MERG Report 2004-2

Heavy Metals and Acid Rock Drainage: A Select Literature Review of Remediation and Recommendations for Applied Research

By Eba Engineering Consultants Ltd.

April 2004

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

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EBA Engineering Consultants Ltd.

Creating and Delivering Better Solutions

April 13, 2004

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Mining Environment Research Group
Department of Energy, Mines & Resources
Government of Yukon
Box 2703
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Attention: Ms. Lois Craig

Subject: Heavy Metals and Acid Rock Drainage
A Select Literature Review of Remediation and Recommendations for Applied Research

Attached is the Literature Review addressing Heavy Metals and Acid Rock Drainage issues in Mining. The report includes a framework for an applied research and development program, the cost of which will need to be worked out with the Yukon if we decide there is sufficient interest. The report also includes a non-technical Executive Summary written at a level appropriate for the general public.

EBA would like to take this opportunity to thank MERG for their contribution to our research. Indeed, the contribution makes the Yukon a partner in our research and development efforts and we would like to continue this partnership in developing a solution to Acid Mine Drainage and Heavy Metals with the Yukon. We plan to continue this research and development and view the Yukon as a valuable partner with much to gain from the work. We also feel that the private sector should be invited, as a third party, to support this research and development. It is evident that the mining sector has the most to gain from our partnership and there is much we can do to encourage them to participate. To discuss this, please call either of the principal authors directly at the telephone numbers listed below.

Thank you again for your support.

EBA Engineering Consultants Ltd.

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Submitted to:

Mining Environment Research Group
Department of Energy, Mines & Resources
Government of Yukon

April 2004

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EXECUTIVE SUMMARY

EBA Engineering Consultants Ltd. has prepared this report, based on literature review, to provide information to assist the Yukon mining industry in remediating environmental problems caused by acid rock drainage (ARD) with its associated heavy metals contamination. There are three main sections to this review. First, the history of ARD is presented. Second, the chemistry and microbiology of ARD and the treatments that are used worldwide, with emphasis on cold climate treatments, are reviewed. Finally, we present the most promising technologies developed in temperate regions, that could be tested under typical Yukon conditions. This is the main challenge given the short growing season and cold temperatures.

Acid mine drainage is caused by oxidization of metal ores, containing sulphur and metal sulfides found in coal. There are three steps in this process. First, oxygenated water, from rain, for example, oxidizes metal sulfides producing acidic water and ferrous iron. When the water becomes moderately acidic, a number of bacteria can assist in further oxidization and increase the acidification of the drainage water. Finally, when the water reaches a pH of 3.5, an iron bacterium, *Thiobacillus ferroxidans*, can further dissolve metal sulfides, such as pyrite, producing ferric hydroxide, which can smother vegetation. Also, the sulphuric acid is acutely toxic. Heavy metals that are toxic, are also present in the ARD.

Some common treatments for ARD identified by EBA including neutralizing the acidity of water using limestones, minimizing water contact with metal sulfides, or using organic amendments to bind with heavy metal contaminated waters. Important developments in using natural wetlands for ARD, have taken place in the late 1990s, which have identified that anaerobic (oxygen free conditions) are important in treating ARD. High sediment loads in streams have been found to limit neutralization by coating carbonates and decreasing microbial reduction of metal, as well as preventing metal uptake by vegetation.

Based on our review, EBA recommends a pilot trial using a series of eight treatment cells. The sequence of treatment cells would be as follows:

1. A settling pond to remove particulate sediment.
2. An organic anaerobic pre-treatment cell to remove oxygen, increase water temperature and regulate water flow.
3. A buried limestone drain to neutralize ARD.
4. An organic anaerobic post-treatment cell to further reduce drainage water, maintain temperatures and increase the holding time of water in the system.
5. A shallow wetland cell with emergent vegetation.
6. A moderate depth wetland cell with emergent and submergent vegetation.
7. A deep wetland cell with submergent vegetation.
8. A long run-out channel for re-oxygenate waters.

EBA recommends this system be evaluated at both orphan and active mine sites.

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1.0 INTRODUCTION

EBA Engineering Consultants Ltd. (EBA), Environmental Practices Group has prepared this report consisting of a literature review and recommendations for applied research. The purpose is to address the need to better understand remediation of heavy metals and acid rock drainage that result from mining activity in the Yukon. This report is partly produced under contract to the Government of Yukon, Department of Energy, Mines and Resources (the Yukon). EBA would like to thank the Mining Environment Research Group (MERG) Contribution Agreement of the Yukon for their partial support of EBA's research. This information is timely, as there is a growing need to protect environmental values and ensure that development proceeds with the safeguards expected of the Yukon's role as land stewards. The information contained in this report has circumpolar applications including Alaska, the Northwest Territories, and other northern regions with a boreal climate.

2.0 OBJECTIVES

There is basically one purpose and that purpose is to provide information that assists the Yukon and the mining industry in managing the risk and remediating the environmental problems caused by acid rock drainage (ARD) and heavy metals. This implicitly focuses on wetlands because the movement of water (mass flow) primarily transports the constituents of concern and wetlands are a viable method to retain and treat ARD runoff. The goal then, is to provide a document that suggests scientifically sound and economically feasible applied research in the form of pilot/test projects that will help ameliorate adverse environmental conditions.

To achieve this goal, this report addresses three objectives:

1. Provide information fundamental to understanding the ARD and heavy metal problem described above for cold northern climates.

2. Provide an understanding of selected remediation techniques (particularly wetlands) such that other researchers can explore the possibilities for improving environmental conditions.
3. Present a recommendation(s) for further study in applied research or a test project that addresses the ultimate goal of the Yukon.

3.0 METHODS

The adopted methodology is essentially a desktop literature review. This is the first logical step in understanding the problem and trying to resolve its issues. This methodology incorporates a number of different methods or techniques.

We critically review the literature across a broad spectrum of disciplines as indicated by, but not limited to, the following journals and information sources:

- Journal of Environmental Quality
- Plant Physiology
- Restoration and Reclamation Review
- Crop Science
- Environmental Science and Technology
- Canadian Mining and Metallurgical Bulletin
- Mining Engineering
- Water, Air and soil Pollution
- Aquatic Toxicology
- Ecotoxicology and Environmental Safety
- Wetlands
- Groundwater Monitoring and Remediation
- Soil Science Society of America
- An assortment of private references from the EBA Library where we have a collection of material from our long history in the mining sector and environmental contamination and remediation.
- An assortment of public references in the form of reports, books from the University of Alberta Library and on-line internet information.
- An assortment of Canadian and American federal, state and provincial reports from the University of Alberta Library and on-line Internet information.

EBA has also included the work of researchers from a wide geographic area representing circumpolar countries and, where appropriate, temperate and tropical countries. We examine climatic and soil conditions in terms of their properties important to remediation issues and some of the early work in treating ARD and heavy metals. We critically review contemporary work with a special focus on wetlands and how it may apply to the north. Then, we synthesize this information with a recommendation for further study in terms suitable for applied research in the form of a test project.

The literature review is presented in three main sections. First, we provide a brief historical perspective on ARD. Secondly, we provide some fundamental chemical information on ARD and examine the issues in broad terms of how researchers in different parts of the world approach the problem and how they may apply to the north. Thirdly, EBA examines the most promising remedies in depth with the aim of contributing to the development of topics for applied research and projects or experiments where remediation concepts and techniques can be further developed and tested under field conditions. Though we recommend an applied research project, any astute researcher will identify a number of research topics.

4.0 LITERATURE REVIEW

Background

The issues surrounding ARD and the movement of heavy metals in the environment goes back to the 1960s and 1970s when governments began, through legislation, to introduce reclamation standards to restore the land to a level of capability equal or better than it was prior to the mining activity. This was a response to the declining soil productivity and polluted waters from a number of different industrial and agricultural sectors. However, in terms of ARD, the mining industry was identified as a critical discrete source (Smith, 1997). Even in the 1970s, experts in the mining industry acknowledged the problem (Down and Stocks, 1977) and identified solutions for cold northern regions of Canada (Leroy, 1973), the United States (Matthew, 1973) and elsewhere (Mander, Ulo and Jenssen, 2002; *Ibid.*, 2003).

With the increasing pressures to protect the quality of air, soil and water from potential contaminants and through the research efforts of the mining sector, continuing improvements in technology and management practices are making the industry a better land steward. Today, there are numerous references to bioremediation (Wickramanayake and Hinchee, 1998) and phytoremediation in wetlands (Leeson, *et. al.*, 2001). International conferences are also held to address the issues such as the Acid Mine Drainage Seminar/Workshop held in Halifax, Nova Scotia (Environment Canada and Transport Canada, 1987) and the Second International Conference On the Abatement of Acidic Drainage (MEND, 1991). Finally, there are the real working remediation projects that showcase the significant contribution that is being made to resolve the problems of ARD, heavy metals and other potential pollutants in the environment (Hedin, *et. al.*, 1994; Smith, 1997; Cole, 1998; Reinhardt, 1999; Hamaguchi, 2000).

The one major drawback to implementing these technologies and natural bioremediation processes in the north has been the apparent limitations associated with climate; the generally cooler temperatures, shorter growing season and longer periods of deep-freeze. These and other factors related to the chemical properties of the minerals, the heavy metal by-products, soil biology, aquatic ecology and hydrology are addressed. First, it is appropriate to describe the range of a few key climatic variables for the Yukon.

The Yukon is subjected to air masses from two source regions, continental and maritime of polar origin. These move across the landscape first under the influence of the dominant easterly winds and then are variable as influenced by the location of the Jet Stream, Sub-polar air masses and topography. Topography has a couple of main effects on temperature and precipitation. With respect to temperature there is an inverse relation to elevation and the general northwest-southeast strike of the valleys directs the in-flow of the relatively temperate maritime air masses and the out-flow of the more extreme continental air masses. With respect to precipitation, the cordilleran landscape in proximity to the ocean has two main effects. One is the orographic effect at the local or meso-scale and the other is the orographic effect at the regional or meta-scale where precipitation generally decreases eastward from the Pacific Ocean to the Northwest Territories.

The other important climatic influence is related to the latitudinal influence and the global circulation of energy and matter. As one heads north through the Yukon, there is a general decrease in the length of the growing season, that is, increasing cooler average temperatures as one progresses north with local exceptions due to elevation and other meso-scale factors. The following four climate stations are selected to represent the north to south range of conditions found in the Yukon (courtesy of Environment Canada, Climate Normals, 1971 - 2000).

Descriptor	Whitehorse	Dawson	Old Crow	Komakuk Beach
Latitude (deg, min)	60, 42	64, 2	67, 34	69, 34
Longitude (deg, min)	135, 4	139, 7	139, 50	140, 10
Elevation (m.a.s.l.)	706	370	251	7
Annual Daily Average Temperature ºC	-0.7	-4.4	-9.0	-11.0
Rainfall component of Precipitation (mm)	163.1	199.9	144.2	83.5
Days with Maximum Temperature > 0 ºC (approximate # of days)	245	208	160	130
Days with Minimum Temperature > 0 ºC (approximate # of days)	140	120	104	75
Length of Season for Microbial Growth (approximate months)	4.5	4.0	3.0	2.5
Degree Days[1] > 5 ºC (approximate ºC)	894	1,006	806	220

1. Degree-days for a given day represent the number of Celsius degrees that the mean temperature is above or below a given base. For example, growing degree-days are the number of degrees above 5° C. If the temperature is less than or equal to 5, then the number will be zero. Values above the base of 5° C are used primarily to estimate the growing requirements of crops. Growing degree-days are used in agriculture as an index of crop growth. Values above represent the average accumulation of degrees above the base temperature for a given year. **Source**: Adapted from Environment Canada, Meteorological Services on-line Climate Normals for 1971 - 2000.

There are two items to note in the above table. First, that the Degree Days index is most meaningful at temperate latitudes where day length does not vary as much as it does at northern latitudes. At latitudes found in the Yukon where diurnal and annual temperature ranges can be quite high this index correlates better with net radiation than it does with annual or monthly daily average temperature. It is provided to assist researchers of temperate latitudes in understanding the change in temperature conditions as one progresses northward. Second, the Length of Season for Microbial Growth is an index defined by the number of days with minimum temperature greater than zero degrees Celsius expressed in terms of a 30 day month. It is presented as a conservative index in that the number of months is rounded down to the nearest half month. The main assumption is that microbial activity will only begin when temperatures exceed the freezing temperature of water. Much of the literature suggests that a more realistic index would use the number of days when the minimum temperature is greater than five degrees Celsius. At temperate latitudes where most of the research with indigenous microbes is conducted, this is likely a threshold temperature when microbial growth and activity generally begins to become significant. For comparison purposes, this climatic parameter is presently not available in the suite of parameters supplied in the Climate Normals. More importantly, there are numerous indigenous reducing microbes quite active in the arctic at temperatures between zero and five degrees Celsius (H. Ziervogel, pers. comm.). These are referred to as **cryophylls** (cold environments) and can be either **facultates** or **obligates** where they either are opportunistic and can make use of a wide range of temperatures or they must have cold conditions to be active, respectively.

The other important climatic component is rainfall or precipitation because it is the medium of mass flow and supplies most of the hydronium for the oxidation-reduction reactions. We are downplaying the significance of this parameter because we are assuming that other sources including snow and glacial ice melt, groundwater and existing surface water will supply sufficient quantities for ARD treatment.

An understanding of this information and other meso-scale climate variables is key to developing effective ARD abatement protocols for a mine site.

The Problem and Its Issues

Within the mining industry, the main minerals of concern are coal and metals. The metal ores commonly include pyrite (FeS_2), chalcopyrite ($CuFeS_2$), sphalerite (ZnS) and arsenopyrite (FeAsS) and are found in rock that is in a chemically reduced state. The mineral extraction process exposes this rock to the atmosphere where oxidation, through a combination of autoxidation and microbial iron and sulphur oxidation, results in large amounts of acid being produced. In association with the acid production, the oxidized compounds can release toxic concentrations of metals such as, for example, those of the parent minerals listed above.

The first oxidation step takes the pyrite, subjects it to the spontaneous oxidation by atmospheric oxygen producing weakly or moderately acidic water in the form of sulphuric acid that is diluted by the ambient water supply. The resulting ferrous ion will further oxidize to a ferric ion and this occurs slowly at the low pH of acid mine waters. If the pH falls between 4.5 and 3.5 the oxidation can be catalyzed by a variety of bacteria (*e.g.*, *Thiobacillus thiooxidans*, *Ferrobacillus ferrooxidans*) and if the pH continues below 3.5, the iron bacterium, *Thiobacillus ferrooxidans* becomes the dominant catalyst for the microbial oxidation. The ferric ion is pivotal in the biogeochemical cycle as it in turn continues the dissolution of pyrite. The overall result typically is the production of two molecules of ferric hydroxide and four molecules of sulphuric acid. The ferric hydroxide precipitates and can smother the aquatic vegetation and increase the biological and chemical oxygen demand (BOD and COD) of the aquatic ecosystem. Though the precipitate may create a chronic toxicity condition, it is the acute toxicity of the sulphuric acid that is of most concern.

The example of pyrite presented is less of a concern in terms of heavy metal toxicity because of the ubiquitous and relatively inert properties of iron. In contrast, the heavy metals (molecular density >5 g/cm^3) such as lead, mercury, arsenic, zinc or copper and some of the lighter metals (*e.g.*, sodium and aluminum) can be acutely toxic to a number of organisms at relatively low concentrations. Where the level of toxicity, chronic or acute, depends on the sensitivity of the organism and its preferential uptake and bio-accumulation of the metal in question.

The most common remedy presently offered by remediation technologists is to neutralize the acid waters with a basic compound such as calcium or magnesium carbonate (Lapakko and Antonson, 1991; Kuyucak, *et. al.*, 1991; Hedin, Watzlaf and Nairn, 1994). Crushed limestone is a very common carbonate rock that is used but its success is inconsistent for a number of reasons. One major obstacle to overcome using carbonates is because of the following chemical reaction. As the pH increases with the addition of calcium carbonate, more of the ferric hydroxide precipitates, coating the limestone particles. This coating acts as a barrier to the ongoing neutralizing properties of the limestone. If the water is devoid of oxygen, it may help to keep the chemical reaction in a reducing state but this seldom happens under field conditions because of the turbulent properties. This issue, along with the limitations of a relatively long winter where temperatures are below zero Celsius for six months, are addressed.

One best management practice (BMP) is to seal the mine conduits as soon as the ore has been exhausted or to cap the rock with an impermeable material and then a layer of soil that can be quickly revegetated in the case of strip mines (Lundgren, Terratema and Lindahl, 1991; Gerencher, *et. al.*, 1991; Hallam, Haile and Brouwer, 1991; Bell, Riley and Yanful, 1995; Chermak and Runnells, 1997). The principle behind these practices is to prevent oxidation and to minimize the amount of water that can dissolve the rock and transport the heavy metals and acid water. This is an approach commonplace today but there are mines that have been in operation longer than this BMP and there are some orphaned mines that are so old that mine operators and regulators of the time were unaware that ARD was a problem.

Another approach is chemical control to inhibit the sulphur- and iron-oxidizing bacteria that produce the acid (Lovett, Ziemkiewicz and Rymer, 1991; Shibley and Dymov, 1991) or bio-chemical control to promote reducing conditions such that the acid can be successfully neutralized (Kuyucak, St.-Germain and Wheeland, 1991; Inoue, 1995). This however, requires that soil or aquatic microorganisms are not significantly harmed by chemical treatment and that when conditions are stable, the microbial populations would return to 'normal' activity. It is clear that any chemical agents used would have to be species specific to avoid harming non-target organisms. In addition, we require an understanding of how the product behaves during the winter months when microbial activity decreases in order to avoid free movement of the product and ensure that non-target organisms are not indirectly affected.

More recently, researchers have been exploring the efficacy of organic amendments as a way to manage microbial populations for alleviating ARD (Pichtel, Dick and Sutton, 1994; Bechard, *et. al.*, 1994; Noah, *et. al.* 1999; Chaney, et. al, 2000; Hamaguchi, 2000; DeVolder, *et. al.*, 2003). Some of these organic materials are considered a waste product (*e.g.*, wood chips, sawdust, pulp fines, fish morts, sewage sludge/bio-solids, manure) and are therefore relatively inexpensive to obtain if in proximity to a mine. Other organic materials such as bacterial cultures, compost, peat moss, activated charcoal and synthetic organic polymers are consumer and industrial products that cost significantly more but could be more cost-effective in an acid remediation program. The remoteness of some mines, the limited availability of some organic materials and the associated transportation costs could be a limitation to experimenting with these materials or implementing them in an ARD reduction/remediation program. Some studies have shown good progress but further work is required to find the right formulation of the appropriate amendment suited for a particular ARD source. Climatic limitations have also been a factor limiting the utility of the concept because if the microbial populations decline through the winter because of the cold then the organic amendments are effectively unable to provide the nutrients and carbon sources for the microbes that contribute to the neutralization of the acids.

There are also patented technologies such as the Pyrolusite Process that uses limestone chips to neutralize the acidity and site-specific laboratory cultured microbes to remove the metals (Reinhardt, 1999). This has had some success in western Pennsylvania (*Ibid.*) as has the vertical flow reactor (also a microbial mitigation reactor) produced and patented by BioteQ Environmental Technologies and Paques (Dickson, 2003). They are presently operating in the Breakwater Resources Caribou Mine in New Brunswick, the Ni-Cu-Co Raglan Mine in Ungava, northern Quebec and a copper mine in Arizona. In Quebec, the Raglan plant is expected to treat 530,000 cubic meters during the operating season of May to November at an annual capital fee of $300,000 until 2009 and an ongoing treatment fee of $1.06 per cubic meter of water treated (*Ibid.*). This may be cost-effective for high market value metals or for active mines but may not be worthwhile for older active mines with an ongoing problem, long-orphaned mines or mines producing lower-value products such as coal.

We often seek a 'silver bullet' solution, a single answer that will resolve the problem. We may find that the complexion of the issues related to ARD require a complex solution or a hybrid of techniques specifically customized for site conditions (soil, slope, aspect, hydrology and climate) unique to each mine operation. Or, if a more general approach can be found, then the solution may have more broad ranging applications for the northern regions that share relatively uniform climatic, hydrologic, pedologic and geologic conditions.

Remediation Solutions

A number of factors have been discussed that need to be integrated into practical solutions. The research community can then carry the potential solutions and promising concepts forward. A process to translate what we presently know into pilot projects is discussed in the following sections.

To begin with, we list the factors directly and indirectly discussed above that need to be integrated into a potentially workable solution. These are presented below without any priority or ranking because a solution will only be found by integrating these factors into a single solution.

- *Solution must be cost-effective*: This means that the cost of doing nothing and allowing the degradation of valued environmental components is an intangible or incommensurate cost that northern communities should not have to accept. This means that within reason transportation, materials, construction and land value costs must be part of the solution.
- *Solution must be able to address the cold conditions and short open water season*: This means that the solution, whether it is able to function year long or seasonally, is able to show statistically significant progress in ARD and heavy metal abatement.
- *Solution must be relatively simple to operate*: This means that once an abatement program is established for a site (*i.e.*, beyond start-up), it must be relatively easy to operate without requiring relatively expensive or highly technical operating costs.
- *Solution must be developed as a Passive System*: This means that the solution should be somewhat self-sustaining, require less maintenance than an active system and therefore cost less over the long term; though initial set-up costs could be relatively high.
- *Solution must use local materials*: This means that expensive imports of materials and supplies required for the construction and long-term operation should be avoided as much as is reasonably possible. This also means that wherever is reasonably possible, waste materials from other local processing streams (*e.g.*, wood waste, sewage sludge or manure) should be used.

- *Solution must conform to an ecological framework:* This implies that it must be effective and environmentally friendly. This means that the treated water is as clean as or cleaner than the water normally expected in the natural environment and that the treatment process itself or its by-products is not deleterious to the natural environment. This also means that the process should not introduce any foreign (exotic) organisms into the natural environment that might replace indigenous (native) organisms. Finally, this means that the system does not accrue an environmental debt.
- *Solution must be flexible*: This means that the process is adaptable to scientific and technological advances that will be made in the future and that the process can readily adopt appropriate advances where appropriate.

We will now examine solutions presented by other authorities and integrate our previous discussion and the factors listed above into a model that can be developed for ARD and heavy metal abatement.

Treatment Wetlands

The history of treatment wetlands is brief but it is estimated that there are over 300 wetland cells in the USA processing from 100,000 to 15 million gallons of municipal wastewater per day. The success rate in this area has been good where BOD was reduced by 73 %, total suspended solids (TSS) by 72 %, total nitrogen by 53 % and total phosphorus by 56 % (Cole, 1998). In the mining industry, the Tennessee Valley Authority has constructed 19 wetlands to treat acid mine drainage (AMD) from coal processing and coal-fired electrical generating plants (*Ibid.*). The more recent treatment wetlands are passive systems that include linked cells that function differently, some are limestone drains and others are vegetated. They are having increased success but Cole (*Ibid.*) does not indicate what that success is. Another example presented by Cole (*Ibid.*), treats wastewater with a pH of 2 and high levels of aluminum. It consists of, "successive alkalinity-producing systems," a rich organic layer over an anoxic limestone drain (*Ibid.*); but again no results are given. One of the main points in Cole's article on the Emergence of Treatment Wetlands is the presentation of the debate between the importance of wetlands with sufficient volume and hydraulic residence time versus the growing importance of saturated soil (*Ibid.*). In 1998, this was relatively new but in 2004 this shift in thinking has largely been made and has expanded to include the dynamics of aerobic and anaerobic conditions. This shift in thinking may be common in temperate climates but in the north, having depth in the wetland may still be important because the design may require the wetland to keep from freezing solid.

Another comprehensive article, this one focusing specifically on Acid Mine Drainage (AMD) by K. Smith (1997), discusses the biological and chemical processes that remove metals and neutralize acidity. Smith (*Ibid.*) presents the results of numerous studies that show very good success at removing metals and remediating acid conditions. One study reported by Kleinmann, 1985 (cited in *Ibid.*) showed how controlling the flow rate by a *Typha* wetland removed up to 95 % of the iron and manganese. In addition, plants can directly remediate metal concentrations through uptake and assimilation. Some plants will preferentially absorb and assimilate specific metals such as arsenic, selenium, iron and manganese. Some of these plants such as *Typha* and *Sphagnum* species are quite tolerant of acid conditions (*Ibid.*). Like Cole (1998), Smith (1997) stresses the importance of anoxic conditions and adds organic matter and the anoxic-oxic interface as critical for the success of AMD treatment. Smith also correctly identifies the sediment load as a potentially limiting factor in the success of treatment wetlands. Waste streams with high sediment loads will coat acid neutralizing carbonates, inhibit microbial reduction of metals and limit vegetation uptake of metals. In this situation, an initial cell to allow the sediment to settle out before continuing through the system would be required (*Ibid.*).

Caps

Chermak and Runnells (1997) took the novel approach to develop a self-generating impermeable cap to reduce the amount of precipitation that could percolate through acid bearing waste rock. Rather than using clay or an impermeable geo-membrane, they conducted an experiment where they added crushed limestone and lime subjected to artificial rain events. The results showed that the materials reacted forming a hardpan layer of gypsum and amorphous iron oxyhydroxide at the amendments upper surface (*Ibid.*). The hardpan was quite effective in reducing the permeability of their experimental columns yielding a promising self-healing system for existing waste rock piles where the objective is to reduce further ARD. Clearly, for this to work under field conditions, there would have to be sufficient topsoil placed on top of the limestone - lime mixture to allow plants to grow. The authors conclude that this technique, "… would aid in producing a favourable substrate for plant growth." (*Ibid.*). This may be true but in terms of maintaining the integrity of the hardpan, the root system of the revegetated surface could breach the hardpan and cause significant hydraulic piping. In terms of a passive treatment wetland, the main point we learn from their experiment is that a good impermeable layer is an effective barrier to oxygen allowing the development of an anaerobic environment that maintains chemically reductive conditions.

Similarly, Bell, Riley and Yanful (1995) working under the MEND program designed a soil cap using glacial till about 60 cm thick to separate acid bearing waste rock from oxygen and to reduce the amount of rainfall that percolates through waste rock piles in New Brunswick. They too were successful over a three year period where lysimeter pH increased from approximately 2.1 to 2.8 over the 1989 to 1990 season to a pH of 3.0 to 3.2 in 1993 (*Ibid.*). Dissolved oxygen (DO) also showed a significant decline over the same period ranging from approximately 10 to 20% in 1990 and dropping to almost 0% in 1992 and 1993 (*Ibid.*). At this point, it may be more significant to note that after the soil cap was first established, endothermic oxidation rapidly pushed the waste rock pile temperature to 50° Celsius. Within a year, the waste rock pile temperature below the cap dropped to 40° C and thereafter, correlated strongly with seasonal temperatures generally ranging from just above zero to 15° C (*Ibid.*). This is significant for our research in the north because at lower temperatures water can contain more DO than at higher temperatures. Thus, it is important that DO be minimized in the reducing portions of the acid abatement process through temperature regulation.

Active Systems

In efforts to control the environments that treat ARD, some researchers have adopted '*active systems*' where flow rates, oxygen concentrations, reactive substrates and microbial populations are tightly controlled. In Japan, researchers found that the high cost of neutralizing AMD using calcium hydroxide was due to the large amounts of ferrous iron in the drainage (Innoue, 1995). They proposed oxidizing the ferrous iron into ferric iron so that less expensive calcium carbonate can be used to neutralize the acid drainage. Under controlled conditions of a closed system, they are able to oxidize approximately 98 % of the ferrous iron within one hour and treat the acid water (pH= 2.5) with limestone increasing the pH to 8.0 upon release to the environment (*Ibid.*). This reduced their treatment costs by approximately 70 % over the previous technology that did not use bacteria. At a copper smelter, they were able to adapt this process for the hydrometallurgical process and the hydrogen sulphide desulphurisation process to remove Cu, Pb, Zn, Fe, As, Cd, other metals and sulphur. In addition to neutralizing the acid drainage water, they were able to recover approximately 150 tons of sulphur per month (*Ibid.*). This technology works well in Japan where mines are commonly located within the economic threshold of the markets they supply. In Canada's north, this is seldom the case and transportation costs are far greater than in Japan even with our lower fuel costs. If environmental conditions favourable for chemically reducing microbes can be created and maintained in a passive system, then greater savings are likely to be realized.

Microbes and Organic Matter

All microbes require a suitable environment for their growth and maintenance. Some sulphur reducing bacteria will exist quite well in finer grained (silt and clay) materials where adsorption sites provide a suitable substrate and the flow of water provides an ongoing supply of nutrients. However, they are more likely to do well if organic material is present. The organic material provides a variety of substrates for microbial species reflecting the organic matter's state of decomposition or mineralisation. The organic matter is also the main source of labile carbon necessary for the growth of large microbial populations. The term *organo-metallic complex* expresses the ability of organic and mineral material to combine into a highly complex molecule. This term is seldom used these days and instead pedologists usually refer to *chelates* to describe the integration of the two materials. However, for our objectives, organo-metallic complex is descriptive, accurate and germane to the issues of ARD and heavy metals. If the bacteria can act as the catalyst that complexes heavy metals with decomposing organic matter then these bound metals are effectively removed from the food chain, thereby reducing toxicity starting from the bottom of the food chain. This benefit can continue up through the food chain to the higher functional groups. Thus, if the autotrophs and smallest heterotrophs (phytoplankton, zooplankton and wetland vegetation) are free of heavy metals, it is likely that so will the higher order organisms that depend on them.

As a case in point, a number of studies have shown that heavy metals can be immobilized by organic matter, given an adequate supply of the organic material is available such as compost, manure or pulp fines (Bechard, *et. al.*, 1994; Pichtel, Dick and Sutton, 1994; Scholz, Xu and Dodson, 2001; Goulet and Pick, 2001; King, *et. al.*, 2002; Scholz and Xu, 2002; DeVolder, *et. al.*, 2003). Not all of the studies exhibit the same level of success but it is important to examine them within context of the experimental objectives and environmental conditions. The information we must glean from these studies is that one of the objectives of wetland treatment of ARD is to remove heavy metals. This does not mean that they disappear but rather that they are removed from transport through the environment. The partitioning of heavy metals in a treatment wetland is a choice between having these metals bound to organic matter that typically becomes sediment or having these metals assimilated by the vegetation. The level of control and the choices we make in designing a treatment wetland will depend on management objectives within the context of an ecological framework. For example, if the vegetation is important to a particular population of wildlife, the choice may be to complex the metals with the organic matter that can then be periodically excavated for return to a metallurgical process. If however, the metals are not acutely toxic or are below a threshold for chronic toxicity, it may be more efficient to design the wetland for plant uptake of the metals and harvest the biomass to remove the metals.

A main factor describing the organic matter is that there is an ongoing supply of labile carbon. Labile carbon is created through the decomposition of more recalcitrant forms such as lignin, some proteins and polymers or is made available by direct supply of an organic material that the bacteria can access (*e.g.*, cellulose or sugar). This is fundamental for the biogeochemical cycling of nutrients and for the development of organo-metallic complexes (Bechard *et. al.*, 1994; Helbert, 1996; Barber, *et. al.*, 2001).

From our review of the literature, it is evident that treatment wetlands are most likely the best solution for ARD and heavy metals. We stated at the beginning of this Subsection that to conform to an ecological framework, it is imperative that the treatment system be a *passive* one. However, tailoring the wetland for the north may require some minimal level of activity to meet the special conditions that the environment demands.

5.0 SUMMARY

A number of factors important to the success of ARD and heavy metal treatment have been discussed and a few techniques used under experimental and operational conditions have shown that statistically significant improvements in treatment have been made (*e.g.*, Reinhardt, 1999; Hamaguchi, 2000). Of all the techniques, it is most likely that a hybrid system that combines the benefits of anoxic conditions, the neutralizing effects of limestone, the microbial formations of organo-metallic complexes, the phytoremediation of vegetation, the hydraulic benefits of a long residence time and implementation of BMPs within an ecological framework will provide the solutions sought for the north.

6.0 RECOMMENDATIONS

We recommend the design of three pilot projects constructed at a much-reduced scale under field conditions. These three projects will reflect the broad range of environmental conditions found in the Yukon and will provide a range of results that will allow interpolation for fine-tuning a system designed and developed at the operational scale. It is also suggested that we include as test subjects a long orphaned mine in a remote site where an active system is not feasible, and two active mine sites with different AMD and heavy metal issues.

The systems will include in sequence the following treatment cells:

1. A settling pond to remove particulate sediment. The design of this cell may be minimal depending on the total suspended solids in the drainage water.
2. An organic anaerobic pre-treatment cell to remove oxygen, increase water temperature and regulate the flow of water.
3. A buried anoxic limestone drain (ALD) or series of drains, to neutralize the acid drainage water.
4. An organic anaerobic post-treatment cell to further reduce the drainage water, help maintain appropriate temperatures and increase the hydraulic residence time.
5. A shallow wetland cell with emergent vegetation and a large ratio of substrate surface area to water volume per unit residence time.
6. A moderate depth wetland cell with emergent and submergent vegetation.
7. A deep wetland cell with submergent vegetation.
8. Finally, to complete the treatment, a long path run-out channel with sufficient slope to re-oxygenate the drainage water before it re-enters the natural drainage network.

Each site will have to be assessed independently, calculations made to ensure sufficient AMD and metal reduction and designed to address all the critical factors identified and discussed in this paper.

Part of the program will require a monitoring study that will last from two to three years where changes in the critical factors are observed and recorded. In each cell, we will need two piezometers located near the in- and out-flows that allows measurements of:

- pH
- Electrical conductivity
- Temperature
- DO
- Redox potential
- Flow rate
- Acquisition of water samples for concentrations of metals of probable concern

In addition to the above, the organic amended compost cells located, pre- and post-ALD will have a series of buried mineralization microcosms that can be terminally sampled to estimate rates of decomposition, amount of metal adsorption and identification of dominant microbial populations.

In addition to the suite of parameters first listed above, the last three wetland cells will be sampled for metal concentration in sediment, root biomass and foliage biomass. Estimates of changes in root and foliar biomass will be made. Field observations on the health, vigour and distribution of plants and aquatic arthropods will also be made and finally, we will enumerate the plankton communities microscopically.

The schedule for this sampling program will be determined upon assessment of the three selected mine sites and is dependent on the assessment of site conditions.

A study of this magnitude is required to resolve this issue.

7.0 CONCLUSIONS

In conclusion, the north offers unique challenges but also offers opportunities such as a large land base upon which to locate the treatment wetlands. The cost for the assessment, design and two to three years of monitoring is likely to be quite small relative to the cost for constructing the treatment wetlands. However, the long-term cost for operating the system is likely to be low and the environmental benefits high.

EBA is prepared to meet with MERG where in partnership we can produce a work program and cost estimate in a phased approach. The first phase is to develop a program for assessing three mine sites. Once that phase is complete, we need a program for designing the three treatment wetlands. After the second phase is complete, EBA is prepared to assist in managing the third phase, the implementation of the construction of the three treatment wetlands. Finally, EBA can provide a program to monitor and evaluate the efficacy and success of the three treatment wetlands so that full-scale projects can be planned.

The viability of treatment wetlands is proven. The challenge is to design them to suit the environmental conditions of the north.

8.0 CLOSING

We trust this report meets your present requirements. Should you have any questions or comments, please contact the undersigned at your convenience.

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9.0 REFERENCES

Barber, L.B., Leenheer, J.A., Noyes, T.I., and Stiles, E.A. 2001. Nature and transformation of dissolved organic matter in treatment wetlands. Environmental Science and Technology. 35(24): 4805-4816.

Béchard, G., Yamazaki, H., Gould, W.D. and Bédard, P. 1994. Use of Cellulosic Substrates for the Microbial Treatment of Acid Mine Drainage. J. Environm. Qual. 23: 111-116.

Bell, A.V., Riley, M.D., and Yanful, E.K. 1995. Evaluation of a composite soil cover to control acid waste rock pile drainage. CIM Bull. V. 88(995): 41-46.

Chaney, R.L., Brown, S.L., Angle, J.S., Stuczynski, T.I., Daniels, W.L., Henry, C.L., Siebielec, G., Li, Y-M., Malik, M., Ryan, J.A. and Compton, H. 2000. In situ remediation/Reclamation/Restoration of Metals Contaminated Soils using Tailor-Made Biosolids Mixtures. In Proc. Symposium on Mining, Forest and Land Restoration: The Successful Use of Residuals/Biosolids/Organic Matter for Reclamation Activities (Denver, CO. July, 2000). Rocky Mountain Water Environment Assoc., Denver. CO. 23 pp.

Chermak, J.A. and Runnells, D.D. 1997. Development of Chemical Caps in Acid Rock Drainage Environments. Soc. Mining, Metallurg & Explor. v. 49(6): 93-97.

Cole, S. 1998. The Emergence of Treatment Wetlands. Environmental Science & Technology. 32(9): 218-223.

DeVolder, P.S., Brown, S.L., Hesterberg, D., and Pandya, K. 2003. Metal Bioavailability and Speciation in a Wetland Tailings Repository Amended with Biosolids Compost, Wood Ash, and Sulfate. J. Environ. Qual. 32: 851-864.

Dickson, E. 2003. A Solution for the Acid Mine Drainage Problem. www. resourceworldmag.com. pp. 50-51.

Down, C.G. and Stocks, J. 1977. Environmental Impact of Mining. Applied Science Publishers Ltd.

Goulet, R.R. and Pick, F.R. 2001. The effects of cattails (Typha latifolia L.) on concentrations and partitioning of metals in surficial sediments of surface-flow constructed wetlands. In: Water, Air and Soil Pollution. 132(3/4): 275-291.

Gerencher, E.H., Wong, J.Y. van Dyk, R., Konasewich, D.E. 1991. The Use of Mine Tailings in Concrete Surface Covers to Control Acid Mine Drainage in Waste Rock Dumps. Tome 4. pp. 69-84. In Proceedings: Second International Conference On The Abatement Of Acidic Drainage. MEND Secretariat and CANMET, September, 1991, Montreal, Canada.

Hallam, R.L., Haile, J.P. and Brouwer, K.J. 1991. Waste Disposal Practices for Control of Acidic Drainage. Tome 4. pp. 85-106. In Proceedings: Second International Conference On The Abatement Of Acidic Drainage. MEND Secretariat and CANMET, September, 1991, Montreal, Canada.

Hamaguchi, R.A. 2000. Innovative Reclamation Research at Highland Valley Copper. Highland Valley Copper Report. 15 pp.

Hedin, R.S., Watzlaf, G.R., and Nairn, R.W. 1994. Passive Treatment of Acid Mine Drainage with Limestone. J. Environ. Qual. 23: 1338-1345.

Helbert, S., 1996. Sewage Sludge Nitrogen: A Field Study of Sludge Nitrogen Dynamics and A Laboratory Study of Ammonia and Nitrous Oxide Gas Evolution. Master's Thesis, Memorial University of Newfoundland, Dept. of Forestry. Unpublished. 171 pp.

Inoue, C. 1995. Oxidation of Ferrous Ions In Mine Drainage By Iron-Oxidizing Bacteria. In: Bioremediation: The Tokyo 1994 Workshop, OECD. 329-333.

King, J.K., Harmon, S.M., Fu. T.T., and Gladden. J.B. 2002. Mercury removal, methylmercury formation, and sulfate-reducing bacteria profiles in wetland mesocosms. In: Chemosphere. 46(6): 859-870.

Kuyucak, N., Mikula, R.J. and Wheeland, K.G. 1991. Evaluation of Improved Lime Neutralization Processes - Part 3 - Interpretation of Properties of Lime Sludge Generated by Different Processes. Tome 2. pp. 31-33. In Proceedings: Second International Conference On The Abatement Of Acidic Drainage. MEND Secretariat and CANMET, September, 1991, Montreal, Canada.

Lapakko, K. and Antonson, D. 1991. Mixing of Limestone with Acidic Producing Rock. Tome 2. pp. 343-358. In Proceedings: Second International Conference On The Abatement Of Acidic Drainage. MEND Secretariat and CANMET, September, 1991, Montreal, Canada.

Leeson, A., Foote, E.A., Banks, M.K. and Magar, V.S. (Eds.). 2001. Phytoremediation, Wetlands, and Sediments. Battelle Press, 2001.

Leroy, J.C. 1973. How to Establish and Maintain Growth on Tailings in Canada - Cold Winters and Short Growing Seasons. pp. 411-449. C.L. Aplin and G.O. Argall (Eds.). In: Tailing Disposal Today. Proceedings of the First International Tailing Symposium, October and November 1972, Tucson, Arizona.

Lovett, R.J., Rymer, T.E. and Ziemkiewicz, P.F. 1991. Trapzene for Treatment of Acid Mine Drainage. Tome 2. pp.35-46. In Proceedings: Second International Conference On The Abatement Of Acidic Drainage. MEND Secretariat and CANMET, September, 1991, Montreal, Canada.

Lundgren, T., Terratema and Lindahl, L.A. 1991. The Efficiency of Covering the Sulphidic Waste Rock in Bersbo, Sweden. Tome 3. pp. 239-255. In Proceedings: Second International Conference On The Abatement Of Acidic Drainage. MEND Secretariat and CANMET, September, 1991, Montreal, Canada.

Manahan, S.E. 1975. Environmental Chemistry Second Edition. Willard Grant Press. Pp. 129-131.

Mander, U. Ulo and Jenssen, P.D. 2003. Constructed wetlands for wastewater treatment in cold climates. WIT Press, pp. 325.

Matthew, F.L. 1973. Pros and Cons of Combined Treatment of Mining and Domestic Wastes. Tailing Disposal Today. pp. 700-713. C.L. Aplin and G.O. Argall (Eds.). In: Tailing Disposal Today. Proceedings of the First International Tailing Symposium, October and November 1972, Tucson, Arizona.

Noah, K.S., Roberto, F.F., Bruhn, D.F., Wey, J.E. and Wollant, D.G. 1999. Cyanide Degradation In Tailings Ponds By Stimulating Indigenous Microorganisms. U.S. D.o.E. - Idaho National Engineering and Environmental Laboratory. GA000175. 7. pp.

Nyer, E.K., Davis, S. and King, I. 2002. Oxygen Revisited. Ground Water Monitoring & Remediation. 22(3): 44-49.

Pichtel, J.R., W.A. Dick and P. Sutton. 1994. Comparison of amendments and management Practices for Long-Term Reclamation of Abandoned Mine Lands. J. Environm. Qual. 23: 766-772.

Reinhardt, C.H. 1999. Acid Mine Drainage in Pennsylvania Streams: "Ironing Out" The Problem. Restoration and Reclamation Review. V. 5.1: 9 pp.

Shackle, V.J., Freeman, C. and Reynolds, B. 2000. Carbon Supply and the regulation of enzyme activity in constructed wetlands. Soil Biology and Biochemistry. Nov. 32 (13): 1935-1940.

Scholz, M., Xu, J. and Dodson, H.I. 2001. Comparison of filter media, plant communities and microbiology within constructed wetlands treating wastewater containing heavy metals. J. Chem. Tech. and Biotech. Aug. 76 (8): 827-835.

Scholz, M. and Xu, J. 2001. Comparison of vertical-flow constructed wetlands for the treatment of wastewater containing lead and copper. J. Institution Water and Environ. Management. Nov. 15 (4): 287-293.

Scholz, M. and Xu, J. 2002. Performance comparison of experimental constructed wetlands with different filter media and macrophytes treating industrial wastewater contaminated with lead and copper. Bioresource Technology Jun. 83(2): 71-79.

Shibley, P.W.M. and Dymov, I.K. 1991. Flocculated Precipitants Reaction Technique Yields Coarse Precipitates. Tome 3. pp. 257-270. In Proceedings: Second International Conference On The Abatement Of Acidic Drainage. MEND Secretariat and CANMET, September, 1991, Montreal, Canada.

Smith, K. 1997. Constructed Wetlands For Treating Acid Mine Drainage. Restoration and Reclamation Review. V. 2.7: 6 pp. (http://www.hort.agri.umn.edu/h5015/rrr.html).

Wickramanayake, G.B. and Hinchee, R.E. (Eds.). 1998. Bioremediation and Phytoremediation. Chlorinated and Recalcitrant Compounds. In: The First International Conference on Remediation of Chlorinated and Recalcitrant Compounds, Monterey, California, May 1998.

Ziervogel, H.D., P.Eng. EBA Specialist in Contaminant Remediation in Cold Regions. Personal Communication. 2004.

10.0 BIBLIOGRAPHY

Azaizeh, H.A., Salhani, N., Sebesvari, Z. and Emons, H. 2003. The Potential of Rhizosphere Microbes Isolated from a Constructed Wetland to Biomethylate Selenium. J. Environm. Qual. 32:55-62.

Calabrese, J.P., Sextone, A.J., Bhumbla, D.K., Bissonnette, G.K. and Sencidiver, J.C. 1991. Application of Constructed Cattail Wetlands for the Removal of Iron from Acid Mine Drainage. Tome 3. pp. 559-575. In Proceedings: Second International Conference On The Abatement Of Acidic Drainage. MEND Secretariat and CANMET, September, 1991, Montreal, Canada.

Cheng, W., Virginia, R.A., Oberbauer, S.F., Gillespie, C.T., Reynolds, J.F., and Tenhunen, J.D. 1998. Soil Nitrogen, Microbial Biomass, and Respiration along an Arctic Toposequence. Soil. Sci. Soc. Am. J. Division S-3 - Soil Biology & Biochemistry. 62: 654 - 662.

de Souza, M.P., Chu, D., Zhao, M., Zayed, A.M., Ruzin, S.E., Schichnes, D. and Terry, N. 1999. Rhizosphere Bacteria Enhance Selenium Accumulation and Volatilization by Indian Mustard. Plant Physiology. 119: 565-573.

de Souza, M.P., Pilon-smits, E.A.H., Lytle, C.M., Hwang, S., Tai, J., Honman, T.S.U., Yeh, L. and Terry, N. 1998. Rate-Limiting Steps in Selenium Assimilation and Volatilization by Indian Mustard. Plant Physiology. 117: 1487-1494.

Dickinson, E. 2003. A Solution for the Acid Mine Drainage Problem. Resource World Magazine. November: 50-51.

Fan, T. W-M, Lane, A.N. and Higashi, R.M. 1997. Selenium Biotransformations by a Euryhaline Microalga Isolated from a Saline Evaporation Pond. Environmental Science & Technology. 31(2): 569-576.

Fan, T.W.-M., The, S.J., Hinton, D.E. and Higashi, R.M. 2002. Selenium Biotransformations into proteinaceous forms by foodweb organisms of selenium-laden drainage waters in California. Aquatic Toxicology. 57: 65-84.

Gao, S., Tanji, K.K., Peters, D.W., Lin, Z.Q. and Terry, N. 2003. Selenium Removal From Irrigation Drainage Water Flowing Through Constructed Wetland Cells With Special Attention To Accumulation In Sediments. Water, Air and Soil Pollution. 144: 263-284.

Gao, S., Tanji, K.K., Lin, Z.Q., Terry, N. and Peters, D.W. 2003. Selenium Removal and Mass Balance in a Constructed Fow-Through Wetland System. J. Environm. Qual. 32: 1557-1570.

Hare, F.K. and Thomas, M.K. (Eds.). 1974. Climate Canada. Wiley Publishers of Canada Limited, Toronto, 1974.

Hendricks, A.C. 1991. The Use of an Artificial Wetland to Treat Acid Mine Drainage. Tome 3. pp. 549-558. In Proceedings: Second International Conference On The Abatement Of Acidic Drainage. MEND Secretariat and CANMET, September, 1991, Montreal, Canada.

Knapp, R.A. 1987. The Biogeochemistry of Acid Generation In Sulphide Tailings And Waste Rock. In Proc.: Acid Mine Drainage Seminar/Workshop. Halifax N.S., March, 1987.

Environment Canada, Transport Canada and the Panel for Energy Research and Development. pp. 47-62.

Lemly, A.D. 2003. Symptoms and implications of selenium toxicity in fish: the Belews Lake case example. Aquatic Toxicology. 57: 39-49.

Lemly, A.D. and King, R.S. 2000. An Insect-Bacteria Bioindicator For Assessing Detrimental Nutrient Enrichment In Wetlands. Wetlands. 20(1): 91-100.

Leroy, J.C. 1973. How to Establish and Maintain Growth on Tailings in Canada - Cold Winters and Short Growing Seasons. pp. 411-449. C.L. Aplin and G.O. Argall (Eds.). In: Tailing Disposal Today. Proceedings of the First International Tailing Symposium, October and November 1972, Tucson, Arizona.

Lin, Z.Q., de Souza, M., Pickering, I.J. and Terry, N. 2002. Evaluation of the Macroalga, Muskgrass, for the Phytoremediation of Selenium-Contaminated Agricultural Drainage Water by Microcosms. J. Environm. Qual. 31: 2104-2110.

Lockhart, W.L., Muir, D.C.G., Wagemann, R., Brunskill, G. and Savinova, T. 2003. Chapter 12. Methods to Assess the Effects of Chemicals in cold Climates. In: SCOPE 53 - Methods to Assess Effects of Chemicals on Ecosystems. 27 pp. Electronic version prepared by M. S. Swaminathan Research Foundation, India. (http://www.icsu-scope.org/downloadpubs/scope53/chapter12.html).

McKenna, J.E. Jr., 2003. Community Metabolism During Early Development of a Restored Wetland. Wetlands. 23(1): 35 - 50.

Sharmasarkar, S. and Vance, G.F. 2002. Soil and Plant Selenium at a Reclaimed Uranium Mine. J. Environm. Qual. 31: 1516-1521.

Switras, S. 1999. The Potential of Phytoremediation Techniques for Selenium Removal. Restoration and Reclamation Review. V. 5.4: 6 pp.

Taddeo, F.J. and Weider, R.K. 1991. The Accumulation of Iron Sulfides in Wetlands Constructed for Acid Coal Mine Drainage (AMD) Treatment. Tome 3. pp. 529-547. In Proceedings: Second International Conference On The Abatement Of Acidic Drainage. MEND Secretariat and CANMET, September, 1991, Montreal, Canada.