-4-1510/01-SQ
CANMET Scientific Authority: Mr. Carl Weatherell
Our File No. M-6080 (010571)
November, 1996

By:

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EXECUTIVE SUMMARY

The south waste rock dump at Mine Doyon, Cadillac, Québec has been generating acidic drainage since 1985, two years after the dump was started. Acid generation increased steadily from 1985 to 1988 and since 1988 the dump has been generating strong acidic drainage which is presently collected and treated with lime.

Between 1991 and 1994 the south dump has been the subject of extensive investigations and studies carried out through the MEND Prediction Committee primarily by Groupe de Recherche en Géologie de l'Ingénieur (GREGI), Université Laval, Sainte-Foy, Québec. The results of these studies have been issued in a series of ten reports. The site investigations included tasks such as drilling and sampling of the rock dump materials; piezometer, lysimeter and thermocouple installations; sampling of acidic drainage, groundwater and pore water; collection of gas samples within the dump; collection of microbiological specimens; measurement of surface temperatures and temperature profiles in the dump; and collection of climatic and hydrologic data. The laboratory and analytical studies carried out included characterization of the physico-chemical and mechanical properties of the different types of waste rock; water chemistry analyses including rapid chemical techniques to monitor acid mine drainage; hydrology and water budget studies; geotechnical and hydrological studies including evaluation of dry barriers; extensive studies of mineralogy and geochemical processes; microbiological enumeration and diversity studies; and predictive modeling of acid mine drainage processes including heat transfer analysis. One of the more important objectives of the studies at the south dump was to measure physical and chemical properties of an actual waste dump and to identify key processes contributing to the generation of acid mine drainage.

The MEND Prediction Committee arranged for a peer review of the studies carried out at the south dump by a designated group of expert consultants (Peer Review Team). The peer review was carried out under five separate technical components identified as (i) hydrology, (ii) geotechnology and hydrogeology, (iii) geochemistry and mineralogy, (iv) microbiology and (v) predictive modeling. The Peer Review Team made a technical and scientific review of the ten reports provided by the MEND Prediction Committee with particular reference to providing a critique of strong and weak points, identifying new information and understanding developed from the studies and suggesting areas for future work. This report provides the peer review commentary on the Mine Doyon study.

The overall conclusion of the peer review is that the Mine Doyon study has provided a new understanding of some specific technical issues and represents a thorough and exceptionally well documented case study. The peer review also identified a number of inconsistencies and occasional technical errors in the reports which should be corrected. The inconsistencies occur mainly in the earlier reports which were issued without the benefit of the complete study results, also budget and time constraints were a contributing factor.

SOMMAIRE EXÉCUTIF

La halde de stériles sud de la Mine Doyon, Cadillac, Québec est génératrice de drainage minier acide depuis 1985, soit deux ans après le début de son utilisation. La génération d'acide a progressivement augmentée de 1985 à 1988 et depuis 1988, la halde sud génère un drainage très acide qui est présentement capté et traité à la chaux.

Entre 1991 et 1994, la halde sud a fait l'objet d'études et de sondages intensifs exécutés par l'entremise du comité de prédiction du NEDEM principalement par le Groupe de recherche en géologie de l'ingénieur (GREGI), Université Laval, Sainte-Foy, Québec. Les résultats de ces études sont présentés dans une série de dix rapports. L'examen du site incluait des travaux, tels le forage et l'échantillonnage du stérile de la halde; l'installation de piézomètres, de lysimètres et de thermocouples; l'échantillonnage du drainage acide, de l'eau souterraine et interstitielle; la récupération d'échantillons de gaz dans la halde; la cueillette de spécimens microbiologiques; la mesure des températures de surfaces et du profil des températures dans la halde; et la cueillette de données climatiques et hydrologiques. Les études de laboratoires et les analyses effectuées comprenaient: la caractérisation physico-chimique et les propriétés mécaniques de différents types de roches stériles; l'analyse chimique de l'eau incluant des techniques chimiques rapides afin de suivre de près l'évolution du drainage minier acide; l'étude de l'hydrologie et du bilan hydrique; des études géotechniques et hydrologiques incluant l'évaluation de barrières sèches; des études approfondies de la minéralogie et de la géochimie; des études de dénombrement et de diversité microbiologique; et la modélisation prédictive du processus de génération d'acide incluant l'analyse du transfert de la chaleur. Un des objectifs principaux des études sur la halde sud était de mesurer les propriétés physiques et chimiques d'une halde de stériles existante et d'identifier les processus clés contribuants à la génération du drainage minier acide.

Le comité de prédiction du NEDEM a mandaté un groupe d'experts-consultants (l'équipe de révision par les pairs) afin de réviser les études réalisées sur la halde sud. La révision par les pairs a été effectuée selon cinq composantes techniques indépendantes, soit: (i) l'hydrologie; (ii) la géotechnique et l'hydrogéologie; (iii) la géochimie et la minéralogie; (iv) la microbiologie; et (v) la modélisation prédictive. L'équipe de révision a passé en revue les aspects techniques et scientifiques des dix rapports fournis par le comité de prédiction du NEDEM en prêtant une attention particulière à l'analyse critique des points forts et faibles, en mettant en évidence l'information et les connaissances nouvelles issues de ces études et en suggérant des avenues pour des travaux futurs. Ce rapport présente les commentaires de l'équipe de révision sur l'étude de la Mine Doyon.

La conclusion générale du comité de révision est que l'étude de la Mine Doyon fournit une nouvelle compréhension de certaines questions techniques spécifiques et elle représente une étude de cas approfondie et exceptionnellement bien documentée. Le comité de révision a aussi identifié, dans les rapports, un nombre d'inconsistance et d'erreurs techniques occasionnelles qui devraient être corrigées. Les inconsistances ont été relevées principalement dans les premiers rapports, soit ceux qui n'ont pu bénéficier des résultats d'études complètes, les contraintes budgétaires et de temps étant des facteurs contributifs.

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1. INTRODUCTION

1.1 Background

The Mine Environmental Neutral Drainage Program (MEND), through its Federal, Provincial and Industrial partners, has sponsored studies from 1990 to 1994 on Acid Mine Drainage (AMD) mechanisms at the south waste rock dump, La Mine Doyon, Québec. The studies were carried out by Groupe de Recherche en Géologie de l'Ingénieur (GREGI), Départment de Génie Géologique, Faculté des Sciences et de Génie, Université Laval, Sainte-Foy, Québec and Dr. Roger Guay representing both EnviroMine Inc., L'Ancienne-Lorette, Québec and Départment de Microbiologie, Faculté de Medecine, Université Laval, Sainte-Foy, Québec.

Most of the results of the studies have been incorporated in a series of ten reports which are referenced at the end of this Chapter. Eight of the reports have been prepared by various personnel of GREGI and two of the reports have been prepared by Dr. Roger Guay. With the exception of two GREGI reports (GREGI, 1991-19 and GREGI, 1994-04), the reports have been issued as MEND documents. The ten reports (referred to collectively as the MEND reports) form the data base for the peer review of acid mine drainage mechanisms at the Mine Doyon south dump. Additional data collection and studies have been carried out after publication of the ten reports, however, this additional information has not been incorporated in the peer review.

1.2 Objectives of MEND Program for South Dump

The overall objectives of the MEND Program at the south dump are provided in the Statement of Work for the peer review, a copy of which is included in Appendix A. These objectives are summarized as follows:

1. Document AMD conditions and evaluate dry cover for control of AMD conditions.

2. Evaluate physico-chemical and mechanical characteristics of four main rock units to assess their susceptibility to weathering and AMD production.

3. Use existing boreholes drilled through the dump to:

    - Sample groundwater at base of dump;

    - Trap microorganisms potentially responsible for AMD;

- Evaluate kinetics of acid production in experimental conditions simulating waste rock dumps; and

- Correlate physico-chemical conditions to the most probable microbiological mechanisms in acid generation under aerobic conditions.

4. Establish the water budget for the south dump.

5. Develop a mineralogical index to describe and characterize mineral transformations in acid producing waste dumps with reference to Mine Doyon.

More detailed objectives for the specific technical components of the south dump study program are given in the individual MEND reports.

1.3 Objectives for Peer Review of MEND Reports

The objectives for the peer review of the MEND reports as provided in the Statement of Work for the project are summarized as follows:

1. Perform a technical and scientific review (including overall judgment of the work and a critique of the strong and weak points of the work) of all aspects of the Mine Doyon work included in the ten MEND reports.

2. Determine what new information and understanding was developed from the project.

3. Indicate how the new information and understanding can be used to predict, abate or control the generation of AMD in waste rock dumps.

4. Suggest areas for future work (and additional information requirements) with a goal to:

   - Increase the understanding of AMD production in waste rock dumps; and

   - Develop viable technology for predicting the effects of remedial technology.

5. Provide an estimate of cost for the suggested future work.

1.4 Peer Review Team and Approach to Review

The Statement of Work for the project indicated that the following organizations and key personnel would provide expert consultants to form the Peer Review Team:

- Geocon, Division of SNC-LAVALIN Environment Inc. (Geocon)
(Mr. Les MacPhie)

- Unité de Recherche et de Service en Technologie Minérale (URSTM)
(Mr. Denis Bois)

- Noranda Technology Centre (NTC)
(Mr. Michael Li)

- Senes Consultants Limited (Senes)
  (Ms. Carol Pettit)

It was further indicated in the Statement of Work that Geocon act as Lead Contractor for the project. Based on the guidelines provided for the project, the following technical components of the review were identified:

- Hydrology
- Geotechnology and Hydrogeology
- Geochemistry
- Microbiology
- Predictive Modeling

The approach taken for the scientific and technical review was to assign primary review responsibility of a specific technical component to the organization with the most relevant experience and personnel for the task. The approach was further refined by assigning secondary review responsibility for each technical component to a separate organization. The primary review responsibility included detailed review of the MEND reports relevant to the assigned technical component and preparation of the peer review comments. The secondary review responsibility included general review of MEND reports relevant to the assigned technical component and review input to the comments prepared by the primary reviewer. The Peer Review Team and assigned technical components resulting from the above approach are summarized on Table 1-1 together with reference to the MEND reports relevant to each technical component. Overall coordination of the peer review was provided by Geocon acting as Lead Contractor.

A draft version of the peer review report was submitted to MEND (who solicited comments from 5 selected reviewers) and the draft report was also provided to the researchers for comment. The comments received were reviewed by the peer review team and the necessary modifications resulting from them were incorporated to produce the present Final Report.

1.5 Organization of Report

Chapter 2.0 of this report provides a brief description of the site location and history. Chapters 3.0 to 7.0 provide the peer review comments on Hydrology, Geotechnology and Hydrogeology, Geochemistry and Mineralogy, Microbiology and Predictive Modeling respectively.

A reasonably consistent format has been used for Chapters 3.0 to 7.0 and the contents of each Chapter essentially follow the peer review objectives defined in Article 1.3. Following the technical and scientific review, each Chapter includes comments on new understandings developed from the Mine Doyon study and the possible application of these new understandings. Also, in accordance with the peer review objectives, areas for future work are identified. A summary of the peer review is provided at the end of Chapters 3.0 to 7.0. Reference should be made to these summaries for specific conclusions on each of the technical components identified for the peer review.

Chapter 8.0 provides brief overall conclusions with respect to the technical approaches used to investigate and analyze the Mine Doyon south dump and with respect to presentation and technical details in the ten MEND reports reviewed.

References are included at the end of each Chapter.

Appendix A includes the Statement of Work for peer review.

At the request of the MEND Prediction Committee, Appendix B (bound separately) contains specific editorial comments on the ten MEND reports to assist in finalizing these reports. Many of the comments in Appendix B have already been discussed as part of the Peer Review Report.

TABLE 1-1

Peer Review Team and Assigned Technical Components

<table>
<tr><th colspan="2">Peer Review Team</th><th rowspan="2">Assigned Technical Component</th><th rowspan="2">Relevant MEND Reports</th></tr>
<tr><th>Primary Review</th><th>Secondary Review</th></tr>
<tr><td><u>Geocon</u>
• Mr. Les MacPhie
• Mr. Bertrand Massé</td><td><u>NTC</u>
• Mr. Luc St-Arnaud</td><td>Hydrology (Chapter 3)</td><td>GREGI, 1994-06
GREGI, 1994-12</td></tr>
<tr><td><u>URSTM</u>
• Mr. Denis Bois
• Dr. Jacques Ouellet
• Mr. Bruno Bussière</td><td><u>Geocon</u>
• Mr. Les MacPhie
• Dr. Narendra Verma</td><td>Geotechnology and Hydrogeology (Chapter 4)</td><td>GREGI, 1991-19
GREGI, 1994-6
GREGI, 1994-12</td></tr>
<tr><td><u>NTC</u>
• Mr. Michael Li</td><td><u>Senes</u>
• Ms. Carol Pettit
• Dr. Jeno Scharer</td><td>Geochemistry (Chapter 5)</td><td>GREGI, 1991-19; GREGI, 1993-03; GREGI, 1993-04; GREGI, 1993-05; GREGI, 1994-04; GREGI, 1994-06; GREGI, 1994-12</td></tr>
<tr><td><u>URSTM</u>
• Mr. Denis Bois
• Dr. Lucie St-Amand
• Dr. François Godard</td><td><u>Senes</u>
• Ms. Carol Pettit
• Dr. Jeno Scharer

<u>NTC</u>
• Ms. Pascale St-Germain</td><td>Microbiology (Chapter 6)</td><td>Guay, 1993;
Guay, 1994;
GREGI, 1994-12</td></tr>
<tr><td><u>Senes</u>
• Ms. Carol Pettit
• Dr. Jeno Scharer</td><td><u>NTC</u>
• Mr. Michael Li

<u>Geocon</u>
• Dr. Kevin Morin*
(Specialist Advisor)</td><td>Predictive Modeling (Chapter 7)</td><td>GREGI, 1991-19; GREGI, 1993-03; GREGI, 1993-04; GREGI, 1993-05; GREGI, 1994-06; GREGI, 1994-12</td></tr>
</table>

* Dr. Kevin Morin of Morwijk Enterprises Ltd., Vancouver, B.C., acted as specialist advisor to Geocon on predictive modeling

1.6 References

GREGI, 1991-19 (Gélinas, P., Choquette, M.P., Lefebvre, R., Isabel, D., Leroueil, S., Locat, J., Bérubé, M., Theriault, D. et Masson, A.). Evaluation du drainage minier acide et des barrières sèches pour les haldes de stérils: Étude du site de la Mine Doyon. Rapport GREGI 91-19, Juillet.

GREGI, 1993-03 (Lefebvre, R., Gélinas, P. and Isabel, D.). Heat transfer during acid mine drainage production in a waste rock dump, la Mine Doyon (Québec). Rapport GREGI 93-03, March. MEND report 1.14.2, March, 1994.

GREGI, 1993-04 (Choquette, M., Gélinas, P. and Isabel, D.). Two rapid methods to evaluate acid mine drainage composition: Total dissolved solids and energy dispersive X-Ray fluorescence spectroscopy. Rapport GREGI 93-04, March, revised December, 1993. MEND report 1.14.2, March, 1994.

GREGI, 1993-05 (Choquette, M., Gélinas, P. and Isabel, D.). Monitoring of acid mine drainage: Chemical data from la Mine Doyon - south waste rock dump. Rapport GREGI 93-05, March, revised December, 1993. MEND report 1.14.2, March, 1994.

GREGI, 1994-04 (Locat, J., Bérubé, M.A., Gélinas, P., et Choquette, M.). Caractéristiques physico-chimiques et mécaniques des principales unités lithologiques à la Mine Doyon. Rapport GREGI 94-04, Janvier.

GREGI, 1994-05 (Isabel, D., Gélinas, P.J., Bourque, E., Nastev, M. and Précourt, S.). Water budget for the waste rock dump at la Mine Doyon, Québec. Report GREGI 1994-05, March. MEND report 1.14.2e, March, 1994.

GREGI, 1994-06 (Choquette, M. and Gélinas, P.). Mineralogical transformations associated with AMD production in a waste rock dump, la Mine Doyon - south waste rock dump. Rapport GREGI 1994-06, March. MEND report 1.14.2f, March, 1994.

GREGI, 1994-12 (Gélinas, P., Lefebvre, R., Choquette, M., Isabel, D., Locat, J. and Guay, R.). Monitoring and modeling of acid mine drainage from waste rock dumps, la Mine Doyon case study. Rapport GREGI 1994-12, August, revised September, 1994. MEND report 1.14.2g, June, 1994.

Guay, R., 1993. Development of a modified MPN procedure to emunerate iron oxide bacteria. Final report by EnviroMine Inc., February. MEND report 1.14.2, March, 1994.

Guay, R., 1994. Diversité microbiologique dans la production de drainage minièr acide à la halde sud de la Mine Doyon. Rapport final par Départment de Microbiologie, Faculté de Médecine, Université Laval, Mars. MEND report 1.14.2, March, 1994.

2. SITE LOCATION AND HISTORY

2.1 Site Location

La Mine Doyon is located between Rouyn-Noranda and Val d'Or, Québec as illustrated on Figure 2-1. More specifically the site is located about 3 km north of Highway 117 and directly northwest of Rivière Bousquet as shown on Figure 2-2. The site is located within the watershed limits of Rivière Bousquet which flows to the northeast from the site to Lac Chassignolle over a distance of about 5 km. Flow from Lac Chassignolle eventually reports to the Rivière des Outaouais system via Lac Preissac and Rivière Kinojevis.

2.2 Site History

The following brief history of La Mine Doyon is extracted from two of the GREGI reports (GREGI, 1991-19 and GREGI, 1994-12). Mine operations started in 1978 and open pit mining was carried out from 1978 to 1989. Underground mining was started in 1989 at which time open pit mining was stopped. During the open pit phase of the operation, two open pits (the main pit and the west pit) were developed and two waste dumps (the north dump and the south dump) were constructed. The north dump was constructed initially and received overburden stripping plus waste rock. The south dump was constructed from 1983 to 1988 and received waste rock from the main pit, minor amounts of overburden and the less reactive waste rock from the west pit. Figure 2-3 illustrates the layout of the Mine Doyon site including the open pits and the dumps.

The original ground within the limits of the south dump was originally drained by two small streams as illustrated by the original ground contours and drainage courses on Figure 2-4. Most of the original ground within the south dump limits drains to the northwest with a smaller part draining to the east. Also a small part of the northeast corner drains to the northeast. The trees were cleared at the south dump before placement of waste rock to the existing configuration shown on Figure 2-5. The existing south dump covers an area of about 53 ha and contains an estimated 21 million tonnes of waste rock having a volume of about 11.5 million cubic metres and an average thickness of about 30 m.

Figure 2-6 is an aerial photograph of the Mine Doyon site taken in 1972 before development of the mine. The outline of the south dump is shown on this figure with respect to Rivière Bousquet. Figure 2-7 is an aerial photograph of the site taken in 1983 and shows the initial fills placed at the south dump as well as the limits cleared for the dump. Figure 2-8 is an aerial photograph of the site taken in 1994 and illustrates the present condition of the south dump.

The acidic drainage problem at the south dump became apparent in 1985, two years after the dump was started. Acid generation increased steadily from 1985 to 1988 and has continued at a reasonably constant rate since 1988. The acidic drainage from the south dump is collected and treated using a high density sludge process (Firlotte et al., 1991).

2.3 References

Firlotte, F.W., Gélinas, P., Knapp, R. and McMullen, J., 1991. Acid drainage treatment at the Mine Doyon: Evolution and future direction. Proceedings of Second International Conference on the Abatement of Acidic Drainage, Montreal, September 16-18, vol. 4, pp. 119-139.

GREGI, 1991-19 (Gelinas, P., Choquette, M.P., Lefebvre, R., Isabel, D., Leroueil, S., Locat, J., Bérubé, M., Theriault, D. et Masson, A.). Evaluation du drainage minier acide et des barrières sèches pour les haldes de stérils: Étude du site de la Mine Doyon. Rapport GREGI 91-19, Juillet.

GREGI, 1994-12 (Gélinas, P., Lefebvre, R., Choquette, M., Isabel, D., Locat, J. and Guay, R.). Monitoring and modeling of acid mine drainage from waste rock dumps, la Mine Doyon case study. Report GREGI 1994-12, August, revised September, 1994. MEND report 1.14.2g, June, 1994.

Figure 2-1
Location Map of La Mine Doyon
(after GREGI, 1994-12)

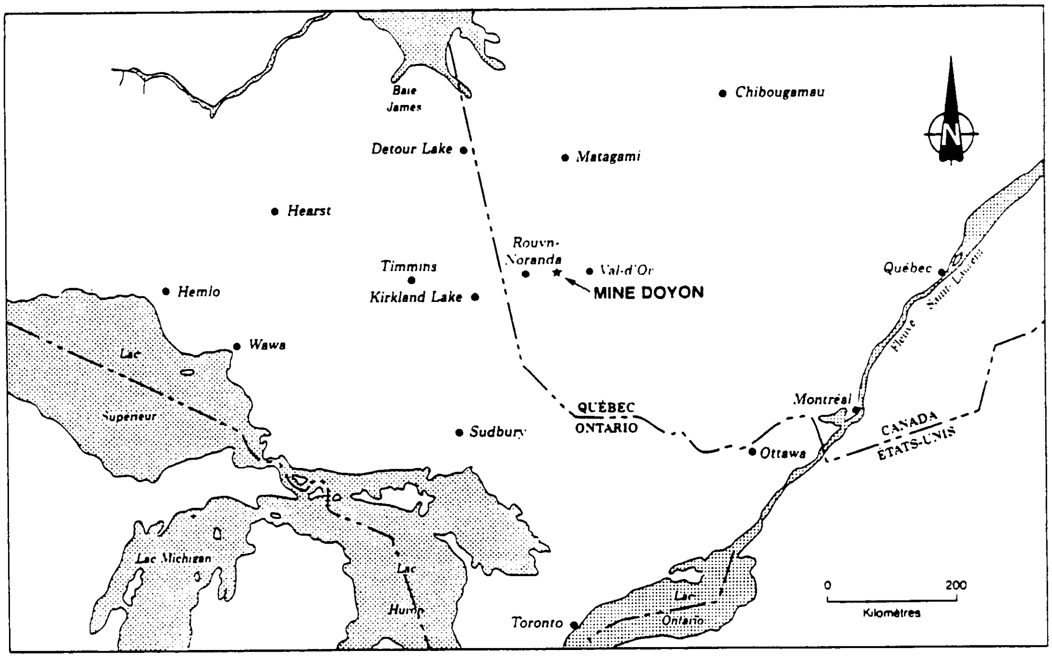

Figure 2-2
Regional Location of La Mine Doyon

SCALE 1:50,000

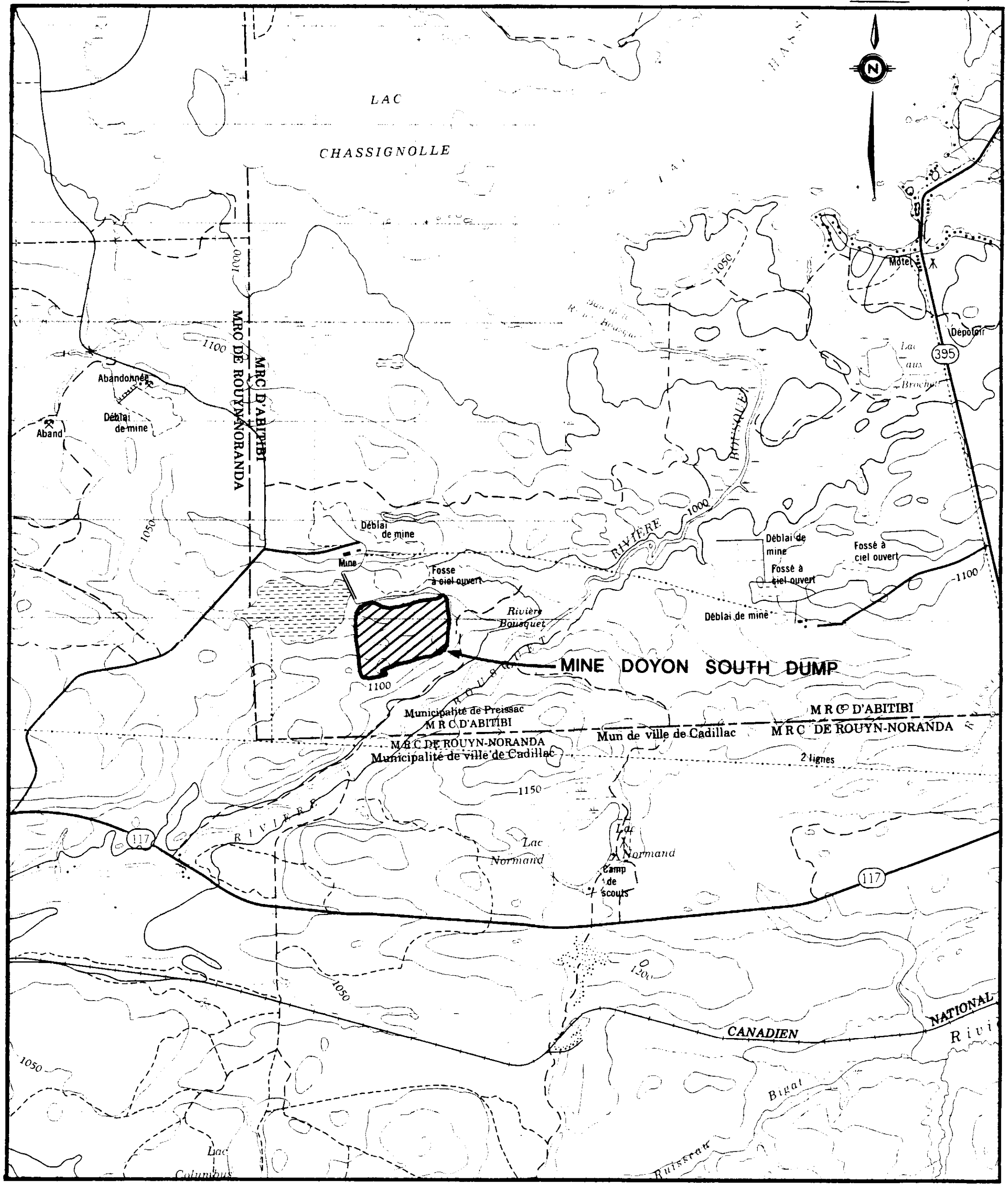

Figure 2-3
Schematic Plan of La Mine Doyon Site
(after GREGI, 1994-12)

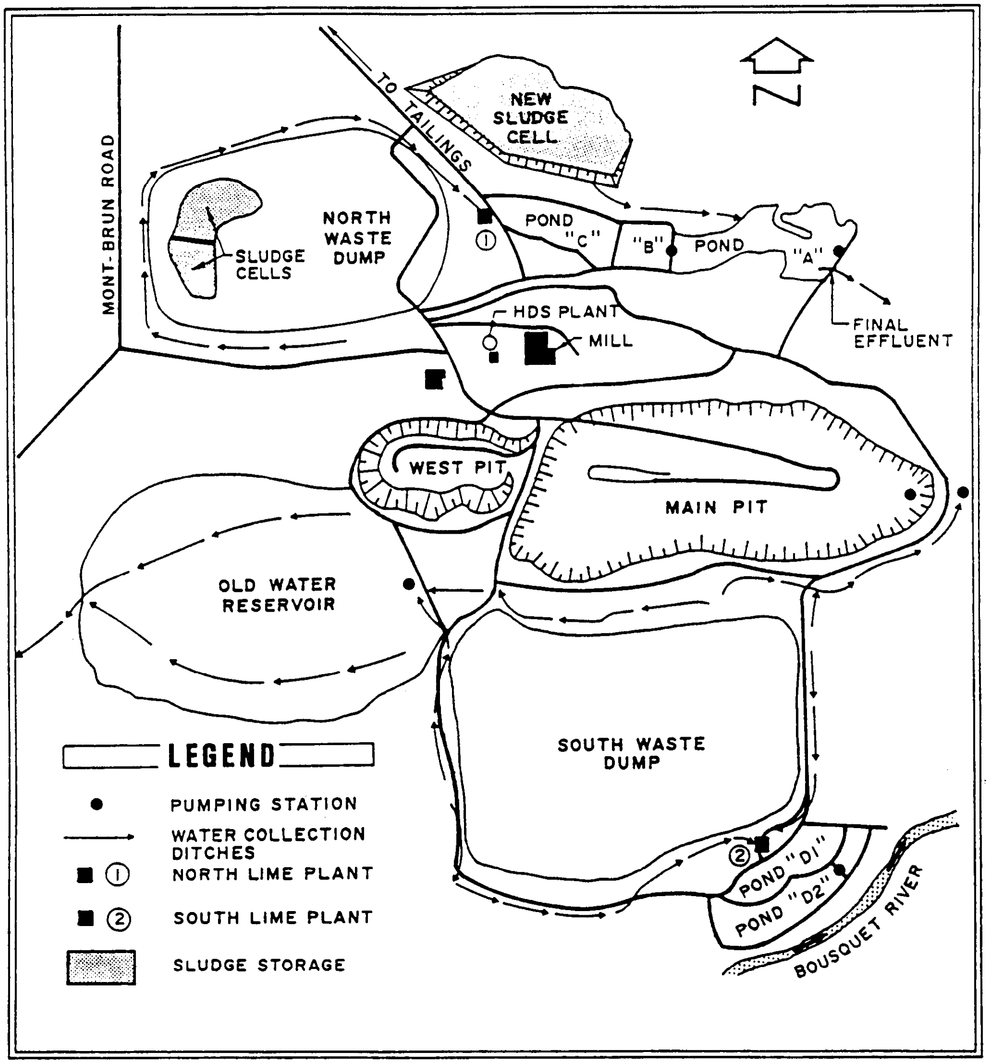

Figure 2-4

Original Topography of South Dump (after GREGI, 1991-19)

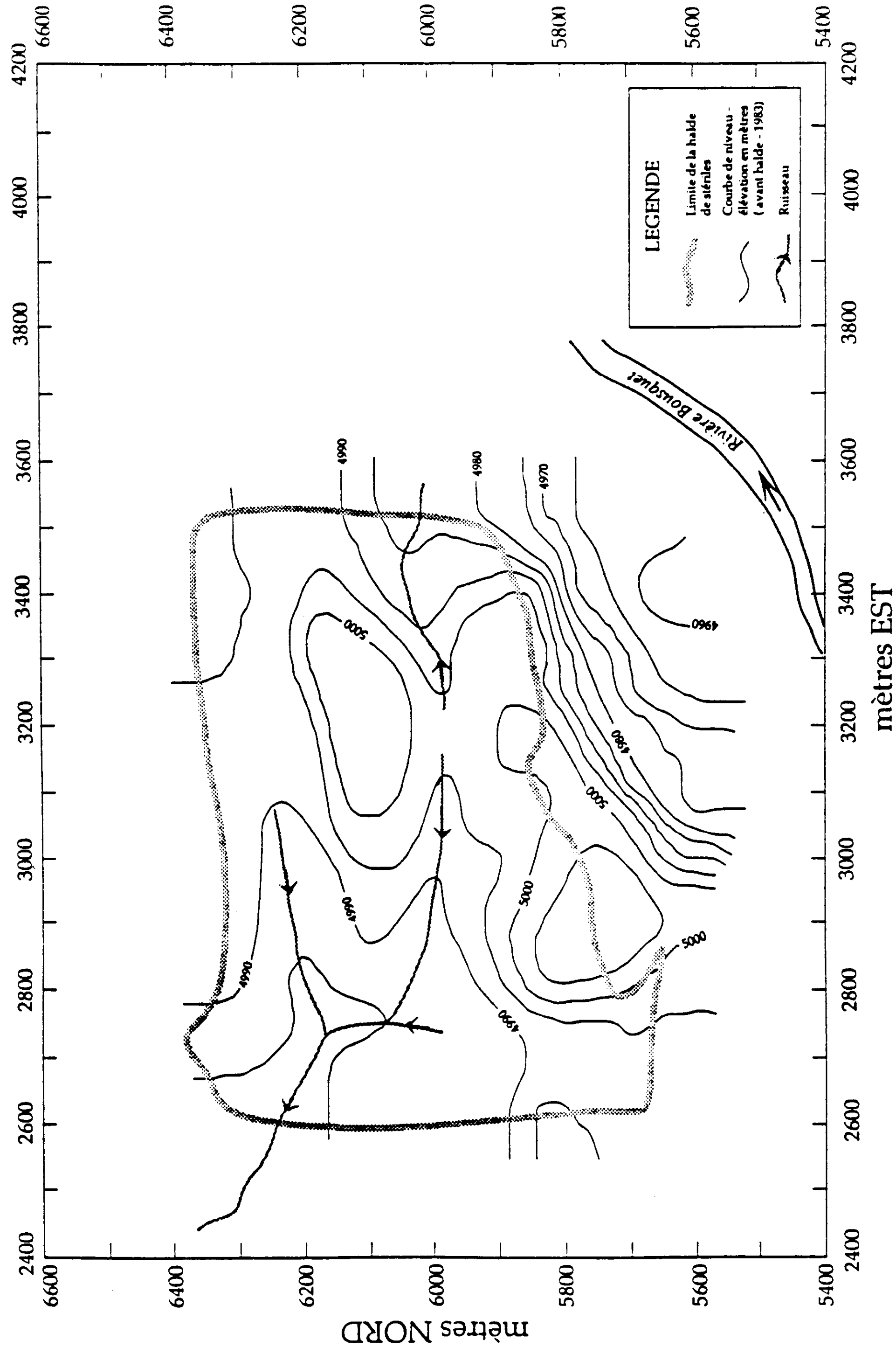

Figure 2-5
Plan of Completed South Dump
(after GREGI, 1994-12)

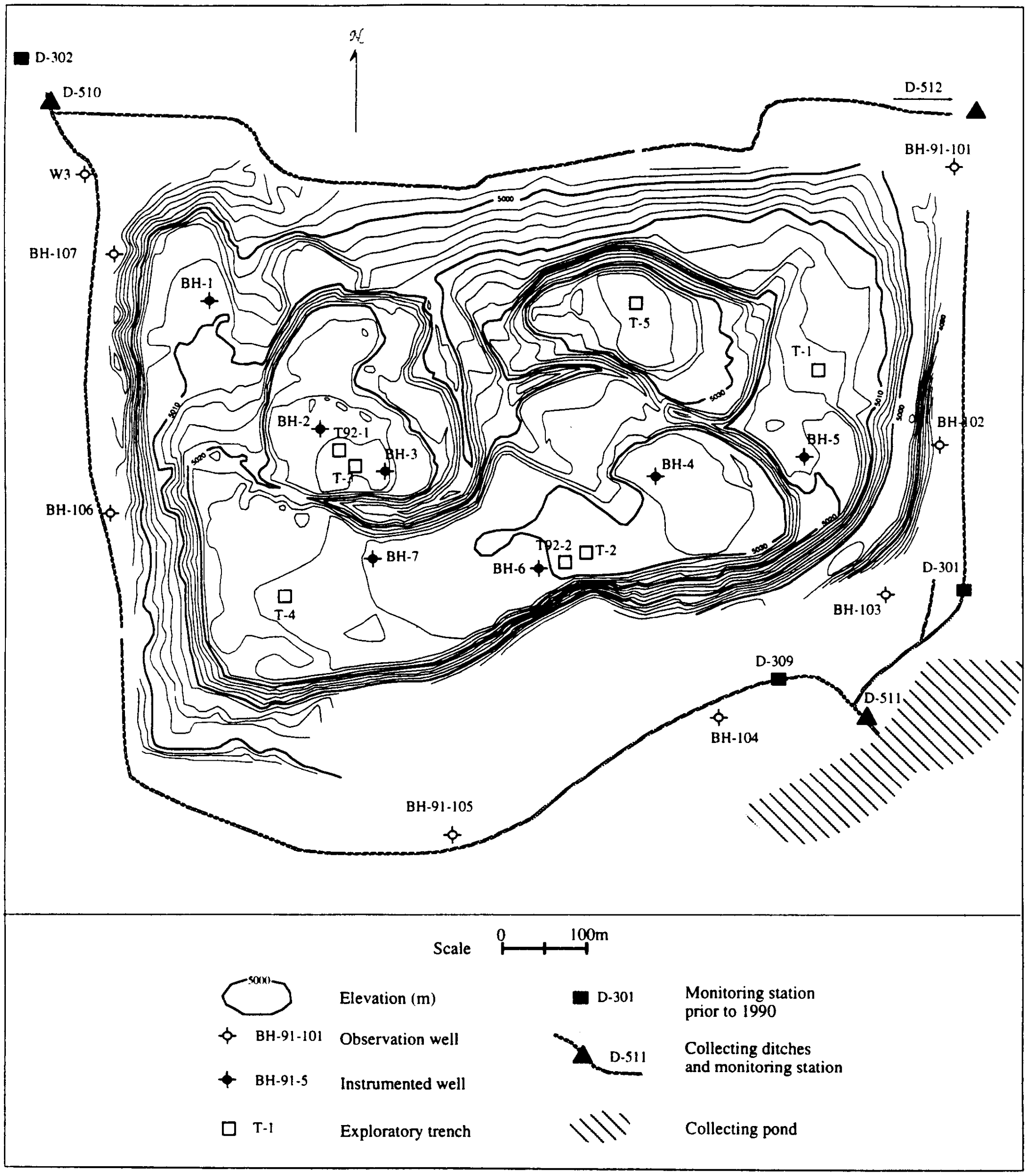

Figure 2-6
1972 Aerial Photo of La Mine Doyon Site
Before Development

SCALE 1:15,000

Figure 2-7

1983 Aerial Photo of La Mine Doyon Site

at Start of South Dump Construction

SCALE 1:15,000

Figure 2-8

1994 Aerial Photo of La Mine Doyon Site and Completed South Dump

SCALE 1:15,000

3. HYDROLOGY

3.1 General

A hydrology study was conducted with the purpose of establishing the water budget for the south waste rock dump at La Mine Doyon. The study was performed by the GREGI research team at Université Laval and the results are presented in a report (GREGI, 1994-05) which is referred to herein as the water budget report. The objectives of the study were described in the water budget report (p.3) and are summarized as follows:

- To present the hydrological data made available by the various ongoing characterization programs at La Mine Doyon;
- To present both classical and innovative methodologies used to monitor the hydrological processes at the mine site; and
- To present a comprehensive water budget of the south dump.

Classical hydrological methods were used for the analysis of meteorological and climatic data collected at nearby weather stations as well as at the automatic weather station located on the site. More innovative methods, like computer modeling, were used to estimate hydrological variables that cannot be measured.

3.2 Hydrologic Data Collection

Regional Meteorological Data

Three weather stations are in operation in the region. They are the Kinojevis River station (#7086630), the Amos station (#7090120) and the Val d'Or airport station (#7098600). The stations are located at distances ranging between 25 and 60 km from Mine Doyon, the closest being the Kinojevis station. At the time of the study, complete daily data sets of precipitation and temperature were available for the years 1991 and 1992.

On-site Meteorological Instrumentation

An automated weather station has been in operation on the site since March 1992. That station records precipitation, temperature and relative humidity and, since June 1992, atmospheric pressure at 15-minute intervals. However, the records are not complete due to various system testing and adjustments, as well as operational errors and a strike of technicians in the spring and summer of 1992.

On-site Hydrological Instrumentation

The local hydrological instrumentation is composed of weir stations, piezometers and lysimeters stations.

The three weir stations, or runoff gauging stations, are located at the end of ditches that circle the south dump. The flowmeters have displays of cumulative runoff volumes which are recorded weekly by the operator. The stations are not operated during winter due to ice formation.

A series of piezometers used to measure water levels are in operation at the south dump since 1991. Infiltration is measured since the summer of 1992 by a series of lysimeters buried at various depths in the south dump.

3.3 Hydrologic Data Analyses

The collected data sets were used to assess the various elements of the south dump water budget. Three different analyses were performed:

- Estimation of annual and monthly hydrologic budgets based on meteorological data and on base flow separation of recorded hydrographs at weir stations;
- Analysis of some single rainfall-runoff events using the unit hydrograph technique; and
- Assessment of the groundwater flow component at the site with the help of a numerical hydrogeological model.

The application of these techniques first required an analysis of the various types of data collected at the site and at nearby weather stations.

Precipitation data

The monthly distributions of precipitation for 1991 and 1992 were derived by weighting the monthly precipitations recorded at the three regional weather stations. The relative weight of each station was assumed proportional to the inverse of the distance between the station and the Mine Doyon site:

$$I_w = \sum_{i=1}^{3} \frac{\frac{1}{r_i} I_i}{R}$$

where I_w is the monthly weighted precipitation at Mine Doyon; I_i is the recorded monthly precipitation at station i; r_i is the distance between station i and Mine Doyon; and R is given by:

$$R = \sum_{i=1}^{3} \frac{1}{r_i}$$

This is a classical method for determining precipitation at a particular location.

Runoff

The data collected at the weir stations were available on graphical support only. Numerical data could only be obtained by manually digitizing the display which was difficult due to lack of adequate time reference. However, weekly runoff totals, hand-recorded by operators, were available. The weekly records were converted into daily flowrates by assigning constant discharges for all days of a particular week. Missing data for the winter periods were interpolated assuming constant base flow rates between sporadical measurements obtained by breaking the ice cover. A more standard method for interpolating winter flows is to assume a recession curve since this better reflects the expected variation of base flow during the winter. The recession curve could be fitted to the available flow data recorded during the winter months.

Figure 5 of the water budget report shows two peaks for the spring snowmelt at station W-511 while only one peak is apparent for the two other stations. The authors explain the discrepancy by the morphology and orientation of each basin. Basin 511 is facing south and is steeper than the others. Snow accumulation at the toe of the dump responds very rapidly to changes in temperature on a day to day basis and little water is contributed by the dump itself. Basin 510 is facing north west and north and it contains about 80% of the waste dump. Its flow is more important and always more evenly distributed than the other basins.

Infiltration

Graphs of cumulative infiltration heights were produced based on measurements carried out at the lysimeter stations. Figures 8 and 9 of the water budget report show a net increase in infiltration during the snowmelt period. The annual infiltration height is about 450 mm at station T92-1 and 300 mm at station T92-2. The smaller infiltration height for the latter station could be explained by its location in a highly reactive zone where strong heat losses are observed at the dump surface. Variability in gradation and compaction of the dump material at these two stations could also be a contributing factor. The authors consider that the spring 1993 infiltration estimates are not reliable because the moisture in the top layer of the soil has not stabilized due to late installation of the gravity lysimeters in summer 1992.

3.3.1 Annual and Monthly Hydrologic Budgets

Base Flow Separation for the Whole Basin

For the entire watershed, the base flow component of recorded runoff hydrographs was obtained by a graphical hydrograph separation method. The results of that analysis are presented in Table 5 of the water budget report and it is mentioned in the text (p.23) that

"...The hydrograph is traced on semilog paper and recession curves appear as linear slopes tangent to the lower part of the hydrograph curve. This kind of graphical presentation is included in Appendix C".

While this method of flow separation is standard, if one looks at the curves of Appendix C it looks very difficult, if not impossible, to trace linear slopes tangent to the lower part of the hydrograph curve. This is due to the linear interpolation method that was used to obtain daily discharges from weekly records. Therefore the results of base flow separation presented in Table 5 are questionable. It is believed that better results would have been obtained if the hydrographs had first been smoothed.

Since 1994, a new digital recording system has been used and more reliable results were obtained.

Waste Rock Dump Base Flow

The base flow component applicable to the waste rock dump was estimated by subdividing the whole watershed into subbasins representative of the type of soil surface. Four types of soils were identified: vegetation, earth fill, bedrock outcrop and waste rock. Table 7 of the water budget report shows the areas for each type of soil surface. An error can be noted in that table for the earth fill area covered by weir station 510: the area of subbasin #18 is missing. This error also affects the results of Table 8: the waste rock dump base flow component should be increased by about 7 to 8%. In any case, it can be concluded that most of the base flow comes from the waste rock dump.

Water Budget

Section 3.1 of the water budget report (p.21) is supposed to result in annual and monthly water budgets. Actually, no such results appear: there is a monthly distribution of precipitation but no monthly distributions of runoff, base flow, infiltration or evaporation.

3.3.2 Single Rainfall Runoff Events Analysis

The purpose of this part of the water budget report (Section 3.2) is to assess the temporal relation between rainfall and runoff for some single rainfall-runoff events on the waste rock dump. It is mentioned that the classical unit hydrograph is used to perform that assessment. Actually, the method used is the so-called "Instantaneous Unit Hydrograph (IUH)" method which differs from the former by the fact that the IUH method corresponds to the runoff resulting form a storm of duration approaching 0. The equation for discharge presented on page 31 of the water budget report also contains an error; it should read:

$$Q_t = \frac{1}{k(n-1)!} \cdot \left(\frac{t}{k}\right)^{n-1} \cdot e^{-\frac{t}{k}}$$

The application of the method appears correct. However, the objective is not fulfilled since it is not possible to derive any information applicable to the waste rock dump in particular. The analysis is based on recorded hydrographs measured at the outlets of the watershed, not near the waste dump. It is therefore impossible to extrapolate the results to the waste dump. Section 3.2.2 of the water budget report could be discarded without affecting any of the conclusions or could be included as an Appendix to the report.

3.3.3 Hydrogeological Modelling

The only comment that will be made here is that the recharge rate used for the modeling is assumed to be 260 mm/year, as per the values in Table 8 of the report. However, it was mentioned in Article 3.3.1 above that an error in Table 7 had as a consequence that the values in Table 8 should be increased by 7 to 8%. This should be taken into account in the hydrogeological modeling.

3.4 Water Budget for Waste Dump

The results of the water budget analysis for the waste dump are presented in Section 3.4 of the water budget report.

Precipitation

Based on the three regional weather stations, the average annual precipitation for the period 1991-1992 is 855 mm, of which about 25 to 30% comes from snow. This is very close to the average precipitation for the period 1941-1970 according to the "Hydrological Atlas of Canada" (Environment Canada, 1978). The Atlas also says that the average annual snow accumulation for the area is 240 mm, which represents 28% of the total precipitation.

Runoff

For the three years for which there were flow rate measurements, the average runoff over the whole watershed was 240 mm. For the years 1991 and 1992, the average runoff is 250 mm. When establishing the water budget, the latter figure should be retained since it corresponds to the runoff for the years for which precipitation data are available.

The base flow for the waste dump was estimated by numerical hydrogeological modeling and the result is 200 mm per year. The water budget report says that base flow was also estimated by hydrograph separation which resulted in 213 mm annually. However, no detail of the latter procedure is given in the water budget report. Moreover, hydrograph separation could only be performed with hydrographs from the whole watershed and the result (213 mm) is therefore representative of the whole basin only, and it should not be directly applied to the waste dump.

The surface runoff is the difference between total runoff and base flow. For the waste dump the surface runoff is therefore estimated at 250 - 200 = 50 mm annually.

Groundwater losses

The groundwater losses were estimated on a preliminary basis by hydrogeological modeling at 70 mm per year, but this figure is by no means definitive.

Evaporation

Direct measurements of evaporation are seldom made and its value is commonly established by the water budget method:

$$E = P - Q_B - Q_R - G - \Delta S$$

where E is evaporation; P is precipitation; Q_B is the base flow; Q_R is the surface runoff; G is the groundwater loss; and ΔS is the change in storage.

From the above equation, the sum of evaporation and change in storage is 855 - 200 - 50 - 70 = 535 mm/year.

According to the "Hydrological Atlas of Canada" the average annual evapotranspiration for the Mine Doyon area is about 400 mm. Since there is no vegetation on the waste dump, the evapotranspiration will consist essentially of evaporation. In normal conditions this is the value expected for the area. However, a waste dump producing acid mine drainage (AMD) is affected with inside temperatures that can be much higher than the surface air temperature. The temperature deep inside the dump can be as high as 65°C (GREGI, 1993-03, p.9). This will result in a high rate of evaporation. Of course, a substantial portion of the water vapor will condense at the surface of the dump, but especially during windy days, part of the water vapor will be transported from the waste dump. Therefore it is expected that the total amount of evaporation in the dump will exceed the annual average for the area and should lie between 400 and 500 mm per year.

In the water budget report, the change in storage was estimated at 213 to 237 mm/year, which reduces evaporation to 308 to 332 mm/year. This seems much too low and the authors probably realized that since in a later report (GREGI, 1994-12, p.4.32) the change in storage was lowered to 40-45 mm and the evaporation was estimated at about 500 mm/year. The authors justify the change by the fact that the retention or change in storage must have been quite high initially due to the probably low water content during the early years of the waste dump. Since then, field capacity must have been reached and the actual lower estimate of the change in storage reflects the continuing disaggregation of rock fragments into smaller particles leading to more capillary retention.

3.5 New Understanding Identified from Review

No new hydrologic techniques were employed to establish the water budget. All the methods used are standard. However, the work carried out represents a detailed application of standard methods to develop the water budget for a waste rock dump.

3.6 Application of New Understanding

The application of new understanding is not discussed since no new hydrologic techniques were used to carry out the water budget for the south dump.

3.7 Future Studies and Associated Costs

It is understood that the on-site weather station is located on the roof top of the mill. This is rather unusual as it will affect the accuracy of the measurements due to wind exposure. It is strongly recommended to move the station to ground level in more appropriate location. For the time being, it is agreed with the authors that the data collected at the on-site station are unreliable.

Better estimates of surface runoff and base flow from the east part of the dump (Stations 511 and 512) could be obtained by installing new weir stations on the ditches closer to the dump. Such installations may also require new sections of drainage ditch and thus the total cost cannot be readily estimated. However, an allowance of some $20,000 to $30,000 is considered appropriate for this task. Flow measurements at these stations should be performed daily.

The main weaknesses of the study (GREGI, 1995-05) concern the evaluation of the change in storage and the estimation of evaporation. The sum of these two components of the water budget is estimated at 535 mm, which sounds reasonable. However, the breakdown into evaporation and change in storage was derived somewhat arbitrarily. As suggested by the authors, some effort should be devoted to obtain a better evaluation of evaporation. The energy budget and mass transfer technique could be employed for that purpose. The cost of analyses related to these studies would be equivalent to about 4 to 6 weeks of technical time.

3.8 Summary

All the methods used in the study are standard and no real innovative technology was employed. Based on the present on-site instrumentation, it is hardly possible to obtain better results for the water budget than those presented. Table 3-1 summarizes the water budget for the waste dump.

Table 3-1

South Dump Water Budget

Component	Symbol	Amount (mm/year)
Precipitation	P	855
Base flow	Q_b	200
Surface runoff	Q_s	50
Total runoff	$R = Q_b + Q_s$	250
Groundwater losses	G	70
Change in storage	S	45
Infiltration	$I = Q_b + G + \Delta S$	315
Evaporation	E	490

The study presents some weaknesses related to evaluation of change in storage and evaporation. Better estimates (or confirmation of existing estimates) could be made for some components of the water budget. A better assessment of base flow and surface runoff would be obtained by exploiting weir stations located closer to the south dump. Finally, it could be possible to better estimate the evaporation losses by employing the energy budget and the mass transfer technique.

3.9 References

Environment Canada, 1978. Hydrological Atlas of Canada. Ministry of Supply and Services Canada.

GREGI, 1993-03 (Lefebvre, R., Gélinas, P. and Isabel, D.). Heat transfer during acid mine drainage production in a waste rock dump, la Mine Doyon (Québec). Rapport GREGI 93-03, March. MEND report 1.14.2, March, 1994.

GREGI, 1994-05 (Isabel, D., Gélinas, P.J., Bourque, E., Nastev, M. and Précourt, S.). Water budget for the waste rock dump at la Mine Doyon, Québec. Report GREGI 1994-05, March. MEND report 1.14.2e, March, 1994.

GREGI, 1994-12 (Gélinas, P., Lefebvre, R., Choquette, M., Isabel, D., Locat, J. and Guay, R.). Monitoring and modeling of acid mine drainage from waste rock dumps, la Mine Doyon case study. Rapport GREGI 1994-12, August, revised September, 1994. MEND report 1.14.2g, June, 1994.

4. GEOTECHNOLOGY AND HYDROGEOLOGY

4.1 Introduction

The Mine Doyon waste rock dump generates a significant quantity of acidic drainage. One of the more efficient methods to prevent the generation of acidic drainage in waste rock dumps is the construction of dry barriers to limit the inflow of oxygen and water into the waste rock (i.e. Yanful et al., 1993; O'Kane et al., 1995). One of the objectives of the MEND project for Mine Doyon south waste rock dump was to evaluate the feasibility of using a dry barrier to limit the generation of acidic drainage. The south dump contains 20.7 million tonnes of waste rock and covers an area of approximately 54 hectares. This Chapter of the report reviews all the aspects related to the design of a dry barrier. These aspects are covered in GREGI Reports 91-19 (including Appendices A, B, C and D) and 94-05 (GREGI, 1991-19 and GREGI, 1994-05).

To evaluate the feasibility of constructing a dry barrier, an inventory and a characterization of the natural materials available in the Mine Doyon area was carried out. Materials originating from mine operations such as mining residues and high density sludge (HDS), were also studied. The physical principles related to dry barriers are explained by the GREGI researchers. As will be seen later, these principles, as explained by GREGI, do not correspond to what is considered today as a typical dry barrier. Computer modeling using the HELP program was also carried out. This software is usually used for landfill sites.

This Chapter also deals with aspects related to the site hydrogeology. The documents covering the hydrogeology of the dump are GREGI Reports 91-19 and 94-05. To evaluate the infiltration into bedrock, some modeling was carried out using the MODFLOW software. As will be seen in Article 4.5, many questions remain with respect to flow through bedrock.

4.2 Materials Inventory

To evaluate the possibility of covering the south dump with a barrier to prevent the generation of acidic drainage, a detailed overburden inventory was carried out in the immediate area of Mine Doyon, that is, within a radius of 10 km. Cartography of the east part of the region was carried out by Tremblay (1974). During the summer of 1990, a detailed aerial photographic survey and the description of 48 visit points, 8 auger holes, 1 test pit and 48 verification points allowed the identification of potential sites containing overburden materials which could be used for the construction of dry barriers. Potential sites were identified for till, sand and gravel, and clay. Till is found over large areas but in thin layers. As for the clay, the crust is at most 1.5 m thick which means that its extraction, in large volumes, would require large areas. The sands and gravels are mainly found in eskers located in the west and southwest sectors.

In addition to natural materials, GREGI studied materials originating from mining operations, namely mining residues (concentrator spoils) and high density sludge (HDS) from the water treatment plant. The mining residues studied originated from the unused tailings area of Mine Doyon. The accumulation area covers about 80 hectares and contains more than 5 million tonnes of mining residues.

4.3 Geotechnical Characteristics of the Various Materials

The various materials studied were characterized from a geotechnical point of view. A summary of the geotechnical properties of each material is presented below.

4.3.1 Clay

The clays from four deposits located close to the Mine Doyon site were studied, namely deposits A8-1, A8-2, A8-6 and A10. The location of the sites studied is presented in Figure 3.4 of GREGI Report 91-19, with the exception of site A10 whose location is not included in any of the documents.

4.3.1.1 General Characteristics of the Deposits

Deposit A8-1 consists of high plasticity silty clay (liquid limit of 60 to 73%) with a liquidity index of the order of 0.2 down to a depth of 1.3 m which increases and varies from 0.7 to 0.8 for depths between 1.5 to 3 m. The hydraulic conductivity (k) of a sample from test pit A8-1-1 was measured at 2.8 x 10^{-10} m/s. It should be noted that all permeability tests for this work were carried out using a flexible wall permeameter and that the samples were compacted to standard Proctor energy.

The geotechnical characteristics of the A8-2 deposit were evaluated through Soundings Pu-A8-2-1 and Pu-A8-2-2. Sounding Pu-A8-2-1, which was carried out to the north of the deposit, indicates the presence of a silt with a low proportion of clay (3 to 17%). Sounding Pu-A8-2-2, taken at the south end of the deposit, indicates a material with a higher plasticity than in the north area (liquid limit of 39% and 28%, respectively) as well as a clay percentage of 45%. The hydraulic conductivity (k) measured on a sample from Sounding Pu-A8-2-2 indicated a k value of 2.2 x 10^{-10} m/s.

As for deposit A10, two samples have shown that it consists of silt or silty sand with little or no clay (0 to 12%).

4.3.1.2 Geotechnical Characteristics of Clay Deposit A8-1-2

To evaluate the possibility of using clay as a component for an impermeable layer, a mixture of samples retrieved from Test Pit A8-1-2 between 0.25 and 1.5 m was subjected to further study. A mineralogical analysis using X-Ray Diffractometry enabled the identification of the mineralogical composition of this mixture. Quartz, plagioclase and calcite are the abundant mineral phases. Also found in lesser quantities are illite, chlorite and traces of dolomite.

The general characteristics of the sample are as follows: the specific gravity density is 2.71, the natural water content is 34-36%, the liquid and plastic limits are respectively 66% and 34.5%, the percentage of clay particles is 75% and the activity is in the order of 0.42.

In terms of compaction characteristics, the standard Proctor test indicates an optimum water content w_{opt} of 33.5% and a dry density of 1394 kg/m^3. On the wet side of optimum, the degree of saturation is about 97%.

Several permeability tests were carried out on the clay. The main findings are as follows:

- The hydraulic conductivity of the saturated soil is of the order of 2 x 10^{-10} m/s on the wet side of optimum Proctor and about fifty times greater on the dry side. This is typical of clay behavior, as reported by several authors (i.e. Mitchell et al., 1965; Leroueil et al., 1992).

- The hydraulic conductivity (k) of the unsaturated clay is smaller than when saturated. On the wet side of the Proctor curve, the unsaturated k is smaller by a factor of 3 whereas the unsaturated k is smaller by a factor of 20 on the dry side. Again, this behavior is typical of clays.

- The hydraulic conductivity is increased by freeze-thaw cycles. After a first cycle, the hydraulic conductivity is increased by a factor of 5 for both saturated and unsaturated conditions. It is noted, based on the tests carried out for this study, that the hydraulic conductivity changes after several freeze-thaw cycles. Indeed, after five freeze-thaw cycles, the hydraulic conductivity is only double what it was originally. A word of caution is, however, warranted with respect to this phenomenon of return to initial hydraulic conductivity. From the literature, this observation is difficult to support. For instance, the work by Mohamed et al., (1993) on clay used as construction material for the experimental cells of the Waite-Amulet site near Rouyn-Noranda did not show this phenomenon.

Tests were carried out to analyze the shrinkage potential of the clay studied. The results obtained show a large shrinkage for the clay. Such shrinkage inevitably leads to cracking and thus, increases the permeability to water and air.

4.3.2 Tills

Potential till sites were identified and are listed on Figure 3.2 of GREGI Report 91-19. These sites are numbered T13-1, T12-1, T14-1, T7-4, T3-5 and T3-1.

4.3.2.1 Geotechnical Characteristics of the Tills

Grain size analyses carried out on 10 samples from the above sites showed that the tills contain from 10% to 30% gravel, 45% to 60% sand and 15% to 30% silt. Till samples recovered close to the tailings area by Golder contained from 9% to 16% gravel, 55% to 72% sand and 18% to 33% silt. Additional geotechnical tests were conducted on the above tills, namely compaction tests (standard Proctor) and direct shear tests.

The standard Proctor compaction tests have indicated a dry density of 2050 and 2090 kg/m^3 at an optimum water content of 6.6 and 8.7% for the Golder and Laval University samples, respectively.

As for the direct shear tests, they were carried out on till samples from deposit T14 which were compacted to conditions similar to optimum Proctor. The results obtained show a friction angle of 37° at high strain whereas peak friction angles of greater than 43° were obtained at low strain.

The till studied was not subjected to permeability tests. However, GREGI Report 91-19 states that the hydraulic conductivity of the till may be estimated at 10^{-5} m/s. The method used or the reference work supporting this value is not mentioned.

4.3.3 Sands and Gravels

The sole geotechnical characteristic studied for the sands and gravels was the gradation. Ten samples were retrieved from deposits S1 and S2, the locations of which are shown on Figure 3.3 of GREGI Report 91-19. The grain size analyses were carried out using those samples. The S2 deposit consists mainly of coarse sand with gravel and sandy gravel. However, one of the samples appears to be much finer and is more like a sandy silt. The S1 deposit appears to be more heterogeneous as the silt fraction varies from 10 to 75%. It is considered that medium to fine sands are present. As for the S4 deposit, no sample was retrieved. However, verification points indicate that it consists of medium to coarse sands with gravel and cobbles.

4.3.4 Mining Residues

The spoils from the concentrator are termed mining residues in this text. In the study, geotechnical tests were carried out on intact mining residues and on mining residues amended with bentonite, high density sludge, Portland cement and lime.

4.3.4.1 Intact Mining Residues

Geotechnical tests were carried out to characterize the mining residues from Mine Doyon, namely tests to determine the specific gravity of solids, the gradation, and the compaction and shear strength characteristics.

The specific gravity of solids was measured at 2.88. The grain size of the mining residues corresponds to a silt with a D_{10} (grain diameter at 10% passing by weight) of 0.0035 mm and a coefficient of uniformity (C_u) of 6. A mineralogical analysis by X-Ray Diffractometry enabled a qualitative determination of the main minerals. The main mineral phases identified are quartz (40%), sericite (30%), chlorite (11%), pyrite (7%) and plagioclase feldspar (4%). These results agree with other research work on the Mine Doyon residues (Aubertin and Bussière, 1991; Bussière et al., 1995).

As for the compaction characteristics, the standard Proctor optimum water content and dry density are 17% and 1730 kg/m^3, respectively. The hydraulic conductivity (k) at optimum Proctor (in unsaturated conditions) is about 2×10^{-10} m/s whereas k when compacted dry of optimum Proctor in saturated conditions is about 2×10^{-7} m/s. The permeability tests were carried out in a flexible wall permeameter under a hydraulic gradient (i) of 10. The saturated k value agrees with values measured on other types of hard rock mining residues (Aubertin et al., 1993b).

The direct shear test results indicate a friction angle of 37° at high strain. This relatively high friction angle is explained by the angular nature of the particles.

4.3.4.2 Mining Residues Amended with Bentonite

To reduce their hydraulic conductivity, the mining residues were amended with bentonite. The permeability tests were carried out at a water content 2% higher than the standard Proctor optimum water content in order to promote hydration of the bentonite. The permeability tests were conducted in a flexible wall permeameter under saturated and unsaturated conditions, and under a hydraulic gradient (i) of 10. The addition of 8% of bentonite was required to reduce the hydraulic conductivity (k) by one order of magnitude. This small reduction is explained by the fact that the mining residues present a uniform gradation. Permeability tests were carried out at École Polytechnique on mining residues amended with bentonite (Aubertin et al., 1995; Ricard, 1994). The permeability tests were conducted at various compaction levels to evaluate the effect of the voids ratio on the value of k. A flexible wall permeameter was used in the study to measure k. The results obtained have shown the effect of bentonite on the hydraulic conductivity. The reduction of k for the addition of about 6% by dry weight of bentonite is approximately one order of magnitude, which is similar to what was measured by GREGI.

The shrinkage of this amended material was also measured. The percent of shrinkage slightly increases with the percent of bentonite. However, this percent is low and is smaller than 2%.

4.3.4.3 Mining Residues Amended with High Density Sludge

The possibility of using a mixture of mining residues and high density sludge (HDS) was examined in the course of this project. Trial percentages of 5% and 10% of sludge were used to amend the residues. The results obtained were not very conclusive. The main difficulties encountered were related to the water content of the sludge which was too high and the impossibility of preparing a homogeneous mix. As a result, the hydraulic conductivity of the mining residues was not affected by the amendment with high density sludge.

4.3.4.4 Other Amendments of the Mining Residues

Other types of amendments were studied to observe their impact on the mechanical properties of the mining residues. The amendment materials used were lime (98% pure hydrated lime), Portland cement as well as HDS. The maximum amount of additives was set at 5% total (by dry weight). The mixtures were made using dry materials (except the mixtures with HDS) and the curing periods were set at 100 days. Two series were made: first a trial series with the addition of 5% of lime, and a second complete series with all of the other additives. For each series, reference samples were prepared in parallel.

The first series of tests showed that the physical and chemical properties of the residues were affected by the presence of lime (4%). The intact strength reaches a value of 1.8 kPa after 216 hours, an increase of 660%, whereas the disturbed strength increased slightly from 0.09 to 0.12 kPa, which corresponds to a 33% increase. These resistances were measured using the Swedish cone.

Secondly, under the same conditions as for the first series, various mixtures of residues with amendments were prepared. The results obtained show that from the start, there is a strength gain which reaches a plateau between 100 and 200 hours. The most significant gain was obtained with a mixture of 2% HDS and 2% cement, for which the strength increased from 0.13 kPa (initial strength) to 90 kPa. It is interesting to note that for this project, the high density sludge is a better additive to cement than lime.

4.3.5 High Density Sludge

High density sludge is produced by a treatment plant at the Mine Doyon site. A characterization of sludge mineralogy and viscosity is presented in GREGI Report 91-19.

The mineralogical composition was evaluated using X-Ray Diffractometry. The main minerals found in the sludge are: bassanite (43%), geothite (27%), gibbsite (18%), quartz (7%), hydroxylapatite (3%) and traces of brucite and manganite.

As for the viscosity characteristics, they were assessed on sludges at a water content similar to those obtained at the mine. The apparatus used to measure the characteristics consisted of a double cylinder ROTOVISCO RV12. The tests were carried out at a temperature of 7°C. Two types of measurements were made for each sample, namely constant velocity tests and dynamic response tests. The former test type is to assess the degree of stability of the mix and the latter enables the evaluation of viscosity and flow threshold. The results obtained show that the behavior of the high density sludge is similar to that of a Bingham fluid; its viscosity is of the order of 25 mPa.s and its flow threshold varies between 4 and 7 Pa. These results on the viscosity of the high density sludge could be useful should their injection into the waste rock dump be considered to lower its porosity.

4.4 Dry Barriers

The dry barriers of the type presented in the GREGI report do not use the capillary barrier principle to prevent the infiltration of water and oxygen. Rather, the barrier type presented in section 4.4.1 of GREGI report 91-19 is intended to reduce infiltration as for sanitary landfill sites (EPA, 1991). The principle of a dry barrier incorporating a capillary barrier zone was known when the work of the GREGI report was carried out. It is now recognized that this type of barrier is effective, in the long term, in reducing the migration of oxygen and water into high sulphur residues. Before going further, a brief explanation of the dry barrier principle is in order. More detail on the prevention of capillary rise may be found in the literature (i.e. Nicholson et al., 1989; Akindunhi et al., 1991; Morel-Seytoux, 1992; Chiu et Shakelford, 1994; Shakelford et al., 1994; Yey et al., 1994; Bussières et al., 1995).

4.4.1 Physical Principles of Dry Barriers

The concept of a capillary barrier involves the theory of unsaturated flow through materials of differing textures (or gradation). A capillary barrier is usually created when a layer of fine material is placed over a layer of coarse material, as is the case for Layers D and E shown on Figure 4-1. In this case, water infiltrating from the surface will only be able to flow through Layer E (considered here as initially dry) when the capillary tension in the material of Layer D is close to zero (that is, the material is completely saturated). A somewhat similar effect may also be created when the layer of coarse material is placed over the fine material layer, as for Layers C and D of Figure 1. This arrangement prevents the capillary rise from the lower layer (that is from Layer D towards Layer C).

A system as the one shown on Figure 4-1 therefore includes a double effect from the capillary barrier, that is one from each side of the fine material layer (Layer D). The drying of Layers C and E, constituted of coarse material with a low air entry value (AEV), thus prevents the migration of water, in an upward direction as well as downward, which helps in maintaining a high degree of saturation in Layer D. To obtain an effectiveness similar to that of a water cover, it is usually considered that a degree of saturation of 90% in the fine layer is required (Aubertin et al., 1993). Layer E also prevents a capillary rise of the water present in the waste towards Layer D, which could thus contaminate the fine material layer. Because of this, the thickness of Layer E must be sufficient to ensure drainage.

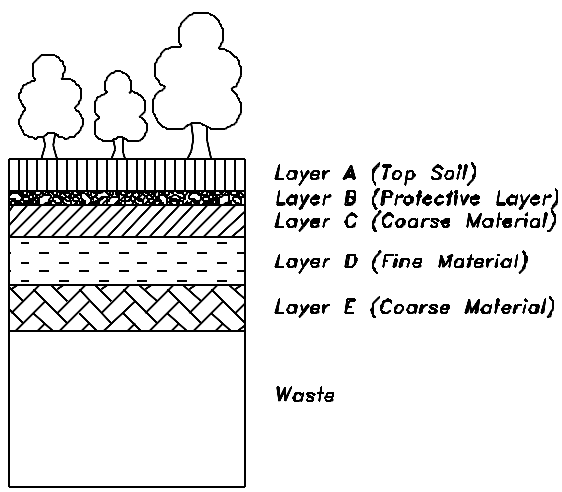

Figure 4-1. Schematic of a Multilayer Barrier Constructed Using the Capillary Barrier Principle (from Bussière et al., 1995).

The choice of materials presented in GREGI Report 91-19 is not suited for cover layers using the capillary barrier principle. When designing a capillary barrier, the most important aspect is the suction contrast between the various materials. It is usually considered that sand may be used for the two draining layers (layers C and E). The thickness of the layers is determined from the suction characteristics of the materials. A thickness of 2 AEV may be considered as a design criterion. As for the fine layer, its suction characteristics must be sufficient to maintain a high degree of saturation, even for extended periods of drought. A silty material is usually considered as most suitable for the fine layer.

4.4.2 HELP Computer Modelling

The computer modeling presented in Section 4.4.2 of GREGI Report 91-19 were carried out using the HELP software (EPA, 1994). This software is used for hydrological analysis of landfill sites. Little information is available on the modeling carried out. It is mentioned in the document that the purpose of the modeling was to numerically simulate flow and lateral drainage. It appears that no particular consideration was given to unsaturated flows; it is however this type of flow which is prevalent in dry barriers.

The computer modeling carried out considered a clay layer 1 m thick placed between two layers of draining sand (0.5 m thick). The upper layer used for revegetation is 1 m thick. Finally, a 0.5 m layer of a material named "support filter" is placed on the waste rock. Several computer analyses were carried out to study the effect of varying the distance to drain and slope using two different hydraulic conductivity values for the drainage sand (10^{-3} m/s and 10^{-2} m/s). The results, for the case of a draining layer with a hydraulic conductivity of 10^{-3} m/s, indicate that the drain spacing has an effect if it is smaller than 80 m. It is also observed that the slope has a major effect on infiltration. The results obtained, when considering a drainage sand with a hydraulic conductivity of 10^{-2} m/s, are significantly different. Indeed, based on the modeling carried out, increasing the slope to values larger than 6% has little effect on the infiltration. As to the drain spacing, an influence occurs only if the slope is smaller than 6%. In summary, it may be said that the computer modeling indicates that the infiltration through such a cover barrier may be limited to less than 20 000 m^3 per year (that is, about 6% of the normal infiltration), with a minimum value of about 12 000 m^3 per year if the hydraulic conductivity is maintained at 10^{-9} m/s.

4.4.3 Applicable Solutions Identified by GREGI

In Section 4.5 of GREGI Report 91-19, solutions applicable to the Mine Doyon south waste rock dump are evaluated for the installation of a dry barrier. The main conclusion of the GREGI report is that *"the solutions considered will have to incorporate a geomembrane sufficiently flexible and strong to conform to the movements of the surface of the dump while maintaining its integrity"*. The main comments which may be expressed on the above section are:

- The solutions suggested are always for an impermeable barrier and not for a capillary barrier. For this reason, the use of silty materials is rejected whereas these materials should have been considered as most desirable.

- In the document, the use of a geomembrane within the barrier is favored even if it is known that such a material must be replaced in the long term.

The use of natural materials for the construction of a dry barrier was eliminated on the basis of settlement of the waste dump surface observed on site. However, settlement measurements were not carried out and no information is available on the subject. A recent site visit did not confirm the occurrence of settlement. Furthermore, it is known that the installation of a dry barrier would reduce the acid generation process and hence, reduce the settlement. It therefore appears premature to reject the use of natural materials as components of a dry barrier, based on visual observations not technically verified.

4.5 Hydrogeology of the Site

4.5.1 Hydrogeological Modelling

Computer analyses were carried out by the GREGI group of Laval University for the Mine Doyon waste rock dump. The results of the analyses are discussed in the following reports:

- GREGI Report 94-05 (MEND 1.14.2e);
- GREGI Report 91-19.

GREGI Report 93-11 by Nastev and Isabel (1993) was referred to with respect to the computer analyses presented in the two above-mentioned reports. However, the latter report was not available to the reviewers. The collection and analysis of hydrological data were discussed in Chapter 3.0 as was the hydraulic budget of the dump prepared by the GREGI group. The relevant comments will therefore not be repeated here.

The following discussion is therefore limited to the computer modeling carried out by the GREGI group. The simulations were carried out using the USGS MODFLOW 2D software (McDonald and Harbaugh, 1984). The hydrogeological modeling comprises two distinct analyses:

- Modeling of the dump foundations
- Modeling of the waste rock dump

The purpose of the first analysis was the reconciliation or calibration of the water levels measured in wells drilled in the dump with the hydraulic conductivity values measured by Golder and Associates (1991). Indeed, a few injection tests (slug tests) carried out in some wells indicated hydraulic conductivity values of the order of 2×10^{-6} m/s at less than 5 m depth within bedrock below the waste rock dump. This hydraulic conductivity value was judged not compatible with the observed piezometric levels. A numerical model was built using MODFLOW 2D to try to assess a hydraulic conductivity representative of the bedrock underneath the dump. Only bedrock was considered in this analysis. An impervious boundary was assigned at 20 m below the pit. The lateral limits were the main pit to the northeast and the Bousquet river to the west. The calibration of this numerical model, using the piezometric levels observed within the dump, yields a hydraulic conductivity value of the order of 10^{-9} m/s for the bedrock. The GREGI researchers concluded that the higher hydraulic conductivity measured during the well tests is due to local fracturing at shallow depth and is not representative of the real permeability of the bedrock.

Although the above conclusion by the GREGI researchers appears justifiable within the present context, its justification is not sufficiently supported in the report. This conclusion is important because it had a deciding influence on developing the conceptual model used in the numerical modeling of the dump. More specifically, this conclusion strongly influences the predictions of the model, namely with respect to the water loss beneath the dump and the geometry of the flow network.

The second model, also made using the USGS MODFLOW 2D software, was used to simulate flow through the waste rock dump. The objective of this second model was the completion of the hydraulic budget for the dump by trying to estimate the groundwater loss.

A model with 4 distinct layers was constructed. The table below presents the hydraulic conductivity of each layer.

Table 4.1

Hydraulic Conductivities Used in Simulations

Layers	k (hydraulic conductivity)
Spoil	1×10^{-3} m/s
Soil	7×10^{-7} m/s
Fractured Rock	1×10^{-6} m/s
Bedrock	3.5×10^{-9} m/s

The second column presents the hydraulic conductivity values assigned to each layer in the model, based on the field and laboratory characterization. For the fourth layer (bedrock), the value used is obtained from the first modeling carried out for the foundations of the dump.

The conditions at the boundaries of the model are:

- constant head to the north (bottom of pit, 4891 m);
- constant head to the northeast (elevation of effluent, 4960 m);
- constant head to the south (elevation of effluent, 4995 to 4955 m);
- constant head to the southeast (level of the Bousquet river);
- constant head to the northwest (4975 m);
- constant head between the dump and the Bousquet river (4957 m).

The infiltration rate was set at 260 mm/year in the model.

4.5.2 Analysis of the Results

As previously mentioned in this document (Article 3.3.1), due to an error in Table 8 of the GREGI report, the infiltration rate would be underestimated by about 8%. This correction should be considered in the numerical model. This error must therefore reflect on the results obtained from the modeling. The water loss through bedrock, based on the analyses, is estimated at 70 mm per year. Some reservations must therefore be applied to this estimation due to the error introduced in evaluation of the recharge rate.

A better characterization of the hydraulic conductivity of the bedrock would allow the numerical model to be improved, as recommended in the GREGI report. The authors recommended conducting numerical simulations using a software capable of simulating multiphase flow. The latter recommendation is not judged advisable. The high concentration in dissolved solids measured in the dump leachate and the temperature variations (40 to 65°C) influence the flow in the waste rock dump. In such a case, a flow as a function of density should be considered instead. Therefore, software using an approach of variable density miscible fluids flow would be more appropriate. However, this problem is complex as the density is then a function of the concentration in dissolved solids and temperature.

The work carried out by GREGI in the course of the hydrogeological modeling is conventional. The approach and type of modeling are standard. The sole objective that the numerical modeling enables is a completion of the hydrogeological budget. This part of the work does not bring about a new understanding of the problem of acidic mine drainage in a waste rock dump in general.

The values of certain parameters differ from one report to the other (1991 vs 1994). For instance, the infiltration in the bedrock was first presented as being in the order of 8% and was finally given as 5% in the 1994 report. No explanation was given in the reports to justify the modifications.

A sensitivity analysis of the parameters used in the numerical modeling would have been desirable. It would then be possible to appreciate the impact of the error raised in Article 3.3.1. Furthermore, the definition of value ranges for the infiltration terms would be more interesting from a technical point of view.

4.6 New Approaches Identified by this Project

The area of work that brought out the most in terms of new knowledge on dry barriers built over waste rock dumps was that which pertained to the improvement of mining residues with bentonite used as construction materials for a barrier. The use of bentonite may reduce the hydraulic conductivity by approximately one order of magnitude. In addition, other work has shown that the bentonite allows an improvement of the water retention characteristics of the amended material (Richard, 1994). As was explained in this report, water retention characteristics are the most important parameters for the design of a dry barrier using the capillary break principle. It would then be possible to use mining residues improved with bentonite as a fine layer component of the dry barrier. This technique could be applicable in cases where the costs associated with the use of this material as construction material for the dry barrier would be lower than those associated with natural materials.

Another interesting aspect of the work is the improvement of mechanical properties with the use of high density sludge (HDS) and cement as amendment. It is quite interesting to note that the HDS (considered as residues) constitutes, in the short term, a better additive to cement than lime. This interesting trend should be investigated further.

The sludge could also be incorporated in a dry barrier to cover the waste rock dump. However, one must not forget that the sludge contains high concentrations of metals and that its stability must be ensured before it is used in any covering application.

4.7 Applications of the New Approaches

It is now a known fact that the use of mining residues, which are normally found in close proximity to waste rock dumps, may be an interesting alternative to soil as a component of a dry barrier (Aubertin et al., 1995). In some instances, an improvement of the mining residues with bentonite may enable them to acquire the permeability and suction characteristics required for their use as a component of a dry barrier with the objective of preventing the generation of acidic mine drainage. This technology could be used for tailings ponds as well as for waste rock dumps.

As for the high density sludges, since they seem to constitute a good additive to cement, they could be used in the underground backfill process. This in turn could enable a reduction of the volume of sludge stockpiled at ground surface and a reduction in backfill costs.

4.8 Future Studies and Associated Costs

As previously mentioned, suction characteristics (or water retention characteristics) are essential should one wish to design a dry barrier. No measurements of these characteristics were carried out in the course of the GREGI study. In the event that Mine Doyon would install a dry barrier, a campaign to measure these characteristics would be essential. Hydrogeological modeling for a non-saturated environment could then enable the determination of the thickness of the various layers of the barrier. The costs associated with this work could range from $20,000 to $50,000.

A study on the impact of using the HDS as cement additive would also be most interesting. A testing program (triaxial and uniaxial tests) could allow a comparison of the results obtained with HDS and those obtained using other additives. It would then be possible to compare the behavior of backfill with HDS versus that of the ordinary backfill (Ouellet, 1995). The costs associated with this work are estimated at $15,000 to $30,000.

The possibility of incorporating HDS in the dry barrier appears to be an interesting development to the study. Of course, the chemical stability of the sludge is the main disadvantage of this alternative. It is anticipated that a technical and economic pre-feasibility study could be carried out for about $30,000.

Another aspect which warrants further investigation is the evaluation of waste dump settlement mentioned by the GREGI researchers. It may then be possible to evaluate the impact of those settlements on the construction costs. Minimal costs would be associated to this work, about $5,000 to $15,000.

As was previously outlined, inconsistent data exist with respect to the hydraulic conductivity of the bedrock. GREGI suggests, with reason, to carry out injection tests on a larger scale to better characterize the hydraulic conductivity of the bedrock. Some variations in the values used for the bedrock would have a significant impact on the numerical modeling results. A modeling considering multiphase flow, as recommended by GREGI, does not appear relevant. Indeed, the high concentrations in dissolved solids and the large temperature variations influence the flow of water. It would be more interesting to consider flow as a function of density. For that purpose, a flow model of variable density miscible fluids would have to be used. This is a complex problem as the density of water is then a function of the concentration in dissolved solids and temperature. However, as mentioned above, the hydraulic conductivity conditions of the bedrock assigned in the numerical model are more important than the density variations of the flow underneath the waste rock dump.

Based on the new data obtained on the hydraulic conductivity, it may be necessary to evaluate the geochemical characteristics and the various properties (direction and speed) of the groundwater flow underneath the dump. The cost of such a study could be in the order of $50,000.

4.9 Summary

The work carried out by GREGI, with respect to the characterization of overburden, is typical of what is done in consulting engineering and appears to have been carried out according to standard practice. However, it does not constitute research work with the exception of the tests carried out on the mining residues-bentonite mixes.

Dry barriers, as presented by GREGI, do not correspond to what is considered today as a dry barrier. The barrier type proposed by GREGI does not use the capillary break principle to prevent the migration of water and oxygen to the sulphurous residues. The capillary break principle was known during the work conducted by GREGI (Nicholson, 1989). Due to this fact, the design proposed in GREGI Report 91-19 is extremely costly and is therefore not optimum. Other waste rock dumps have been restored over the last few years in Canada using dry barriers and a much simpler design. For instance, the "*Equity Silver Mines*" site even used the waste rock as a coarse layer to provide a capillary break with the fine material (Okane et al., 1995), thereby reducing the construction costs.

It is obvious that the rejection of dry barriers as a means of restoring the south dump of Mine Doyon was done prematurely by GREGI. It may even be said that, based on the current knowledge, a dry barrier appears as the most applicable restoration method for this site. However, before this technology is applied, a comparative study of the various available options would have to be made leading to selection of the most suitable restoration solution for the south dump.

As mentioned previously, the hydrogeological modeling carried out is conventional and does not result in new knowledge in this field. The main objective of this modeling is to know the infiltration rate below the dump in order to complete the hydrologic budget. However, the results obtained show that about 5% of the water seeps below the dump.

In conclusion, it may be said that the amount of work carried out by GREGI is considerable and that the work was carried out in accordance with standard practice. However, on a geotechnical and hydrogeological level, little progress was made in terms of comprehension of the phenomenon of acidic mine drainage generation in waste rock dumps.

It should be noted that the comments presented in this Chapter refer only to the content of the GREGI reports submitted to MEND (refer to Introduction Table 1-1). These comments are intended to provide a different point of view and to enhance the comprehension of readers who will use the reports.

Considering the clarifications which were given to us by the GREGI researchers during this review and which do not appear in the MEND reports, it is worth noting that:

- the GREGI researchers have rejected the use of mining residues (with or without amendments) or sludges because of their high initial cyanide concentration;

- based on the observations made on the bedrock and on data available to the GREGI team, it did not appear necessary to study in more detail the flow characteristics beneath the dump.

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5. GEOCHEMISTRY AND MINERALOGY

5.1 General

The Mine Doyon project is certainly one of the best waste rock studies MEND has so far sponsored in terms of advancing our understanding of AMD processes taking place in waste rock dumps. To our knowledge, it is the most comprehensive in the world in terms of the scope of disciplines encompassed.

The geochemical and mineralogical work of the Mine Doyon project is particularly illuminating. Its multi-disciplinary approach in tackling the AMD problems is exemplary. The study has generated new insights into the geochemistry and mineralogy of AMD-related processes in waste rock dumps. Some of the investigative tools used are innovative, and some of the computation and interpretation techniques are unique. The most significant aspect of this work is probably that it draws our attention to the importance of phyllosilicate mineral weathering.

No major flaws and gaps have been identified by this review; however minor to somewhat significant flaws are almost inevitable in a project of such scope and scale. The reviewers have noted the excellent achievements and also have pointed out some flaws. The following reports have been reviewed for this chapter: GREGI, 1991-19; GREGI, 1993-03; GREGI, 1993-04; GREGI, 1993-05; GREGI, 1994-04; GREGI, 1994-06; GREGI, 1994-12.

The reviewers consider the part of this study that characterizes natural materials for possible sources of soil covers for the waste rock pile as unrelated to geochemistry and mineralogy, and thus have exempted that part from review in this chapter. This Chapter on geochemistry and mineralogy incorporates some comments by SENES who provided a preliminary review of this technical component (SENES, 1995) as well as secondary review input.

5.2 Solid Characterization - Field Work

5.2.1 Work Performed

The Mine Doyon study carried out extensive field sampling and field solid characterization. The solid sampling program consisted of the following components:

- Seven boreholes (BH-1 to BH-6, drilled in 1991 and BH-7, drilled in 1992) on the south dump, 21-47 m deep, all penetrating successively through the waste rock, the original top soil where present, and the upper part of the bedrock, from which drill cuttings were collected as composites at approximately 1.5 m intervals;

- Five exploratory trenches (T1 to T5) on the south dump, 3-5 m deep, from which grab samples were taken at approximately 0.5-1.5 m, unequal intervals; and
- Two large surface pits (T92-1 and T92-2) on the south dump used for lysimeter installations, each 15 m wide and 5 m deep, from which bulk and composite samples were taken.

Field geochemical and mineralogical characterization included the following components:

- Logging visual observation and classification;
- Paste pH; and
- Particle size segregation for size distribution analysis.

5.2.2 Methodology

Drilling

Within the normal resource constraints, dry drilling is the best available technique to acquire reasonably representative samples from large waste rock piles. At Mine Doyon, a reverse air circulation, down-the-hole hammer drill with an eccentric bit was used. Compressed air brought drill cuttings from the depth of the drill bit to the surface, allowing composite samples to be collected according to the drill bit depth. The dry drilling method, however, suffers from two drawbacks, neither of which can yet be overcome with the present drilling technology:

- The rock is broken in the drilling process, creating new surfaces and fines which are not representative of the in-situ conditions;
- The moisture associated with the rock is dried off when the drill cuttings are blown up the borehole, disallowing subsequent pore water extraction.

The positioning of boreholes BH-1 to BH-6 at the Mine Doyon was based on two considerations:

- To encompass different lithologic units contained in the south dump (refer to Rapport GREGI 1994-12, pp. 1.2-1.6; Rapport GREGI 91-19, pp. iii-iv and Rapport GREGI 91-19 Annexe A, p. 5); and
- To follow the surface streams on the original topography (refer to Figure 2.1a on p. 90 in Rapport GREGI 91-19).

The three main lithologic units were all well sampled: sericitic schist (unit 4B, about 50% of the south dump) and intermediate tuffs (unit 3, about 30% of the south dump) by boreholes BH-1, BH-4, BH-

5, BH-6; and felsic volcanoclastics (unit 4A, 15% of the south dump) by BH-2 and BH-3. Bore hole BH-7, which was drilled one year later than the others to retrieve samples for mineralogical studies, encompassed all three lithologic units. At the same time, the three zones identified (Rapport GREGI 91-19, p. iv) were also well represented.

Bore holes BH-1, BH-2 and BH-3 were located on original surface stream paths under the south dump draining towards the north west; BH-5 on the original surface stream path draining towards the east; BH-4 on the divider of the two local water sheds; and BH-6 and BH-7 on a plateau of the original topography in the mid-south. These arrangements allow the tracking of ground water quality evolution as it flows through the original top soil and bedrock formations through ground water monitoring, thus facilitating the assessment of contaminant migration in ground water.

All seven boreholes were drilled through the entire depth of the south dump and further into the original top soil and the upper bedrock. This practice allows the ground water gradients in the top soil (free water table) and in the bedrock (confined water table) to be monitored separately. The change in water quality as the water percolates down through the waste, the top soil, and bedrock can be quantified. Altogether, they provide indications of contaminant migration patterns in both horizontal and vertical directions.

The practice of compositing drill cuttings at 1.5 m intervals is acceptable, balancing the needs of identifying vertical spatial variations and reducing sampling and analytical costs.

Trenching

The five surface trenches were distributed around the top of the south dump to sample various lithologic units contained in the south dump (Rapport GREGI 1994-12, p. 2.1; and Rapport GREGI 91-19 Annexe A, p. 5): T1, T2, and T4 were located in zones where sericitic schists dominated; T3 was located in the very low grade ore pile (felsic volcanoclastics); and T5 was in the non-reactive "green rocks". Samples were taken stratigraphically to yield mineralogical evidence of weathering in the top 5 m of the dump. Excavation was achieved by hydraulic backhoes.

The locations of the five trenches seem adequate; the excavation, sampling, and logging of the trenches were straightforward and appear appropriate.

Pitting

Two large pits (T92-1 and T92-2) were excavated into two lithologic units (felsic volcanoclastics and sericitic schist, respectively) for solid sampling and lysimeter installation (Rapport GREGI 1994-12, p. 2.1 and p. 2.4). The solids were used for particle size analyses, mineralogical studies, and water content determinations. Detailed descriptions of sampling, sample preservation, and sample handling have not been given in the reports. The reviewers assume that all established solid sampling procedures have been followed and the solid samples obtained are of acceptable quality.

5.2.3 Data Quality

Observation and Logging

The observations of color, stratigraphy, texture, secondary precipitates, alteration, lithologic units, mineralogy, particle size, etc. of the trenches and the boreholes BH-1 to BH-6 are well documented according to depths and in detail in Rapport GREGI 91-19, Annexe A, pp. 22-30 and pp. 36-51, respectively. The well installations in boreholes BH-1 to BH-6 are clearly illustrated graphically in the same report, pp. 15-20. The stratigraphy of the five trenches are demonstrated graphically on pp. 31-35 (same report) and that of the boreholes BH-1 to BH-6 in Figure 2.3 (p. 93) of Rapport GREGI 91-19. These logging data are considered by the reviewers to be of high quality and sufficient detail for the purpose of this study.

Paste pH

The paste pH was obtained by mixing one part of solids with 2.5 parts of water (by volume) and then measuring the pH of the mixture with a glass electrode (see Rapport GREGI 91-19, Annexe A, p. 6 for description). The results are presented in Rapport GREGI 91-19, Annexe A, pp. 52-56 and graphically illustrated in Figures 2.5 and 2.6 (p. 95-96) of Rapport GREGI 91-19.

The measurement of paste pH is a relatively simple procedure and, when followed correctly, it is not prone to errors. The paste pH profiles correspond well with alteration observations and anticipations based on lithologic information. In addition, when comparing the paste pH's with the pH's of leachate deriving from the same samples (Rapport GREGI 93-05, Appendix D-1, pp. 53-59), we have noticed that the vast majority of the leachate pH's duplicate their paste pH's within an error margin of approximately 0.2 pH units (This was not noted in the report). There are a few exceptions, noticeably for samples from borehole BH-1, samples 1-3 and 11, where the earlier paste pH's are much higher than the later leachate pH's. These differences can be explained by pyrite oxidation during storage and handling.

Although descriptions of field quality control for paste pH measurements are lacking from the reports, the above agreement suggests reliable paste pH data.

Particle Size Segregation

Particle size segregation was performed on four bulk field samples as part of the Mine Doyon study (Rapport GREGI 1994-12, p. 2.6). This involved taking a "large" sample from the large pits (the report did not specify how "large" the bulk samples were), removing boulders greater than 0.5 m, screening the remaining through a 70-mm sieve, weighing the oversize and undersize portions, and splitting a subsample of the undersize portion for subsequent conventional sieve analysis in a laboratory.

Size distribution is a critical factor in scaling up laboratory test results to a large waste rock pile, yet its determination for waste rock is extremely difficult for two reasons: the heterogeneity of waste rock piles and the large sample mass requirement for a representative sample.

The heterogeneity of waste rock piles derives from size segregation of waste during dump construction, variation in size distribution in the original material hauled to the dump (caused by variation in blasting efficiency and brittleness of the rock), varying degrees of post-depositional physical and chemical disintegration (such as crushing by truck traffic and chemical weathering), and so on. Depending on the dump-building method, a typical dump usually contains coarser material in the lower portion of a lift, finer material in the upper portion of a lift, and very fine material on the surface. Thus, if a bulk sample is taken from the surface of a waste rock pile, it is likely to be finer than the average of the entire pile. Besides the vertical size variation, there is a lateral variation, which is usually a function of the lithology of the waste rock: the more brittle rock is likely to be broken finer during blasting and is more easily broken down further by physical disintegration. Similarly, chemically reactive waste rock is more prone to disintegration by chemical weathering. As a consequence, it is justified to conduct separate size analyses for different lithological units.

The minimum mass of a representative sample depends on the top particle size of the material being sampled. For example, the minimum representative sample mass for a material with a top particle size of 0.5 m is about 10 tonnes and for a material with a top particle size of 1 m, 75 tonnes (Cummins et al., 1973, p. 27-16). Clearly, it is difficult to segregate such large quantities of waste rock in the field.

To obtain a reasonably accurate estimate of the size distribution of a waste rock dump, the researcher should ideally follow these steps: (1) excavating a bulk sample over the height of an entire lift; (2) removing large rocks (e.g., > 0.25 m) and taking enough sample to be representative for the corresponding top size (e.g., for 0.25 m top size the sample should be greater than 2.5 tonnes) and performing sieve analyses; (3) estimating the percentage of waste rock greater than the cut-off size (i.e., 0.25 m) in the pile; and (4) conducting size analysis for each lithological unit according to steps (1) to (3) above. However, such an exercise is clearly quite expensive and rarely justified in terms of cost.

The particle size segregation carried out at the Mine Doyon followed only step (2) above; it is doubtful that enough samples (10 tonnes) were taken for the cut-off size used (0.5 m). Figure 2.3 in Rapport GREGI 1994-12 shows that the deeper (1 m) material is coarser than the shallower (surface) material and that the sericitic schist has a much different size distribution from the felsic volcanoclastics. If the average size distribution is used to represent the waste rock dump, it is likely to overestimate the amount of fine fractions. The study correctly pointed out that the finer fraction accounts for most of the surface area in the dump. However, because no estimates of the >0.5 m fraction were given, it is impossible to estimate the absolute amount of the finer fraction in the dump, therefore, any properties dependent on the total surface area in the waste rock dump cannot be quantified. The size distributions determined in this study should, therefore, be treated as rough estimates for the entire dump.

5.2.4 Summary

Field solid sampling was achieved by means of dry-air drilling, surface trenching and surface pitting. The drilling method employed is state-of-the-art for sampling waste rock dumps; the trenching and pitting methods are consistent with industry standards. The locations of boreholes, trenches, and pits are properly selected, and the sampling and compositing intervals agree with accepted practice.

Observation and logging of samples from the boreholes, trenches, and pits are adequate; the results are well documented; and the graphical presentations are clear. The paste pH data appear reliable. The particle size distributions determined, however, are not truly representative of the entire waste rock pile and thus should be regarded as a rough estimate. The percentage of the size fraction greater than 0.5 m is not quantified, making it impossible to determine the total surface area of the material in the waste rock pile.

5.3 Solid Characterization - Laboratory Work

5.3.1 Work Performed

The list of geochemical, mineralogical and mechanical properties of solids characterized in this study is impressive:

- Qualitative mineralogy by XRD (X-Ray Diffractometry), using both conventional powder mounts and innovative oriented mounts, of all 23 samples (20 waste rock, 2 top soil, and 1 bedrock samples) from borehole BH-7, 9 waste rock samples from pit T92-1 taken at 0.5 m equal intervals from surface to a depth of 4.0 m, and 9 waste rock samples from pit T92-2 also taken at 0.5 m equal intervals from surface to a depth of 4.0 m, as well as qualitative mineralogy by XRD, using only conventional powder mounts, of 106 (nearly all) samples from boreholes BH-1 to BH-6;

- SEM (Secondary Electron Microscopy) with EDX (Energy Dispersive Analysis) of selected samples from the large pits and borehole BH-7;

- Leaching by distilled water, followed by leachate chemical analysis, of nearly all drill cuttings samples from boreholes BH-1 to BH-7;

- Chemical analyses of pore water squeezed from 9 waste rock samples from pit T92-1 taken at 0.5 m equal intervals from surface to a depth of 4.0 m, and 9 waste rock samples from pit T92-2 also taken at 0.5 m equal intervals from surface to a depth of 4.0 m;

- Whole-rock chemical analyses of the three rock types contained in the south dump: 45 sericitic schist (unit 4B) samples, 43 felsic volcanoclastic (unit 4A) samples, and 15 intermediate tuffs (unit 3) samples (note that this work was not done for the MEND study but rather was done by Savoie et al. (1991) in a separate study. It is listed here because the results were employed in this study for data interpretation);

- A form of ABA (acid-base accounting) calculated using sulphide analyses and carbonate analyses of the three rock types contained in the south dump: 45 sericitic schist (unit 4B) samples, 43 felsic volcanoclastic (unit 4A) samples, and 15 intermediate tuffs (unit 3) samples (note also that this work was not done for the MEND study but rather was done by Savoie et al. (1991) in a separate study. It is listed here because the results were employed in this study for data interpretation);

- Hydrogen peroxide tests using certain size fractions of the three rock types selected from the trench samples from the south dump, in an attempt to determine specific surface area of reactive sulphides;

- Image analyses using certain size fractions of the three rock types selected from the trench samples from the south dump to determine specific surface area of sulphides; and

- Los Angeles Abrasion Tests, Micro Deval Attrition Tests; $MgSO_4$ Disintegration Tests and Acoustic Celerometry using selected samples representing the three lithologic units.

5.3.2 Methodology

XRD

Common mineralogical techniques for mineral mixtures such as waste rock include transmissive and reflective optical microscopy and XRD. Each method has its pros and cons. Optical microscopy is normally employed to yield qualitative information but is also able to provide semiquantitative mineral abundance on the basis of visual estimates. If it is coupled with image analysis, the accuracy of the mineral content determination improves dramatically. XRD can be used qualitatively to identify minerals present in a sample or quantitatively for seasoned samples to generate accurate mineral abundance. XRD patterns are not easy to interpret, especially for minor minerals (which are often the minerals of interest) when masking interferences exist between different minerals.

The reviewers consider XRD an appropriate choice for mineralogical examinations in this study, although the quantitative aspects could potentially be improved by introducing chemical information in interpreting the XRD data. The researchers stated that due to *"the many variables involved and the impossibility to prepare adequate standard mixtures (with the same mineralogical, physical and chemical characteristics), reliable quantitative information cannot be obtained by XRD."* (Rapport GREGI 1994-06, p. 12.) While this statement is true, knowing the semiquantitative mineralogy, the researchers could have perhaps conducted chemical analyses (whole rock analyses, CO_2, S, minor and trace element analyses) of the same rock samples and calculated the quantitative mineralogy of the samples (SENES, 1995). If this were successful, the quantitative information would have enhanced the interpretations of mineralogical transformations.

This study used two different methods of preparation for XRD analysis: powder mounts and oriented mounts (Rapport GREGI 1994-06, pp. 11-18). Under oriented mounts, samples are either mounted in the natural state or in glycerolated state, the latter used to swell expandable minerals such as smectite. The researchers report that *"results from oriented mount analysis revealed some new data not detected by the powder method."* (p. 15) The oriented mounts (in natural and glycerated states) are instrumental in the detection of the swelling minerals; they also provided evidence for epitaxial crystallization of jarosite within muscovite.

The researchers determined vertical mineralogical profiles and used this information in combination with other information to deduce vertical dynamic geochemical and mineralogical interactions. This is an exemplary approach especially suited for this kind of research. The use of oriented mounts to study mineral alteration in a waste rock environment, to our knowledge, is new and innovative, and certainly has generated insightful information regarding the alteration mechanisms and pathways of silicate minerals.

SEM with EDX

The use of these electronic surface analytical techniques is effective, and has yielded useful information about mineral weathering and secondary mineral precipitation. It is particularly enlightening in demonstrating the compositional changes during the progress of silicate mineral transformation.

These techniques are primarily research tools. Their use in routine monitoring at mines is unlikely.

Leaching of Drill Cuttings

The simple leaching technique used in this study (described in Rapport GREGI 93-05, pp. 2-3 and Rapport GREGI 1994-12, p. 5.21) is an effective method for obtaining data on stored acidity within the waste rock dump (SENES, 1995). The researchers noted that *"... rapid drying of small quantities of acid leachate produced solid crystals and an amorphous gel.... Upon adding distilled water, more than 95% of the dried leachate went back into solution."* (Rapport GREGI 1994-12, p. 2.7) The quick, reversible dissolution of previously precipitated solutes guarantees that the acidity deposited on the drill cuttings by air drying will be leached back into solution.

The leachate must be distinguished from the pore water originally present in the waste rock pile: the pore water contains only part of the total acidity stored in the waste pile, since some acidity exists in the solid form, whereas the extracted leachate contains nearly all of the acidity stored. The pore water is likely to be so concentrated that the concentrations of many of its constituent dissolved species are limited by solubility constraints, whereas the leachate solution is probably dilute enough for most secondary minerals to be undersaturated (refer to Table 5.10, Rapport GREGI 1994-12, p. 5.20 for a comparison of the two). Consequently, the leachate can not replace the role of pore water in, for example, providing saturation indices of secondary minerals.

Two features of the leaching technique used in this study may bias the data on stored acidity. First, newly broken surfaces caused by drilling exposed fresh sulphides as well as fresh acid-consuming minerals, which may contribute acidity or alkalinity during storage and leaching, thereby modifying the original stored acidity values. Second, the study used the -2 mm fraction of the rock cuttings for leaching but generalized the results to the entire heap on a mass basis. The validity of this approach is questionable. We will comment on this issue later in the data interpretation articles.

Pore Water Analysis

Pore water has been in contact with waste rock for a relatively long time, approaching equilibrium conditions. Pore water chemical profiles can provide insightful information about acid generation, acid neutralization, and mineral transformation. In this study, pore water was extracted in the field using a manually operated pressure device, achieving solid/liquid separation as soon as the sample was excavated. The reviewers regard the collection and analysis of pore water in this study as a successful application.

Whole Rock Analysis

Whole rock analysis is a long established chemical procedure to account for the composition of a rock sample. When used in conjunction with mineralogical information it can help provide quantitative accounts of the mineralogical composition of a rock sample. When whole rock analyses are conducted before and after weathering, the chemical and mineralogical changes that have occurred can be deciphered.

This study has not made extensive use of this chemical tool. The only whole rock analysis presented in the reports is that in Rapport GREGI 1994-06, p. 133 on the composition of the three rock units, which is taken from a separate study (Savoie et al., 1991).

ABA

The acid-base accounting (ABA) data presented in this study were taken from another report (Savoie et al., 1991). The maximum potential acidity (MPA) is calculated from average sulphide content, in agreement with common practice. An overall weighted average is then calculated for the south dump according to the proportions of each rock type. The MPA (or sulphide content) so derived is adequate for the calculation of acid generation.

The use of carbonate content to calculate neutralization potential is questionable. As the study has demonstrated, the waste rock pile contains very little carbonate minerals, which accounts for the quick acidification shortly after the deposition of the waste rock. The study has also pointed out the importance of acid neutralization provided by silicate minerals such as chlorite and muscovite. Since the silicate neutralization potential is excluded, the neutralization potential (NP, calculated from carbonate content) and thus the net neutralization potential (NNP) (Rapport GREGI 1994-06, p. 132, Appendix D and Rapport GREGI 1994-12, p. 1.9, Table 1.1) is underestimated.

The underestimation of NP and NNP has not caused subsequent misinterpretation, since they are not used in interpretive exercises. The remaining duration of acid generation is calculated only from sulphur balance.

Hydrogen Peroxide Test

The hydrogen peroxide test used in this study to evaluate the reactive sulphide surface area, as pointed out by SENES (1995), is similar to numerous versions of tests using hydrogen peroxide to oxidize sulphide to estimate various parameters related to sulphide content, sulphide reactivity, acid-base balance, etc., including the Sobek Total Sulphur Estimation by Peroxide Oxidation (Sobek et al., 1978, pp. 69-72), the Hydrogen Peroxide Test (Coastech Research, 1989), the Net Acid Production (NAP) test (Coastech Research, 1991), and Net Acid Generation (NAG) test (Finkelman et al., 1986, pp. 521-534; Oshay et al., 1984, pp. 13-14).

Generally speaking, the peroxide-based tests have only had limited success in specific applications under specific circumstances. It is now accepted that such success depends on the mineralogical properties of the material under testing and the objectives of the tests. As a means of determining sulphide content, sulphide reactivity, and net acidity, the peroxide tests have met with criticism and have not been widely applied.

The Mine Doyon study tried to use hydrogen peroxide tests to determine specific reactive sulphide surface area by comparing the pH-time and temperature-time profiles of the samples with those of a standard material (Rapport GREGI 94-04, pp. 19-21 and Rapport GREGI 1994-12, pp. 3.7-3.8). Because the details of arriving at the percent reactive pyrite surface area from profile comparisons are not reported, the validity and accuracy of the figures given in Table 4 of Rapport GREGI 94-04 are impossible to evaluate.

The researchers concluded that the hydrogen peroxide tests were unsuccessful in determining the reactive surface area of pyrite of the four rock types due to differences in grain size and specific area between the samples and the standard, and recommended more testing under various conditions. The reviewers' opinion is that, unless the researchers are able to prepare a standard having all characteristics (including size distribution, mineralogical composition, reactivity of sulphide and acid-consuming minerals, etc.) but reactive specific pyrite surface area identical to the samples, the hydrogen peroxide test is not likely to succeed in determining the reactive specific surface areas of samples.

Image Analysis

This study used image analysis of SEM photographs to *"measure typical surface area of pyrite grains in different rock types and compare sizes"* (Rapport GREGI 1994-12, p. 3.8; and Rapport GREGI 94-04, p. 21). This stated objective has certainly been achieved. The pyrite grains are relatively easy to identify on the SEM image, and computer-aided image analyses are quite accurate in determining the percent area occupied by pyrite grains.

Since the image analysis is based on polished sections, to achieve an acceptable representativity of the rock type being studied, enough samples must be used to average out the variations from specimen to specimen within that rock type, and enough fields should be analyzed to average out the variations from image to image within a single specimen. From Table 5 (Rapport GREGI 94-04), the number of images used (three) appears adequate for mafic tuffs, volcanoclastics, and intrusive rock, as the image-to-image variations observed are small, while more than three images should have been employed for sericitic schist to derive the average because of the large image-to-image variation (5.5% to 34%). Since only one specimen was used for each rock type, the degree to which the averages presented in Table 5 are representative of their corresponding rock types is open to debate. We understand that the purpose of the image analyses was to obtain "typical", not "representative" information about the pyrite surface areas of different rock types. Thus, despite the questionable representativity, we consider the image analysis a successful application.

Attention should be paid to the fact that the percent pyrite area determined through image analysis is physical instead of reactive surface area. It is determined on freshly polished cross sections, not on the rugged and irregularly-shaped waste rocks in their natural state. Nevertheless, the information generated by image analysis is useful. For example, the representative percent pyrite surface area in a given rock type obtained from image analysis can be applied to the total surface area of that rock type to calculate the total pyrite surface on that rock type area within a waste rock pile.

Mechanical Tests

This study attempted to relate the results of several mechanical tests to weatherability (and thus its effect on the rate of acid generation) of different waste rock types. We consider this attempt a useful exercise and an important first step towards introducing mechanical properties of waste rock into the equation of AMD prediction.

The three standardized tests (Los Angeles Abrasion, Micro-Deval attrition, and Magnesium Sulphate Disintegration) are well known and each test provides a measure of the percentage of mass lost to fine particles. All three tests are performed on a particle size subset of heap samples, therefore the results may be difficult to relate back to the field. It seems that the abrasion and attrition tests are somewhat aggressive and would likely overestimate the natural production of fine particles within a static waste rock dump, although an upper limit estimate is useful for estimating the potentially maximum effect of weathering on production of AMD. The Magnesium Sulphate test is particularly interesting and would seem to be the most suitable test for investigating the weathering conditions within the heap for the following reasons (SENES, 1995):

- It simulates wet/dry cycles which take place within the heap;
- It simulates the crystallization pressure as exerted by freezing (ice formation) and by secondary mineral (gypsum and jarosite) precipitation between layers of phyllosilicates, as demonstrated by this study (Rapport GREGI 1994-06);
- It attacks existing weakness planes and microfractures, just as natural weathering does, i.e., the test is lithology-dependent;
- It uses magnesium sulphate as the attacking agent, in parallel to the site conditions where seepage quality has shown that magnesium and sulphate chemistry is particularly relevant.

It would seem logical that this particular test should have been examined with more vigor. The researchers however chose to focus their attention on the results from the Los Angeles abrasion test without justification (SENES, 1995).

Acoustic celerometry was used to characterize properties similar to those given by the three standard tests. This test has the advantage of being non-destructive, rapid, inexpensive, and able to provide information on anisotropy. The disadvantage is that the test cannot quantify the production of fines.

The data presented in Table 3 of Rapport GREGI 94-04 suggest that this test provides a qualitative comparison of the strength and anisotropy of various rock types; however, it is not clear how the measurements of speed of compression and shear waves could be used to predict specific surface area increases resulting from weathering, unless this method is calibrated by some other reliable determinations of such properties. In the reviewers' opinion, this test, at the present time, is potentially suitable for use as a screening tool for selecting materials for standard weathering tests, and maybe also for classifying waste rock according to weatherability.

All four tests yielded similar rankings of the four waste rock types in terms of mechanical strength and thus inferred resistance to weathering. Further (quantitative) application of any of these methods requires further research to correlate test results to other weathering tests and field observations on a wide variety of rock types. Future researchers should pay particular attention to the Magnesium Sulphate test and acoustic celerometry.

5.3.3 Data Quality

<u>XRD and SEM-EDX</u>

The data quality in XRD depends on several factors: the representativity of the samples used in making the specimen, the quality of specimen preparation, the resolution of the incident angle, the condition of the equipment, and the capability of the computer or human to interpret the diffractograme. None of these experimental aspects has been presented in the report, therefore it is impossible to make a judgment. Nevertheless, since XRD is a mature analytical technique and the research group is experienced, and since the XRD data are coherent with other experimental data, we <u>infer</u> the XRD data to be reliable.

As with XRD, the experimental aspects such as sample selection, specimen preparation, equipment operation and data processing of the SEM-EDX studies are not discussed in the reports; it is difficult to evaluate the quality of the data generated with certainty. The facts that, first, SEM-EDX is a mature surface analytical technique; second, SEM-EDX yielded data in agreement with XRD data (epitaxial precipitation of jarosite between mineral planes in weathered muscovite and presence of swelling minerals); and third, SEM-EDX observations revealed evidence of mineral weathering that is consistent with chemical data (loss of K and Al from, and gain of Mg by, muscovite undergoing alteration), all <u>suggest</u> that the SEM-EDX data are credible.

The XRD and SEM-EDX are employed in this study to generate <u>typical</u> information using <u>typical</u> rock samples, and the data collected should be regarded as such. The study did not attempt to generate <u>representative</u> data using <u>representative</u> samples, which requires more strictly controlled rock samples for specimen preparation and more experimental observations of each specimen to average out the sampling error and run-to-run variations. As a result, it is impossible to evaluate quantitatively how widespread the observed phenomena are in the waste rock pile by the XRD and SEM-EDX data alone.

Leaching of Drill Cuttings and Pore Water Analysis

The reviewers consider the drill cutting samples as having adequate representativity, both in number and in location, of the entire dump and all three main rock types contained in the dump. The pore water samples are appropriate typical cases of the two rock types examined.

Quality assurance and quality control measures (i.e., field and laboratory blanks, spikes, duplicates; laboratory standards, cross-laboratory checks, etc.) are not described in the reports. We assume that acceptable QA/QC procedures and GLP (Good Laboratory Practice) have been followed to ensure the data quality of the chemical analyses.

Whole Rock Analysis and Acid-Base Accounting

These chemical data are taken from the study by Savoie et al. (see footnote 2) and their quality can not be assessed.

Hydrogen Peroxide Test

The test was a preliminary evaluation of its capability in characterizing reactive pyrite surface area; the researchers have concluded that the test was unsuccessful.

Image Analysis

As explained in Article 5.3.2 (methodology), this analysis was employed to yield typical rather than representative information. In this capacity, we consider the data generated to be reliable, since the SEM and image analysis techniques are accurate and robust. It would have been preferable to look at more images for specimens that exhibited large variations.

Mechanical Tests

No QA/QC descriptions are given in the reports, thus it is impossible to evaluate the data quality of the mechanical test results presented. The fact that all mechanical test results gave similar rankings of the strengths of the four rock types examined somewhat suggests a general acceptability of the test results, albeit this says nothing about the accuracy and repeatability (precision) of the data. The data given in Annexe B.3 of Rapport GREGI 94-04 are confusing, ill-captioned, and poorly explained in the main text.

5.3.4 Summary

An impressive number of solid characteristics have been determined in this study. The techniques used include surface analytical instruments (XRD, SEM-EDX), chemical analyses of water associated with solids (leachate and pore water extracted from solids), chemical analyses of solids (whole rock analyses and ABA), surface area determinations (hydrogen peroxide tests and image analyses) and physico-chemical rock weatherability tests (Los Angeles Abrasion, Micro Deval Attrition, $MgSO_4$ Disintegration, and acoustic celerometry).

We consider drill cutting leachate analysis, whole rock analysis, and ABA to be appropriate means in obtaining representative data. We regard the use of XRD, SEM-EDX, and pore water chemical analysis to be adequate as means to gather typical data on the various lithologic units. We view the use of hydrogen peroxide test, image analysis, and mechanical tests to be useful, innovative, but preliminary attempts in introducing new quantitative parameters in solid characterization for AMD prediction.

The methodologies used in this study for solid characterization are generally well conceived and applied, although some pitfalls and subtleties need to be taken into consideration when interpreting the data generated. Improvements could be made to solid characterization by coupling XRD with whole rock analysis, by using titration method instead of carbonate analysis for determination of NP, and by focusing more attention on the $MgSO_4$ test. We do not think the hydrogen peroxide test worth pursuing as a method for determining reactive sulphide surface area.

The reports presented little QA/QC information related to various solid characterization tests, making evaluation of data quality difficult. Our impression is that the majority of the data presented in the reports are of reliable quality for the purpose of this study.

5.4 Water Chemistry - Field Work

5.4.1 Work Performed

The field work related to water chemistry includes the following components:

- Installation of six monitoring wells within, and seven monitoring wells around, the south dump;
- Installation of twelve gravity lysimeters at two locations in the dump;
- Installation of three weirs and accompanying instrumentation to monitor flow rates in the three perimeter collection ditches, and installation of a meteorological station at the plant site; and
- Collection of ground water samples from monitoring wells, leachate samples from the lysimeters, and drainage samples from the collection ditches; and field measurements associated with these water samples.

5.4.2 Methodology

Monitoring Well Installation

The locations of the six monitoring wells within the south dump are well selected (see review comments in Article 5.2.2 under "Drilling"). The site selections for the seven monitoring wells around the dump are also adequate, enveloping the waste dump and providing information on upstream background ground water quality variations and downstream ground water quality evolution.

All monitoring wells are appropriately installed according to industry standards. Piezometers are terminated in both original top soil and in bedrock to monitor the ground water flow in the two regimes and the water quality change as downward infiltration takes place. The wells are properly sealed between the two piezometers and the details of well installations are well documented (Rapport GREGI 91-19, Annexe A, pp. 15-21).

Lysimeter Installation

Twelve lysimeters (polyethylene half barrels) were installed at two locations encompassing two of the three major rock types in the south dump (Rapport GREGI 1994-12, p. 2.4). At each location, two (duplicate) lysimeters were positioned at each of the three depths of 2.0, 3.0 and 5.0 m below the surface. A piezometer head was installed in each lysimeter, which was backfilled with non-reactive 2-cm waste rock gravels. The water levels in the piezometers were calibrated to allow water volume readings without emptying the barrels. The water in the lysimeters can be sampled or emptied from the piezometers by a pump from the surface. The lysimeter arrangements in this study are well designed and can provide a valuable reference to other sites for similar exercises. The chemistry of the water collected from the lysimeters is an important and non-substitutable part of the data set for this study.

There is an inevitable drawback to this excavation-and-burial installation of lysimeters: the original waste rock was disturbed, disrupting the original air supply patterns and infiltration channels, resulting in artificial changes in hydrological and chemical properties of the waste rock and the infiltrating water. Although the waste rock was carefully backfilled, and the researchers recognized that some time was required for the system to establish a new equilibrium, nobody really knows how long it will take for the backfilled waste rock to restore its pre-excavation state (the researchers suggest one year), or whether this is possible at all. Nevertheless, there are no better alternatives to the arrangements at Mine Doyon and; in this sense, they represent "best available technology."

Flow Measurement Instrumentation and Weather Station

Flow rate data are necessary for the calculation of loadings, thus the mass balance of chemical species such as sulphate and acidity. The original instrumentation included an automatic weir monitor connected to a chart recorder. The researchers later found that the recorded charts were virtually useless because the absolute time reference cannot be determined due to frequent power failures. A data logger with an independent circuit referencing absolute time has since been installed, which should be sufficient to correct the problem.

A weather station was installed at the mill to collect data on precipitation, temperature, relative humidity, and atmospheric pressure. It would have been better if the weather station had been installed on the south dump. The researchers used precipitation data from three regional weather stations, not the data collect by the weather station at the mill, for hydrological interpretation (Rapport GREGI 1994-05).

Field Water Sample Collection and Measurement

Water sampling was achieved through programmed autosamplers, manual collections, Waterra pumps, and peristaltic pumps, depending on the sources of samples (Rapport GREGI 1994-12, p. 2.5 and Rapport GREGI 91-19, pp. 6-7). Except during the freezing season, weekly samples were taken from the collection ditches at the weirs, complemented by additional sampling during special events such as spring melt. Ice was broken to collect occasional samples during the freezing season. Samples were taken from the monitoring wells and lysimeters irregularly. Samples were treated in the field, when necessary, by filtration and preservation. The monitoring wells were purged 4-8 times the static piezometer volume, when possible, before water quality samples were taken. Water samples were stored in refrigeration for a short time before being sent to various laboratories for physical and chemical analyses.

Water sampling, sample handling, and sample storage practiced in the Mine Doyon study are consistent with well-established industry standards. This should be sufficient to ensure that the water samples arriving at analytical laboratories had acceptable quality and had not undergone undesirable chemical changes.

It appears from the reports that no physical or chemical measurements of the water samples were made in the field. All analyses seem to have been conducted in laboratories.

5.4.3 Data Quality

No water chemistry data were collected in the field. Physical data collected in the field that are relevant to calculation of mass balances of chemical species include flow rate records, water volumes in the lysimeters, and weather information. The quality of these data is beyond the scope of this chapter.

5.4.4 Summary

Field work in the Mine Doyon study relevant to water chemistry includes installation of monitoring wells, lysimeters, flow measurement devices, and a weather station; and collection of data and water samples from these facilities. The installation of monitoring wells at Mine Doyon is textbook quality. The lysimeter design is exemplary. The sampling, handling and storage of water are in accordance with industry standards. However, the flow measurement instrumentation were at one time defunct (this has now been corrected); and the weather station should have been installed at the south dump instead of the mill.

5.5 Water Chemistry - Laboratory Work

5.5.1 Work Performed

The laboratory work conducted on water chemistry includes the following components:

- Measurements of physico-chemical parameters of the water samples collected from monitoring wells, collection ditches, and lysimeters consisting of pH, Eh, and conductivity;

- Measurements of chemical parameters of the same water samples consisting of some or all of the following: total dissolved solids (TDS), acidity, sulphate (SO_4^{2-}), major dissolved metals (K, Na, Ca, Mg, Al, Fe_{total}, Fe^{2+}, Fe^{3+}), and trace dissolved metals (Cu, Pb, Zn, Cd, Pb, Mn); and

- Development of a correlation for calculating certain chemical parameters (SO_4^{2-}, Fe_{total}, Mg, and Al) from TDS or conductivity, and adaption of an analytical method (Energy Dispersive X-Ray Fluorescence Spectroscopy, or EDXRF) to rapidly measure the concentrations of selected metals in AMD.

5.5.2 Methodology

Measurement of Physico-chemical Parameters

The routine techniques for instrumental measurements of pH, Eh and conductivity have long been established and development of electronic circuitry, on-board microprocessors, and more sensitive probes over the last two decades has made such measurements even more reliable, rapid, and convenient. A qualified technician following correct procedures can make these measurements accurately. The instruments used, listed on p. 5.3 of Rapport GREGI 1994-12, are common commercial models with demonstrated quality, and the reviewers regard their use as being appropriate.

Measurement of Chemical Parameters

The methods used to determine chemical parameters, including TDS, acidity, SO_4^{2-}, major dissolved metals (K, Na, Ca, Mg, Al, Fe_{total}, Fe^{2+}, Fe^{3+}), and trace dissolved metals (Cu, Pb, Zn, Cd, Pb, Mn), as described on p. 5.3 of Rapport GREGI 1994-12, are well-established standard procedures; we consider their use in this study to be adequate. The researchers also adapted the EDXRF method in this study to analyze water samples collected from the gravity lysimeters and pore water samples extracted under pressure (see Article 5.6.4 for detailed discussion). In the later phase of the study, the researchers reduced the number of directly-measured parameters and used TDS or conductivity to calculate some of the unmeasured parameters (SO_4^{2-}, Fe_{total}, Mg, and Al), according to an empirical correlation developed from the database of the earlier phase (see Article 5.6.4 for detailed discussion).

An important aspect of chemical determinations necessary for interpretation of analytical results is not reported: the preservation of Fe^{2+}/Fe^{3+} ratio. To preserve the Fe^{2+}/Fe^{3+} ratio, nitric acid should not be used since it oxidizes Fe^{2+}.

Chemical Correlation and EDXRF

The researchers developed an empirical relationship from the database accumulated during the earlier phase of the study to calculate some important water quality parameters (SO_4^{2-}, Fe_{total}, Mg, and Al) from TDS (or conductivity) (Rapport GREGI 93-04, p. 5). The method has the advantage of being simple, quick, and inexpensive, and has performed reasonably well for the concentrated samples at Mine Doyon. The same calculation was much less successful for AMD solutions having a TDS less than 25,000 mg/L. The relatively satisfactory performance for the more concentrated solutions was possible because the composition of AMD samples from this site was virtually constant in terms of ratios among different chemical species. This strategy may not be applicable at other sites; an update of the empirical correlation is required from time to time as the water chemistry evolves. A more detailed discussion of this subject is offered in Article 5.6.4.

EDXRF, normally used to examine solids, was modified in this study to analyze dissolved metals by standardizing the steps of evaporating an aliquot of liquid sample on a piece of membrane filter. The precipitate/residue spot on the filter is then bombarded with X-ray; the secondary fluorescent X-rays characteristic of the elements present in the sample are detected. The resultant plot of incident X-ray energy versus fluorescent X-ray counts is used to determine the concentration of each element by comparison with standard calibration curves: the energy position identifies the element and the number of counts indicates the concentration. This analytical method is technically sound and offers some advantages such as being relatively quick, inexpensive, productive, and requiring only a tiny aliquot (20 µL) of sample, the last feature being very useful in analyzing pressure-extracted pore water because of the small volume normally obtained. There are a few disadvantages, an important one being the reliance of the method on the premise that the ratios among major dissolved elements in the sample must be constant for acceptable performance. This seriously limits the method's wide applicability. Nevertheless, since this requirement was met by most of the Mine Doyon AMD samples, EDXRF worked reasonably well in this study. More discussion on this subject can be found in Article 5.6.4.

5.5.3 Data Quality

Measurement of Physico-chemical Parameters

The measurement of pH, Eh and conductivity can be done accurately when the correct procedures are strictly followed. The key to quality data of these physico-chemical parameters is preservation of the sample integrity. The quality of the data obtained appears to be acceptable.

Measurement of Chemical Parameters

No QA/QC descriptions are given in the reports, thus it is impossible to evaluate with certainty the quality of the chemical data presented in the reports. On the assumption that adequate QA/QC procedures were followed, and because of the fact that the solution chemical analyses involved in this study, with the exception of the correlation method and EDXRF, are long established routine laboratory work, we assume the results of the chemical data to be acceptable.

As with the case of physical measurements, the key to quality chemical data lies in the appropriate sampling, handling, storage, and prompt analyses of the water samples to minimize chemical changes of the solutions in the target analytes. This may require the field sample to be split into two or more subsamples, each treated and preserved according to the target analytes. For example, the samples should be filtered and unaltered for determinations of TDS, acidity and SO_4^{2-}, while they should be filtered and preserved with acid for analyses of dissolved metals. The samples seem to have been appropriately handled in the field program (see Article 5.4.2 under "Field Water Sample Collection and Measurement"), although insufficient information precludes a thorough evaluation.

Chemical Correlation and EDXRF

The data used for calculation of chemical parameters not directly measured are either TDS or conductivity. For comments regarding the data quality of these two parameters, see discussions under "Measurement of Chemical Parameters" above. The quality of the calculated chemical data is discussed in Article 5.6.4.

QA/QC information (i.e., use of blanks, duplicates, spikes, standards, etc.) is not given in the reports concerning the routine use of EDXRF to determine chemical parameters (Fe_{total}, Mg, Ca, Al, and SO_4^{2-}), therefore it is impossible to evaluate the quality of the data determined by EDXRF in this study. Nevertheless, an approximate assessment of the general quality of this analytical method can be made from the information given in Tables 4, 6 and 7 of Rapport GREGI 93-04. The reported method detection limits (MDL) based on analyses of 7 duplicate standard samples are 55 for Fe_{total}, 35.5 for Mg, 32.2 for Ca, 18.5 for Al, and 38.1 for SO_4^{2-} (note that the Mg and Ca concentrations of the standard used fell below the corresponding MDL). These MDL's are adequate for concentrated solutions, as is the case for most of the Mine Doyon AMD samples, but are not very useful for environmental monitoring of dilute solutions such as background or discharge samples. The accuracy of the method, signified by the relative errors computed from the mean detected concentrations given in Table 6 and the true concentrations given in Table 4, are as follows: -7.2% for Fe_{total}, -6.5% for Mg, 13.2% for Ca, 11.6% for Al, and 45.3% for SO_4^{2-}. Using an acceptability criterion of 10%, it is clear that the accuracies for Ca, Al, and especially SO_4^{2-}, are unacceptable for the S-40 (used to evaluate MDL for dissolved metals) and S-100 (used to evaluate MDL for SO_4^{2-}). With respect to precision (repeatability), an examination of Table 6 shows that all parameters except SO_4^{2-} have a standard deviation greater than 10% of the mean detected concentrations, indicating an unsatisfactory performance of this method for the S-40 standard as far as the four dissolved metal concentrations are concerned.

To reduce the relative errors in accuracy and precision, the EDXRF method must be used to analyze solutions much more concentrated than the S-40 and S-100 standards, which is what was done in this study. It is stated on p. 10 of Rapport GREGI 93-04 that all samples were diluted to approximately the mid-point of the SO_4^{2-} calibration curve (p. 19), which is about 6000 mg/L, 160 times the MDL. The approximate dilutions were made on the basis of SO_4^{2-} of the original solutions estimated from conductivity or TDS, using the relationship developed in this study. If we use 10 times the MDL's as the minimum concentrations of feed samples to EDXRF for acceptable analyses (i.e., 550 for Fe_{total}, 355 for Mg, 322 for Ca, 185 for Al, and 381 for SO_4^{2-}), we find that a great majority of analytical results provided in Tables 7 and 8 (except those reported as less than detection limits) are above these minimum concentrations. The use of EDXRF for these samples is justified. Notice one error in Table 7 (p. 12) where the Ca by EDXRF is reported as 12 mg/L while the MDL for Ca is 32 (that entry should instead be reported as less than MDL).

Further discussion of the EDXRF method is given in Article 5.6.4.

5.5.4 Summary

The laboratory techniques used for water chemistry include instrumental measurements of physico-chemical parameters (pH, Eh, and conductivity), routine chemical analyses (TDS, acidity, SO_4^{2-}, and dissolved metals) by AAS and wet methods, and EDXRF. An empirical correlation was also used to calculate chemical parameters from TDS or conductivity measurements.

The selection of laboratory analytical methods is generally adequate. The correlation method seems effective for this particular study because of the special characteristics of the AMD samples from Mine Doyon; it may not apply at other sites. The EDXRF technique has detection limits useful for analyzing concentrated AMD solutions but is unsatisfactory for characterizing more dilute solutions such as those from background or discharge monitoring. To be successful, EDXRF must be applied to solutions with concentrations above certain minima, which is the case with the majority of the samples analyzed. This study failed to report an important aspect of chemical analysis necessary for correct interpretation of chemical data: the preservation of Fe^{2+}/Fe^{3+} ratio.

The reports have not presented much QA/QC information related to acquisition of the chemical data, making evaluation of data quality difficult. The reviewers have relied on the maturity of analytical techniques, competence of the research team, and agreement among the data generated by different methods to infer about the data quality. Our impression is that the majority of the data presented in the reports is of reliable quality for the purpose of this study.

5.6 Review Comments by Report

This article reviews seven (among ten) Mine Doyon reports which have more or less geochemical and/or mineralogical components. The seven reports are arranged chronologically according to their publication dates, and each report is discussed in three aspects (where applicable): strengths, weaknesses, and specific comments.

This article deals with content matters only; it does not deal with aesthetic problems such as typographical errors, grammar and style, content organization, and cross references.

5.6.1 Rapport GREGI 91-19

This is the earliest (written in July 1991) of the Mine Doyon series of reports. It documents most aspects of the project up to 1991 and provides preliminary interpretation of data. It has three annexes which contain all the data up to the time of the report. Some of the preliminary interpretations given in this report are enhanced, expanded, or modified in later reports, which are divided into separate volumes according to disciplines (i.e., geochemistry, microbiology, hydrology, etc.).

Strengths

The major strengths of this report are as follows:

- It is an all-in-one report, setting out the multidisciplinary framework, and providing good directions and recommendations for data acquisition for the work to follow;
- It documents effectively the early project data in detail, enhanced by well-designed illustrations and graphs; it also describes experimental methodology;
- It recognizes the importance of silicate weathering and mineralogical transformations, and discovers the correlation between various physico-chemical parameters, which was used later to reduce the number of chemical analyses;
- It contains an excellent review of AMD literature, which presumably ensured good understanding of the geochemistry and mineralogy of AMD processes by project personnel, and thus improved the overall project quality.

Weaknesses

The major weaknesses are as follows:

- The geochemical and mineralogical interpretations are incomplete, not well-explained, and not well-supported;
- The description of experimental methodology is oversimplified;
- QA/QC procedures for data acquisition are not well-documented.

Specific Comments

The interpretations in this report are repeated (and expanded) in later reports. Comments on these interpretations are given in the following articles under various reports, and will not be repeated here.

5.6.2 Rapport GREGI 93-03

For the most part, this report is about monitoring and modeling of heat production and heat transfer (therefore physical aspects) of the south dump. It involves very little geochemistry or mineralogy, although the results from this report have important geochemical implications. The only geochemical aspect involved in this report is related to the conversion of heat production to sulphate production.

The adoption of the heat production value of 1410 J/mol FeS_2 oxidized (or 705 J/mol SO_4^{2-} produced) implies complete oxidation of pyrite to sulphate:

$$FeS_2 + 3.5O_2 + H_2O = Fe^{2+} + 2SO_4^{2-} + 2H^+ + 1410\,J$$

Despite the fact that this study has identified intermediate sulphur species (such as elemental sulphur) in the process of pyrite oxidation, we believe that the intermediate species are short-lived and their amounts are probably steady. For the purpose of modeling heat production and transfer, the assumption of total pyrite conversion to sulphate is well-made.

5.6.3 Rapport GREGI 93-05

This report, dated March 1994, is an updated compilation of chemical data for the Mine Doyon project and contains few interpretations.

Strengths

The major strengths of this report include the following:

- It is a documentation of updated chemical data and experimental methodology;
- It provides a sulphate mass balance.

Weaknesses

The major weaknesses of this report are the following:

- QA/QC procedures used in data acquisition are not reported, so the quality of the chemical data cannot be fully assessed;
- There are some flaws in the interpretation of data (see the specific comments below).

Specific Comments

On p. 3, third paragraph, the authors state that *"since the original water content of each sample is unknown, acidity was calculated using a water content of 5.7%, which is the mean water content of the dump."* This approach assumes that all the acidity extracted from the drill cutting samples by the leaching procedure resides in the liquid phase (i.e. the 5.7% moisture), and thus may have overlooked the importance of "solid" forms of acidity, such as melanterite, hydronium jarosite, schwartzlite, etc. If the solid forms of acidity do indeed represent a significant portion of the total acidity in the unsaturated zone, this approach could have grossly over-estimated the acidity concentration in the pore water, and could potentially account for the observations in Figure 5 (p. 13) that many of the calculated pore water acidity values, especially those in the more acidic boreholes, are much higher than their corresponding measured acidity values in the piezometers. This point was not noted in the report.

In Table 1 on p. 6, the total stored soluble sulphate is calculated by a direct scale-up of the leaching results of the <u>-2 mm</u> fraction of the -2 cm drill cutting samples, instead of the entire -2 cm drill cutting samples. This is problematic. The correct calculation should scale up the leaching result according to the <u>whole</u> drill cutting sample, not just the <u>-2 mm</u> fraction of it. To illustrate, suppose (1) the whole -2 cm drill cutting sample is representative of the waste dump, (2) the -2 <u>mm</u> fraction represents 20% by weight of the whole drill cutting sample, and (3) the acidity loading per unit weight of the +2 mm fraction is 1/5 of that of the -2 mm fraction; the calculated total sulphate storage would be 45,387 tonnes, not 126,077 tonnes as calculated in the report. As a result, the stored sulphate figure given in Table 1 likely has over-estimated this quantity by 2-3 fold. Consequently, in the statement on p. 5, *"...it represents 7 years of active oxidation,"* the number 7 should be replaced with 2 to 3.5. If this contradicts the other calculations, a source of error has to be sought somewhere else, for example, the estimate of pyrite oxidation rate per year (16,443 t/y), or the assumption that this rate is constant.

Researchers should have conducted at least one leaching experiment to compare the stored acidity per unit weight for different size fractions.

In Figure 2 on p. 10, all graphs show a data-point-free window in both the horizontal and the vertical axes: This could be an indication of some characteristic processes in the acid generation-neutralization reactions, e.g., depletion of a buffering mineral. Looking into the reasons behind this observation could potentially add to the geochemical and mineralogical interpretation of data. This point is not discussed nor is the observation mentioned in the report.

One good exercise for checking the quality of solution analyses is to perform a charge balance computation, which can be easily done for some of the chemical data compiled in this report. An acceptable chemical analysis should show a charge imbalance of less than 10%. Despite the large volume of solution analytical data, no such check has been mentioned in this report.

5.6.4 Rapport GREGI 93-04

This report describes a correlation method to calculate certain chemical parameters from TDS or conductivity and an analytical technique using EDXRF to analyze relatively concentrated AMD samples.

Strengths

The main strengths of reported methods are as follows:

- Both methods have performed satisfactorily for the more concentrated AMD samples from the south dump;
- Both methods are based on sound fundamental principles and are technically feasible;
- The chemical correlation method has the advantage of being simple, quick, inexpensive, capable of handling concentrated AMD solutions, and can possibly eliminate the need for analyses of some chemical parameters under certain circumstances;
- The EDXRF technique also has the advantage of being quick, inexpensive, productive, capable of performing multi-elemental determinations and handling high solution concentrations, and requiring only a minute (20 μL) amount of liquid sample, which is especially beneficial for analyzing pressure-extracted pore water because of its small volume;
- Both methods could have "niche" applications when circumstances warrant.

Weaknesses

The primary weak points of the reported methods include the following:

- Both methods rely on the premise that the solutions being analyzed must follow a constant "signature", i.e., the composition of the solutions should remain "constant" (except for dilutions) for adequate performance of the methods;
- The correlation curves and calibration curves must be updated as the solution chemistry (the "signature") changes with time;
- Although both methods worked well at Mine Doyon, they may not work well at other sites if the water chemistry is not suitable;
- Both methods only work well with relatively concentrated solutions; they are not successful for dilute solutions such as those encountered during background (baseline) and discharge monitoring;
- The calibration method cannot be used for trace element concentrations;
- The EDXRF method involves complicated, expensive, and specialized equipment and is prone to operator/environmental/background errors.

Specific Comments

Add to the end of the last paragraph under this heading the following text (SENES, 1995):

The correlations between acidity, Al, Fe_{total}, Mg, SO_4^{2-} and TDS and conductivity are given on p. 4 with impressive coefficients of determination. These correlations are developed using 69 ground water samples from boreholes and 41 seepage water samples from weirs collected during two seasons (spring and summer) of one year (1991) (see p. 2). In the case of Mine Doyon, the seepage quality has been monitored since placement, and an exhaustive monitoring program carried out in 1990 had shown that the chemical patterns of AMD were well-established. Therefore, it was probably acceptable to develop correlations based on six months' data. However, it could be dangerous to rely entirely on the calculated values for some parameters, particularly at sites with less well-established AMD chemistry. Chemical analyses should be done regularly at these sites, perhaps several sampling intervals apart to check the performance of the correlation curve; more frequent and complete analyses should definitely be carried out if successive deviations from the correlation curves are detected. The limitations of the correlation method should be made clear to anyone who comes to use any of the calculated chemical parameters.

The authors stated (p. 3) that *"these correlations are significant to explain the processes of acid generation in the dump. Results indicate that leachate samples from the base of the dump and the ditches can be viewed as a single solution, showing more or less dilution. It is thus possible to establish relationships for the calculation of the concentration of major contributors like*

Fe, SO_4^{2-}*, Al, Mg and acidity based on simple parameter measurements such as TDS or conductivity."* This qualifying statement is very important and should be emphasized in the report. A test of the similarity of borehole/well data and seepage data appears to be necessary to apply their approach to other sites (i.e., does dilution explain the differences in concentration levels?). It is questionable whether these correlations should be applied to leachates from the drill cutting samples—do the leachates have "signatures" different from the ground water samples and the drainage samples from which the correlations were developed? The researchers should have analyzed more of the leachate samples to validate the applicability of the correlations.

The application of EDXRF is again qualified for acidic leachate from the south dump where the ratio of one element on another is almost constant (i.e. dilution accounts for differences in concentrations). An important drawback of this method is the requirement for unique standard solutions to prepare the calibration curves. The standard must have a composition similar to the leachate. The method requires the dilution of highly concentrated samples with nitric acid to a narrow concentration range for best performance. The detection limits are high compared with conventional chemical analyses (e.g., AAS, ICP, wet chemistry). The analyte concentrations should be above a certain minimum for reliable analytical results (refer to Article 5.5.3 for comments on the accuracy and precision of this method).

Tables 7 and 8 (p. 11-12) compare analytical results by conventional chemical analyses, the correlation method, and EDXRF. For the piezometer samples, the correlation method and EDXRF are approximately equal in acceptability; both can sometimes give very erratic numbers. The detection limits of the EDXRF method are clearly too high for the pressure-extracted pore water with respect to Fe, Al, and Mg.

5.6.5 Rapport GREGI 94-04

This report describes attempts to relate results of several mechanical tests to weatherability (and thus its effect on the rate of acid generation) of different waste rock types at Mine Doyon. Hydrogen peroxide tests and image analyses are also used to characterize pyrite surface areas.

Strengths

The major strengths of this report are as follows:

- It is the first systematic attempt known to the reviewers to compare different mechanical tests, and to relate the results to field and laboratory observations of waste rock weatherability in an AMD study;

- It is the first attempt known to the reviewers to use acoustic celerometry to study AMD generation from waste rock;
- Different mechanical tests, the hydrogen peroxide tests, and the image analyses yielded approximately agreeable results;
- It looked, albeit with a rough calculation method, at the effect of particle shapes on specific surface area.

Weaknesses

The reviewers consider the following as the main weak points of this report:

- The use of the results from different mechanical tests is qualitative in nature;
- The hydrogen peroxide test to determine reactive specific surfaces of pyrite has failed (as the authors pointed out);
- The authors should have focused more attention on the Magnesium Sulphate test instead of the Los Angeles Abrasion Test as they did in the report;
- The calculation of specific surface areas is flawed (see specific comments below).

Specific Comments

The two formulae at the bottom of p. 13 are incorrect. The correct formulae are:

$$S_g = 7 \cdot l^2$$

$$N = \frac{M}{2.7 \cdot l^3}$$

These errors are carried to the formula at the top of p. 14, which should be corrected to

$$SS_{plate} = \frac{7}{G_s \cdot l}$$

This error is reflected in Figure 5, where the line representing the plate-shaped particles is incorrectly located below that of the cubic particles. The correct position for the line should be above the line of cubic particles, but below the line of disk-shaped particles. It is obvious that the specific surface area of elongate, platy particles is greater than that of cubic particles when both pass through the same screen aperture.

This error is not carried in the calculated specific surface areas of acidic volcanoclastics (the only rock type for which a plate shape is assumed for its particles) in Tables 2 (p. 16), 6 (p. 23), and all tables in Annexe B.3 (pp. 58-70), because these surface areas are not calculated using the incorrect formula; a different route was used.

All numeric entries in Table 6 (p. 23) are incorrect: these are the quantities (specific areas after tests)/(specific surface areas before tests); that is, the multiples of after-test specific surface area over the before-test specific surface areas expressed in percentages, computed using each of the three shapes (cubic, disc, and plate) for each of the four rock types. All the numeric entries should be decreased by 100 to obtain the *"percent increase of specific surface areas" ("l'augmentation de la surface spécifique")*, as noted in the caption of the table. In contrast, the figures under "augmentation" in Table 2 (p. 16) are correctly calculated.

The calculation of specific surfaces in all the tables contained in Annexe B.3 (pp. 58-70) suffers from two flaws. First, the bottom sieve for the size analysis (0.08 mm, or approximately 200 mesh) is too coarse. The correct procedure should be screening the before- and after-test material using all the standard sieves, with the bottom sieve being 400 mesh (0.038 mm), and taking the -400 mesh material and carrying out a size analysis all the way down to 0.001 mm (1 µm) using another method such as settling or automatic size analyzer. The -200 mesh material has a dramatic influence on the specific surface area. For example, in the top table on p. 60, the specific surface for the size fraction passing 0.08 mm is calculated in this report using 0.04 mm (half of the sieve opening), which gives a value of 648.148 cm^2/g. If this fraction were further sieved and if we found that 50% is retained on the 0.038 mm sieve, 25% is greater than 0.01 mm, and 25% is less than 0.01 mm, we can calculate the specific surfaces as in Table 5-1:

Table 5-1

Calculation of the Effect of -200 Mesh Fraction on Specific Surface Area

Size Fraction	% by Weight	Specific Surface cm^2/g	% Weight x Specific Surface
-0.080 mm +0.038 mm	50	439.4	219.7
-0.038 mm + 0.010 mm	25	1080.2	270.0
-0.010 mm (use 0.005 mm)	25	5185.2	1296.3
Specific Surface of the -0.08 mm Fraction (cm^2/g)			1786.0

The recalculated specific surface (1786 cm^2/g) almost triples that presented in the report (648 cm^2/g). The effect of this on the specific surface of the entire before-test material is to increase its specific surface from 10.53 cm^2/g to 21.91 cm^2/g, that is, more than doubling the old specific surface!

The second, less pronounced flaw is the use of discrete average grain sizes for the calculation of specific surfaces. In this report, the specific surface of the -20 mm + 14 mm fraction, for example, is calculated using an average grain size of 17 mm (average of the two sieve openings). Then the specific surface of the entire sample is calculated by a weighted average of the specific surfaces of individual size fractions that make up the sample. It would have been more accurate if a numerical integration method was used (Cummins et al., 1973, pp. 27-34 to 27-37).

5.6.6 Rapport GREGI 1994-06

This is an outstanding report of the Mine Doyon series, documenting most of the new geochemical and mineralogical discoveries of this study and presenting some enlightening geochemical and mineralogical calculations/interpretations.

Strengths

The major strengths of this report are summarized briefly below:

- The investigative and interpretive techniques are scientifically sound;

- The integration of information from different analyses (XRD, SEM-EDX, and chemical analyses) is exemplary;
- It has, for the first time, unveiled direct mineralogical evidence of phyllosilicate weathering, buffering, and evolution paths in an acidic waste rock dump environment;
- It has, for the first time, presented evidence for the formation of clay minerals from acidic alteration of phyllosilicate minerals;
- It has revealed the role of secondary mineral (i.e., jarosite and gypsum) growth in the physical disintegration of host rock, with the support of direct microscopic observations;
- It includes an illuminating comparison between measured and calculated depth profiles of silicate dissolution and secondary mineral precipitation;
- It uses an interesting approach to calculate vertical mass transfer;
- Conventional mount and oriented mount are coupled innovatively to yield information on mineralogical transformations.

Weaknesses

This report has the following weak points:

- The mineralogical calculation/interpretation is based on data from only one borehole, BH-7 (SENES, 1995);
- The XRD-revealed mineralogy is qualitative in nature; it could have been rendered more quantitative by making use of whole rock analyses of the drill cutting samples to enhance the mineralogical interpretations (SENES, 1995);
- The data collected in this project are not used to their fullest extent in the mineralogical interpretation (see specific comments below);
- The innovative oriented mount for XRD is not documented clearly enough for others who are interested in this approach to follow.

Specific Comments

In the mass transfer calculations shown in Table 3 (p. 32), K and Na could have been included in the mass balance equations. It would be interesting to note the results after addition of these two elements to see the stability of the mathematical solution.

XRD and drill cuttings leach were conducted on virtually all samples from boreholes BH-1 to BH-7 (see Article 5.3.1). The authors should have used at least one other borehole to validate the mineralogical observations and mass transfer calculations on BH-7. This would be a very worthy exercise, adding to the confidence in the entire mineralogical study.

Other interesting calculations could have been made using existing data. For example, the percent acid neutralized within the waste dump can be calculated from the concentrations of K, Na, Mg, Ca, Al, Mn in pore water and toe seepage, and the water balance. This percentage would add to our insight into the acid generation-consumption processes taking place inside the dump. The rate of silicate dissolution, too, can be computed from data such as annual acidity-alkalinity balance in pore water and toe seepage.

The following comments are made by SENES (1995):

Figure 9 (p. 26) shows that the top 3 m of borehole BH-7 is nearly neutral while the leachates below 4 m are acidic. Several reasons could be responsible for this observation: the near-surface part of the dump could be too cold to support bacterial activity for accelerated AMD generation; the surface could have been compacted by truck traffic such that air permeability becomes a limiting factor to oxidation; the acid generated could have been neutralized in situ by acid-consuming minerals; or the acid could have been washed down by infiltrating water. Which one of these factors (or others) is dominant? The report does not explain this clearly.

The reference on p. 24 to the lower left part of Figure 6c to illustrate the jarosite rhombohedron within the muscovite is difficult to locate; Figure 8c shows this much more clearly.

Figure 12 on p. 36 shows the results of mass transfer calculations in an excellent manner, and, when compared with the mineralogical observations given in Table 1 (p. 12), is very illuminating. The similarities are remarkable; trends and relative magnitude have been reproduced quite well, all lending credibility to the mass transfer calculations. However, the authors neglected to suggest this powerful comparison.

The recommendations offered in the report (p. 37) do not follow logically from the work presented in the report. The reviewers do not consider the lack of water quality data to be a "main weak point" of this study. The researchers should be commended for using two different methods (pressure extraction and leaching extraction) to obtain pore water samples from the waste rock; most investigators simply rely on seepage samples and rock analyses to estimate pore water quality. In our opinion, under-utilization of collected data is a problem than *"lack of data"*, given the understanding that one of the objectives of the project was simply accumulation of data. No attempt was made to correlate pore water and leachate quality data with seepage data.

5.6.7 Rapport GREGI 1994-12

This report is an excellent overview and summary of the entire Mine Doyon study. It pulls together all the pieces comprising the study and integrates them into a coherent document. It also presents some work which has not been documented in other reports (e.g., infrared thermography and numerical modeling).

Since this report integrates separate reports in the Mine Doyon series, most of the strengths and weaknesses of the earlier reports also apply to this report. Many parts of this report have duplicated the texts and structures of the earlier reports, thus many of the specific comments made earlier on the separate reports are also valid for this report. The strengths, weaknesses and specific comments will not be repeated here, and the reader is referred to earlier articles for those statements. What appears below are strengths, weaknesses and specific comments unique to this report.

Strengths

The main strengths of this report include the following:

- It integrates earlier reports and some so-far-unreported work in a concise, logical, and coherent manner;
- It introduces some information missing from earlier reports, provides necessary bridges between components, and makes the entire Mine Doyon study a whole picture.

Weaknesses

The weaknesses of this report are the following:

- Many parts of this report are word-for-word reproduction of the earlier reports, and as a result, many errors in the earlier reports have also been duplicated.
- Cross references to other reports are not made in a clear, systematic manner; some links with previous documents are missing.

Specific Comments

On pp. 1.8 and 1.9, the calculation of NP, and thus the NNP, is based on carbonate analysis (CA). This gives biased (underestimated) NP and NNP (see Article 5.3.2 under "Acid-Base Accounting").

In Article 2.3.4, pp. 2.9 to 2.10, equations (4) and (7) are incorrect. The correct equations are

$$S_w = \frac{W_c(1-n)r_s}{nr_w}$$

$$n = \frac{r_s(W_c + 1) - r_b}{r_s(W_c + 1)}$$

The porosity calculated by the two methods agree excellently.

On p. 3.2, fourth paragraph, the error made earlier in calculating the surface area of a plate has been corrected. However, the plot in Figure 3.1 has not been corrected accordingly (see Article 5.6.5 for discussion of this error). In addition, the ratios stated at the bottom of p. 3.2 (i.e., 1.47 (disc) : 1.17 (platelet) : 1.00 (cube)) are incorrect, the correct ratios should be 4.00 (disc) : 1.17 (platelet) : 1.00 (cube).

On p. 3.4, the numbers in Table 3.2 are different from those given in Table 2 of Rapport GREGI 94-04, yet the size distribution curves (p. 3.5), which supposedly underlie the calculations of these numbers, are identical to those presented on pp. 56-57 of Rapport GREGI 94-04. How this is possible is not explained in the report. In addition, the determination of specific surfaces in this report suffers from the same two drawbacks as discussed in Article 5.6.5 under "Specific Comments."

The discussion of the large amount of data generated from monitoring AMD at the weir stations (pp. 5.7 to 5.14) is largely qualitative (except the calculation of sulphate and acid production), and does not add much insight to this study.

The report states in the second paragraph of p. 5.43 that *"chlorite dissolution will contribute in neutralizing the pH of the solution as seen in equation (6). However, if the pH remains low, Al will likely remain in solution and contribute to acidity."* This statement is confusing; it conveys the connotation that chlorite dissolution will contribute less towards reducing the solution pH when Al is in solution. This is untrue. As a matter of fact, when Al stays in solution, the dissolution of chlorite contributes more towards reducing the solution pH, because the precipitation of Al is acid-generating and thus lowers the pH of the solution. In addition, the statement appears to confuse the concept of acidity and pH. Acidity measures the total dissolved concentration of precipitatable metals, while pH measures the activity of H^+ ions. It is possible for a solution to have a high acidity yet not very low pH; conversely, it is also possible for a solution to have a very low pH yet not very high acidity. The statement should be modified to this: "The contribution of complete chlorite dissolution to acid neutralization depends on the pH of the solution in contact with the chlorite undergoing dissolution. When the solution pH is below approximately 2.5, both Fe^{3+} and Al^{3+} will remain in solution, therefore each mole of chlorite completely dissolved will neutralize 16 moles of H^+, as shown in equation (6). When the solution pH is between approximately 2.5 and 3.5, Fe^{3+} precipitates but Al^{3+} still remains in solution, thus each mole of chlorite dissolve will neutralize 14 moles of H^+. Finally, if the solution pH is greater than about 5, both Fe^{3+} and Al^{3+} precipitate; the dissolution of one mole of chlorite will neutralize only 8 moles of H^+."

The statement on the same page following equation (7.1) that *"...in some circumstances, a net decrease in acidity will result, mainly by reducing Fe(III) concentration of the solution"* is inaccurate. The precipitation of jarosite from a solution always reduces the acidity of that solution, not just *"in some circumstances,"* as equation (7.1) shows that jarosite takes 3 Fe^{3+}, which is equivalent in acidity to 9 H^+, out of the solution but puts 6 H^+ back into the solution in the meantime, causing a net loss of acidity equivalent to 3 H^+ from the solution.

5.7 New Understanding Identified from Review

New understandings relevant to geochemistry and mineralogy from this project are divided below into two parts: techniques and knowledge. In the techniques are included field investigation tools, laboratory analytical methods, and computational and interpretive techniques. Knowledge incorporates observations, facts, theories and hypotheses. To qualify for "new understanding", the techniques or knowledge must be new, or involve a component which is innovative, to the field of AMD research.

5.7.1 Techniques

This review considers the following as new techniques in this project for geochemical and mineralogical studies:

1. The coupled use of conventional mount and oriented mount for XRD analysis of rock and soil samples to identify swelling minerals and preferred orientation of mineral growth.

2. The coupled use of SEM and EDX for studying the progress of phyllosilicate mineral alteration and the path of alteration.

3. The combined use of Los Angeles Abrasion Test, Micro Deval Attrition Test, $MgSO_4$ Disintegration Test and image analysis to characterize the weatherability and its effect on AMD generation, of water rock samples.

4. The use of acoustic celerometry for determining the mechanical strength and anisotropy of rocks leading to evaluation of weathering potential for AMD prediction.

5. The use of correlation methods to calculate chemical parameters for AMD monitoring.

6. The adaptation of the EDXRF technique for analyzing AMD samples, especially when the volume involved is extremely small.

7. Collection of water samples from buried lysimeters for characterization of water quality in the unsaturated zone of an acid-generating waste rock dump.

8. Calculations of vertical mass transfer in a waste rock dump from chemical analyses of drill cuttings leachates and comparisons of the inferred mineralogical changes with experimental observations.

5.7.2 Knowledge

Some of the following has long been known but lacks field evidence for their support. Where such field supports are afforded by the Mine Doyon study, they are included as "new knowledge" below. New geochemical and mineralogical knowledge added to the AMD literature by this study include the following:

1. For the Mine Doyon case, the different rates of AMD generation by waste rocks can partially be predicted by the waste rocks' mechanical properties, as determined by the various mechanical tests used in this study.

2. For AMD with well-defined chemical characteristics, good correlations between different chemical parameters exist to such a degree that some chemical parameters can be calculated from others with acceptable accuracy, and such correlations can be taken advantage of to reduce loads of chemical analysis for AMD monitoring.

3. Weathering of silicate minerals is well defined at Mine Doyon. It is shown to be able to contribute significantly to acid neutralization in a waste rock pile. When high concentrations of Al and Mg are encountered in the drainage of a waste rock dump which is known not to contain significant amount of Al and Mg oxides and hydroxides, fast weathering of aluminosilicates, which contributes to acid consumption, should be suspected.

4. It is observed that iron hydroxide precipitates can coat fresh or partially oxidized pyrite; jarosite can crystallize inside muscovite between the sheets; and gypsum can form along schistosity planes. The latter two processes help break up minerals and rocks and expose fresh pyrite for oxidation, accelerating acid generation and weathering of waste rock.

5. Evidence is observed for progressive weathering of phyllosilicate mineral: chlorite undergoes complete dissolution, releasing Fe, Al, and Mg to contacting solutions; muscovite and paragonite are transformed to a smectite-like, swelling mineral phase by losing structural Al, K, Na and gaining Mg before being completely transformed. The final residual phase for all three minerals is amorphous silica.

6. The primary minerals, secondary minerals, and the solution interact with each other to achieve the observed mineral transformations, as well as pore water and seepage composition. Weathering of all three minerals (chlorite, muscovite, paragonite) releases Al, which account

for the high Al concentrations in the pore water, leachate, and seepage. Muscovite releases K and paragonite releases Na, which are necessary for the formation of K-jarosite and Na-jarosite, respectively. Dissolution of chlorite releases Mg, which is taken up by muscovite and paragonite, by transforming themselves to a smectite-like intermediate weathering phase. Oxidation of pyrite generates acid which creates a suitable environment for jarosite formation. Part of the acid generated is consumed by the dissolution of all three minerals.

7. Chemical profiles of leachate extracted by leaching drill cuttings can be used to calculate vertical mass transfer, which describes the loss of primary minerals and gain/loss of secondary minerals at different depths. The mineralogical information so derived can be compared to observed mineralogical profiles, and in the case of Mine Doyon, the calculated mineralogy reproduced most of the important features of the observed mineralogy, indicating the success of this approach.

5.8 Application of New Understanding

This article considers the applicability of the new understandings identified in Article 5.7, which include new techniques and new knowledge, for two broad categories of people: AMD researchers and mine operators. AMD researchers are mainly interested in finding out the mechanisms of acid generation, consumption, and transport; developing means of predicting AMD rate and duration; and searching for methods to prevent or mitigate AMD. Mine operators are more concerned with the practical aspects of AMD: monitoring AMD for compliance, decommissioning acid-generating materials in the most cost-effective way, and estimating the cost of the decommissioning of such materials. Regulators, consultants, and other interested parties may also find this information useful.

5.8.1 Techniques

For ease of presentation, the same numbering as that of Article 5.7.1 is used for identifying techniques. For each technique, its applicability for AMD researchers and mine operators, when appropriate, is discussed.

1. **Coupled Use of Conventional Mount and Oriented Mount for XRD Analysis** This is a very special technique and can be used by other researchers to study mineral transformation during weathering processes. It is not likely to be used by mine operators.

2. **Coupled Use of SEM and EDX** These are also specialized techniques most suited for AMD researchers in their quest for mechanisms of mineral alteration. It is not likely to be used by mine operators.

3. **Combined Use of Los Angeles Abrasion Test, Micro Deval Attrition Test, $MgSO_4$ Disintegration Test and Image Analysis** These tests are not yet fully developed for characterization of AMD from waste rock. Researchers can further explore these tests and find one or two that are most suitable for the above purpose. A large amount of test work is required to validate and calibrate these tests to field observations quantitatively. Once one or two tests are fully developed, they can be used by researchers and mine operators alike as a tool in the AMD prediction toolbox, especially during the early stages of mine development.

4. **Acoustic Celerometry** This is an interesting new test for waste rock characterization. The same can be said about this test as about those in (3) above.

5. **Correlation Method to Calculate Chemical Parameters for AMD Monitoring** This technique would be interesting to operators of mines whose AMD has well defined characteristics and has been monitored for some time. The correlation can then be developed using a historical database, and the technique can be used to reduce the number of chemical analysis of AMD samples. This technique, however, will be useful to a limited number of mines (where drainage is heavily contaminated and its chemical composition is stable over time). When this method is used for AMD monitoring, the validity of the correlation should be checked periodically; the data so generated should be clearly marked as "calculated values"; and the limitations of the method should be conveyed to those who use these numbers. As a monitoring tool, this technique would have little value to AMD researchers.

6. **EDXRF** This technique may be used by researchers under situations similar to those at Mine Doyon, i.e., when a large number of very contaminated samples, some of which are available only in tiny volumes, need to be analyzed, and when the necessary equipment is already available. We do not see this technique spreading to the mining industry for routine AMD monitoring because of the high expense and special expertise associated with running the equipment.

7. **Collection of Water Samples From Buried Lysimeters** This is a simple, relatively cheap technique to collect unsaturated-zone samples from waste rock piles which otherwise are difficult to obtain. It can be used effectively by AMD researchers as well as mines who wish to monitor unsaturated zone water quality.

8. **Calculations of Vertical Mass Transfer** This is a computational/interpretive technique that can be adopted by other AMD researchers and, when used properly, can generate very useful insight into the AMD processes taking place within a waste rock pile. Its use, however, involves intensive data collection (sampling by drilling, chemical analyses of leachate extracted from drill cuttings, and XRD analyses of drill cuttings), and thus is probably limited to relatively large AMD research projects. It is not likely to be used by mine operations.

5.8.2 Knowledge

The same numbering as that of Article 5.7.2 is used for identification purpose. For each piece of new knowledge, its applicability for AMD researchers and mine operators, when appropriate, is discussed.

1. For AMD researchers, this piece of knowledge adds a little more incentive for selecting and standardizing some of the available mechanical tests through field validation and calibration for the purpose of AMD prediction. It may even be worth attempting quantitative use of the test results in mathematical predictive models. Mine operators should wait until such tests are proven before they accept them for routine use.

2. For mine operators whose situation justifies the use of the correlation method for AMD monitoring, this knowledge should give them confidence in adopting it. For researchers, this knowledge is nice to have.

3. Acid consumption by silicate minerals is portrayed by some researchers as being too slow to contribute significant NP. This knowledge should give these researchers serious second thoughts. Silicate minerals, especially phyllosilicates, can potentially offer large buffering capacity where infiltrating water moves very slowly, affect water quality, and should not be overlooked. For mine operators, when high concentrations of Al and Mg are encountered in the drainage of a waste rock dump which is known not to contain significant amount of Al and Mg oxides and hydroxides, they should suspect and investigate fast weathering of aluminosilicates.

4. This knowledge adds to our AMD literature and contributes to our general appreciation of AMD-generating and AMD-consumption processes. It also gives modellers a little more confidence in writing their AMD prediction algorithms. For mine operators, this knowledge may help them understand their field observations and their drainage chemistry.

5. For both researchers and mine operators, this knowledge points to the need for collecting complete AMD chemistry for research. It also helps explain why AMD prediction and characterization are site-specific. The dynamic nature of the interactions between minerals and solutions shows that AMD processes are indeed complex, and prompts mine operators not to trust AMD predictions by mathematical models blindly. The knowledge can also have applications beyond AMD prediction: it can provide clues in predicting stability problems in waste rock dumps (such as subsidence and failures) from mineralogy and petrology of the waste rock; it can help reveal mineralogical transformations taking place in a heap leaching operation and the effects of the mineralogical changes on solution chemistry, value recovery, and pollution control; and, it can even help to pinpoint soil conditions for plant growth for reclamation purposes. In addition, the comments made for point (4) above apply as well.

6. See point 5 above.

7. This knowledge gives researchers confidence in using the mass transfer calculations as an interpretive tool.

5.9 Future Studies and Associated Costs

In the reviewers' opinion, the geochemical and mineralogical work conducted by the Mine Doyon research team is self-contained and mostly complete. There are no major gaps left to fill and no major flaws to correct. Nevertheless, there are a few aspects to improve on. These are given below, along with roughly estimated costs associated with them.

Trace Element Geochemistry

The report mentioned that in the 1991 data collection campaign dissolved trace metals such as Cu, Pb, Zn, Ni, and Cd were measured. These data have not been discussed in any of the ten reports. We all recognize the importance of the presence of trace metals in mine drainage, because they are major contributors to aquatic toxicity. Although most of the trace metals can be removed easily by precipitation in treatment processes, we still need to know their levels in mine drainage, and what controls their solubility, to assess the environmental consequences of ground water leakages, accidental spills, and uncontrolled discharges because of unusual high floods. In this sense, it is a little surprising that the Mine Doyon research team opted to leave the trace metal geochemistry untouched, given the outstanding work they have performed on mineralogy and geochemistry of major elements. As a matter of fact, the geochemical controls of dissolved trace metals in AMD are a primary concern for many AMD research projects around the world.

It would be very worthwhile to study the trace metal geochemistry (i.e., what controls the releases of trace elements from primary minerals and what controls their concentrations in AMD) using the existing database and relate it to the geochemical and mineralogical findings already made. This work may be an excellent candidate for a graduate thesis to be supervised by one of the original research team members. The approximate cost of this work is estimated at $20,000 - $25,000. It is not recommended to conduct a large, new sampling campaign or a large amount of extra chemical analyses of old samples.

Further Analysis of Monitoring Data

The vast amount of water monitoring data are only qualitatively examined in the Mine Doyon reports. The reviewers consider this an under-utilization of these data. It is possible to perform cause-and-consequence and statistical analyses on the precipitation, water quality, and drainage flow monitoring data to study the parameters controlling the release of acidity and contaminants from the waste rock dump (including hydrological, hydrogeological and geochemical parameters). If meaningful relationships are produced by this exercise, the temporal and spatial variations in acidity and contaminant loadings may be better understood. (It was learnt recently that this is being undertaken as part of a separate MEND project.)

The cost of this research is estimated at about four weeks of professional time of an expert specialized in geosciences and statistical analysis, or about $13,000.

Validation of Mineralogical and Geochemical Conclusions from BH-7 Data

One weakness of the work dealing with mineralogical transformations is the use of only one borehole's data for the mineralogical and geochemical conclusions. It would be worthwhile to validate the conclusions through a similar exercise, using data from another borehole (there are six remaining boreholes to choose from). It is understood that XRD and leachate chemical data are available in the existing database; thus (qualitative or semiquantitative) mineralogical profiles can be constructed and vertical mass transfer calculated without further testing. Only limited SEM-EDX examinations are needed, provided that the drill cuttings have been well preserved. Otherwise, the SEM-EDX work can be omitted. The estimated cost of this work is $15,000.

Correction of Flaws and Quality Control of Reports

Some relatively minor flaws are identified in this chapter, and others in other review chapters. These should be corrected. The quality control of the ten reports submitted for review has been quite poor and should be redone according to an acceptable standard. Since these two aspects do not belong exclusively to geochemistry and mineralogy, a cost estimate will not be given here.

5.10 Summary

The reviewers consider the geochemical and mineralogical work in the Mine Doyon project an illuminating study. No major flaws are identified by the review, and no major gaps are left to fill. Some minor to somewhat significant flaws were found and presented in this chapter. The following summarizes the main conclusions reached in this chapter.

Solid Characterization - Field Work

The drilling method used is state-of-the-art for sampling waste rock dumps and the trenching and pitting methods are consistent with industry standards. The locations of boreholes, trenches, and pits are properly selected, and the sampling procedures agree with accepted practice. Observation and logging of samples are first class and well documented. The paste pH data appear reliable. The particle size distributions determined, however, are not representative of the entire waste rock pile, and the percentage of the size fraction greater than 0.5 m is not quantified, making it impossible to determine the total surface area of the material contained in the waste rock pile.

Solid Characterization - Laboratory Work

An impressive number of solid characteristics have been determined. The use of drill cutting leachate analysis, whole rock analysis, and ABA appear appropriate as means of obtaining representative data; the use of XRD, SEM-EDX, and pore water chemical analysis seems adequate as a means of gathering typical data. Hydrogen peroxide test, image analysis, and mechanical tests are useful and innovative, but are only preliminary attempts. The methodologies are generally well conceived and applied, although some pitfalls and subtleties call for attention when interpreting the data. Improvements could be made by coupling XRD with whole rock analysis, by using a titration method to determine NP, and by focusing attention on the $MgSO_4$ test. The hydrogen peroxide test is not worth pursuing as a method for determining reactive sulphide surface.

Water Chemistry - Field Work

The installation of monitoring wells at Mine Doyon is of textbook quality. The lysimeter design is exemplary, although it may not be suitable at all sites, such as where large boulders dominate. The sampling, handling and storage of water are in accordance with industry standards. However, the flow measurement instrumentation were at one time defunct (this has now been corrected). The weather station should have been installed at the south dump instead of the mill.

Water Chemistry - Laboratory Work

Selection of laboratory analytical methods is generally adequate. The correlation method seems effective for this particular study. The EDXRF technique has detection limits useful for analyzing concentrated AMD solutions but unsatisfactory for characterizing more dilute solutions. EDXRF appears to be successful in this study. The method for preservation of Fe^{2+}/Fe^{3+} ratio for chemical analysis is not reported.

Review Comments by Report

The geochemical and mineralogical components of seven of the ten reports of this study have been commented on report by report. Major strengths, major weaknesses, and most prominent specific comments are documented.

New Understanding Identified from Review

New understandings from this project are identified as techniques and knowledge. Techniques include field investigation tools, laboratory analytical methods, and computational and interpretive techniques. Knowledge encompasses observations, facts, theories and hypotheses.

Application of New Understanding

The applicability of each of the new understandings (technique or knowledge) is considered for two broad categories of people: AMD researchers and mine operators.

Future Studies and Associated Costs

No major gaps are left to fill in this study. Four potential future studies are identified.

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6. MICROBIOLOGY

6.1 General Points

The objective of the Mine Doyon study on microbiological diversity was: *"to evaluate the influence of temperature and anoxic conditions on the activities of ferro-oxidizing and thiooxidizing bacterial strains within the south waste rock dump of Mine Doyo*n" (Guay, 1994, p.63).

Despite major differences of opinion among scientists working on the study of acidic mine drainage (AMD), with respect to the relative importance of the different reactions involved, it is generally acknowledged that bacterial leaching of sulphide minerals is the result of a complex process involving the direct action of bacteria as a catalyst, the indirect action from ferric ions and the electrochemical interaction of the different minerals present on specific sites. All these reactions are interconnected and they lead to AMD which is a major problem in the mining industry for the closure of reactive tailings deposits and waste rock dumps.

Thiobacillus ferrooxidans and *Leptospirillum ferrooxidans* are bacterial species that have been linked to AMD generation in different mining environments, but in fact, a rather widespread microbial community develops in these altered environments and their diversity is probably more extensive than initially thought.

The Mine Doyon study examined this microbial diversity from several different aspects: microbiological analysis of borehole cutting samples, microbiological analysis of groundwater and the influence of various physico-chemical parameters on the oxidization of ferrous iron to ferric iron on reference strains and isolates taken from the study site. Evaluation of the physico-chemical parameters are particularly important with regard to the presence or absence of oxygen, based on the generally recognized fact that the ferro-oxidizing bacteria mentioned above are obligate aerobes.

Successful AMD prevention strategies using dry or wet barriers depend on the restrictive conditions imposed by the anaerobic environments created by the barriers. Temperature is another physical parameter that needs to be evaluated with regard to growth of the microbial community present. As a species, bacterial communities can only tolerate certain differences in temperature and this can act as a limiting factor. However, as a group, bacteria can grow in a wide range of temperatures according to the temperature tolerated by each species. A wide range of temperatures can thus be a factor influencing microbial diversity.

Autotrophism of ferro-oxidizing bacteria along with specific diet needs, seriously limits the use of conventional bacterial counting methods. The work carried out on the description of a bacterial counting method for ferro-oxidizing bacteria has the objective of providing a more accurate counting method by avoiding the main difficulties related to the use of solid media.

6.2 Microbiological Diversity

6.2.1 Isolation and Culture of Microorganisms from Borehole Cuttings and Physiological Properties of the Isolate Growth

Following the drilling of observation well No.1 at the Mine Doyon south waste rock dump, cutting samples (21) were retrieved at depth intervals of 1.52 m over the total length of the borehole (total depth of 30.5 m). In order to verify the behavior of the isolated strains with respect to the increasing temperature, and also to evaluate the thermophilic conditions of the isolates, two different approaches were used. The first approach consisted of culturing isolated strains at 25°C and then culturing its positive subculture at a temperature of 5°C higher than the first one in a new culture media (dilution at 1/100). This approach was repeated until a growth temperature of 40°C was reached. The second approach was the direct culture of 3.0 g in the culture media for which each sample was hatched at each of the following temperatures: 25, 30, 35, 40 and 45°C.

The results from the first approach showed little positive growth at temperatures higher than 35°C. This was an unexpected result for the author who wanted to isolate thermophilic species. On the other hand, the second approach allowed the isolation of moderately thermophilics able to grow at temperatures of 40 and 45°C. According to the author, ferrous iron oxidizing rates (criteria used to measure the oxidizing activities of the isolates) seemed greater for strains sampled in the first 10-12 meters of the borehole. However, the results presented in Table 4 (Guay, 1994, p.24) showed a rather uniform distribution of the oxidizing rates.

Strengths of this Section

The preservation and characterization approaches employed to isolate the various strains were successful in preserving what appears to be the main representatives of the microbial community present at various levels.

Sampling and sample handling were well conducted. The proposed approach can even be of interest for scientists working in this field. The use of two subculture approaches to evaluate the mesophilic or the thermophilic conditions of the isolates appeared to be very appropriate and should be kept in mind for the future.

The growth and the oxidizing activity at temperatures exceeding 42°C are not usually encountered for the thiobacilli strain. Despite the fact that the identification and characterization of the strains could have been taken further, the growth and moreover the microbial activity at 45°C can be expected to be significant. Species responsible for this microbial activity would be of the moderately thermophilic type.

Weaknesses of this Section

It would be painstaking for someone to reproduce the sampling approach used; information to put together the protocol of sampling would have to be obtained from different sections such as the "Material and Approaches", the "written section on results" and the "figures and tables of results". The composition of the nutrient solution at pH 2.0 is not described in the report (Guay, 1994, p.6). Is it from the 9K solution (Silverman and Lundgren, 1959)? Regrouping all the relevant information in the section on "Materials and Approaches" would facilitate reference to these approaches.

As mentioned above, culture sampling approaches have been judiciously selected and conducted. However, it would be appropriate to modify the second approach in order to be able to isolate thermophilic species that would most likely be lost by dilution in the course of the first subculture series. Despite the fact that the reasons given to explain the absence of moderately thermophilics appear acceptable, it would have been interesting to also isolate thermophilic strains and to evaluate their contribution to the total oxidizing activity.

6.2.2 Microbiological Analysis of Groundwater

This analysis is two-fold. One aspect is related to sampling of groundwater and the other to culturing of isolates taken from well Nos. 1, 2, 4 and 6 at depths varying from 30.5 to 42.5 m. This sampling was conducted jointly with an evaluation of the preferential colonization on four types of minerals: pyrite, sphalerite, calcopyrite and sulphur. For this, a bacteria trap device was developed. These devices were placed in the wells, then withdrawn after 40 days. A series of chips from each of these minerals were treated upon their withdrawal from the wells for analysis under scanning microscope and the rest of the chips, as well as groundwater, were kept for microbiological analysis.

The results presented in this section of the work by Guay (1994) are related more to the colonization of different media, as detected by the scanning microscope. Tables 5 and 6 (Guay, 1994, pp. 33 and 34) present the author's observations. Based on photographs (Guay, 1994), the author believes that a certain microbiological diversity is present in the groundwater because of the presence of many morphological types observed. Based on the shapes and dimensions of the bacteria, it is believed that thiobacillis on pyrite, calcopyrite and sulphur in well Nos. 1 and 4 is probable. In this last well, sphalerite would also be a medium, according to the text, but there is a mention of uncertain colonization for the same medium in the same well in Table 6.

Strengths of This Section

The microorganisms trap device is innovative and can prove to be of interest for other sites which require similar sampling. This approach has simulated colonization conditions on different media and has also isolated groundwater samples by making the best possible effort to preserve the microbial community diversity present in the dump. This is an effort worth mentioning.

Weaknesses of This Section

It is not mentioned if the various minerals introduced in the bacteria trap device had been previously sterilized or if they had been under the effect of an early stage of oxidization.

Results noted ++++ on Table 6 (Guay, 1994, p.34) indicate the appearance of significant colonized surfaces by microorganisms, and as anticipated by the author, there could be more than one bacterial type adsorbed. One can question why photographs showing very different appearances (well No. 2-E on pyrite and well No. 4-K on pyrite also) are presented to be similar. Magnifying scales could be the explanation. Since this is a comparative study, it would have been appropriate to have more comments on these photographs. It is also uncertain, given the scale presented, if there is colonization on calcopyrite in well No. 4-I.

However, the possibility that certain structures resembling bacteria could rather be the result of iron hydroxide crystallization in the form of low pH globules, e.g. Figure 9-A (Guay, 1994, p.26), is not discussed in the results (no abiotic controls) nor in the interpretation. At best, on Table 6 (Guay, 1994, p.34), well No. 6-N (pyrite) is noted "uncertain" in regards to bacterial colonization, while well No. 6-M (calcopyrite) is noted as "weak colonization". Based on the photographs, the difference is not obvious.

Biological diversity is discussed and the results presented show the efforts taken to preserve a potential microbial diversity that could have been present under two different conditions: more than one bacterial type, and pleomorphism of *T. ferrooxidans*. The pleomorphism of *T. ferrooxidans* is described in Appendix II instead of Appendix I as indicated (Guay, 1994, p.37).

The microphotographs mentioned above are the only ones given in regard to the diversity of the isolates coming from groundwater. The morphological variations described would be based on the observations made from these microphotographs. The different morphological conditions described in the text and presented in Appendices I to IV are thus the result of an association between structures already described (Appendices 1 to IV), and observations made from the microphotographs in the report. Unless the original photographs are more convincing than the prints in the report, only the dimensions and the global shape can be compared. Under these conditions, the nature of the microorganisms is more an appraisal than a formal identification. A summary of the physico-chemical characteristics of each sampling point, along with the suspected adsorbed species on the minerals, and the estimated species present in the groundwater, would have facilitated the overall understanding of the community dynamics present at these sites.

The author mentions that his results on the microbiological diversity in hostile environments such as groundwater are in contradiction with the conclusions of many scientists who identified these environments as being colonized by relatively uniform bacteria communities. Since the authors are not mentioned, it is difficult to verify this statement. However, this diversity would be more representative of a real ecological system even under such a hostile environment. Besides, standard and recent references confirm this: Brierly (1978), Harisson (1984), Hutchins et al (1986) and Schippers et al (1995).

The bacterial count was conducted using a modified method of the most probable number (MPN). The reference given (Lafleur et al., 1993, p.15) does not appear in the list of references. This method is described in a separate report discussed in Article 6.4 of the present document.

Table 1 rather than Table 7 (error on page 13 Guay, 1994) gives the chemical composition of the groundwater in well No. 4 that was used to prepare the culture media. The use of water coming from a natural environment to isolate indigenous strains in groundwater is a good approach. However, this water is not well characterized. Indeed, only 4 of the physico-chemical parameters (pH, redox potential, conductivity and density) were directly measured. Ion concentrations were calculated from correlations that are not included. Direct ion concentration measurements would have been more appropriate. Moreover, basic salt (phosphate, potassium, ammonium) concentrations were not specified, nor were the solubility limit for the carbon dioxide (source of carbon for the autotrophic bacteria) in this heavily mineralized water.

One can also question why groundwater that was used to prepare the culture media did not come from well No.1. Indeed: *"the ferro-oxidizing conditions of the strains were only observed in well No.1"* and it is also mentioned that *"the physico-chemical conditions of the groundwater were very different from one to the other"* (Guay, 1994, p.25).

6.2.3 Influence of Energizing Media and Temperature on the Microbial Oxidation of Ferrous Ion

The objective of this series of experiments was to evaluate the oxidation potential of indigenous bacteria at the site, which consisted of the bacteria isolated from groundwater (see Article 6.2.2) in regard to ferrous iron, when put in the presence of ferrous sulphate, elementary sulphur and pyrite within the energizing media possibly present in the waste rock dump. In the "Approach" section, it is mentioned that the metabolic activity on various sulphurized media had been measured by acidification of the culture media or by volumetric measurement of the residual concentrations of Fe^{2+}. However, the section on "Results" does not indicate concentrations of ferrous iron non values of pH measurements. The inoculum used was made from a groundwater specimen retrieved from each well, added to 4 volumes of a sterilized solution of basic salts (9K media without ferrous sulphate).

Table 7, which shows a bacterial count corresponding to the tested media and to the different hatching temperatures, adds to the credibility of the possible microbiological catalyzed oxidation.

Strengths and Weaknesses of This Section

The methodology for this series of experiments would need to be clarified. Was the control composed of a volume of water sterilized by filtration to which was added 4 volumes of 9K solution (without ferrous sulphate)? A weak activity from bacterial origin could still be observed in such a control: an enzyme whether from extracellular origin (most likely the case), or whether from bacterial burst could survive in sufficient numbers in the filtrate to allow their detection. In this way, the control would not really be abiotic. The author appears concerned by this fact when he mentions that, *"We have moreover noted that a certain chemical reducing and even biological activity with regard to the presence of iron could take place in the culture media used (hatched or sterile)*", (Guay, 1994, p.38). From a microbiological standpoint, this media control proved to be necessary, but is does not seem to be an appropriate abiotic control to indicate the chemical activity of the in-situ system regardless of the degree of biological activity. It should be noted, however, that activity from a microbiological origin that could be present in the control is very little when compared to that in the tests, and it is also reasonable to think that the difference could be significant.

For this series of experiments, microbiological activity was only measured by ferrous iron oxidation. Sulphur and pyrite oxidation have unfortunately not been quantified. A rapid decrease of ferrous iron means that the sulphurized medium is slowly oxidized giving a low ratio of Fe^{2+}/Fe^{3+}. Fe^{2+} is a readily oxidizable substrate for *T. ferroxidans*. The amounts of elementary sulphur or pyrite added to the inoculated tests, Figures 11B-C, 12B-C, 13B-C, 14B-C and 15B-C (Guay, 1994, pp. 41 to 54) are not specified.

The sterile controls show an increase in Fe^{2+} concentration, in particular at higher temperature (42°C), which suggests loss by evaporation.

Even if the connection between a number of microorganisms and the oxidizing activity is not perfect, this series of experiments does show that Fe^{2+} can be oxidized in the presence of microorganisms. However, this is not new information.

6.3 Anaerobic Respiration by *Thiobacillus ferroxidans*

Isolates coming from groundwater in well No. 4 have been cultured in the presence and in the absence of oxygen, the latter to simulate field conditions under 30 m of waste rock. Upon complete aerobic oxidation of ferrous iron, elementary sulphur or sterile pyrite has been aseptically introduced into the vials, which were subsequently hatched under stationary and anaerobic conditions. High microbal growth was evaluated as well as pH conditions.

According to the author, the most important finding would be the confirmation of anaerobic respiration by an isolate containing an undetermined mixture of undefined acidophilic strains of ferro-oxidizing activity.

In the presence of elementary sulphur, the author has determined rates of anaerobic reduction of Fe^{3+} of 85 mg/L•h for a collection strain (ATCC13661) and of 55 mg/L•h for indigenous bacteria. Figures 16 and 17 of the report show the aerobic oxidation of Fe^{2+} and the anaerobic reduction cycles of Fe^{3+} in the presence of elementary sulphur for both pure and mixed culture. It would have been interesting to add to these figures the pH evolution as well as the control behavior. For Figures 16 and 17, an error has been noted in the vertical axis unit: Fe^{2+} should read g/L rather than mg/L.

The author mentions that the presence of elementary sulphur as an intermediary in the oxidation of pyrite has not been confirmed (Guay, 1994, p.57). In the presence of pyrite, the anaerobic reduction has not given results which can be reproduced. An approximate rate of 25 mg/L•h has been mentioned. It would have been interesting to include the experimental results related to this.

<u>Strengths and Weaknesses of This Section</u>

The methodology employed in this section would need to be clarified: the media composition, as described in the "Materials and Approaches" section (p.15), would be: *"100 ml of groundwater from well No. 4 sterilized by filtration, to which would have been added ferrous sulphate at a final concentration of 11.5 g/L and ammonium sulphate at 3 g/L"*. While for the same experiment, the description in the "Results" section (p.56) is: *"Figures 16 and 17 present the results for the growth of T. ferrooxidans ATCC13661 and for the bacterial isolates from well No. 4 on a culture media composed of 4 volumes of 9K media to which was added a volume of sterilized groundwater"*. Also, as mentioned earlier, the chemical composition of groundwater shown in Table 1 includes a certain number of parameters calculated from correlation curves for which the origin and the integrity have not been discussed.

The same discussion mentioned for the preceding experiment (Article 6.2.3) applies to the control sample. The presence of an acceptable abiotic control is necessary to distinguish chemical activity from microbiological activity. If the aerobic control is acceptable, it is not necessarily the case for the anaerobic control.

A more acceptable control for the anaerobic environment would be to filter part of the aerobic culture in order to remove the bacterial cells and to precipitate them with hydroxide iron present before starting the first anaerobic cycle. Even though this control would not constitute a perfect abiotic control for the reasons mentioned above, it would at least allow an estimate of the system's activity in the absence of anaerobic bacteria and of the significant availability of ferric iron and sulphur or pyrite.

The stability of the size of the bacterial population is not discussed (10% increase). Is the population in a stationary stage and the anaerobic cycle more an adaptation mechanism than a useful metabolic way for energy production? Or do the restrictive conditions of the media in well No.1 allow a significant growth of the community? It would be logical that the anaerobic respiration for these bacteria always described as being strictly aerobic, would be an adaptation mechanism giving them a certain quantity of energy in order to survive. A longer period of time for energy generation in anaerobic conditions would then be normal.

The study of anaerobic respiration is exclusively based on the transformation of Fe^{2+} to Fe^{3+} (this latter parameter is not actually measured) and its theorical transformation by electrons taken from elementary sulphur (S°). The absence of a similar reaction with the control would allow one to extrapolate that the reaction is complete and totally microbially mediated. This is an attractive model but the results are not conclusive.

Anaerobic respiration from elementary sulphur has been well described among authors referenced by Guay (1994, p.61). On the other hand, the ability of *T. ferrooxidans* to achieve anaerobic respiration from pyrite is still controversial. Certain studies like the ones by Suzuki et al (1990) and Sugio et al (1992) have shown the anaerobic reduction of Fe^{3+} in the presence of pyrite. Unfortunately, these studies did not include the use of sterile controls. Therefore, the bacterial contribution to the purely chemical redox mechanism cannot be determined from their results. Lizima and Suzuki (1989) have found, in an anaerobic reduction vial, Fe^{3+} in the presence of pyrite. For this test, the presence of bacteria doubled the Fe^{2+} production after 100 minutes in comparison with indirect leaching (abiotic mechanism). The action of *T. Ferrooxidans* has been demonstrated since additional Fe^{2+} must come from pyrite alteration. These authors mention that they have not studied in detail the bacterial reduction of Fe^{3+} in the presence of pyrite. This is the reason the rate equation and the kinetic parameters have not been determined. However, there is still a doubt as to the origin of the additional ferrous iron noted in the presence of bacteria: could it come from the inocolum?

General Comments on the Report

The results on diversity are in general interesting, but more could have been said on their interpretation as well as on their meaning in regard to previous work. Some of the results, even though interesting, are rather preliminary results and more work would be needed (i.e. identification and characterization of the isolates).

The model presented on Figure 18 of the report is interesting and proves to be an honest effort to tackle the problem in terms of ferro-oxidizing activity at different levels of the south waste rock dump of Mine Doyon. However, we do not believe in the presence of a significant amount of elementary sulphur in this waste rock dump. Indeed, the mineralogical characteristics of the borehole cuttings from well No.1 are presented in Appendix V, page 70 of the report. Elementary sulphur does not appear. Moreover, it is well known (Silverman, 1976; Dutrizac and McDonald, 1974, and Lowson, 1982) that very little elementary sulphur is produced in the course of pyrite oxidation.

6.4 The Modified MPN Method

6.4.1 Context

The modified MPN method (Guay, 1993) is based on the adaptation of already existing methods (micromethods) and also use of a conventional presumptive test for the detection of coliform bacteria: the method for the most probable number (MPN) of coliform bacteria present in water. The MPN method is a statistical calculation based on a bacterial population size estimate from dilutions and from the number of positive replicates obtained for each dilution. Results are then interpreted using standard tables (American Public Health Association, 1976). The author (Guay, 1993) rightly states that the autotrophy of *T. ferrooxidans* is a key limiting factor for the use of conventional methods prepared essentially for the heterotrophs.

The author lists the main approaches used before to avoid this difficulty in order to estimate the size of a population. Various methods are mentioned, which can be divided into 2 categories. One category can detect organic matter or biomass (direct counting in the Petroff-Hausser chamber, most of the in-situ immunological techniques for the detection of material, and all of the biomass scanning techniques) and the other category can detect viable cells (agar dilutions and agar membraned filters, etc.). Each of these approaches have their deficiencies. The lack of specificity and the weak correlation with cells viability restrict the use of biomass detection approaches while the weak recovery on solid media constitutes the main difficulty for the detection of viable cells.

According to the author, the relative toxicity of the geling substances used (agar) would account for the rather unsuccessful performance of the solid media to sustain viable units. There seems to be common agreement on this point in the literature referenced by the author and also in other literature not mentioned here but related to the same subject.

The difficulties inherent to an acceptable detection of viable *T. ferrooxidans* cells would be related to the unavailability of solid cultured media being able to support the growth of *T. ferrooxidans* and also to the lack of precision of the methods used.

6.4.2 Proposed Solution

Based on the discussion above, the author proposes the following method:

1. Viable cells detection in liquid media.

2. Increase in the accuracy and in the reliability of the MPN technique by adapting it as a microtechnique which would result in two major advantages in comparison to the original technique:

    - increase in the accuracy of the approach by the use of more accurate instruments adapted to microtechnique (serologic techniques, Elisa, etc.) and by the use of smaller volumes which could also increase the accuracy for serial dilutions;

    - increase in the replicate numbers, which greatly improves the reliability of this approach in comparison with the original approach;

3. control of the approach by direct counting and by detection of viable cells using the dilution technique on a petri dish.

For this last part, a highly purified geling agent was used: Type I, low EOO agar by Sigma which should read Type I, low EOO agarose. The use of agarose instead of agar, according to the articles consulted, would be more appropriate, and would explain the contradiction between the described toxicity when using certain agar types and the increase of what appears to be the same toxic substance in their culture media. Indeed, the reference quoted (Johnson et al, 1987) mentions Agarose Type I.

6.4.3 Results and Discussions

First, the author presents the bacterial count from his three base suspensions which were diluted to obtain a number of bacteria between 18 and 2 x 10^4. Then, the MPN technique was applied on these diluted suspensions and was controlled by counting in Petroff-Hausser chambers and by dilution on petri dishes. The correlation seems rather good for two of the three Thiobacilli tested. The explanations given appear to be relevant. However, the discussion and also all that is related to the culture media is rather painstaking to follow among the references mentioned. In fact, the author goes rapidly over relevant considerations that are not mentioned in the report: the choice of agarose instead of agar, the choice of media. The reader must consult many articles to understand these choices. The author mentions that care is required with isolates taken from the environment because of the possible contamination by heterotrophic microorganisms. Based on the fact that the Fe TSB media contains tryptone froth medium which is more favorable for microorganism growth that are more demanding on the nutrient level than strictly mineral media, it appears more likely that this Fe TSB media would be prone to this problem.

In the results presentation, do the variations given represent maximum differences or standard deviation values? Which method was used to calculate the regression coefficients? Was estimation of conformity by the limits of two methods or by a statistical approach?

6.4.4 General Comments on the Report

The choice of the MPN technique to detect *T. ferrooxidans* bacterial population is not new. This technique was used before by Johnson et al (1987), reference No. 4 in the report (Guay, 1993). However, without the adaptations proposed by the author, this technique is rather painstaking and requires the use of many replicates to be accurate. This difficulty appears to be avoided by the proposed technique. Despite this, another inconvenience remains: in a mixed population taken from the environment, all of the non-oxidizing populations will be detected, not only *T. ferrooxidans*. Nevertheless, the technique described appears interesting in quantifying ferro-oxidizing viable cells within a shorter time span.

By its format, this report is closer to a scientific article submitted for peer review. In this context, it would appear normal that the reader has to refer to the articles presented in the bibliography to complement the information provided. However, given the fact that this report is for sale to scientists and not only to microbiologists liable to use this technique, it would be more appropriate to have a stand-alone document in order to be able to reproduce the technique without having to consult other documents. A description of the materials and dilution techniques, of the media composition, of the modified approach for reading results and also a table of references for interpretation of the MPN results would make this report easier to use.

6.5 New Knowledge Related to the Work

The author would have noticed many different morphological types on the surface of the waste rock dump materials and in the groundwater. The diversity would also be more significant than described previously on the different submerged minerals in the groundwater. As mentioned previously, it would be logical to think that a certain microbial diversity would be present in a hostile, disturbed and nutrient limited environment. Additionally, a well adapted microbial population is likely to develop under such conditions. But at the same time, it is essential that bacteria identified on the mineral surface are in fact bacteria. Moreover, it might not be the proof of diversity in itself but the improvements in microorganisms sampling and culture methods that will put in evidence this diversity. In this way, the bacteria trap device is interesting and innovative as well as the culture and sampling method in two distinct approaches.

On the other hand, the section on anaerobic respiration only sheds new light on the fact that it can also be observed in mixed indigenous bacterial communities. But this approach in itself has been previously described by other authors cited, for reference strains, under similar conditions, and for the same measured parameters.

According to the author, the fact that isolated microorganisms taken from borehole cuttings were able to grow first, then to oxidize ferrous iron at 45°C, while in previous works, this activity was rapidly decreasing after 40°C, is new. In fact, this novelty could be greater than expected if the bacteria part of this reaction are mesophilic thiobacilli rather than moderately thermophilic. The temperature of 45°C appears to be a non return threshold value for many mesophilic bacterial species. Mesophilic strains can occasionally grow at 45°C because of special genes included in plasmides (genetic information independent from bacterian chromosomic DNA) which in certain cases can be transferred to another bacteria. The presence of these plasmides with acidophilic species of thiobacilli would just add to this rather complicated situation.

The adaptation of the MPN technique in the field of microtechnique constitutes a great improvement to conduct acidophilic chemolithotrophic bacterial count. This modified technique allows the use of less biological material for analysis purposes and greatly increases the accuracy of the method because of the remarkably precise microtechnical instruments used. This technique also reduces the time required by the technician on the first day.

Summary Figure No. 18 of the document on microbiological diversity (Guay, 1994) constitutes a first interesting attempt to identify the different processes involved at different levels within the dump.

6.6 Application of New Knowledge

The new knowledge described in previous Article 6.5 provides a better view of the problems related to the various mechanisms involved at different levels in the dump.

Some of the results presented are preliminary results on non-characterized mixed communities. However, these results show that in a complex system such as the south waste rock dump, things are not as simple as eliminating a bacterial species by simply cutting-off oxygen. Nevertheless, it is obvious that AMD production does not stop immediately by capping the south waste rock dump with an oxygen-tight barrier. Indeed, indirect leaching by Fe^{3+} and anaerobic respiration on pyrite (if present) are simultaneously going to keep producing AMD. When all ferric iron is reduced to Fe^{2+} by these 2 mechanisms, AMD production will cease since Fe^{2+}, in the absence of oxygen, cannot be reoxidized to Fe^{3+} (oxidizing agent for the indirect leaching and electron receiver for the anaerobic respiration).

6.7 Subsequent Studies and Related Costs

It appears worthwhile to isolate and to characterize strains from borehole cuttings and to grow them at a temperature equal to or greater than 45°C. It would also be necessary to isolate and to clearly identify the strains coming from groundwater and to evaluate beyond any doubt anaerobic respiration in the presence of pyrite.

In this sense, choosing Fe^{2+} as the sole parameter to measure strain activity, iron oxidation and its subsequent reduction from a medium, appears questionable. Indeed, ferrous iron oxidation and the reduction of ferric iron are involved in spontaneous reactions (chemical) as much as in enzymatic mediation reactions from microbial origin. It would be appropriate to identify another parameter to measure the activity of microorganisms. One alternative would be to substract the contribution from a strictly chemical origin (indirect leaching) for which the kinetics would have been previously determined, from the results obtained in the presence of bacteria.

When anaerobic respiration from pyrite has been clearly demonstrated, its kinetics will have to be evaluated (rate equation and kinetic parameters including the influence of temperature) in order to estimate its contribution in the present state of the system and its potential contribution when the system is modified to limit the oxygen supply for AMD prevention. A global numerical model of the site using the kinetics of indirect leaching and of anaerobic respiration as well as thermal effects, would be necessary.

Such a model would allow the prediction of the time span required before AMD production ceases after capping the waste rock dump with an oxygen-tight barrier.

From a more fundamental point of view, it would also be interesting to determine the metabolic pathways involved in aerobic respiration mechanisms on elementary sulphur and pyrite. For the most part these pathways have not been addressed in the references mentioned.

The estimated costs to conduct the three studies related to the microbiology of the south waste rock dump of Mine Doyon are presented in Table 6.1. The positive identification of mesophilic and thermophilic species related to AMD are comparatively costly because it requires sampling on the site.

Table 6.1
Approximate Costs of Microbiological Studies

Priority	Research	Costs
I	**Identification of strain from drill cuttings and groundwater** The literature is not very convincing on the existence of this phenomenon. If ferric iron can serve as an electron acceptor, the elimination of an oxygen barrier (cover barrier) will not stop the production of AMD. However, when all the ferric iron present will be reduced to ferrous iron, the production of acid mine drainage will stop. It is important to understand the kinetics of the phenomenon to predict the time scale before which AMD can eventually stop (months or years).	**$70,000**
II	**Kinetics of anaerobic respiration of *T. ferrooxidans*** The understanding of metabolic pathways is interesting from a scientific point of view, and can allow the identification of methods to control the phenomenon of anaerobic respiration (if existing).	**$40,000**
III	**Metabolic pathways of anaerobic respiration** The relative contribution of thermophilic micro-organisms compared to that of mesophilic micro-organisms to the production of AMD is important to verify. However, identification of bacterial strains associated with AMD is relatively costly because field sampling is required.	**$45,000**

6.8 Summary

The bacteria trap sampling device constitutes an innovative approach for retrieving in situ microorganisms.

The isolation technique using two different approaches (subcultures with thermal gradient and direct hatching at different temperatures) is also new.

The MPN technique to quantify viable *T. ferrooxidans* cells is not new. However, the micromethod adaptations proposed by the author contribute to make the technique more accurate and reliable. Nevertheless, one inconvenience remains: the approach cannot determine the different ferro-oxidizing species. The approach also remains rather lengthy in time (about 10 days).

Many elements of the report on microbiological diversity are in fact preliminary results. The identification of the species having colonized the various solid media, is based only on microorganism morphology. No more advanced biochemical tests have been conducted to confirm the presumed identification. The author mentions (Guay, 1994, p.63) that he thinks that he has identified the moderately thermophilic *sulfobacillus thermosulfidooxidans* twice. However, thermophilic species have not been isolated by either of the approaches. Results on anaerobic respiration of *T. ferrooxidans* and of a mixed site indigenous population, in the presence of pyrite and ferric iron, are interesting but incomplete. The quantification of the strictly chemical contribution of the process, the identification of a reliable abiotic control and the reproductibility of the results are key elements that remain unsolved. Even the kinetics (rate equation and kinetic parameters) as well as the metabolic pathways of this process remain to be clarified.

The comments presented in this section are related only to the GREGI reports submitted to MEND. The objective of these comments is to give a better understanding and insight of the issues for the readers of the reports.

We would like to mention that additional comments and details on the methodology, not appearing in the MEND reports and given by the GREGI team during the review process, assisted in clarifying the research conducted.

6.9 References

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7. PREDICTIVE MODELLING

7.1 General

Predictive models are based on concepts and underlying assumptions regarding the mechanisms of acid generation in waste rock and use mathematical relationships as abstract representations of the important physical, geochemical and biochemical processes that control acid generation. Since 1988, the Mine Environment Neutral Drainage (MEND) program has supported research to provide a comprehensive, scientific, technical and economic basis to predict with confidence the long-term management requirements for reactive mine wastes. The predictive modeling studies at Mine Doyon are part of this program.

Early studies produced two independent estimates for the possible duration of acid mine drainage (AMD) at this site. These were prepared based on (i) heat balance and (ii) sulphate and iron mass balances.

Other studies at this site have produced two conceptual models that could be used to support predictive modeling of AMD:

- A conceptual model of air circulation in the heap was developed based on field data (temperature, gas profiles); and,

- A conceptual model was developed to describe the mineralogical transformation of aluminosilicates associated with acid generation and formation of secondary minerals and precipitates (e.g., jarosite, gypsum).

Mathematical models for predicting AMD can be classified into two rather broad groups: i) empirical models, and ii) mechanistic models.

Empirical models are based on statistical relationships (e.g. correlation's, regression) between water quality constituents or variables such as time (e.g., Morin et al. 1993). This approach requires the compilation of a chemical database from field monitoring data. Statistical analysis is then performed on the field data. Often the goal is to establish a single master variable and relate water chemistry to this. Other goals may be to identify special or temporal trends in the dataset. Predictions based on statistical methods do not reveal the complex geochemical interactions which ultimately determine future conditions in the waste rock pile, but may be used to interpret them. Models based on statistical data from a site are by nature, site-specific.

At Mine Doyon, an empirical approach was used to develop statistical correlation's that were applied to predict the concentrations of certain aqueous species (e.g., sulphate, acidity, iron, etc.) in heap water samples based on measurement of the conductivity and/or the level of total dissolved solids (TDS).

Mechanistic models comprise kinetic, thermodynamic (equilibrium), and mass transport expressions based on fundamental scientific knowledge (e.g., Scharer et al., 1994; Perkins and Gunter, 1994; Davis and Ritchie, 1986). The strength of mechanistic models is that they apply well known and proven scientific principles of conservation of mass, momentum, and energy. These models are based on theoretical equations and the solution involves simplifications (e.g., simplified geometry, uniform properties, idealized initial and boundary conditions) and parameter estimates. The high degree of abstraction applied to model structure and parameter estimation procedures may result in poor model performance under field conditions, especially when adequate data are not available for model calibration. However, these models can be instrumental for examining the effects of various options for rehabilitating waste rock dumps, and for evaluating potential long-term requirements for managing reactive mine wastes.

As pointed out correctly by one of the principal authors of these modeling studies, an often *"overlooked, impact of mechanistic numerical models is their impact on our understanding of processes. A model based on sound physical and geochemical principles tells us how the system represented by the model behaves. It may not be the perfect representation of the actual system studied, but even the departures of the model from the observed behavior tells us something about the true system. Mechanistic models thus deepen our fundamental understanding of the system studied which is something empirical models cannot provide despite their often important practical value"* (Lefebvre, 1996).

Several different mechanistic models have been developed and applied at Mine Doyon:

- Detailed thermal modeling was performed to assess heat production from sulphide oxidation and transport of heat within the waste rock heap by conduction and advection;

- A mathematical model (TOUGH AMD) was developed to simulate the transport and consumption of oxygen, and production of sulphate, as related to pyrite oxidation. The model was applied to gain a better understanding of the current conditions and processes occurring within the heap, and to examine the effects (benefit) of placing a cover on the dump.

Subsequent sections of this chapter (i) discuss thermal modeling studies, (ii) provide our assessment of the available data for predictive AMD modeling at Mine Doyon, (iii) discuss other studies at Mine Doyon which can be considered to support predictive modeling of AMD; and (iv) provide our detailed review comments regarding the TOUGH AMD model.

7.2 Thermal Modelling

7.2.1 Comments by Primary Reviewer

The thermal modeling is described in the report "Heat Transfer During Acid Mine Drainage Production in a Waste Rock Dump - La Mine Doyon, (Québec)" (GREGI, 1993-03), and is also summarized in Chapter 6 in the overview document, "Monitoring and Modeling of Acid Mine Drainage from Waste Rock Dumps. La Mine Doyon Case Study" (GREGI, 1994-12). Their study addresses thermal energy transport and temperature variation within the south waste rock dump at Mine Doyon. The database comprises approximately 2 years of weekly temperature observations taken at various depths at 6 locations within the waste rock pile. Theoretical development largely followed previous work by Stallman (1965) for Fourier-type analysis, and papers by Cathles and Apps (1975), Davis and Ritchie (1986), Pantelis and Ritchie (1991), and Jaynes et. al. (1983) for developing and solving one-dimensional energy balances. The theory was developed and the data was presented in a logical manner.

The authors developed trigonometric functions to represent the cyclic temperature variations in the dump. In addition, they included a linear time-dependent term for long-term trends. The solution includes a combination of the linear and trigonometric terms. In our view, the sampling period presented in the report was far too short to assess any significant long-term temperature trends in the dump. One of the authors has indicated (Lefebvre, 1996) that subsequent thermal data, not presented in the report, has confirmed the long term trend identified in this study.

The thermal energy balance was expressed by a second order differential equation. The general equation includes a heat conduction, a heat convection, and a kinetic term expressing the heat of reaction generated by pyrite oxidation. The authors employed simplistic, first order reaction kinetics for expressing pyrite oxidation. There are several problems with their approach:

- The reaction rate constant (K_{ox}) was assumed to be independent of temperature in spite of voluminous kinetic data indicating a strong temperature dependence;
- Their estimate of the heat source term (GREGI, 1993-03, Appendix C, Equation C.4), is applicable if oxygen transport is due to diffusion only, but is not proper if convective mass transport is involved;
- The oxygen concentration implied by Equation C.4 is not consistent with oxygen concentration patterns shown by the authors;
- The volumetric heat capacity of humid air was assumed to be constant, although its dependence on temperature is well known, and is due to a large extent, to latent heat effects.

The analytical solution of the model contains one measured parameter (temperature gradient at the dump's base) and three fitted lumped parameters (A, B and E). Unfortunately the one measured and two of the three fitted parameters are both site- and run-specific, i.e. they must be estimated from the available data at a given position and time. Consequently their value as a predictive tool is questionable. Furthermore, the derivation and the statistical validity of the parameter estimates are not stated. In any case, the parameter estimates resulted in unrealistic expectations of transport parameters, for example, the effective diffusion coefficient (D_e).

In spite of the limitations discussed above, the modeling effort has several positive aspects. The analytical solution of the conduction/advection model is elegant and simple to apply. The proposed modeling effort, if correctly applied, can give a definition of the transport parameters, which may need to be verified by other methods before used in a more comprehensive model.

In conclusion, the proposed temperature/heat models have a useful role as an initial step for a more comprehensive analysis of AMD generation.

The principal author of the report explains that one of the intentions of their study was to draw attention to the potential of thermal data as characterization and monitoring tools for waste rock dumps; *"it is very simple matter to install thermistors and follow temperature changes with time ... thermal properties can then be determined* (following their approach) *and indications of pyrite oxidation rates can be obtained. Temperature is also a very good global indicator of the natural evolution of AMD with time and can give reliable information on the impact of AMD mitigation measures"* (Lefebvre, 1996).

7.2.2 Comments by Secondary Reviewer

The following comments regarding the thermal modeling studies described in the report "Heat Transfer During Acid Mine Drainage Production in a Waste Rock Dump, La Mine Doyon (Québec)" (GREGI, 1993-03) are provided by Li (1995).

General Comments

The fact that the heat production rates calculated from two different models - simple conduction model and conduction and advection model - agree with each other so well is not reassuring. Does this indicate that both methods are robust enough that both heat production rates derived are acceptable, or is this just a coincidence? Given the crude assumptions (some of which, as the author stated, are known not to be true) used for the models, the authors should delve deeper into this aspect, since this is very important.

Specific Comments

The Greek letter α is used for heat capacity (GREGI, 1993-03, bottom line on p. 6) and for the cosine coefficient in equation (12) and so on (GREGI, 1993-03, p. 11). This is confusing; a different symbol should be used for heat capacity.

The letter q is used to denote heat flux (GREGI, 1993-03, pp7, 8, & 14) while it is also used to stand for fluid flux on p. 14, equation (20). In addition, fluid flux has been signified by the bold letter **v** previously (p. 8, equation (10)). I suggest the use of bold letter **v** to denote *fluid flux* throughout the report.

The authors should explain why "*the base temperature is taken as 5°C which is slightly higher than the average air temperature in the area*." (GREGI, 1993-03, p. 13, line 10). The reference to figure 10 should in fact be figure 11 (GREGI, 1993-03, p. 13, line 11).

Regarding Equation (19), the integral is inaccurate. The accurate answer is obtained by the following integration:

$$DHc(t) = \int_0^L CvDT(z,t)dz$$

Replacing $DT(z,t)$ with $DT_0\, e^{-az} \sin(2pt/t\text{-}bz)$ (p. 13), integrating the above expression while treating t as a constant, we obtain

$$DHc(t) = CvDT_o \int_0^L e^{-az} Sin(2pt/t - bz)dz$$

$$\Delta Hc(t) = Cv\Delta T_0 \left[\frac{e^{-az}}{a^2 + b^2}[b\cos(2bpt/t - bz) - a\sin(2pt/t - bz)]\right]_0^L$$

When z = L, e^{-az} is very small and can be neglected, thus

$$\Delta Hc(t) = Cv\Delta T_0 \frac{e^{-az}}{a^2 + b^2}[a\sin(2pt/t) - b\cos(2pt/t)] \qquad \text{(A)}$$

To obtain the maximum of $DH_c(t)$ with respect to time t, take its first derivative and let it be zero,

$$\frac{\partial D\,H_c(t)}{\partial t} = 0$$

and solve for t, we obtain

$$\tan\left(\frac{2pt}{t}\right) = \frac{a}{-b}$$

$$t = \frac{t}{2p}\,atan(-\frac{a}{b}) \qquad \text{(B)}$$

Equations (A) and (B) derived above will be used later in the specific comments for Appendix D (GREGI 1993-03, p. D2) to make calculations.

Regarding Equation (20), compared with Equation (10), the term Q(x) is missing from this equation. This suggests that the influence of the heat source is negligible. This point should be stated here and the reasons for this explained.

"*Water infiltration cannot explain upward advective heat transfer. ...In any case, infiltration cannot exceed precipitation, so water flow cannot be the main contribution to advective heat transfer*." (GREGI 1993-03, p.17, line 9). The analysis given here contradicts the suggestion in other parts of the reports that there is probably internal water circulation within the waste rock dump. If water is vaporized in the hotter regions of the dump and rises to the colder regions of the dump and then condenses there, significant heat can be transferred from the hotter to the colder regions by evaporation/condensation, and by convective heat transfer of the vapour. Also, such internal circulation of water can increase the downward water flux through a certain plane to well above that accounted for by the annual infiltration flux of, say, 0.5 m. This point should be considered.

Wells #2 and #6 are excluded from the calculation of average thermal conductivity (GREGI 1993-03, p.18). Reasons should be provided for this exclusion.

The "*negative values of Q*" referred to on p. 19 (line 6), is invisible in Figure 13b (p. 42) since the lowest scale value is 0. Figure 13b should be modified to include negative Q values for consistency.

The meaning of "b" in Equation (36) is not explained in the parameter list (p. 20); "b : depth of base" should be added at the end of the parameter list.

The basis for the asumption "*if convection cells are supposed having about the same dimensions vertically as the ones observed horizontally*..." (p. 23) should be explained.

The meaning of Figure 12 (p. 41) needs more clarification in the text.

Regarding Appendix A (GREGI 1993-03), there are many typographical errors in the equations presented on page A2, which will make reading very difficult. The correct formulas are given below, with the corrections underlined.

$$F(T_0, m, a, b) = \sum_{i=1}^{n} [T_i - (T_0 + m\,\underline{t_i} + a\,C_i + b\,S_i)]^2 \qquad \text{(A.4)}$$

$$\frac{\P f}{\P \underline{T_0}} = 2 \sum_{i=1}^{n} [(T_i - T_0 - m\underline{t_i} - a\,C_i - b\,S_i)(-1)] = 0 \qquad \text{(A.5)a}$$

$$\frac{\partial f}{\partial m} = 2 \sum_{i=1}^{n} [(T_i - T_0 - m\underline{t_i} - a\,C_i - b\,S_i)(-t_i)] = 0 \qquad \text{(A.5)b}$$

$$\frac{\partial f}{\partial a} = 2 \sum_{i=1}^{n} [(T_i - T_0 - m\underline{t_i} - a\,C_i - b\,S_i)(-C_i)] = 0 \qquad \text{(A.5)c}$$

$$\frac{\partial f}{\partial b} = 2 \sum_{i=1}^{n} [(T_i - T_0 - m\underline{t_i} - a\,C_i - b\,S_i)(-S_i)] = 0 \qquad \text{(A.5)d}$$

In the next sentence, the upper limit in the summation sign should be n instead of m. The correct forms of equations (A.6)a-b should be as follows.

$$\sum T_i = nT_0 + \underline{\ }m \sum t_i + \underline{\ }a \sum C_i + \underline{\ }b \sum S_i \qquad \text{(A.6)a}$$

$$\sum T_i\, t_i = nT_0 + \underline{\ \ m} \sum t_i^2 + a \sum C_i \underline{\ }\, t_i + b \sum S_i \underline{\ }\, t_i \qquad \text{(A.6)b}$$

An underlined space indicates that something has been deleted from the (incorrect) equations. In the matrix equations (A.7) and (A.8), the element on the upper left corner in the first matrix is n, not m.

In equations (A.10) and (A.11), use DT_0 to replace A to maintain consistency of symbols. The discussion below equation (A.11), "*Relationship A.11 for the calculation of angle P holds when a and b are positive... (next paragraph)..., the complementary angle (P+2p) is used instead*," including the table between the texts, is confusing and unnecessarily complicated. Realizing that tan(P) is a monotonous function of P in the close-ended interval [-p/2, p/2] and noting that tan(-p/2)=-∞ and tan(p/2)=∞, the discussion (including the table) can be simplified as follows:

Relationship A.11 always holds. If we limit angle P in the close-ended interval of [-p/2, p/2], there is only one angle P Î [-p/2, p/2] corresponding to each value of -a/b. The angle P' desired for plotting against time can be obtained by P + np, where n = 0, 1 or 2 and is easily determined as the value that makes each successive depth show the smallest, positive increase in the phase shift P' from the previous depth.

On p. A4 (second paragraph, line 5), $T(T_o,m,a,b,t_i)$ should be replaced by $T_i(T_o,m,a,b,t_i)$; and, T^* should be replaced by T_i^*. Equations (A.12) and (A.13) are incorrect. They should be corrected as follows:

$$SST = \sum_{i=1}^{n} \left(T_i - \frac{\sum_{i=1}^{n} T_i}{N} \right)^2 \qquad \text{(A.12)}$$

$$SSR = \sum_{i=1}^{n} \left(T_i^* - \frac{\sum_{i=1}^{n} T_i^*}{N} \right)^2 \qquad \text{(A.13)}$$

The tables on pages A5-A6 should indicate that "Atten." is $\ln(A/A_0)$ to make reading easier.

Regarding Appendix B (GREGI 1993-03), in equation (B.6) c, the coefficient before Δ**T** is 2p/t, not $2\pi/t$.

Regarding Appendix C (GREGI, 1993-03), the parameter list following equation (C.1) should be modified; delete c, r, and t from the list as they do not appear in the equation.

Regarding Appendix D (GREGI, 1993-03), the cyclic annual variation in heat stored within the dump (MJ/m^2) (shown on pages D2-D5) has been recalculated using the equations (A) and (B) derived earlier in the comments for the main report (GREGI 1993-03, p. 14). The following table compares the recalculated values with the original values presented in the report.

Well #	DT_0		a		DH_c(max)		DH_c(max), %	
	Recalc.	Original	Recalc.	Original	Recalc.	Original	Recalc.	Original
1	13.1	13.1	0.336	0.336	123.0	**77.1**	7.3	**4.6**
2	12.5	12.5	0.168	0.168	117.8	**147.2**	7.7	**9.6**
3	14.9	14.9	0.163	0.163	192.3	**180.8**	53.7	**49.9**
4	12.2	12.2	0.221	0.221	133.4	**109.2**	6.5	**5.3**
5	13.4	13.4	0.239	0.239	139.8	**110.9**	13.9	**11.0**
6	15.5	15.5	0.363	0.363	163.2	**84.5**	5.6	**2.9**

It can be seen that the original calculation presented in the report has resulted in large errors for Well #6 and Well #1.

In Appendix E (GREGI, 1993-03), the six graphs of temperature versus depth (pp. E14-E19) are missing the following components:

- The horizontal axis title "Date";
- The vertical temperature axis title "Temperature, °C"; and
- The legends for the graphs.

7.3 Assessment of Available Data for AMD Modelling

Predictive modeling for assessment of AMD requires a good database for characterizing:

- Site conditions (e.g., temperature, precipitation, evaporation, etc.);
- Waste rock properties (e.g., physical, chemical, geochemical, mineralogical, etc.);
- Heap characteristics (e.g., construction method, configuration, porosity/void volume, moisture content, rock particle sizes, etc.);
- Transport of oxygen and water (e.g., permeability, infiltration rates, temperature gradients, etc.);

- Kinetic factors (e.g., chemical and biological rates for sulphide oxidation, weathering/dissolution rates for major buffering minerals); and
- Water quality at various locations (i.e., infiltration water, porewater, seepage).

Recent documents prepared for MEND (SENES, 1994a and 1994b) describe the sampling requirements for collecting site-specific data for characterizing waste rock for decision making regarding monitoring, management, etc. and data required for prediction and AMD modeling. One of the principal researchers of the Mine Doyon studies (Pierre Gelinas) contributed to both of these documents, and La Mine Doyon is presented as a case study in the review document (SENES, 1994a).

The various sampling requirements (data categories) for waste rock are summarized in Table 7-1. We have indicated whether this data is available from the Mine Doyon studies. It is obvious that the site is well-characterized. Additional review comments are provided below.

One of the researchers (Lefebvre 1996) comments: *"the integrated and extensive characterization of the South Dump could provide ... to the whole AMD research community, a dataset complete enough to support the development of predictive models ... the care taken in the development of the characterization database should make it a lasting contribution to AMD research"*.

The layout of the boreholes was selected to reflect the three former drainage sub-basins under the heap, and trenches were situated at several locations, according to rock type. Therefore the sampling program did not have a statistical basis, but was appropriate and adequate for characterizing the heap.

The listing of geochemical sampling in the overview document "Monitoring and Modeling of Acid Mine Drainage from Waste Rock Dumps. La Mine Doyon Case Study" (GREGI, 1994-12, p. 5-2) is extensive and there is definitely not a lack of data for this site.

The overview document also provides estimates of Acid-Base Accounting (ABA), which we believe, are the only ABA data and percentage by weight mineralogy (sulphides and carbonates) data actually presented in any of the reports (GREGI, 1994-12, Table 1.1). In fact, few of the other reports show analytical results for chemical characterization of the waste rock, other than XRD (X-ray diffraction) analyses. Savoie et al, (1991) carried out the chemical analyses of composite samples (15 to 45) of each of the three major rock types and calculated summary statistics (means and standard derivations). This information is presented in Appendix D of the report "Mineralogical Transformations Associated with AMD Production in a Waste Rock Dump. La Mine Doyon-South Waste Rock Dump" (GREGI, 1994-06).

Table 7-1

Sampling Categories for Waste Rock

Data Category	Data Required for Modeling, Prediction, or Validation (yes/no)	Data Available from Mine Doyon Studies (yes/no)
Sampling Program	Yes	Yes, but no statistical basis
Elemental Content	Yes	Yes , but analyses not provided
Mineralogy	Yes	Yes, well described
Mineral Form	Yes	Yes, excellent information
Static Tests	Yes	Yes, some
Dynamic Tests	Yes	Yes, lysimeters but no columns or humidity cells
Hardness and Weathering	Yes	Yes, examined four methods
Water Monitoring	Yes	Yes, at numerous locations
Pore Water	Yes	Yes, two methods: washing and press extraction
Seepage	Yes	Yes
Groundwater	Site-specific	Yes
Surface water	Yes	Yes, assume available but not provided
Water Quality-Field Analysis	Yes	Yes
Water Quality -Lab Analysis	Yes	Yes
Gas Sampling	Yes	Yes, oxygen and carbon dioxide
Temperature Profile in Heap	Yes	Yes
Water Permeability	No	No
Air Permeability	Yes, if convection controls	Yes, but not successful
Oxygen Diffusion	Yes, if diffusion controls	No, convection controls
Particle Size	Yes	Yes, at various locations
Porosity	Yes	Yes
Water Content	Yes	Yes
Flow Monitoring	Yes	Yes
Infiltration Monitoring	Yes	No, proposed
Biological Monitoring	No	Yes, special study
Meteorology	Yes	Yes
Thermal Analysis	No	Yes, infrared surveys
Drilling	Site-dependent	Yes
EM Surveys	No	No

No data were provided from laboratory kinetic studies (i.e. no column testwork or humidity cells). The rate and extent of acid generation was examined by extraction testwork on drilling samples and by installation of field lysimeters at two locations. However the lysimeter data presented was for initial monitoring and was not interpreted with respect to possible extent of AMD production in the dump.

The authors investigated several different hardness tests (e.g., Los Angeles, Micro-Deval, Magnesium Sulphate, and Acoustic Celerometer) and concluded that *"the most convenient measurement of rock toughness, degree of weathering and internal fissuration is given by the acoustic celerometer test. This method is simple, cost-effective and yields results that compare favorably with the more involved tests using aggregates such as Los Angeles or* $MgSO_4$ *test"* (GREGI, 1994-12, p.3-9). Although this new method shows promise it requires more work to establish relationship(s) between measured compressive and shear wave velocities in the rocks to the existing surface area or possible increase in surface area (and therefore reaction rates) as a result of weathering and production of more fine particles. The other tests (Los Angeles, Micro-Deval, and Magnesium Sulphate) provide a direct quantitative measure of additional fine particles that could be used to calculate additional reactive surface area as a result of weathering processes, which is an important parameter required for prediction/modeling of AMD.

Mineralogical and geochemical processes occurring within the heap are well described in the report "Mineralogical Transformations Associated with AMD Production in a Waste Rock Dump. La Mine Doyon-South Waste Rock Dump" (GREGI, 1994-06). The rock samples were described macroscopically and microscopically, and paste pH, total rock chemical analyses and XRD were used to characterize the materials. However, the total rock chemical analyses of waste rock samples from the heap do not appear to have been presented (or discussed) in any of the reports. The 1991 report "Évaluation du drainage Minier acide et des barrières sèches pour les haldes de stériles: Étude du site de Le Mine Doyon" (GREGI, 1991-19, Tables 3.3 and 3.4*)*, present an estimation of normalized mineralogy of tailings samples (residues) and treatment sludges (high density sludge) based on chemical analyses of these materials (i.e. % SiO_2, Al_2O_3, Fe_2O_3, CaO, etc.). It is not clear if chemical rock analyses were carried out for waste rock samples, but an estimation of normalized mineralogy could have been useful for geochemical interpretations and predictive AMD modeling.

Water samples were collected from many different locations, using different methods: seepage at weir stations; groundwater from wells; water from lysimeters; washing/extraction of drill cuttings; and pressure extraction/squeezing of moist rock samples. In our opinion, there is adequate water quality data for calibrating an AMD model; however, one of the secondary reviewers (Morin, 1995a) disagrees in this area.

Instrumentation was installed in the boreholes (e.g. piezometers, gas sampling tubes, thermistors) in a very efficient manner. Temperature and gas profiles indicate that thermally driven convection is the key mechanism controlling oxygen flow through the waste rock dump. There is adequate temperature and gas data for AMD modeling.

Measurements of differential air pressure were attempted but were unsuccessful; the authors concluded atmospheric pressure variations were too small to verify their proposed technique (air permeability too large); therefore they planned to investigate use of automatic loggers and dedicated pressure cells. Convection is obviously the dominant mode of oxygen transport in the heap.

Particle size test work included examination of particle size distribution of the fine particles (for two major rock types) at two depths in the heap (0 and 1 m); however they could have looked at a deeper level (e.g. 5 m from lysimeter installation), and possibly at older (weathered) versus newer areas of the heap. The authors identified that *"for all properties depending on the specific surface area (m^2/kg), the 10% fine fraction has approximately 50 times more surface area than larger blocks. Thus water content, degree of saturation, oxidation rates and reactive permeability are dominated by the relative abundance of the fine fraction"* (GREGI, 1994-12, p.2-6). The particle size distribution for fines is important for AMD modeling, and is adequately characterized at this site.

A detailed hydrological evaluation was carried out to perform a water balance for the heap. This work provided several estimates that are required for predictive modeling of AMD generation in heaps (GREGI, 1994-12, Table 4.12). The water budget summary is shown on an average annual basis. This would be sufficient if modeling predictions were also carried out on an average annual basis; however, several models use monthly (or shorter) time steps and require monthly estimates of infiltration to account for seasonal effects (which can significantly influence rate and character of AMD). There appears to be sufficient data collected for the authors to estimate monthly infiltration flows (e.g. monthly precipitation records, estimates of snowfall, spring run-off, lysimeters, etc.) and a few average daily flow estimates are provided (GREGI, 1994-12, p.4-34). Observations of changes in volume and quality of flows at the weir stations suggests seasonal (monthly) estimates are necessary to better understand the heap.

Most sites would simply estimate infiltration flow by comparing estimates for inflow (i.e. precipitation less evaporation) and total flows collected. Therefore the authors' explanation of the effect of water storage on the difference between precipitation and flow (GREGI 1994-12, p.4-34) is particularly relevant for performing water balances on heaps. The heap water content was reported to increase from 2% (initially) to 10-12% (volume basis) over a 10 year period due to storage of waters inside the heap. They believe the heap has now reached values close to field capacity; but also note that weathering processes gradually create more fine particles that can retain more moisture. This shows that it is important to measure current moisture content, in relation to field capacity, in order to accurately estimate current and future water storage and infiltration flows.

Chemical and biological oxidation of sulphides should be considered in an AMD model. Several biological studies were carried out at Mine Doyon. Micro-organisms were isolated from rock samples collected during drilling programs by resuspending into liquid media, and from the groundwater in piezometers extending into the base of the heap using bacterial traps. For predictive AMD modeling, it is usually sufficient to confirm that sulphide-oxidizing bacteria are present and that the dominant bacterium is *Thiobacillus ferroxidans*, for which kinetic rates for growth and biological sulphide oxidation are well-established. The biological studies confirmed this; however these studies also suggested that the biological oxidation of sulphur and sulphides in an anoxic environment may also be important. In our opinion, their interpretations regarding anaerobic biological respiration using ferric ions as electron acceptors are not supported by the physical and chemical evidence provided in the reports; furthermore, the potential contribution of this process can be considered to be insignificant in comparison to the chemical influence of ferric ion on the long-term generation of AMD.

The authors conducted infrared surveys and made numerous recommendations regarding aerial surveys for infrared thermography (although it is unlikely that others would attempt such surveys). Infrared measurements conducted 10 months apart demonstrated that temperature distributions at the surface attributed to air convection patterns are stable. This is not usually required, but is useful information for AMD modeling. The infrared surveys supported the development of their conceptual model of air circulation in the heap.

7.4 Studies in Support of Predictive Modelling

7.4.1 Heat and Mass Balances

An early 1991 report "Évaluation du Drainage Minier Acide et des Barrières Sèches pour les Haldes de Stériles: Étude du site de La Mine Doyon" (GREGI, 1991-19) provides an overview of the history of the site, and the initiation of field programs carried out to install instrumentation and obtain samples for characterizing the heap (waste rock and water quality). The early report is not a MEND document; however, it does describe some interesting initial predictions of AMD production at the site that are not discussed in the 1994 overview MEND document "Monitoring and Modeling of Acid Mine Drainage from Waste Rock Dumps. La Mine Doyon Case Study" (GREGI, 1994-12).

The 1991 report presents results of preliminary heat modeling using a simple model that did not consider water infiltration and oxygen convection. This simple model was used to estimate the amount of pyrite oxidized based on heat generation. The rate of pyrite oxidation was estimated as 7000 tonnes per year, which translates to a theoretical time of 102 years for total oxidation of pyrite.

The above estimate was compared to another independent estimate obtained by performing mass balances on sulphate and iron concentrations measured in leachate; which gave times of 85 years (for sulphate) and 92 years (for iron). Both sets of estimates were based on average pyrite content of 3.5%.

The use of two independent methods of estimating the rate and extent of sulphide oxidation and acid generation provided more confidence in their average estimate of approximately 100 years. The mass balance method is simple and could be easily applied at other sites with adequate seepage data and a good estimate of average pyrite content of the heap. The heat balance approach used a simple model but the calculation procedure outlined in the 1991 report (GREGI, 1991-19, Annexe D) is not as simple, and is therefore not likely to be used at many other sites.

The authors caution that these time estimates for the complete oxidation of pyrite are only theoretical, and the only use of the calculated AMD production rate is to indicate the magnitude of the problem (GREGI, 1991-19, p. xiii).

The calculations provided in the 1991 report demonstrate the possible extent of AMD generation at this site. Subsequent thermal modeling included conduction and advection (GREGI, 1993 93-03), and later physical modeling (TOUGH AMD) also considered convective heat transport (GREGI, 1994-12). Neither of these more refined modeling studies were used to provide estimates of the possible extent of AMD beyond the current time period, or beyond the simulation time period (15 years). The principal researcher (Lefebvre, 1996) explains that subsequent modeling was *"used mainly to interpret the present conditions of the South Dump and to evaluate potential control methods. Further characterization, mainly of the changes in physical properties with time, and further model refinements would be required to make* (the TOUGH AMD model) *a more reliable predictive tool".*

The 1991 report provides an overview of the mechanisms of acid mine drainage and a comparison of the various features of the existing AMD models at that time (GREGI, 1991-19, Annexe C, Lefebvre 1991, Table 2, p.14). Several of these AMD models were not commercially available and therefore could not be used as the starting point for development of an AMD model for waste rock. The author lists the following desirable features for an AMD model for Mine Doyon:

"1) Employs a shrinking reaction core model;

2) Reaction rate controlled by oxygen transport only, to simplify the kinetic considerations;

3) Considers grain size distribution of the wastes;

4) Provides simple chemical speciation, requiring few inputs. Modeling of reactions using specialized programs such as PHREEQE could be used to complete the results of a physical model;

5) Utilizes diffusion and convection as mechanisms of oxygen transport;

6) Simulates the generation and transfer of heat;

7) Considers infiltration; and

8) *Considers geometry of the heap"* (English translation of GREGI, 1991-19, Annexe C, Lefebvre, 1991, p.17).

The author selected an existing multi-phase, multi-component numerical model (TOUGH2) to simulate the majority of the above processes, and decided that a new module should be added to consider the sulphide oxidation reaction. The development and application of this model (TOUGH AMD) is described in the 1994 overview document (GREGI, 1994-12). The final model was not used to consider variable grain sizes, and did not include simple chemical speciation. Subsequent studies have not presented any modeling of geochemical reactions using programs such as PHREEQE (or MINTEQ) to complement the physical modeling of the heap. Although, we have recently been informed that such work is presently underway (Lefebvre, 1996).

One of the secondary reviewers (Morin, 1995a) has identified a possible inconsistency regarding the sulphate mass balance used to estimate the time to sulphide "burn out" (GREGI, 1991-19) and the sulphate mass balance used to estimate the retention of sulphate within the dump (reportedly, 60% of annual production). Peer review comments on the retention of sulphate are provided in Chapter 5.0, Article 5.6.3.

It is our opinion that their estimate for sulphate retention as 60% of annual production is likely an overestimate. The agreement between the two independent estimates for time for total oxidation of sulphides obtained from (i) heat balance and (ii) mass balances suggests that no more than 10% of the sulphate produced was being retained inside the heap, at that time (1991). The retention of sulphate would most likely have increased continuously since that time. The principle form of the stored sulphate is assumed to be the mineral jarosite. It is unlikely that this mineral would be present in such significant quantities to represent 60% of the annual sulphate production.

One of the principal authors of the report (Lefebvre, 1996) explains that *"the form of accumulated sulphate within the dump is not only in a mineral form but also in a very large part as a very high concentration leachate"*. He does not believe that their evaluation of retained sulphate is overestimated as the evaluation rests on more than one method and matches the leachable sulphate determined from drilling cuttings.

In a more recent document (GREGI, 1993-05), the authors state that the *"present rate of pyrite oxidation is 16,443 t/y, merely 1% of the total estimated initial mass of pyrite (1,471,394 t)"* (GREGI, 1993-05, p. 6). Therefore, if sulphide oxidation were to continue at the current rate, the pyrite would be completely oxidized within the next 100 years. Subsequent modeling using the TOUGH AMD model provided estimates of the sulphide oxidation rate, (expressed as kg O_2 /m^3 d), at various locations within the heap, as well as estimates of the unreacted pyrite mass fraction (GREGI, 1994-12); however, this information does not appear to have been used to obtain a revised estimate of the possible duration of the AMD release at this site.

7.4.2 Mineralogical Model (Conceptual)

A conceptual model of the mineralogical transformations of aluminosilicates under acidic conditions, is illustrated in the report "Mineralogical Transformations Associated with AMD Production in a Waste Rock Dump. La Mine Doyon - South Waste Rock Dump" (GREGI, 1994-06, Figure 11, p.30). Developing a good understanding of possible mineralogical transformations and associated geochemical reactions is particularly important for predictive modeling of AMD in waste rock.

The mineralogy report (GREGI, 1994-06, Section 3.2) also describes their estimation of the mineralogical mass transfer in a borehole based on differences of species/element content between consecutive samples of porewater (expressed on a dry basis). This was an interesting approach, and in this case it was successful; however, we do not feel this approach could be as easily (and successfully) applied to other sites as it depends on *a priori* knowledge of the specific minerals and their chemical composition and confirmed absence/presence along the borehole profile, as well as accurate extraction and analyses of the porewater concentrations.

The authors did not discuss the possibility of extending their examination of mass transfer in a borehole into simplified mineralogical and geochemical modeling of the entire heap, or at least part of the heap. However they did state that a lack of water quality data prevented them from performing geochemical modeling of interactions between mineral phases and porewater; although, they did not specify what type of modeling they had intended to carry out.). We do not consider that there is a lack of water quality data for this site. However, one of the secondary reviewers' comments disagree in this area (Morin, 1995a).

7.4.3 Method for Prediction of Water Quality (Empirical)

The reports "Two Rapid Methods to Evaluate Acid Mine Drainage Composition: Total Dissolved Solids and Energy Dispersive X-ray Fluorescence Spectroscopy" (GREGI, 1993-04) and "Monitoring of Acid Mine Drainage: Chemical Data from La Mine Doyon, South Waste Rock Dump" (GREGI, 1993-05) describe the development and application of a method for estimating the levels of certain aqueous parameters in heap leachates and seepages. The correlation equations were developed through statistical analysis of the water quality database. This empirical approach is reasonable and could be useful for other sites; but may not be appropriate for other sites with less well-established AMD and a smaller water quality database. This has been discussed in Chapter 5.0, Article 5.6.4.

The authors developed a correlation matrix for 13 water quality parameters; although they do not specify how this correlation matrix was generated (presumably, Pearson correlation coefficient) (GREGI, 1993-04, Table 1). Other mine operators could easily perform a similar assessment with their site data, but may need some additional guidance.

Correlation equations were developed to predict the levels of acidity, aluminum, iron (total), magnesium and sulphate based on measurement of the total dissolved solids (TDS) and/or conductivity (GREGI, 1993-04, Table 2). The relationships for calculating the chemical composition of water samples were applied to:

- Groundwater samples from monitoring wells;
- Seepage samples from collection ditches;
- Leachate samples from lysimeters; and
- Porewater samples from leaching (extraction) of waste rock drilling samples.

A review of the calculated values presented in various reports shows the use of equations to calculate some parameters was acceptable for water samples collected from the monitoring wells and the collection ditches; but was not very successful for estimating the acidity or iron levels in seepages from the lysimeters. This was not noted in the monitoring report (GREGI, 1993-05).

The authors state that *"these correlation's are significant to explain the processes of acid generation in the dump. Results indicate that leachate samples from the base of the dump and the ditches can be viewed as a single solution, showing more or less dilution. It is thus possible to establish relationships for the calculation of the concentration of major contributors like Fe, SO_4, Al, Mg and acidity based on simple parameter measurements such as TDS or conductivity" (GREGI, 1993-05, p.3)*. This qualifying statement is very important for application of this empirical method at other sites. A test of the similarity of borehole/well data and seepage data, and possibly other water quality data, appears to be necessary to apply this approach at other sites, (i.e. does dilution explain the differences in concentration levels?). Such an analysis would be useful in preparation for AMD predictive modeling.

The correlation's developed from 1991 data (spring, summer) were applied to monitoring conducted during 1992 (spring, summer, fall), and appear to have been acceptable. It would be interesting to determine whether the same correlation's could still be applied during 1993 and 1994. Since fewer analytes would actually be measured in subsequent years, there would not be a lot of additional data available for updating the correlation's.

Their empirical method was developed as a means to reduce chemical analyses requirements (i.e. costs) and was successful in this regard. However, the correlation's developed rely on measurement of TDS and/or conductivity and therefore cannot be extended to predict future water quality.

A review of the correlation matrix presented in Table 1 (GREGI, 1993-04, p. 3) shows there was also a good correlation between sulphate and the other aqueous parameters. This suggests that similar equations could have been developed to predict the levels of other parameters based on the sulphate concentration. These types of equations would possibly be more useful for supporting predictive AMD modeling, which typically involves calculation of the release of sulphate from oxidation of sulphide.

7.5 TOUGH AMD Model

7.5.1 Review Comments

The monitoring and modeling report (GREGI, 1994-12, Chapter 7: "Numerical Model of AMD Production in Waste Rocks") presents the development of the TOUGH AMD model. The authors acknowledge that: numerous physical and geochemical processes are involved in AMD production; most of these processes are coupled; and that numerical modeling allows the simultaneous quantitative representation of most of these coupled processes. However, the focus of their work was to gain a better understanding of the physical processes involved in AMD. (Geochemical processes were not represented in the AMD model that was developed.)

Their overall approach was to study physical processes of heat/temperature and oxygen transport and consumption as related to pyrite oxidation. This work represents a considerable undertaking; it was well-planned and presented; and provided a solid understanding of the current condition within the South Dump. We do not consider, however, that such an approach may be appropriate for prediction of AMD for other sites for the following reasons.

- An intensive field program is required for temperature and oxygen data (they recommend at least one year of monitoring). Although an extensive dataset is desirable to support predictive modeling, the collection of temperature and oxygen profiles requires a drilling program which may not be technically feasible at some sites;

- No information about geochemical processes occurring within the heap was used in the modeling; therefore, no interpretations or conclusions can be made regarding water quality and stored oxidation products. Their approach was to study the basic physical behavior of the system first. We believe that the geochemical behavior should be examined concurrently with the physical process;

- There are several inherent problems with the underlying assumptions of their conceptual approach, which are outlined below.

The authors identify the need to consider gas, liquid and solid phases; however they have chosen to underestimate the importance of the solid phase. *"If we suppose that properties of the solids may be treated globally, it is not necessary to include specifically a solid phase and its components* *in the system"* (GREGI, 1994-12, p.7.2). While this is understandable since their focus is on heat and gas transfer, such an approach would not be acceptable for geochemical applications.

The authors selected an existing hydrological model (TOUGH2) as it appeared to be the most suitable for representing AMD because it already represented the "physical processes" involved in AMD. They reference a literature review by Mangold and Tsang (1991) which considered subsurface hydrological and hydrochemical models. Incidentally, an earlier review of available AMD models was performed by Lefebvre (1991), and is presented in Rapport GREGI, 91-19 (Annexe C).

The TOUGH AMD model employs the shrinking reaction core model. The inherent assumptions are:

- Uniform sized spherical particles;
- Pyrite is essentially "free" and completely oxidizable;
- Particle remains the same size, only the pyrite core is consumed;

In our opinion, the reaction core model described in Section 7.2 and illustrated in Figure 7.1 (GREGI, 1994-12) is actually more suited for simulating fine particles, such as tailings.

The studies conducted at Mine Doyon included field observations of particle size distribution, mineralogical examination of particle geometry for the main rock types, and estimation of the reactive surface area for pyrite using several different methods. Therefore, there was a lot of information available for describing the particle geometry and the reactive surface area; however, none of these studies were discussed in their description of the TOUGH AMD model. For example, Section 3.7 (GREGI, 1994-12) states that a *"geometric description is needed for shrinking-core reaction models and it was shown that different rock types break in blocks of different shapes that can be analyzed as cubes, platelets or disc"* (GREGI, 1994-12, p.3.9). The researchers do not explain why they chose to use a sphere for their shrinking reaction core model. Moreover, particle size hardly remains constant in an acidic environment.

In an earlier report (GREGI, 1991-19), the author notes *"pyrite oxidation in schists is a shorter term phenomenon than in other units where alteration is controlled by oxygen diffusion (shrinking core models) through large sound blocks"* (GREGI, 1991-19, p.x). This is interesting as the later model TOUGH AMD, (GREGI, 1994-12) was based on the shrinking core model and did not distinguish between the more reactive sericite schists and the other rock types.

The authors did not distinguish between chemical and biological oxidation of sulphides, and they did not consider the effect of pH. Oxygen is considered the only oxidant for sulphide, avoiding need for chemical speciation of leachate, (e.g. ferric ion). *"The volumetric oxidation rate is also supposed independent of the geochemical conditions within the leachate, such as pH, Eh and ion concentration. This same supposition was made by Cathles and Schlitt (1980), as well as*

Pantellis and Ritchie (1991) to avoid having to perform speciation calculations as for the model developed by Jaynes (1983)" (GREGI, 1994-12, p.7.5). The effect of pH on sulphide oxidation rate is significant; their neglect of the pH effect could only be justified under the specific conditions encountered at Mine Doyon, where the pH of the leachate quickly acidified and has remained below 3. Investigators attempting to model a heap at other sites should be warned against neglecting the effects of changes in pH and geochemical conditions as heaps (gradually) become acid generating.

One of the principal researchers (Lefebvre, 1996) agrees with this point, and comments that *"the numerical model is not universally applicable, but in convection - dominated sites ..., it is the physical processes that determine the global oxidation rate ... . In such cases, which are likely numerous considering the normal physical properties of waste rocks, ... an approach such as ours* (researchers)*, with appropriate improvements, could greatly raise the industry's ability to predict AMD production and manage present and future waste rock dumps".*

The TOUGH AMD model considers air and oxygen, but the (chemical) effect of carbon dioxide is not considered. This is particularly important with respect to biotic oxidation of sulphides.

The temperature dependence of the oxidation rate was incorporated using a temperature factor, instead of using well-established relationships, e.g. Arrhenius relationship. This is curious considering the TOUGH model actually has an option for employing the Arrhenius relationship (GREGI, 1994-12, p.7.15).

Their reaction core model provides a relationship that is used to express the volumetric oxidation rate as shown in Equation 7.1 (GREGI, 1994-12, p.7.6). There are several questions that can be raised regarding this approach.

- The global volumetric kinetic constant K_{ox} depends on the first order kinetic constant k_{ox}, and a few physical or geometric terms, e.g. surface area of pyrite per unit volume (a^{rock}_{Py}), radius of rock particle (R), thickness of the layer in which pyrite oxidation takes place; we assume this means layer "b" in Figure 7.1. Incidentally, the numerical value of "R" (radius of rock particle) is not stated anywhere in the report.

- *"The first order kinetic constant k_{ox} (m/s) represents the rate of oxygen consumption during the surface oxidation reaction of pyrite, and has a relatively constant and well-determined value (Otwinowski 1993)"* (GREGI, 1994-12, p.7.6). The value of k_{ox} is relatively constant, at a given pH and temperature. Therefore K_{ox} (global volumetric kinetic constant) is essentially constant and determined by physical or geometric terms, one of which (a^{rock}_{Py}) is not well-characterized. Chemical and visual methods employed for characterizing the reactive surface area of pyrite did not provide consistent estimates (see discussion in Chapter 5, Article 5.3.2).

- Equation 7.1 (GREGI, 1994-12, p.7.6) contains three factors, X_T (temperature), f(X) and X_{wo}, all of which are assigned values between 0 and 1. We have previously commented on their use of a temperature factor.

- The factor X_{wo} is defined as the oxygen partial density in the liquid phase kinetic factor. This definition is somewhat ambiguous and therefore meaningless.

- Figure 7.3 (GREGI, 1994-12, p.7.8) also suggests that $X_T = 1$ for temperatures less than 65 ºC which means there is no reduction in rates for colder temperatures. Figure 7.3 suggests the oxygen mass fraction in air reaches 0.02(?), this maximum should be 0.20. Also it is not clear how the apparent nonlinearity of the profiles for X_T and X_{wo} was handled in their model.

The most important factor appears to be f(X), which is described in Equation 7.3 (GREGI, 1994-12, p.7.7). While the general form of this equation appears to be correct, there are no intermediate equations provided to show how Equation 7.3 was developed. A few additional questions can be raised:

- Figure 7.2 (GREGI, 1994-12, p.7.7) shows profiles of f(X) versus (1-X); we assume the lines of constant (td/tc) should really be (τ_d/τ_c).

- The terms τ_d and τ_c depend on the initial particle size; however, the initial particle size is not specified in the report.

The terms τ_d and τ_c are not additive. These two processes occur simultaneously. The idea of adding these terms originates from Cathles, who has since revised this approach. The additive combination can only be done if one term, i.e. either τ_d or τ_c, dominates; Figure 7.3 shows that this is clearly not the case.

Table 7.1 (GREGI, 1994-12, p.7.13) presents the phases and components of the system. The air component should be split into oxygen and other gases. The heat component is missing. The solid phase should also be included to account for the conduction of heat term shown in Equation 7.16 (GREGI, 1994-12, p.7.11).

Equation 7.15 (GREGI, 1994-12, p.7.11) contains a term for the diffusive flux of component K in the gas phase, $f_K{}^g$. This term is based on a local concentration gradient at the boundary surface; this cannot be accurately estimated from volume averaged mass balances such as shown in Equation 7.12 (GREGI, 1994-12, p. 7.10).

"The advective mass flux of phase (liquid or gas) is determined by the general form of Darcy's law for multiphase flow multiplied by the phase density:" (GREGI, 1994-12, p.7-11 and Equation 7.17),

$$F_b = K \frac{K_{rb}}{m_b} r_b \left(P_b - r_b g \right)$$

where $P_\beta = P_{reference} + P_{c\beta}$

There are several problems with the above equation:

- The equation is conceptually and dimensionally incorrect;
- F_b is not a flux term, i.e. units are not kg/(m^2·s);
- The term $r_b g$ is not a pressure term (kg/(m^2·s^2));
- The ΔP term is missing, unless $P_b = \nabla P$;
- The term P_{cb} is not defined;
- There appears to be a missing distance term (Δz).

"*The diffusive mass flux is proportional to the gradient in partial density of the component in the gas phase* r_k^g *(kg/m^3)*" (p.7.12, GREGI, 1994-12). The **gradient** should be expressed as follows, and not as shown in Equation 7.18 (GREGI, 1994-12, p.7.12).

$$\frac{¶\, r_g\, w_k^g}{¶\, x}$$

Also, the units of Equation 7.18 for f_κ^g, do not correspond to a flux term (i.e. are not in kg/(m^2.s).

It is not stated how the conversion factor F_h (-12.58 MJ/kg O_2) shown in Equation 7.19b was obtained (GREGI, 19941-2, p.7.12). We assume this was calculated from the enthalpy of the reaction.

In general, there is a recurring problem with terminology as shown by the following examples.

- "*Thermodynamic equilibrium conditions are assumed locally*" (p.7-3 and again on p.7-13, GREGI 1994-12). Thermodynamic equilibrium would preclude any net reaction; we assume that they really mean steady-state or near steady-state conditions.
- "*In waste rock dumps, pyrite is contained in rock **blocks** and surrounded by other minerals ... pyrite oxidation proceeds from the surface of waste rock **blocks** ... a zonation appears within the waste rock **blocks** ... the rate of oxygen diffusion in the **blocks** ...*" (p.7-4, GREGI 1994-12). We assume they really mean waste rock particle, as the use of the term block generally has a much larger connotation such as zone or possibly heap.

- Their use of the terms "*primary variable*", "*second primary variables*", "*secondary parameters depending on the primary variables*" is confusing. It would be better to use terms such as independent variables, dependent variables, and calculated parameters.

In general, it is difficult to distinguish between the dependent, independent or predicted variables. The dependent variables appear to include: temperature, oxygen mass fraction, air flow rate and oxidation rate. Other predicted variables appear to be determined by coupling to these dependent variables.

Table 7.2 (GREGI 1994-12, p.7.17) lists the physical properties (or inputs) used in the simulation of the base case. Some of these parameters are unconventional and have not been defined, as shown by the following examples.

- The volumetric oxidation constant $K_{ox} = 0.75 \times 10^{-6}(s^{-1})$ was previously defined in Equation 7.1 as the global volumetric kinetic constant. It would have been interesting to know what values were used for k_{ox}, a^{rock}_{Py}, γ, δ to calculate K_{ox} in Equation 7.2 (GREGI 1994-12, p.7.6).

- The ratio of diffusive/chemical total times, $t_d/t_c = 2.5$, is assumed to really refer to τ_d/τ_c. It is not clear why was a value of 2.5 chosen for the base case when this ratio was previously presented as ranging from 0 to 3 on Figure 7.2 and Figure 7.4 (GREGI 1994-12, p.7.8 and 7.9).

- The standard diffusion coefficient $D_o = 2.13 \times 10^{-5} m^2/s$ is assumed to be for oxygen in air.

- The temperature diffusion coefficient $\theta = 1.80$ has no meaning without dimensions. This can't be the temperature kinetic factor X_T (also not well defined) as it has a value between 0 and 1.

- The van Genuchten factors "m" (0.23) and " α" (0.504 Pa^{-1}) have not been defined.

The base case simulation is for 15 years and includes the 9 years the dump has been in place. It would have been helpful if the authors had presented field data to demonstrate the calibration of the model and the accuracy of the predictions.

We do not agree with the statement that "*It would be unrealistic to model the behavior of the dump for a longer period given the uncertainty in our (*their*) knowledge of the site and in particular the absence of data on the evolution of physical properties in time which could affect significantly the behavior of the dump*" (GREGI 1994-12, p.7-16). One of the main purposes of modeling is to predict what could happen in the future. If the model can be shown to (i) accurately simulate current (observed) conditions and (ii) display correct (expected or understandable) responses to changes in parameter values, then we should have some confidence in future predictions.

The figures presented in this report did not show the agreement with field measurements; although we can see that the model did recreate some of the described trends and could be used to examine the effects of changes in parameters, with some success. There is perhaps a need for a separate report e.g. summarized/abstracted from the Ph.D. thesis (Lefebvre, 1994), to describe their modeling work including: theoretical basis for model showing step-by-step development of equations; description of methods used to estimate important parameters; calibration to field data; simulation of various scenarios to examine effect of changes in (physical) parameters; and, discussion of potential application to other sites.

Finally, one of the secondary reviewers offered the following additional comment. *"The movement of air, water, and solids throughout the dump are likely controlled by the stratigraphy of rock types in the dump, including the continuity and slope of the layers and in-situ grain sizes. Interestingly, stratigraphy is not discussed in any reasonable detail in this report only tidbits are found, such as "Well #5 has fine grained overburden material within the waste rock" (GREGI, 1994-12, p. 6.11). Therefore, a fundamental control on observed distributions of water, gases, and solids is missing. This raises a question on the value of modeling in Section 7 which attempts to "identify the parameters having the greatest impact on the behavior of the system" (GREGI, 1994-12, p. 7.16)"* (Morin, 1995b).

7.5.2 Comments Regarding Application of The TOUGH AMD Model

The results of simulations performed with the TOUGH AMD model are presented in Section 7.5 of the report "Monitoring and Modeling of Acid Mine Drainage from Waste Rock Dumps. La Mine Doyon Case Study" (GREGI, 1994-12). The illustrations of the predicted conditions (e.g. oxygen concentration, temperature, air velocity, etc.) at specific locations within the heap are quite effective for supporting their interpretation of the physical processes taking place.

Only selected examples of application of the model are presented in the overview document (GREGI, 1994-12). Additional work was obviously carried out but this is not specifically described. The reader is referred to Lefebvre (1994) for a more detailed account of the modeling work.

From Section 7.5.3 and Figure 7.7 (GREGI, 1994-12, p.7.21), we can conclude that the process of water vapor transfer by advection is responsible for redistribution of water within the dump, and results in a more uniform water content within the heap; also, evaporation results in precipitation of salts within the heap. The authors note that water vapor condenses in cooler areas near the surface which contributes to more infiltration. They report water saturation variations within the dump from 37.5% to 41.5%. This small variation indicates a fairly uniform moist environment.

From Section 7.5.4 and Figure 7.8 (GREGI, 1994-12, p.7.23), we can see that their model has predicted about 30% of the pyrite has been consumed, but very little pyrite has been oxidized at the core of the heap (GREGI, 1994-12, Figure 7.6c, p. 7.19). The authors state that *"a dump with* *smaller lateral extent would have much less pyrite remaining*" (GREGI, 1994-12, p.7-22). Information regarding the impact of dump size on global pyrite oxidation is provided in Lefebvre (1994).

The sulphate concentrations shown in Figure 7.8c (GREGI, 1994-12, p.7.23) are very high (>200 g/L) because their model does not include precipitation of sulphate (e.g. as gypsum and jarosite). Porewater concentrations as high as 150 g/L sulphate have been reported elsewhere in the document, and they could have shown an additional curve for average sulphate concentrations measured during this time period for comparison to the predicted values in Figure 7.8c.

Section 7.5.5 and Figure 7.9 (GREGI, 1994-12, p.7.25) show the effect of changes in permeability on the model prediction; although the authors do not actually instruct the reader to make a visual comparison of Figure 7.9 (permeable/anisotropic case) and Figure 7.6 (base case). The authors state this illustrates the need for careful characterization of waste rock dumps to predict their behavior, and they recommend development of field methods to determine anisotropic permeability. They conclude that permeability is the key parameter determining convection. The results presented support this.

Section 7.5.6 and Figures 7.10 to 7.12 (GREGI, 1994-12, pp. 7.27 to 7.29) presents a modeling study of the effect of a border membrane (i.e. a cover to prevent lateral air entry into the sides of the dump). Figures 7.10a and 7.11a depict formation of an eddy flow pattern inside the heap when a membrane is present. This is likely an artifact of the boundary definitions and/or the numerical methods used in the model. A few other modeling groups had initially reported similar predictions of eddy patterns but eliminated them after correcting their model(s). Eddy formation on a large scale was not observed in the field studies at Mine Doyon, and has not been observed at other sites. Figure 7.12 shows their simulation of the installation of the border membrane, compared to the base case. The oxygen consumption rate and the oxygen mass fraction are predicted to drop quickly; temperature is predicted to gradually decrease, but the sulphate is predicted to decline very slowly due to lower infiltration (i.e. dilution) and due to slow release of stored AMD. We can conclude that their AMD model is correctly predicting the (expected) effects, and would be useful for examining other (similar) decommissioning options for the heap.

The authors discuss the possible need for internal neutralization (i.e. addition of alkaline) (GREGI, 1994-12, p.7.26); however, their model cannot be used to evaluate the need for neutralization of stored AMD. Geochemical capabilities would need to be added to the model to consider storage and release of AMD, as well as dissolution of buffering minerals. Under the low flow conditions resulting from a cover on the heap, the dissolution of buffering minerals can significantly change the character of the seepage. These buffering minerals typically provide available buffering too slowly under normal (higher) infiltration conditions.

Section 7.5.7 (GREGI, 1994-12) briefly comments on the limitations of the TOUGH AMD model and future research. The authors explain that "*differences between the model predictions and field* *observations point out limitations in the numerical model and in* (their) *general knowledge of some of the key processes related to AMD production*" (GREGI, 1994-12, p.7.30). We would have preferred to see some comparison of model predictions and field observations.

The authors conclude that their general knowledge about the key processes related to AMD is limited. We do not consider that their knowledge is limited; some of the knowledge gained in other studies at the site was just not applied in development of their model (e.g. mineralogical studies, reactive surface area, weathering characteristics, water chemistry database, etc.).

7.6 New Understanding

The previous sections present our detailed comments from our review of the studies performed at Mine Doyon. The following points summarize our comments regarding the key areas of "new understanding" derived from these studies:

- The studies at Mine Doyon are an excellent example of how to carry out waste rock sampling and examination for collection of information required for AMD prediction and modeling;

- The thermal models developed for this site can provide a definition of the transport parameters that can be used in subsequent AMD modeling; although these parameters should be verified by other methods before use;

- Hardness tests (e.g. Los Angeles, Micro-Deval, and magnesium sulphate) were shown to provide a direct quantitative measure of the additional fine particles that could be produced as a result of weathering processes; this information could be used to calculate additional reactive surface area as a result of weathering, which is an important parameter required for prediction/modeling of AMD;

- The storage of water inside the heap was shown to be important, and influenced by weathering processes which gradually create more fines that can retain more moisture. Their work shows it is important to measure current moisture content in relation to field capacity, in order to accurately estimate current and future water storage and infiltration flows;

- The process of water vapor transfer by advection is responsible for redistribution of water within the dump, and results in a more uniform water content. Also, evaporation results in precipitation of salts within the heap; and condensation of water vapor in cooler areas near surface contributes to more infiltration;

- Two independent estimates for the possible duration of AMD at this site were prepared based on (i) heat balance and (ii) sulphate and iron mass balances. The use of two independent methods provided more confidence in their average estimate of approximately 100 years although the mass balance approach did not allow for consideration of stored acidity within the dump. The mass balance method is simple and could be applied at other sites; however, the calculation procedure for the heat balance is not simple and requires an extensive temperature monitoring program to estimate heat parameters;

"The 100 year estimate is based on continued AMD production at the present rate and is (an estimate) used only to put into perspective the vast potential quantity of AMD remaining to be produced at the site. The actual time which will be required to produce all this potential AMD will be much longer since the production rate is expected to decrease with time (the thermal data indicate this is presently occurring)" (Lefebvre, 1996).

- Mineralogical studies produced a conceptual model of the mineralogical transformations of aluminosilicates under acidic conditions. Developing a good understanding of possible mineralogical transformations and associated geochemical reactions is particularly important for predictive modeling of AMD in waste rock;
- The researchers used an empirical approach to develop correlation equations for predicting the levels of acidity, aluminum, iron (total), magnesium, and sulphate based on measurements of total dissolved solids (TDS) and/or conductivity. This empirical method allowed them to reduce chemical analyses requirements and costs; however the correlation's developed rely on measurement of TDS and/or conductivity and therefore cannot be extended to predict future water quality;
- Physical modeling using the TOUGH AMD model developed for this site showed the model recreated some of the described trends for air circulation in the heap, and could be used to examine the effects of changes in parameters, with some success.

7.7 Future Studies and Associated Costs

7.7.1 Field and Laboratory Studies

The following field and lab studies were proposed by the researchers in the overview document "Monitoring and Modeling of Acid Mine Drainage from Waste Rock Dumps. La Mine Doyon Case Study" (GREGI, 1994-12, Section 7.5.7):

- Further study of water infiltration in a coarse heterogeneous porous media;

- Further study of mass transport in the unsaturated zone;
- Further study of leachate geochemical behavior, i.e. interaction with rocks and mineral precipitation;
- More site characterization with integrated monitoring and modeling programs;
- Developing methods to better characterize permeability (e.g. water infiltration and gas convection); and
- Characterize changes in physical properties of waste rocks with time, especially effect of mineral precipitation on permeability.

From our review of all of the documents describing studies conducted at this site, we can conclude that there is currently enough data to attempt all of the above, and then to reassess if more field/lab studies are really required. Therefore, the associated costs for these future studies would represent labor costs for additional assessment of the existing data.

With respect to infiltration estimates, the authors note that *"important issues such as seepage velocity, or the average residence time in the dump cannot be analyzed with the present data"* (GREGI, 1994-12, p. 4-35). They recommend controlled infiltration tests using simulated rainfall and field tracer tests and special sampling techniques for the unsaturated zone (neutron probes, suction lysimeters). Considering that the lysimeters are already in place, the proposed field program would likely provide some interesting information; however, a range of seepage velocities could be estimated from monthly infiltration flows, and the average residence time could be characterized using a distribution based on the range of estimates prepared for characterizing water storage in the heap. The authors also state that evaporation should be evaluated using energy balance and mass transfer technique (turbulent transfer of water vapor by eddy motion); in our opinion, the heat (temperature) and gas studies conducted on the dump should have provided enough data for (preliminary) evaluations of evaporation. Therefore these additional studies would represent at most two to three weeks of technical time.

7.7.2 Technical Assessments of Existing Data

In our opinion, the amount and quality of the data and information available from the studies conducted at Mine Doyon is extensive and impressive. It should be noted that our technical critique did not consider that there may have been time and possibly budgetary constraints that could have significantly influenced the scope and direction of the research programs, and possibly restricted the researchers' ability to complete their tasks of assessment and integration of this vast amount of information, before submission of the documents. This aspect probably explains most of the preceding comments from our detailed technical critique of these studies. Therefore, our recommendations for further studies are primarily for additional technical assessment of the existing database. We consider it appropriate to provide the original researchers with the opportunity to complete their assessment of the site. There has been the benefit of time (i.e. retrospect) for reconsidering the data and information collected from the studies, and there is now a detailed peer review (critique) of the studies at Mine Doyon that provides additional insight (and some hindsight).

We have identified several areas where additional technical assessment could be carried out to support AMD modeling: leaching or extraction tests; lysimeters; and buffering by aluminosilicates.

Leaching/Extraction Tests

The leaching test work conducted with drilling samples appears to be fast and easy to apply to a large number of samples (i.e. it was carried out on 150 samples), and would be useful to characterize porewater/rock samples at other sites; however some additional interpretation is required to support use of this information in AMD prediction/modeling. The water quality data obtained from resuspension of the precipitates formed on the rock samples from air drilling is not exactly porewater quality data, as some of the species may have actually been present as secondary mineral precipitates before drilling/sampling. Furthermore, the water quality data from extraction of borehole cuttings does not indicate which minerals/precipitates are present or the possible quantity of minerals/precipitates. The borehole samples (rocks) would need to be chemically analyzed and/or the mineralogy should be described using petrographic or XRD analyses to obtain this information. Therefore an additional assessment should be performed to:

(i) Compare extracted (resuspended) porewater quality to "real" porewater quality obtained using a pressure press (i.e. corresponding values from Tables 5.6 to 5.9 with Table 5.10, (GREGI 1994-12); and

(ii) Compare the corresponding rock analyses of the borehole samples and extractant water quality at various locations/depths in the heap (this could include use of chemical speciation models such as MINTEQ or PHREEQE).

The data already exists; therefore this additional assessment would represent minimal additional effort and cost, perhaps two to three weeks of technical time.

Lysimeter Study

The reports provide some initial data from the field lysimeters (i.e. from 11 August 1992 to 7 July 1993). Assuming that they have continued to monitor the lysimeters on a regular basis, an in-depth assessment of the lysimeter information should be carried out to:

- Evaluate the operational performance associated with installation of sets of lysimeters at various levels in the heap;

- Examine the development of the (measured) water qualities in relation to the observed characteristics of the rocks (i.e. mineralogy, particle sizes, etc.); and

- Determine whether the results of the lysimeter studies can be extrapolated to estimate the possible extent of AMD generation from the heap.

This additional assessment would require two to three weeks of technical time, assuming the lysimeters have continued to be monitored and that the available data is adequate for such an in-depth assessment.

Buffering Provided by Aluminosilicates

Future work to evaluate the neutralization potential and possible water quality impact of the aluminosilicates would be very worthwhile. Such experiments could determine when the neutralization actually begins, as well as the rate at which these minerals can dissolve to provide buffering. Studies from the published literature describe the kinetic dissolution rates of some of these minerals (e.g. sericite, biotite) and the dependence on pH, but the mineral form and therefore the reactivity of aluminosilicates tends to be somewhat site-specific. Any experimental methods or testwork developed to evaluate the possible ranges of weathering and neutralization provided by aluminosilicates would be applicable to other sites and very useful for predicting AMD.

Lefebvre (1996) indicates that some of the above areas for further work identified from this peer review may be addressed by a Ph.D. study being carried out on *"the geochemistry of the dump, including geochemical modeling, a further assessment of the composition of extracted pore water as well as samples from the gravity lysimeteres (the ones discussed in the reports) plus suction lysimeters (more recent installations not discussed in the reports)"*.

7.7.3 Further Model Development

The authors' recommendations for further work (Section 7.5.7 GREGI, 1994-12) are primarily oriented towards better characterization of the physical processes determining AMD. The new information would likely be used to refine the TOUGH AMD model which is primarily a physical model. In our opinion, extensive refinements are not necessary as the model has already been shown to be useful for examining the physical effects of various cover options. In our view, the most significant information that could be incorporated into their model is already available from the mineralogical, geochemical and water quality studies performed at this site.

Based on our review of their modeling work presented in the overview document (GREGI, 1994-12), the following steps could be taken to improve the capabilities of the current (physical) TOUGH AMD model:

1. Examine and review boundary layer assignments or numerical methods, that resulted in the prediction of eddy formation inside the heap. This phenomenon has not been observed;

2. Develop an alternate model concept to the reaction core model for describing the reactive surface area of pyrite that considers the rock type, and the results of the physical weathering (hardness) studies, mineralogy studies and visual observations. The presence and creation of fine particles has been shown to have a significant effect on sulphide oxidation rate, moisture content, permeability, etc., and should be considered in their model;

3. Validate the model by comparing model predictions to field data.

Lefebvre (1996) considers that *"a refinement of the model grid near the surface would improve the representation of the exchanges (hear, gas and moisture) taking place at the surface"*, and additional capabilities could be easily implemented for the reaction core model; however, the capability to represent the effect of the creation of fine particles would be the most important. This particular capability is currently being developed for TOUGH2 by researchers (collaborators) at the Lawrence Berkeley National Laboratory. Lefebvre (1996) agrees with the need to further validate the TOUGH AMD model.

The following additional steps would be required if, at a future date, it should be decided that it would be useful to incorporate geochemical and mineralogical processes into the TOUGH AMD model:

- Determine the key controlling minerals and reactions and the limits on reactivity/solubility. This may require additional laboratory testwork designed to evaluate these reactions;

- The water quality (seepage, groundwater) at this site has been consistent for a long time, therefore, it should be relatively straightforward to characterize and simulate the effects of the controlling minerals;

- Incorporate algorithms for simple chemical speciation into the model or alternatively, assess whether the empirical approach used to develop correlation's for predicting water quality parameters based on TDS or conductivity can be used to predict other parameters based on the concentration of sulphate. These equations could then be added into their model to provide "approximate" water quality predictions for short-term simulations;

- Incorporate temperature and pH dependence for the expressions describing the kinetics of sulphide oxidation;

- Add new solid phases to the model: pyrite, precipitated sulphate minerals (e.g. gypsum and jarosite, possibly as single solid sulphate phase), and buffering minerals (e.g. sericite, muscovite and chlorite);

- Calibrate the model by comparing the modeling estimates of remaining pyrite, remaining sericite and precipitated sulphate minerals, to the measured levels from analyses of borehole and trench samples; predicted oxygen and temperature to levels measured in the field programs; and model predictions of porewater and seepage quality to measured values.

The above steps would improve the predictive capabilities of the TOUGH AMD model and would allow examination of possible changes in seepage quality resulting from various decommissioning options. The improved AMD model would need to be sufficiently versatile or rigorous to apply directly to other sites, although it would be most appropriate for use at sites with similar mineralogy (i.e. pyrite associated with sericite schists and no carbonates).

One of the principal researchers considers that the foremost *"improvement to the numerical made* (would be) *the addition of basic capabilities to represent leachate buffering and mineral precipitation"* (Lefebvre, 1996).

7.8 Summary

7.8.1 Overview

In conclusion, several different mechanistic, empirical and conceptual models have been developed and applied at Mine Doyon.

- Hydrological modeling was carried out and used to prepare a detailed water balance for the heap. This work provided several estimates required for predictive AMD modeling;

- A conceptual model of air circulation in the south waste dump was developed based on field data (temperature, gas profiles). This was refined through detailed thermal modeling and physical modeling of the heap. The thermal models developed for this site can provide a definition of the transport parameters that can be used in subsequent AMD modeling; although these parameters should be verified by other methods before use;

- Prediction estimates based on (i) heat balance and (ii) sulphate and iron mass balances, both indicated the current AMD situation could persist for the next 100 years. The use of two independent methods provided more confidence in their average estimate of approximately 100 years although the mass balance approach did not allow for consideration of stored acidity within the dump. The mass balance method is simple and could be applied at other sites;

however, the calculation procedure for the heat balance is not simple and requires an extensive temperature monitoring program to estimate heat parameters;

- The researchers used an empirical approach to develop correlation equations for predicting the levels of acidity, aluminum, iron (total), magnesium, and sulphate based on measurements of total dissolved solids (TDS) and/or conductivity. This empirical method allowed them to reduce chemical analyses requirements and costs; however the correlation's developed rely on measurement of TDS and/or conductivity and therefore cannot be extended to predict future water quality;

- Mineralogical studies produced a conceptual model for describing the mineralogical transformation of aluminosilicates and clearly demonstrated the importance of aluminosilicates in an acidic system. Developing a good understanding of possible mineralogical transformations and associated geochemical reactions is particularly important for predictive modeling of AMD in waste rock;

- Physical modeling using the TOUGH AMD model developed for this site showed the model recreated some of the described trends for air circulation in the heap, and could be used to examine the effects of changes in parameters, with some success;

- The TOUGH AMD model can be used to examine various cover options. Simulations of a border membrane showed the long-term sulphate concentrations are predicted to remain high. This result is expected due to slow release of sulphate stored within the heap as gypsum and jarosite.

All of the above efforts have provided a good understanding of the processes occurring in the heap and the possible extent of generation of acid mine drainage. These studies have indicated which management options are likely to be successful and have provided estimates for evaluating long-term treatment requirements. In our opinion, the studies at this site are essentially complete. Recommendations for further field studies have been discussed but we do not consider that additional data is required. Several additional technical assessments could be carried out using the available information.

7.8.2 TOUGH AMD Model

The following points summarize the TOUGH AMD model:

- Considers the physical processes of heat/temperature and oxygen transport/consumption in a waste rock heap;

- Estimates the pyrite reaction rate;

- Couples oxygen consumption (due to pyrite oxidation) and production of sulphate to an existing hydrological model TOUGH2;
- Considers water, oxygen, gas, and energy transport;
- Can employ either uniform physical conditions (e.g. porosity, particle size) or heterogeneous properties;
- Employs the shrinking reactive core model;
- Assumes uniform geometry for heap;
- Provides gas velocity, oxygen flux, oxidation rates, heat flux, water flux sulphate flux at various locations inside the heap;
- Can be used for theoretical studies; and
- Can be used to examine the effects of placement of a cover (and other mitigation measures) on the heap.

The following points summarize our critique of the TOUGH AMD model.

- It is a physical model, no geochemical processes are considered;
- An extensive field program (temperature, oxygen measurements) is required to characterize conditions at numerous locations within the heap;
- There are several inherent problems with their conceptual approach:
    - assumes uniform-sized spherical particles which may not be realistic for waste rock;
    - pyrite is "free" and completely oxidizable;
    - particles remain same size;
    - weathering (creation of more fine particles) is not considered;
    - oxygen is the only oxidant;
    - the reaction rate is independent of pH and aqueous ions;
    - temperature effects are oversimplified;
    - bacterial activity is not considered;
    - chemical speciation is not included;
    - several important input parameters are not adequately defined;

- the equations describing the theoretical basis have several problems with dimensions/units; and,
- there is an obvious problem with the boundary layer assignment or numerical method (i.e. prediction of eddy currents is not realistic);

- The model has not yet been fully validated by comparison of predictions to measured field data.

The following points summarize our recommendations for improving the capabilities of the current (physical) TOUGH AMD model.

- Examine and review boundary layer assignments or numerical methods, that resulted in the prediction of eddy formation inside the heap. This phenomenon has not been observed;
- Develop an alternate model concept to the reaction core model for describing the reactive surface area of pyrite that considers the rock type, and the results of the physical weathering (hardness) studies, mineralogy studies and visual observations. The presence and creation of fine particles has been shown to have a significant effect on sulphide oxidation rate, moisture content, permeability, etc., and should be considered in their model;
- Validate the model by comparing model predictions to field data.

We have also provided recommendations regarding steps that could be taken to incorporate geochemical and mineralogical processes into the TOUGH AMD model.

7.9 References

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8. CONCLUSIONS

The overall conclusion of the peer review with respect to the technical approaches used to investigate and analyze the Mine Doyon south dump is that state-of-the-art and innovative techniques were used and that the Mine Doyon case study has advanced our understanding of some specific technical issues. In addition the work carried out represents a thorough and exceptionally well documented case study.

The overall conclusion of the peer review with respect to presentation and technical detail is that the ten MEND reports contain a number of inconsistencies and errors which should be corrected so that the reports represent a more accurate record of the Mine Doyon study. Budget and time constraints have apparently contributed to the above situation.

Specific conclusions related to the five technical components (Hydrology, Geotechnology and Hydrogeology, Geochemistry, Microbiology and Predictive Modeling) identified for the peer review are given in the summary at the end of Chapters 3.0, 4.0, 5.0, 6.0 and 7.0 respectively.