48 Months (Phase II)
PROGRESS REPORT
Final Version (abridged)

Prepared by:
Michel Aubertin and Bruno Bussière

In collaboration with
Mostafa Benzaazoua, Mamert Mbonimpa, and Gérald J. Zagury

Industrial NSERC Polytechnique-UQAT Chair
Environment and Mine Wastes Management

Chaire industrielle CRSNG Polytechnique-UQAT
Environnement et gestion des rejets miniers

http://www.enviro-geremi.polymtl.ca/

June 2010
## Table of Contents

Preamble

1- Progress towards Objectives ........................................ 1
2- Research Team ...................................................... 10
3- Training ............................................................... 11
4- Collaboration with Industrial Partners and Other Sponsors ...... 12
5- Other Collaborations .................................................. 13
6- Change in University Research Capability .......................... 14
7- Dissemination .......................................................... 15

Appendix 1 – List of Publications (2006-2010)
Preambule

This progress report, which has been approved by the Chair’s participants, presents the main elements of the work conducted by the Industrial NSERC Polytechnique-UQAT Chair over the last four years or so, i.e. since the beginning of Phase II. The Chair’s research program includes 8 projects as part of its second mandate.

The work performed during Phase I of the Chair (June 2001 to May 2006) is described in a progress report submitted to NSERC in May 2005; the proposal for Phase II, with the detailed research program, was also presented at the same time. A progress report was also produced in May 2008, 24 months into Phase II.

In addition to the mandatory progress reports presented to NSERC, the Chair issues summary reports twice a year to provide updates on the most recent accomplishments. These reports are discussed with the Chair’s Partners during the meetings of the Scientific and Orientation Committees. The summary reports are written alternatively in French (Fall) and English (Spring). Once approved by the Committees, the reports are placed on the Chair’s web site, in the restricted area. Minutes of past Committee meetings are also available in the protected area of the web site.

Additional information on this report and on other matters related to the Chair can be obtained by contacting the Chairholders directly:

Michel Aubertin, ing., Ph.D.
Professor, Chairholder
Dept. CGM, École Polytechnique
Campus Université de Montréal
C.P. 6079, Station Centre-Ville
(2900, Édouard-Montpetit)
Montréal (Québec) H3C 3A7
Tel.: 514-340-4711, ext. 4046
Fax: 514-340-4477
michel.aubertin@polymtl.ca

Bruno Bussière, ing., Ph.D.
Professor, Associate Chair
Université du Québec en Abitibi-Témiscamingue
UER Sciences appliquées
445, boul. de l’Université
Rouyn-Noranda (Québec) J9X 5E4
Tel.: 819-762-0971, ext. 2531
Fax: 819-797-4727
bruno.bussiere@uqat.ca
In addition to NSERC, the authors of this report would like to acknowledge the Partners of the Chair (Phase II) for their support.

www.polymtl.ca/enviro-geremi
1- Progress towards Objectives

Mining activities generate a variety of waste products that must be managed safely to protect the environment. In this regard, special attention must be paid to the hydrogeotechnical and hydrogeochemical behaviour of mine wastes, particularly when they are reactive and prone to generate acid mine drainage (AMD) or contaminated neutral drainage (CND). The mandate of the Industrial NSERC Polytechnique-UQAT Chair is to investigate issues related to the environment and mine waste management. The research work aims at developing tools and techniques that lead to improved practices for solid and liquid waste disposal. The main materials being investigated include waste rock from the mine, tailings produced by the mill, liquid effluents, and sludge generated by the water treatment plant.

The research program of the Chair for Phase II includes 8 interrelated projects. This program was initially planned for five years (2006-2011), but an extension was officially granted so that the work of the Chair could go on until the end of 2012, without additional funding from NSERC or from the Industrial Partners. The studies are mainly conducted by highly qualified personnel (HQP) being trained through the Chair’s program (see section on Training); the individual research programs of the HQP often encompass more than one of the 8 projects. The following section briefly summarizes the objectives and progresses made over the last four years; some of the most representative papers, reports, and thesis [with numbers related to the list presented in Appendix A] are also identified before each sub-project. The main participants are also presented (in addition to the Chairholders). The report provides additional comments on the significance and benefits of the research work.

Project 1: Improved surface disposal of tailings

Tailings produced from the milling of extracted ore are made of finely ground rock flour with a large surface area and water content. The classical methods for disposal of tailings as a slurry may raise some geotechnical and geochemical issues, particularly when they contain reactive minerals. This important project addresses various specific problems related to the physical and chemical stability of tailings and of their retaining structures. The project also includes components on the desulphurisation of tailings at the mill and on the behaviour of paste tailings, which are considered as promising new means for better management of milling wastes. The main progresses have been in the following areas:

A- Predictive methods for hydrogeological properties [20, 189, 192, 193]: Extensions of the modified Kovács (MK) model, initially developed to predict the water retention curve (WRC) of stiff soils and tailings, have been formulated to describe (and in some cases predict): i) the WRC of compressible materials using the volumetric shrinkage curve (VSC), ii) the unsaturated hydraulic conductivity function from the WRC, iii) the hysteresis of the WRC of granular soils. The MK model parameters have also been related to those of well-known descriptive models (i.e. Brooks and Corey; van Genuchten; Fredlund and Xing) for granular soils (sand and silts, which include tailings). Additional work is underway to refine the testing procedure and interpretation method for assessing shrinkage (with or without cracking) of fine grained materials (including tailings and clayey soils). This work will be completed within the next year, but some additional improvements may still be needed afterwards.

B- Water budget and deep infiltration [16, 20]: The research conducted on the response of paste (dewatered) tailings under a relatively hot and dry climate includes an investigation of surface fluxes. This study is being conducted with physical models (instrumented columns) combined with material characterisation, and numerical simulations performed with the VADOSE/W and SIGMA/W (Geoslope inc.) models (see Project 6). This work also involves studying volume
changes through consolidation testing and under suction-induced shrinkage (see component A). This study is complementary to another study on the hydrogeochemical response of paste tailings under a variety of conditions, with and without cement (see component E). The actual water budget is also being assessed for 2 mine sites in Abitibi (under a relatively humid climate), which are being investigated for optimising their reclamation using numerical and laboratory physical models. A good understanding of water movement is a critical parameter for mine site reclamation, especially when an elevated water table technique is used in the reclamation scheme (see Projects 6 and 7). This component of the research will extend to the end of Phase II.

C- Mechanical/physical stability [11, 12, 57, Master thesis of N. Pépin, PhD thesis of M. James]: An investigation is conducted on the liquefaction potential of mine tailings and on related control measures that can be used to minimise the associated risks. This work comprises shaking tests on a seismic table, cyclic tests on small scale samples, a piezocone field investigation, and numerical simulations of various scenarios that include the geotechnical influence of reinforcement and draining columns made of waste rock. Most of the work on this topic is completed, but complementary work (related to modelling of shaking table tests and of consolidation) is still underway.

D- Environmental desulphurization [78, 87, Report of V. Derycke]: Different materials that could benefit from a desulphurization stage before their disposal are presently investigated. The concentrate of a mine (which contains a coarse grained pyrite) and a tailing that contain arsenopyrite are being tested; the objective is to reduce the environmental impact by concentrating problematic minerals. In addition to improving our knowledge of the flotation of coarse-grained pyritic materials and of arsenopyrite, this study involves the development of criteria (in term of sulphide recovery) to characterize non problematic fractions (i.e. tailings that are non acid generating or not producing contaminated neutral drainage). Another component focuses on using desulfurized tailings as a cover material to be placed on reactive tailings with an elevated water table (see Project 5), which has been shown to be a promising approach. The environmental and mechanical impact of using the sulphide concentrate from the desulphurization process in cemented paste backfill was also investigated. The remaining parts of this study will continue until the end of Phase II.

E- Thickened and paste tailings [19, 88, 135, PhD thesis of T. Deschamps]: This study focuses on the hydrogeochemical and geotechnical behaviour of surface paste tailings. It includes an assessment of consolidation, evaporation, and desiccation. Column tests were also installed to evaluate the evolution of the paste geotechnical properties and to study the influence of different deposition scenarios on these properties. A series of columns containing uncedmented and cemented sulphidic paste tailings (homogeneous or with cemented layers) were used to assess the response of sulphide surface paste tailings to wetting (flushing) cycles. The results indicated that using cemented layers constitutes a very promising approach to limit AMD production, at least in the short term. An intermediate-scale physical model (200x100x50cm) is also used to further investigate the long term hydrogeochemical behaviour of surface paste tailings. Results obtained were compared to hydrogeochemical numerical modelling (see Project 6) using a code that combines fractured and porous media. In parallel, 2 experimental cells (uncemented and partly cemented) are presently under construction at the Laronde mine to further validate the laboratory and modelling results. This project will continue until the end of Phase II.

Participants: In addition to the 2 Chairholders (who participate in all projects), the people involved in this project are: V. Martin, T. Deschamps, M. Gosselin, I. Hadimi, M. James, N. Pepin, H. Guimont, T. Pabst, F. Saleh, M. Jaouhar, F. Prétot, V. Derycke (graduate students); L. Li, A. Maqsoud, K. Koffi (researchers and pdf); M. Benzaazoua, M. Mbonimpa (UQAT), R. P.
Project 2: Optimizing surface disposal of waste rock

Waste rock piles can occupy a large surface area. Such piles can have a significant impact on mine water quality, especially when they contain chemically reactive minerals. The geotechnical stability of piles can also be a source of concern. This relatively large project aims at developing methods for the characterisation of waste rock piles (in the lab and in situ) and developing models that can be used to assess their response. Another objective is to propose alternative disposal methods that would minimise their environmental impact. The main areas of progress have been in the following sub-themes:

A- Field characterisation with hydrogeological and geophysical methods [1, 5, 62, Master theses of O. Anterrieu and R. Intissar]: Extensive field investigations have been conducted on two existing waste rock piles located in the province of Quebec: one from an underground mine and one on a large size waste rock piles from an open pit mine. The hydro-geophysical techniques developed during Phase I and the early part of Phase II on the smaller (acid-generating) waste rock pile have been modified to integrate the impact of the larger size of the dumps and the different mineralogy of the waste rock (the second pile is non-acid generating). Infiltration and other in situ characterization tests have been conducted, and others are planned for this summer to finalize the field portion of this investigation. The interpretation of the data will be done in the months following the field tests using analytical and numerical techniques (Part C). The study also includes laboratory testing of waste rock samples (see component B). The work, which is related to Project 6, will continue until the end of Phase II.

B- Laboratory testing and predictive methods [54, 73, 95, Master thesis of M.A. Hernandez]: This part focuses on the measurement of hydrogeological and geophysical properties in large size columns. Saturated and unsaturated conditions are considered in the many tests conducted or in progress. Migration of fine particles into waste rocks and localised flow have been identified as a potentially important factor that may affect hydrogeological tests results obtained from the lab tests. Predictive models for saturated hydraulic conductivity $k_{sat}$ and the water retention curve WRC are being modified, so that they better represent the behaviour of waste rocks that have widely distributed grain size curves. These properties serve as input for the numerical simulations (component C). The laboratory testing and predictive model development will last until the end of Phase II.

C- Hydrogeological modelling [30, 148, PhD thesis of B. Lahmira]: A series of numerical simulations have been conducted with Hydrus-2D to simulate the unsaturated behaviour of waste rock piles (based on actual cases property of our industrial partners). The modelling work (see also Project 6 for the hydro-geochemical component) includes parametric analyses to interpret field tests and to investigate the effect of material properties (with deterministic and stochastic values), pile’s internal structure and geometry, boundary (climatic) conditions, and alternative construction methods. Another investigation has been performed with the code TOUGH-AMD to assess fluid (water and air) movement through waste rock piles with temperature and density gradients. The modelling work is expected to continue until the end of Phase II.

D- Modified disposal approaches [89, 179, 184]: This component focuses on two aspects. The first is investigating (using numerical methods) actual and alternative pile configurations and construction methods in order to assess (and minimize) the risk of producing contaminated leachates (AMD or DNC). The second aspect focuses on the use of waste rock inclusions
(isolated heaps and continuous fills) within impoundments to promote consolidation and higher liquefaction resistance of tailings; this aspect is investigated with numerical and physical (shaking table) modelling (see Project 1- component C and Project 5). The work related to this component will continue until the end of Phase II.


Project 3: Disposal in mine openings

The use of backfill has become an important component of mining operations, favoured in recent years by the development and general use of cemented paste backfill (CPB). The effect of backfill on the environment must, however, be assessed to make sure that returning mine wastes to underground mine openings is safe and environmentally sound. The main progress has been in the following areas:

A- Open pit backfilling [22, 125; PhD thesis of F. Ben Abdelghani]: This investigation, which is complementary to Project 7 (water covers) and Project 6 (water quality), includes a series of numerical analyses to evaluate the response of open pits filled with tailings or waste rocks. The simulations, conducted with the code Hydrogeosphere, have been used to analyse the flow of water and contaminants around pits, in fractured rock masses with various characteristics. Additional work was done to develop modelling tools to assess reactive transport in fractured media. This sub-theme is ending in 2010. The underwater storage of highly sulphidic tailings in open pits is also being investigated (see Project 7).

B- Behaviour of backfill in underground stopes [13, 42, 44, 45, 70; PhD thesis of E. Yilmaz]: Part of this work focuses on the hydrogeotechnical properties of laboratory CPB samples (consolidated and unconsolidated) prepared with the recently developed CUAPS (Curing Under Applied Pressure System) cell and in conventional moulds. The lab test results are used to evaluate the evolution of CPB properties (k<sub>sat</sub>, air permeability, WRC, consolidation parameters, microstructural properties, etc.) with curing; this aspect is crucial to predict the short and long term behaviour of CPB in underground stopes. Another part of the study addresses gravitational consolidation (self-weight) of cemented paste backfill using large size column tests under various conditions (fully-drained, half-drained, and undrained). This work is complemented by a series of simulations performed with FLAC and Sigma/W to evaluate the stress and strain distribution and pore water pressure in backfilled stopes under a variety of situations and for different backfill properties. Analytical solutions were also developed to assess the state in backfilled stopes and the total and effective stresses on barricades. This component of Project 3 is expected to continue until the end of Phase II.

C- Geochemical and environmental behaviour of cemented paste backfill [10, 58, 59, 197; Master thesis of E. Fried]: A study is underway to assess the risks of chemical instability of cemented paste backfill and hydraulic backfill due to the oxidation of sulphidic minerals (using lab and field measurements), which can lead to serious consequences (due in part to the exothermic oxidation reactions). The project also includes an investigation of metal stabilization in arsenic rich cemented paste backfill using various kinetic tests (namely humidity cell, monolith leaching test, selective dissolution tests) and geochemical modelling. The influence of other parameters such as sulphate concentration and presence of phyllosilicate minerals on the
chemical and mechanical behaviour of CPBs has also being investigated. This work, which is closely related to Project 3B, is expected to continue until the end of Phase II.


Project 4: Properties of AMD treatment sludge

The most common method for controlling acid mine drainage (AMD) during mine operation is chemical treatment by neutralisation with lime, followed by precipitation of metals and solid-liquid separation. The sludge produced by treatment plants must be disposed of and stored in a secure manner. The behaviour of treatment sludge is, however, poorly understood. The main objective of this relatively small project is to use new measurement methods (developed during Phase I and early Phase II) to characterize the hydromechanical behaviour of sludge during the sedimentation and consolidation stages. The results are being used to simulate sludge behaviour over time, and to assess various disposal schemes. Progress is being made in the following areas:

A- Characterisation of various sludges [114,198]: Laboratory testing of sludge has been conducted to determine their sedimentation and consolidation properties. An improved experimental set up (instrumented column) was designed and used to measure the targeted properties of sludge and modified (amended) sludge. These results are used to develop models for the numerical simulations (component B). The testing part of the project has been completed; the results are being interpreted using numerical tools.

B- Design methods for disposal areas: Simulations are being conducted to analyse the column tests results (produced in A), to assess current disposal methods, and to develop new deposition schemes. The model relies on properties obtained from the laboratory measurements. The numerical analyses, mainly conducted with Sigma/W, will continue until the end of 2010.

Participants: L. Pedroni (graduate student); Greg Kennedy (EPM) (researcher).

Project 5: Use of wastes on mine sites

Improved approaches are being used by mines to reduce, recover, recycle and re-use the wastes produced on the site. This helps to minimise the amount of waste products and reduces the impact of the mine operation. The objective of this project is to explore various means to valorize mine wastes. The main areas of progress are:

A- Use of low sulphide tailings as cover material [18, 33, 86; PhD thesis of I. Demers]: This work evaluates the performance of mono- and multi-layered covers made of low-sulphide tailings as oxygen barriers (see also Project 7). A series of column tests with different configurations were performed (some are still in operation) in the laboratory on fresh or already oxidized tailings from two mines. The main parameters being studied include cover thickness and material hydrogeological properties, sulphide content in the cover material, effect of covering preoxidized tailings, and the position of the phreatic surface (water table). Water quality of the percolated waters from the different columns was followed along with oxygen concentrations over the thickness of the cover. From these results, the performance of covers is evaluated. Modelling work, performed with VADOSE and MIN3P (see Projects 6 and 7), is also being conducted to complement the testing program. The results confirm that low sulphide tailings with an elevated water table can be efficient in reducing AMD from fresh tailings, and
that indirect oxidation has a significant impact on cover performance when covering pre-
oxidized tailings. This project will end in 2011.

**B- Co-disposal of waste rock in impoundments** [12, 41, 187; PhD thesis of M. James]: Some of
the work mentioned above (in Projects 1 and 2) refer to the placement of waste rock inclusions
(as heaps and continuous fills) into tailings impoundments in order to add reinforcement
elements and to favour drainage and consolidation of the tailings. When the coarse-grained
waste rocks are acid generating, this approach also helps control water flow and oxygen
availability (to prevent AMD). The concept is studied here using lab and field data and
numerical modelling (using the FLAC and Sigma/W codes). In parallel, the effect of waste rock
inclusions on the consolidation of tailings is also being assessed with analytical solutions. This
project will continue until the end of 2012.

**Participants**: I. Demers, I. Doumbouya, M. Rousselle, M. James, M. El Jaouar, F. Prétot, N.
Pepin, H. Guimont, T. Pabst, R. Toussaint, C. Reid (undergraduate and graduate students); M.
Benzaazoua, M. Mbonimpa (UQAT), L. Deschênes and R. Chapuis (EPM), G. W. Wilson
(UBC) (collaborator).

**Project 6: Water quality prediction**

To meet environmental standards, mine effluents must contain low contaminant
concentrations and satisfy component-specific or bulk toxicity tests. This important project,
which is at core of the Chair’s program, aims to improve the experimental procedures for
conducting characterisation and predictive tests. Another key goal is to develop mathematical
tools for the prediction and modelling of the hydrogeochemical response of mining wastes. This
project is closely related to many others (particularly Projects 1, 2, 3, 5, and 7). The main areas
of progress are:

**A- Mine waste characterisation** [60, 79, 140, 161; DEA report of H. Bouzhazha]: A new
approach has been developed based on a computer program (SEM-XMAP) that combines X-ray
dot mapping images acquired by SEM to identify and quantify cementitious phases in cemented
paste backfill (CPB). In parallel, ATD-ATG was also used (and a database was developed) to
characterized the same phases. Selective dissolution tests were used to better characterize the
metal stabilization process in CPB. The use of multispectral image analysis with optic
microscopy was also investigated as an automatic means to quantify the mineralogy of mine
wastes. Different sorption tests were used to evaluate the sorption potential of mine wastes with
a CND potential. Additional work is also being performed to isolate the reaction rate parameters
in sulphidic wastes (in normal and cold conditions), and to obtain other hydrogeochemical
properties of tailings from various mine sites using techniques that were partly or totally
developed by the Chair. The lab and some field work will continue until the end of Phase II.

**B- Prediction of acid mine drainage (AMD)** [6, 69, 94, 144; Master thesis of M. Gosselin]: A
project was dedicated to the modification of standard kinetic tests to obtain more reliable results.
A new humidity cell set-up has been proposed which integrates oxygen consumption and water
content measurements. A statistical analysis of column test results was also performed; the
results indicate that a good reproducibility can be achieved when a good set-up methodology and
rigorous control of the boundary conditions are used for the column tests. A comparison of
interpretation methods to assess the long term AMD potential of low sulphide tailings has also
been presented. This study showed that the method proposed in the ASTM standard (humidity
cell test) often tends to overestimate the neutralisation potential. Also, numerical and semi-
analytical solutions have been developed to predict gas flux and oxygen consumption through
partially saturated soils and tailings. This part of the project finally includes the development of
modelling tools for assessing the effect of various disposal scenarios and reclamation techniques (see also component D). This work will continue until the end of Phase II.

C- Prediction of contaminated neutral drainage (CND) [7, 8, 80, 115, 116; Master thesis of G. Pepin, PhD thesis of B. Plante]: Work is being done to better understand the geochemical mechanisms that explain Ni release and to assess the influence of adsorption on the behaviour and generation of CND, using waste rock samples and pure minerals from a mine located in eastern Québec. Also, comparisons are being made for geochemical results from laboratory kinetic tests and in situ experimental cells, to assess, among other factors, the influence of scale. This component also involves kinetic tests (columns and weathering cells) to evaluate the CND generation potential of different rock types from a Nordic mine under normal and cold conditions. The lab and field work aims at understanding the mechanisms related to the generation of CND, and at developing predictive tools, which will serve to modify waste rock the management practices (see also Project 2). This work will continue until the end of Phase II.

D- Numerical modelling of hydro-geochemical processes [56, 103, 156, 195, 196]: Water flow and geochemical reactions in mine wastes are the key components of numerical models that simulate the hydrogeochemical behaviour of mine wastes. The existing MIN3P model (developed by U. Mayer, Waterloo-UBC) has been applied (with some modifications) to simulate laboratory columns tests on reactive tailings with an elevated water table and to model field conditions that include mono- and multi-layer covers (see Project 7). Other developments are underway to improve the available modelling tools for CND generating waste rock (which include a sorption component; results from component C will be used for that purpose), and to simulate the hydrogeochemical response of fractured porous media. This work will also continue until the end of Phase II.


Project 7: Evaluation of cover systems

Approaches to limit the generation of AMD from sulphidic mine wastes generally focus on eliminating one (or more) of the three main components of the acidification reactions: oxygen (air), water, and the sulphide minerals themselves. The most common technologies involve the use of soil or water covers placed over the reactive wastes. This project investigates the behaviour of various types of cover systems. Progress in this theme has been made in the following areas:

A- Single-layer covers and elevated water-table [4, 17, 18, 159; PhD thesis of M. Ouangrawa; Master thesis of G. Cosset]: The first component of this study aim at evaluating the efficiency of single-layer covers to limit the AMD generation from already oxidized tailings (using samples from the two mine sites). Small and large columns have been installed with different configurations; some use natural soils while others used low sulphide tailings for the covers (see also Project 5). Wetting and drying cycles with measurements of oxygen concentration, water content and suction are performed to analyse the hydrogeochemical behaviour of the different tailings-cover systems. A comparison between these results and in situ measurements is also included. Another component of this sub-project consists of evaluating the use of the elevated water-table technique with column tests and numerical simulations to develop a predictive
approach to assess the efficiency of the combined techniques under different situations. Part of this project will continue until the end of Phase II.

B- Multi-layer covers with capillary barrier effects (CCBEs) [15, 21, 23, 28, 67, 102, 130, 167; Master thesis of F. Cissokho]: The performance of inclined CCBEs to limit water infiltration or $O_2$ migration was evaluated using numerical modelling of water flow (and oxygen migration) through flat and inclined CCBEs and direct measurements within an actual layered cover on a mine site. The impact of different factors on cover performance was investigated with numerical modelling and (in one case) in situ measurements, including: inclination, length, material properties, and presence of a suction break. A geophysical investigation was also performed in situ to assess the distribution of moisture (water content) in an existing CCBE. An investigation on passive and active direct measurement methods for oxygen concentration was also conducted. A methodology to characterize the evolution of vegetation on CCBEs was developed and applied to another mine site. In parallel, 120 small in situ test plots (3m x 3m) have been constructed in 2008 to investigate natural bio-intrusion barriers. This part of the project aims at evaluating the capacity of allelopathic plants (which can inhibit germination and growth of a certain species of plant) to limit long term degradation of CCBE caused by tree-roots invasion. This sub-project will continue until the end of phase II.

C- Water covers [100]: The performance of a water cover placed over highly reactive tailings (submerged pit) is being investigated; this study involves both laboratory and field tests on an existing site. Different scenarios are simulated in the lab using tailings that contain > 85% pyrite: stagnant water cover, fully aerated water cover, fully aerated water cover without resuspension, and fully aerated water cover with 10 cm of sand on the tailings. Another aspect of this work relates to water seepage modelling (saturated and unsaturated) and contaminants transport for rock wastes and tailings disposed in mine openings (pits and stopes) in fractured rocks (see Project 6). This component will continue until the end of Phase II.

Participants: M. Ouangrawa, F.B. Abdelghani, M. Gosselin, J. Hamdi, A. S. Awoh, T. Pabst, R. Toussaint, L. Saavedra, G. Cosset, I. Demers, F. Cissokho (undergraduate and graduate students); E. Smirnova (pdf), A. Maqsoud (researchers); R. Simon, R. P. Chapuis and M. Chouteau (EPM), M. Benzaazoua, Y. Bergeron, F. Tremblay, and M. Mbonimpa (UQAT), N. Thiffault (MRNF), R. Therrien and J. Molson (ULaval) (collaborators).

Project 8: Passive treatment systems

Passive methods for AMD treatment can offer several potential advantages such as a high efficiency for metal removal at low pH, improved sludge characteristics, lower operation and maintenance costs, reduced use of chemicals, and minimal energy consumption. This project focuses on passive bioreactors and calcareous drains. The main areas of progress have been in the following sub-themes:

A- Passive bioreactors [105-111, 158; PhD thesis of C. Neculita]: This project investigates passive treatment systems made with biofilters. The study included laboratory investigations on reactive mixtures used in passive biological reactors. The focus has been placed on a better understanding of metal removal mechanisms, ecotoxicity of treated effluents, and long term efficiency of treatment systems in the particular case of highly contaminated AMD. Biofilters can improve significantly water quality, but high concentrations of iron can reduce the system ability to treat highly contaminated AMD (especially when iron concentrations >3000 mg/L). The use of multi-stage treatment systems to solve this problem is presently investigated; an in situ pilot treatment system should be constructed before the end of Phase II. Also, additional
work on the treatment of CND (contaminated with Ni and/or As) using passive bioreactors is underway; it will continue until the end of Phase II.

B- Limestone drains [28, 61, 91, 152; PhD thesis of R. Potvin; Master thesis of C. Poirier]: Limestone drains (LDs) simulated with an intermediate scale physical model in the lab were studied for two different scenarios (oxygenated and anoxic drains) and various residence times. Results showed that typical LDs cannot treat efficiently an effluent that is highly contaminated with soluble metals. One of the main problems is due to the presence of iron that tends to precipitate at the effluent, thus reducing the pH (typically from 6 to 3). Also, LDs are generally not efficient enough to reduce metal concentrations to the expected levels. Column tests were also performed to evaluate the impact of the mineralogy and grain size of the limestone, and of the AMD quality on the neutralization capacity. Finally, numerical modelling of the flow inside drains and in situ tracer tests have also been conducted to better understand the hydraulic behaviour of such systems. This sub-project is now completed.

Participants: R. Potvin, C. Poirier, C. Neculita, T. Genty, A. Z. Hamani (graduate students); A. Maqsoud (researcher); G.J. Zagury (EPM), M. Benzaazoua (UQAT), C. Neculita (now at KAIST, South Korea), B. Vigneault (CANMET), Yves Dudal (INRA, Montpellier, France) (collaborators).

The projects describe above shows that the Industrial NSERC Chair is working on a variety of issues that are important for the mining industry, which represents a vital component of the Canadian economy. The Chair’s research is providing new or improved tools and techniques for the characterisation, modelling, and evaluation of various mine wastes and their management and rehabilitation practices. The Chair is also very active in training highly qualified personnel (see next section), who become the much needed specialists that help the industry achieve its goals. In addition to its technical impact, it should also be recalled that the Chair (with its partners and collaborators) is actively contributing to the mining engineering program at the Ecole Polytechnique de Montréal (EPM) and at UQAT, and to the development of the Abitibi-Témiscamingue region (which depends mainly on natural resources). Because of the Chair, UQAT can now provide the local mining industry a unique expertise in mining environment and mine waste management, which helps to maintain its high level of competitiveness.
2- Research Team

As stated in the 24-month report, the creation of the Industrial Chair has provided a critical mass of professionals, working on a variety of interconnected topics. The Chair’s team has grown significantly since it was created in 2001. This expansion has lead to a diversity of expertise, which covers areas such as hydrogeology, geotechnique, geochemistry, geophysics, mineral processing, and biochemistry, with strong components in lab and field characterisation techniques and numerical modelling. The basic team is formed by the two Chair holders (M. Aubertin and B. Bussière) and the three main collaborators (Profs. G.J. Zagury, M. Mbonimpa, and M. Benzaazoua) who have co-authored this report. They are working closely with three Researchers (Dr J. Molson, L. Li are now with ULaval and Genivar respectively, and A. Maqsoud) and six Professors from Polytechnique (Robert P. Chapuis, Richard Simon, and Michel Chouteau) and UQAT (Tikou Belem, Yves Bergeron and Francine Tremblay). The descriptions of the 8 Projects presented above have also identified several external collaborators working for other research organisations. Many students are involved in the research program; they have also been identified above. A summary of the corresponding number of students per category is included in the next section, while a complete list appears in Appendix 2. The Industrial Partners of the Chair are identified below in Section 4.

The most significant contributions and accomplishments from the Chair’s main proponents during Phase I have been recalled in the 24 months report issued in 2008, together with rewards and prizes received. Additional recognitions have also been received since Phase II started. For instance, the CRC chairs of Bruno Bussière and Mostafa Benzaazoua has been renewed in 2008; these renewals were accompanied with two CFI grants (for a total of approximately 700k$). Mostafa Benzaazoua has been awarded, with Pr. Rachid Hakkou from Marrakech, of one of the 8 International Development Research Centre Chair (IDRC Chair on Management and Stabilization of Mining and Industrial Waste). Bruno Bussière was a member and then became Chair of the NSERC Grant Selection Committee for Civil Engineering (2008-2010). Michel Aubertin was a member of the NSERC Discovery Acceleration Supplement Committee (2008); he has been named President of the Canadian Geotechnical Society for 2009 and 2010. More details on these and other acknowledgements are given in the summary reports produced twice a year.
3- Training

The Chair has been attracting a fairly large number of students since it started. During Phase I, more than 60 graduate students and 12 undergraduate students worked on projects directly related to the Chair’s research program, significantly exceeding the original goal of 22 graduates. Since the beginning of Phase II, despite a context that does not currently favour recruitment (because the market-place offers so many attractive positions), 28 graduate students (i.e. 11 Ph.D., 15 Masters, and 2 PDF) have graduated and 31 are in training (i.e. 13 Ph.D., 9 Masters, 5 DESS, and 4 PDF). Undergraduate students are also actively involved in the research program (27 students which include 4 in progress). The initial goal was to train 12 Ph.D. and 14 Masters; it can thus be expected that the Chair will again exceed its original objectives in terms of HQP. At this point, it is estimated that approximately 25 % of the total funds provided to the students mentioned here can be linked to other sources (such as FQRNT, CRD, research contracts, student grants, etc.). The following table summarizes the state of HQP training.

<table>
<thead>
<tr>
<th>Type of Trainee</th>
<th>Number</th>
<th>% time spent on projects</th>
</tr>
</thead>
<tbody>
<tr>
<td>Undergraduate students</td>
<td>27</td>
<td>100%</td>
</tr>
<tr>
<td>DESS/DEA</td>
<td>5</td>
<td>100%</td>
</tr>
<tr>
<td>Master’s students</td>
<td>24</td>
<td>16 at 100% &amp; 8 at 50%</td>
</tr>
<tr>
<td>Doctoral students</td>
<td>24</td>
<td>20 at 100% and 4 at 50%</td>
</tr>
<tr>
<td>Postdoctoral Fellows</td>
<td>6</td>
<td>1 at 100%; 4 at 50%, 1 at 20%</td>
</tr>
<tr>
<td>Research Associates</td>
<td>4</td>
<td>2 at 100% and 2 at 50%</td>
</tr>
<tr>
<td>Technicians (partly paid by the Chair)</td>
<td>4</td>
<td>4 at 50%</td>
</tr>
<tr>
<td>(Secretary paid by universities)</td>
<td>2</td>
<td>25 %</td>
</tr>
</tbody>
</table>

Most students conduct their project in collaboration with one or more industrial partner(s). They also participate in the preparation of publications (see Appendix 1) for conferences and for refereed journals, and many have presented their research results to the Chair’s partners and during local and national technical meetings. This gives them invaluable experience for communicating their expertise. The demand for their services is high; recent graduates have been hired as specialist in mine waste management, environmental geotechnique and hydrogeology.
4- **Collaboration with Industrial Partners and Other Sponsors**

The Chair is working closely with 7 companies that contribute financially and technically to the research program. These are:

- **Agnico-Eagle**, regular contacts over the last 4 years with:
  Louise Grondin, Sylvain Boily, Jean-François Doyon, and Rosaire Émond.

- **Barrick Gold**:
  Jacques McMullen, Mei Lin Shelp, Peter Kondos, and John Martschuk (Toronto office);
  Mike Papadakis, Bulyanhulu mine, also Johnny Zhan and John Meyer (Salt Lake City office).

- **QIT-Fer et Titane - Rio Tinto**:
  Dominique Beaudry and Donald Laflamme (from the Sorel office); also exchanges with the personnel at Mine Tio (in Havre-St-Pierre).

- **Rio Algom – BHP-Billion**:
  Maxine Wiber (Toronto), Denis Caron, Daniel Adam and Normand Martineau (Abitibi office).

- **Xstrata**:
  Robert Prairie et Jacques Moulins (Montreal), Marie-Pier Bédard, Boubacar Camara and Jacques Leclerc (Abitibi).

- **Golder Associés**:
  Michel Julien, Mayana Kissiova, Ann Lamontagne, and Anne-Marie Dagenais (Montreal).

- **SNC - Lavalin Inc.**:
  Denis Isabel (Québec), Marc Arpin, Mike James, and Les MacPhie (Montreal).

The Chair also interacts with the Ministère des Ressources naturelles et de la Faune du Québec (MRNF), for research activities that relate to mine sites managed by the provincial government. Complementary funding has been obtained to work on these additional sites. The main contacts are: Johanne Cyr, Jean Dionne and Louis Marcoux in Quebec City, and Robert Lacroix in Val-d’Or.

Regular exchanges are taking place between the researchers and students and the participating mining companies, consulting firms, and government agencies, and these have been very fruitful. Some publications (see Appendix 1) were also written with the industrial partners. Presentations (between 4 and 6) by students are organised during each meeting of the Scientific Committee (twice a year). Important conferences have also been organised jointly with the industrial partners (and students); some of these are identified below in Section 7. Also, because many projects are conducted in the field, or are using samples collected in the field, most students need to be in touch directly with the mining operations. The Chair thus continues to maintain very close ties with companies and public organisations.
5- Other Collaborations

The contributions of external collaborators are also acknowledged: Professors Ward Wilson (UBC), René Lefebvre (INRS-ETE), René Therrien (Univ. Laval), Pierre Moszkowics, Denise Blanc (INSAG-lyon, France), Philippe Marion, Mukendi Kongolo, and Philippe deDonato (INPL, Nancy), Eric Pirard (Université de Liège), U. Mayer (UBC), J. Rose (CEREGE Aix en Provence, France), Carmen Neculita (KAIST), and Rachid Hakkou (Marrakech, Morocco). These individuals are collaborating on the projects described above in various ways, including by co-supervising student projects.

In addition, a number of visiting researchers have spent time (a few days to a few weeks) at one or both of the Chair’s locations, in Montreal or in Abitibi (including all collaborators identified above). Many of them gave seminars during their stay. These exchanges have created a very prolific environment, which is believed to be quite beneficial for researchers and students alike. The Chair also keeps in touch with other active groups around the world, directly or indirectly through their interaction with the Chair Partners, visitors, and invited guests (such as Gilles Tremblay of MEND, who sometimes attends the Scientific Committee meetings, and provides an important linkage with international programs such as INAP and MISA). The Chair also interacts with experts from other research organisations who are invited to participate on evaluation committees of students’ Theses; in recent years, these have included P. Simms (Carleton U.), R. Nicholson (Ecometrix), J. Duchesne (ULaval), M. Grabinsky (UToronto), G. Ballivy (USherbrooke), A. Fourie (UWestern Australia), A. Rouleau (UQAC), L. Catalan (Lakehead U.), P. Champagne (Queens), M. Nastev (GSC), G. Mercier, P. Drogui, and M. Tyagui (INRS).
6- **Change in University Research Capability**

As mentioned earlier, the Industrial Chair provides a critical mass of researchers (professors, research associates, graduate and undergraduate students, technicians) working on a variety of topics that are often interconnected. Individual researchers benefit from the expertise and experience of others. Working as a team has also allowed members to apply for additional grants, which have provided funds to complement the research program. This synergy between researchers has also opened important new areas of research related to the environment and mine wastes management, including the underground disposal of tailings, the use of waste rock inclusions in tailings impoundment, the passive treatment of contaminated leachate, and the flow of potentially contaminated water in fractured rock around pits and stopes.

Since the Chair was created in 2001, new laboratory facilities have been built at both Universities, and new equipment has been purchased with funds from the Chair’s budget and with additional funds from other sources. A list of the main equipment purchased during Phase I was presented in the final report (in 2005). Additional equipment (such as oxygen optic sensors, echo-log probes, hydrogeochemical instruments for piezometers, LECO furnace, an update of UQAT SEM, roots digitizer, Ionic chromatograph, mobile laboratory, small loop-test, and column testing material) has been added recently, with funds obtained from various organisations (i.e. FQRNT, CFI, NSERC). Additional (in kind) laboratory support is provided by both universities, as part of their contribution to the Chair’s activities. These facilities are being used by the authors of this report, and by the other collaborators of the Chair (and their students). The growth of the research team has made the Chair one of the major players in the field of mine wastes management on the national and international scenes.
7- Dissemination

The Chair’s main proponents are working hard to ensure that their results are being transferred to their Partners and to the related community. For this purpose, they publish regularly in journals and conference proceedings. A list of 204 recent papers is presented in Appendix 1. The recent production can be summarized as follows:

<table>
<thead>
<tr>
<th>REFERENCE/TITLE 2006-2010 (SEE APPENDIX 1 FOR DETAILS)</th>
<th>SUBMITTED</th>
<th>ACCEPTED/PUBLISHED</th>
</tr>
</thead>
<tbody>
<tr>
<td>REFERREED JOURNAL ARTICLES:</td>
<td>5</td>
<td>73</td>
</tr>
<tr>
<td>CONFERENCE PRESENTATIONS/POSTERS:</td>
<td>10</td>
<td>112</td>
</tr>
<tr>
<td>OTHER (INCLUDING TECHNICAL REPORTS, NON-REFEREED ARTICLES, ETC.):</td>
<td>-</td>
<td>4</td>
</tr>
<tr>
<td><strong>TOTALS:</strong></td>
<td><strong>15</strong></td>
<td><strong>189</strong></td>
</tr>
</tbody>
</table>

The Chair is also actively contributing to a number of initiatives to promote technology transfer, by participating in various national and international gatherings. In addition to the presentations given during the Scientific Committee meetings, the 2008 Symposium on *Mines and the Environment* has been organised in collaboration with other organisations (i.e. URSTM, CIM, MRNF, AMQ, MEND). A symposium on Modelling Tools for Improving Mine Waste Management was held at the Quebec City in 2008, during a conference being organised by the GAC-MAC organisation. B. A specialty conference on mine wastes management was recently held during the ACFAS Congress in Montreal (11-13 May 2010). Busière was a member of the organizing committee of the 2009 CLRA conference held in Quebec city. M. Aubertin was a member of the organizing committee of Paste 2010 (held in Toronto, 2-6 May 2010), an international conference on densified tailings. Also, a number of workshops, seminars, short courses, and graduate courses have been presented on different topics of interest, such as AMD prediction, cover technology, modelling techniques, underground waste disposal as backfill, surface disposal of paste tailings, and reclamation methods (to mention only the main ones offered over the last few years). It is also worthwhile to recall that the Mineral Engineering Masters Program of École Polytechnique is being offered at UQAT as a formal extension (since 2004). Students are thus able to enrol directly in Abitibi and complete their entire program at UQAT. Several new courses have been created as part of this extension. Some of these are offered by video transmission, thus allowing students at different locations (i.e. Montreal, Rouyn-Noranda, Val d’Or) to follow the course from their own town.
Appendix 1 – List of publications (2006-2010)

2010


2009


53- Mbonimpa, M., Aubertin, M., Bussière, M. (2009) Discussion on "Effects of different drying rates on shrinkage characteristics of a residual soil and soil mixtures" by Henry


63- Potvin, R., Bussière, B., Benzaazoua, M., Zagury, G.J., St-Arnauld, M., Cyr, J. (2009) Efficacité des drains dolomitiques installés au site de L’ancienne mine Lorraine, Témiscamingue, Québec. 34th Annual Meeting and Conference of the CLRA, 23-25 August 2009, Quebec City, Quebec [on CD Rom].


68- Smirnova, E., Bussière, B., Tremblay, F., Cyr, J. (2009) Vegetation succession and root penetration on the Lorraine cover used to limit acid mine drainage. 34th Annual Meeting and Conference of the CLRA, 23-25 August 2009, Quebec City, Quebec [on CD Rom].


2008


77- Benzaazoua, M. (2008) Le contrôle du drainage minier à travers une gestion optimale des rejets miniers et une restauration efficace de sites d'entreposage. International Congress of


2007


Montreal, Quebec, Canada. Canadian Institute of Mining, Metallurgy and Petroleum (CIM).


2006


A list of additional publications for the period 2001-2005 is available on the Chair’s web site. The web site also contains a description of many students’ projects.