

AN OVERVIEW OF MINING WASTE MANAGEMENT  
ISSUES IN WISCONSIN

A REPORT TO THE NATURAL RESOURCES BOARD

BY

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## **EXECUTIVE SUMMARY**

Metallic mineral development in northern Wisconsin carries with it potential for very serious environmental harm. Much of this potential impact is associated with the disposal of the large volumes of mining waste which could be generated by mining operations. If not properly managed, waste created by mining of sulfide mineral deposits, such as those in northern Wisconsin, has the potential to create acidic drainage conditions which can persist for many years and result in extensive environmental degradation. Such conditions are well-documented at mine sites throughout the United States and Canada. Citing the past failures of the mining industry to properly manage and reclaim sulfide waste materials, concerned citizens have petitioned the Department of Natural Resources to prohibit mining of all orebodies containing sulfide minerals, until adequate technology exists to deal effectively with the waste management issue. The Natural Resources Board denied the petition, based on the lack of legal authority to adopt such a policy, but requested additional information pertaining to mining waste management and reclamation.

The problem of acid mine drainage has been widely known for many years and it was the main reason the federal government enacted the Surface Mining Control and Reclamation Act in 1977 to regulate the coal mining industry. Since enactment of that law, a great deal of experience has been gained in handling and successfully reclaiming acid-generating wastes in the coal industry. In addition, tremendous amounts of research have been conducted over the past twenty years throughout the United States and Canada studying the mechanisms which cause acidic drainage as well as the means to prevent and control such occurrences as they relate not only to coal mining but also to metallic mining. Development of control measures are founded on the generally accepted premise that acid generation will be controlled by reducing the availability of at least one of the three components needed for acid formation; sulfide minerals, water and oxygen.

For the most part, state, federal and provincial governments are now requiring that new and proposed mining waste facilities be designed in a manner which prevents or controls the formation and migration of acidic drainage or seepage. Such controls, including placement of covers and liners, are also being applied to closure of existing facilities and reclamation of abandoned sites. Through these applications and continuing research activity, various control technologies have been shown to be effective in controlling acid formation. However, at most of these sites, the control technology was implemented after the acid-generating condition was fully developed and the effectiveness of the control measures are reflected in a reduction of acid generation, not a complete cessation of acid generation. Long-term monitoring data from metallic mining waste sites are currently lacking, but preliminary results indicate the acid generation process can be controlled through various control measures. In addition, technology applied in other industries, such as the coal mining and solid waste management industries, have applicability to metallic mining waste sites, as well.

There are no ideal metallic mineral mining sites which can be pointed to as the model approach in preventing acidic drainage industry-wide. This is the case for several reasons. First and foremost is the fact that due to the short history of comprehensive regulation, sites which have been designed, operated and closed using appropriate control measures do not exist. Regulators from various state, federal and provincial agencies do not interpret this to indicate that such sites

cannot be developed. Rather, it is felt that successful sites will be developed as the current pollution prevention technology is applied to new sites from the onset of operation. Second, while specific control measures are proving to be effective in retroactively controlling acid generation at some sites, effectiveness is not guaranteed at other sites due to unique characteristics of each mining operation and associated waste material, in combination with varied environmental features of the sites. Any proposed mining project must be evaluated in terms of the specific nature of the anticipated waste materials and its site characteristics in order to develop an effective waste management design.

Wisconsin's regulatory approach for mining waste facilities is essentially to regulate such sites in accordance with the same technical criteria and principles as those applied to other solid waste facilities. One of the basic elements of Wisconsin's regulatory program is to prevent acidic drainage from mining sites. An exhaustive evaluation of the site selection and facility design of any proposed mining waste site is required, and prospective mining wastes must be thoroughly characterized with respect to their acid generation potential, leaching characteristics and chemical, mineralogical and radiological composition. The Department must also set specific performance standards which must be met by the waste facility.

If a facility is approved for construction and operation, the regulations also provide for extensive ongoing monitoring and inspection of the facilities. The laws also require a performance bond posted by the operator to assure proper closure of the waste site, and a separate financial instrument to guarantee monitoring and long-term care of the site for an additional forty years after closure, and they specify that the owner of the facility is perpetually liable for long-term care and maintenance of the site. Finally, every prospective mine must be reviewed through the comprehensive permitting process, which includes a contested case public hearing at the end of the process, during which such issues as potential acid drainage are thoroughly evaluated. Unless it is shown that a proposed project will meet the criteria established in the laws and codes, the necessary permits will not be issued.

Department of Natural Resources staff believe appropriate application of currently available and developing technology for pollution prevention combined with the comprehensive regulatory controls provided in state laws and rules are capable of providing the necessary level of environmental protection for future mining projects in this state. Staff share the view that a project should not be advanced if it cannot be designed, operated and closed in a manner which would effectively control the development of long-term acidic drainage and seepage conditions.

## **An Overview of Mining Waste Management Issues in Wisconsin**

### **BACKGROUND**

The Wisconsin Department of Natural Resources was recently petitioned by groups of concerned citizens to amend the applicable administrative codes to prohibit mining of any sulfide based ore body in the state. The primary reason for this petition was a concern on the part of the petitioners that mining such ore bodies will invariably lead to the generation of acidic drainage and ultimately to widespread contamination of groundwater and surface water. The petitioners assert there is no proven disposal or reclamation technology available to ensure long term stability of waste resulting from mining sulfide ore bodies. Further, the proponents of the petitions maintain that mining of sulfide ore bodies should be prohibited in Wisconsin until adequate technology is developed and proven to be successful.

The petition to ban sulfide mining was referred for review and action to the Wisconsin Natural Resources Board, the seven member citizen board which establishes policy for the Department. The Natural Resources Board considered the petition at its December 1994 meeting and took oral statements from over thirty speakers advocating adoption of the petition. Department legal staff indicated to the Natural Resources Board that the state legislature, not the Natural Resources Board, has the authority to adopt such a prohibition. Further, legal staff explained that the legislature, in developing the statewide mining policy, established a process under which each individual mining proposal is reviewed on its own merits to determine compliance with the applicable laws and rules and ultimately whether or not the necessary permits and approvals should be issued or denied. Department technical staff also indicated to the Natural Resources board that, in its opinion, the regulatory controls over mining operations provided adequate safeguards to protect against environmental contamination. Staff further stated that effective reclamation technology exists to prevent the generation and uncontrolled release of acidic drainage.

The Natural Resources Board voted to deny the petition based on information presented by the Department staff. However, given the extent of citizen input and the concerns expressed at the meeting, the Natural Resources Board also requested that Department staff prepare a "white paper" to expand on the problems associated with mining sulfide ore bodies, particularly as related to disposal of the associated waste materials. In addition, the Natural Resources Board requested that the paper include discussion of the technology available to deal with such waste materials and examples of where this technology has been successfully implemented. This paper is not intended to comprise a complete technical treatment of the issues related to mining waste management but

it will provide a basic summary of those aspects of the issue which are relevant to proposed activity in Wisconsin.

## **INTRODUCTION**

Wisconsin has a long history of mining activity beginning with pre-settlement recovery of lead in southwest Wisconsin and mining of native copper near Lake Superior by the Native Americans living in the area. Larger scale mining operations began in the 17th century when French explorers undertook recovery of shallow deposits of lead in the southwest portion of the state. Mining activity expanded to include zinc resources, and extensive underground zinc-lead mines were developed and continued in operation until the late 1970s. In addition to lead and zinc mining in southwest Wisconsin, the state has also experienced significant iron mining activity, primarily in and around Iron, Ashland, Jackson and Florence Counties. Large-scale iron mining operations began in the late nineteenth century and continued until 1982 when the open pit mine near Black River Falls permanently closed due to depressed market conditions. While there has been very limited recovery of other metals in the state, production of lead, zinc and iron dominated the metallic mining industry in the state through the 1980s.

Until the early 1960s, the Precambrian rocks of northern Wisconsin were viewed as being favorable only for the occurrence of iron deposits and possibly copper deposits similar to those found in the upper peninsula of Michigan. That view changed after the discovery of several zinc, lead and copper ore bodies in Canada in areas with geologic similarities to northern Wisconsin. Those discoveries and the advancement of airborne geophysical technology led to increased exploration activity in northern Wisconsin with the focus being deposits of base metals, such as zinc, copper and lead. Late in 1968, Great Lakes Exploration Company, which was a subsidiary of Kennecott Copper Corporation at the time, made the first significant discovery of a non-ferrous ore body in northern Wisconsin with the discovery of the Flambeau ore body near Ladysmith in Rusk County.

The Flambeau ore body, and other discoveries after it, are classified as submarine volcanic massive sulfide deposits, meaning they originated with volcanic activity in an oceanic environment and they consist of over 50% sulfide minerals by weight. Some of the sulfide minerals contain valuable and recoverable metals, such as copper and zinc, while a large portion of the other sulfide minerals are a subeconomic mix of iron and sulfur. Thus far there have been four announced mineral deposits in the state which could some day be developed. These would include the Flambeau ore body, the Crandon ore body in Forest County, the Bend deposit in Taylor County, and the Lynne deposit in Oneida County. The Crandon ore body is about ten times larger than the next largest of the deposits and contains estimated reserves of about 60 million tons. At the present time, the Flambeau ore body is the only deposit being mined, but the permitting process is underway for the Crandon Project.

## MINING WASTE

Mining a typical ore body in Wisconsin would directly generate several types of waste materials. These include overburden (glacial till and sand and gravel) which could overlie the ore body and must be removed in the case of a surface mine, and various types of waste rock, which either overlie or abut the ore zones and must also be removed in order to access the ore. Of these materials, waste rock is generally the only waste type which could pose a significant long term environmental threat, as it could contain significant sulfidation.

Another source of waste is related to ore processing facilities. In order to recover the metals contained in these deposits, the ore must go through a smelting and refining process. There are no smelters located in Wisconsin and there are no plans to construct such a facility within the state. Therefore any products from a metallic mine in northern Wisconsin would be transported to a facility in another state or Canada. Given the extreme costs of transporting material such a distance it will generally be necessary to concentrate the ore at the mine site prior to shipping, to reduce transportation costs. As an example, the Crandon ore contains less than 120 pounds of zinc in every ton, but after concentration, the material would contain about 1100 pounds of zinc per ton. Thus, through concentration, the volume of material to be transported is greatly reduced but it also results in generation of a substantial volume of waste material which must be disposed of at the mining site.

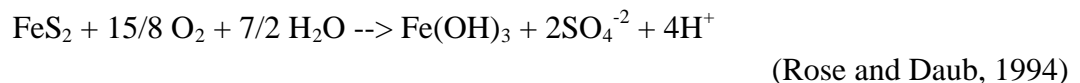
The most likely concentration process for the known mineral deposits in Wisconsin would be froth flotation. The first step in the concentration or milling process involves crushing and grinding the ore to an extremely fine particle size, essentially reducing the solid ore to a powdery mixture of individual mineral grains. This ground ore is then mixed with water to create a pulp that is directed to a series of tanks or cells. Here, through the addition of the proper mixture of chemicals, air and agitation, the valuable mineral particles can be induced to adhere to bubbles in the solution, which rise to the top of the cell to form a surface froth that can be collected as a concentrate. By varying the addition of reagents, it is possible to recover separate concentrates for several of the valuable metals contained in the ore, such as copper, zinc and lead, in the case of the Crandon ore body. Metals like gold and silver will normally be recovered at a later stage of mineral processing, when the concentrates are smelted.

The tailings (waste minerals remaining after recovery of the concentrates) are usually transported in slurry form to a disposal facility, where the solid particles are allowed to settle and the clarified water is returned to the mill for reuse. In some underground mines, such as the proposed Crandon project, a portion of the tailings can be used for backfilling the underground workings to provide structural support and facilitate more complete and efficient removal of the ore body.

## ACID GENERATION AND NEUTRALIZATION

Waste rock and tailings generated in association with mining of a sulfide ore body can contain significant quantities of sulfide minerals, such as the iron sulfides, pyrite and pyrrhotite, as well as some of the unrecoverable, economic sulfide minerals. The presence of sulfide minerals is important because these minerals are the primary source of acidic drainage associated with many mining sites around the world. Sulfide minerals, when exposed to oxygen and water can progress through a series of chemical reactions where acid is eventually produced. The dissolution of iron sulfide minerals generates the majority of acid produced by mining wastes (Lapakko, 1991). Oxidation of pyrite, the principle mineral of concern, can ultimately result in the production of two units of acid for each unit of sulfur contained in the pyrite.

Initially, the rate of this reaction is quite slow, but as the system becomes more acidic, the rate can be dramatically accelerated by the presence and activity of iron- and sulfide- oxidizing bacteria. Recognizing there are several intermediate steps, the overall reaction for the oxidation of pyrite in the presence of water is represented by the following equation:



The end products of the above reaction are solid iron hydroxide which typically precipitates out of solution in the form of a yellow-red sludge, dissolved sulfate and hydrogen ions which contribute to the degree of acidity of the solution. As the pore waters within the waste become more acidic, other metal sulfide minerals present in the waste mass also begin to dissolve, contributing additional metal ions to the solution. When allowed to proceed unabated, a fully developed acid drainage situation can be characterized by waters containing high levels of dissolved solids, heavy metals, and sulfate and that has an extremely low pH.

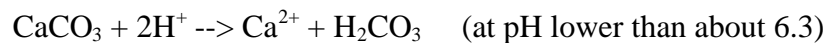
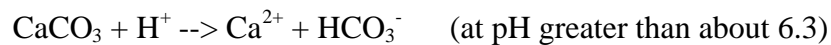
The rate at which the sulfide minerals oxidize is heavily dependent on the pH of the pore water. As reported by Kleinmann and others (1980), the rate of oxidation is slow when the pH is in the near neutral to mildly acidic range, increases as the pH drops below 4.5, and then increases even more as the pH goes below about 3.0. The increase in oxidation rate below a pH of 4.5 is primarily due to the influence of bacteria which serve to accelerate the oxidation of iron sulfide minerals. Bacterial activity occurs when the pH is greater than 4.5, but its impact on the rate of oxidation is maximized when the pH is below 3.5. (B.C. Acid Mine Drainage Task Force, 1989).

While sulfide mineral dissolution does occur naturally, the mining process may result in a much more extensive reaction and higher reaction rates. This is because the mining process relocates the sulfide minerals from a fairly isolated location in the ground to the surface, where the minerals are much more easily exposed to water and oxygen, which are the two other necessary



components to develop acid drainage. Also, mining tends to break the rock into smaller fragments, dramatically so in the case of tailings, thereby increasing the surface area of the sulfide minerals available for oxidation. Both of these factors serve to increase substantially the rate at which the sulfide mineral dissolution occurs, and therefore the development of acidic conditions is also accelerated.

Another important chemical process which can take place in nature and in waste piles is the dissolution of carbonate minerals such as calcite (CaCO<sub>3</sub>), the predominant mineral in limestone. As opposed to the sulfide minerals which have the capacity to generate acid, carbonate minerals are capable of consuming acid, thereby buffering the solution. Other carbonate minerals, specifically dolomite, and some non-carbonate minerals as well, have the capacity to disassociate in the presence of acidic solutions to consume the generated acid. However these minerals do not react as quickly as calcite nor are they generally as reactive at near neutral pH. For that reason, this discussion will focus on the dissolution of calcite. The acidic waters created by the oxidation of the sulfide minerals can react with the carbonate minerals, and the hydrogen ion, which represents acidity, is then combined with oxygen and carbon to form dissolved bicarbonate ions or weak carbonic acid along with dissolved calcium ions. These reactions are represented by the following equations:



(Lapakko, 1994)

As mentioned above, other non-carbonate minerals such as pyroxene, olivine and some feldspars are also capable of consuming some acidity, but are not generally as important or as efficient as the carbonate minerals in maintaining near-neutral conditions (Lapakko, 1994). The dissolution of carbonate minerals is important because if they are present in sufficient amounts, they are capable of neutralizing most of the acid produced by the sulfide minerals present. The minerals capable of neutralizing acidic drainage tend to react such that pH of the drainage progress through a step-like sequence of increasing acidity. In simplified terms, the pH of the solution will remain relatively constant as one of the mineral groups buffers the solution, then exhibit a fairly rapid decrease in pH once that particular controlling mineral has been consumed. The change in pH will then level off as another buffering mineral begins to react. While the oxidation of sulfide minerals occurs concurrently with the dissolution of the neutralizing minerals, if enough neutralizing material is present, the resultant pore water will remain in a near neutral condition and the subsequent dissolution of other metal-bearing minerals will be greatly inhibited.

## **PREDICTIVE TESTING**

Given that both acid-producing and acid-consuming reactions will likely occur within a waste pile, in order to best manage the waste disposal it is desirable to predict whether or not the waste material, as a whole, will generate acidic drainage. Predictive testing procedures have evolved over the years to help answer this question. Unfortunately, there is a paucity of data available which correlates the predictive results with actual drainage water quality from waste facilities. In order to extrapolate predictive test results to expected field conditions one must first obtain representative samples of the prospective waste material by conducting an extensive sampling program. The sampling program should be designed to collect sufficient numbers of samples from different geologic units and also should reflect the proposed mine plan by sampling discrete areas in the proposed mine (B.C. Acid Mine Drainage Task Force, 1989).

There are basically two distinct approaches which can be used to determine the reactive nature of prospective waste materials. The first of these are termed *static tests* and are intended to determine the overall acid-producing and acid-consuming potential, or neutralization potential, of the waste materials. These two parameters are calculated based on relatively simple chemical analyses and provide a quick and relatively inexpensive means to determine the gross potential of the waste to generate acidic drainage. Those two values are then either expressed as a ratio or a sum and the net neutralization potential is determined. These tests are used as an initial screening tool to identify those wastes which are clearly acid-producing or conversely those with either little acid-generating material or excessive neutralizing material. Uncertainty arises when the results indicate that the wastes are only marginally acid producing or neutralizing.

Some wastes initially identified as having a net positive neutralizing potential have indeed been acid-producing and others which were classified as acid-producing were found to have greater neutralizing capacity (Morin and Hutt, 1994). For that reason, except in the case of extreme acid or base values, it will be necessary to conduct additional testing of the waste. Such tests are termed *kinetic tests*, and are essentially laboratory simulations of the weathering and oxidation processes. Actual procedures may vary, but most tests include exposure of the wastes to air and water and subsequent collection and analysis of the drainage emanating from the test cell. The tests are conducted over a long period of time (several months at a minimum), and the characteristics of the leachate give an indication of the rates of the various chemical reactions taking place and the ultimate drainage water quality. The results of the kinetic tests can then be used to determine the proper handling and possible treatment of the wastes during the mining operation.

### **ACID MINE DRAINAGE IN THE U.S.**

The problem of acidic mine or acidic rock drainage is not a new phenomena. It has been widely recognized in the United States for well over a century. Initially, acidic drainage was associated with coal mining in the Appalachian region in the eastern U.S., but over time the problem has

been identified throughout the country and found not to be restricted to coal mining. In the western part of the country, mining of metallic ores containing sulfide minerals has led to the development of widespread acidic drainage problems in addition to those associated with coal mining sites. The chemistry of the problem, specifically the dissolution of sulfide minerals, is the same regardless of whether the site is a coal mine or some other type of mining operation. For that reason, information from research projects or actual field applications pertaining to the prediction, prevention and treatment of acidic drainage from mining sites is generally transferrable from non-metallic (coal) to metallic (copper, lead, zinc, gold, etc..) mining sites.

Historically, mining waste disposal sites were located more out of a matter of operational convenience rather than concern for the potential environmental impacts of the facility. Waste rock was simply dumped in areas adjacent to the mine and tailings were typically deposited in valleys or other low areas which served to contain the slurried wastes. Once mining was completed, the operators commonly abandoned the sites without conducting any site restoration except to salvage useable equipment or other materials from the site. The barren piles of waste would be left, posing a long-term threat to water quality through erosion and sedimentation, as well as the development of acidic drainage as described above.

As general environmental awareness progressed and the problems became more visible, mining and mining waste disposal practices also began to change. In the United States, this was first institutionalized on the federal level for the coal mining industry with the passage of the Surface Mining Control and Reclamation Act in 1977, which imposed controls on coal mining operations and required reclamation of these mining operations.

The situation in regard to metallic mining has lagged behind the coal mining industry. There is no federal equivalent to the Surface Mining Control & Reclamation Act which pertains to metallic mining sites. Rather, individual states have developed laws and rules which best suit their particular environment and needs. Through implementation of such regulations, it is becoming more common for mining waste sites to be subjected to locational criteria and to include engineering features intended to reduce the environmental impacts from the construction and operation of the facility.

However, new mining operations are not infallible by any means, as evidenced by recent experience near Summitville, Colorado. Severe environmental problems have arisen there as a result of a poorly constructed mining facility in the late 1980s and have been compounded by inadequate bonding requirements. The points to be made are that stringent controls on siting, construction, operation and reclamation of mining waste facilities are necessary, and that costs associated with such controls are increasingly considered a predictable and reasonable cost of doing business.

It is also important to keep in mind that there is only a short history of well-regulated metallic mining sites in this country. Consideration of potential environmental impacts when designing a mining waste site is a relatively recent phenomenon. Similarly, specific technological approaches to deal with the problems posed by metallic mining waste disposal are also quite new and lack a long track record to prove their effectiveness. However, the bases for much of the technology currently applied to metal mining sites come from the coal industry, which does have a significantly longer period of regulation and research.

Recently, a great deal of research focusing on metallic mining sites has been initiated. Much of this work has been conducted in Canada in areas geologically similar to northern Wisconsin. In addition, experience gained in the solid and hazardous waste management industry in landfilling wastes is also applicable to mining sites, since management of each kind of waste shares the primary goal of isolating the waste from the surrounding environment. This is especially important since the design and construction of solid waste facilities has reached a high level of sophistication and effectiveness. As is the case in Wisconsin, several other states also approach the design of a mining waste facility in a manner similar to other solid waste facilities.

Even without intervention, not all metallic mineral mines produce acidic drainage. There are two primary reasons why this is the case. First, not all metal mines contain sulfide minerals. If sulfide minerals are not present, acid-generating reactions described above will not take place, and subsequent reclamation and long-term site stabilization are considerably simpler. The vast iron deposits which were mined in northern Wisconsin are an example of such an occurrence. Second, the ore minerals may be situated in a carbonate-rich environment. In such a case, carbonate minerals exist to such excess that the acid neutralizing capacity of the host rock far exceeds the acid generating capacity of the sulfide minerals, and the waters remain near neutral. The mines of southwest Wisconsin which occur within limestone and dolomite units, are an example of this situation. The isolated occurrences of acidic drainage in the area are related to piles of roaster waste, which are more akin to a smelting waste than mining waste.

In regard to the more typical flotation tailings and the mines themselves, elevated levels of sulfate in groundwater have been recorded, the water remains near neutral, and no anomalous concentrations of metals have been reported in association with the mining activity (Evans and Cieslik, 1985, and Nessman, 1995). Similar situations also occur in the western U.S. where many sulfide orebodies are situated within carbonate strata, such as the Stillwater platinum mine in Montana and the Homestake gold mine in South Dakota (Platenburg, 1994, and Durkin, 1994).

## **PREVENTION OF ACIDIC DRAINAGE**

### General

In cases where mining wastes are determined to be potentially acid-producing, steps can be taken either to prevent the acidic drainage from forming or to control the release of contaminated water from the facility to the surrounding environment. Over the past twenty years extensive research has been conducted to develop technology to prevent, control or treat acidic drainage from mining wastes. Much of this work has developed in association with reclamation of coal mining sites or in conjunction with remedial actions taken at inactive or abandoned metal mining sites. Based on an assessment of this research it is apparent that each individual site must be evaluated on the basis of its unique nature to determine the most effective and practicable prevention and control measures for implementation at that particular location. Further, it is also obvious that there are no universally applicable measures. Although in theory some approaches could have widespread applicability, they may not be practicable due to other factors, such as legal constraints, availability of materials, or prohibitive costs.

Measures taken to inhibit the formation of acidic conditions within the waste material involve limiting the availability of at least one of the three components necessary to generate acidic drainage, specifically, sulfide minerals, water or oxygen. Options for reducing the availability of sulfide minerals are not as numerous as those for reducing oxygen or water influx and also are not as widely practiced through the mining industry.

### Processing Options

The most technologically viable means of reducing the availability of sulfide minerals in a waste mass is to recover and thus remove the pyrite from the tailings material. Pyrite flotation, using a process similar to that discussed above, is possible and would serve to remove most of the sulfide minerals from the waste, in the form of a pyrite concentrate. However, total recovery of all sulfides is not achievable, so that the remaining wastes may nevertheless be acid-generating. These materials will likely require disposal in an engineered facility. In addition, the concentrated sulfide material which is recovered still needs to be either treated, disposed of in a secure location, or an alternative use for the material would need to be identified. At this time, a viable market for large volumes of sulfide minerals from mining wastes does not exist since North America has abundant sources of both iron and sulfur.

Another "processing" approach to reduction of acidic drainage specifically from tailings facilities involves manipulation of the manner in which the tailings material is deposited in the tailings basin. While this method will not change the chemical composition of the tailings material, the physical properties of the waste mass are affected so that susceptibility to acid-generation is reduced. Rather than being deposited with a very high water content, the tailings are handled in a way that reduces the water content of the tailings slurry. When deposited in the tailings basin, the thickened tailings exhibit lower permeability and increased moisture retention capability, both of which serve to reduce the influx of oxygen to the wastes, thereby decreasing oxidation (Woyshner

and St-Arnaud, 1994). Performance of facilities using thickened tailings deposition, such as the Kidd Creek mine near Timmins, Ontario should continue to be monitored. This approach is one of several operational and design alternatives that can be incorporated into a waste disposal facility.

Two other approaches to waste treatment or processing which could reduce the potential for sulfide waste minerals to oxidize include in-situ vitrification and phosphate encapsulation. In-situ vitrification would involve melting the waste material and allowing it to solidify into a more impermeable and hence less reactive mass. Treating the waste with phosphatic solutions induces formation of an encapsulating coating of iron phosphate on the mineral grains which then serves as a barrier to oxidation of the sulfide minerals (Evangelou, 1994). Neither of these options have been used to any extent in actual applications, and cannot yet be considered viable treatment alternatives.

### Barriers To Oxygen and Water Influx

Given the paucity of viable options to remove or reduce the oxidation potential of the sulfide minerals themselves, most modern control technologies focus on means to prevent or decrease the availability of oxygen or water to the sulfide waste materials. Both oxygen and water are necessary in order for the oxidation process to be initiated, and therefore, elimination of one or both of these components will also be effective in the prevention of acidic drainage from sulfide mining waste facilities. The primary method to achieve the goal of reducing oxygen or water influx is construction of some sort of cover system over the waste material. A variety of different materials have been explored for use as covers, but the emphasis should be on selection of materials which are readily available, technologically feasible to construct, and have assurance of long-term stability.

The use of water as a barrier to oxygen influx to waste material has been gaining great attention over the past decade. Under this approach, waste material is deposited under water and is permanently submerged below a free standing column of water. Water is an effective barrier because the rate of oxygen diffusion through water is very low, as is the solubility of oxygen in water. These two characteristics combine to reduce the availability of oxygen to the waste material. Research and experience with facility closures primarily in British Columbia, Ontario, and Sweden have demonstrated that oxidation of reactive sulfide-mining wastes is drastically reduced when the wastes are inundated (Fraser and Robertson, 1994, Davé and Vivyurka, 1994 and Broman and Göransson, 1994). The results generally indicate that if fresh tailings are deposited under water and kept in a saturated condition, the rate of oxidation is very slow and generally limited to a thin surface layer. Highly acidic conditions do not develop and, the rate of metals release from the submerged waste material is also extremely low. Given those findings, many regulators and researchers, particularly in Canada, view water covers as the most promising

means of dealing with acid-generating mining waste materials.

Subaqueous (underwater) disposal and permanent storage of tailings material may be accomplished in either natural or man-made impoundments. While natural lakes have been used successfully as tailings disposal facilities in Canada and elsewhere, under the constitutional public trust doctrine in Wisconsin, tailings disposal in a natural lake would be prohibited. Man-made impoundments and artificial reservoirs for tailings disposal are attractive in terms of preventing oxidation of sulfide wastes, but there are also various concerns with such an approach. Water retention facilities must be carefully designed, constructed and maintained to ensure long term stability, an adequate source of water must be secured to maintain the appropriate water cover over the wastes in times of drought, and maintenance of a column of water may result in increased seepage through the bottom of the facility. Nevertheless, artificial impoundments merit serious consideration when designing waste management facilities for future mining sites.

An approach similar to the water cover described above has been employed in the coal mining industry as well. Fine-grained, sulfide-bearing coal wastes have been reclaimed in a manner which results in the formation of a wetland over the waste disposal facility (Nawrot, et al, 1987). Maintenance of saturated conditions over the wastes limits the influx of oxygen, and the establishment of vegetation, with the accumulation and subsequent decay of organic material on the surface, also has the effect of consuming oxygen. Nawrot (1995) reports that monitoring of the surface water and groundwater quality and the aquatic ecosystem in the area of one such reclaimed facility, the Ayreshire impoundment in Indiana, is showing no evidence of acidic drainage about 11 years after completion of reclamation.

In cases where it is not feasible to rely on a water cover to isolate the waste materials, dry cover systems can be designed to reduce exposure of the waste to oxygen and water. Investigators have evaluated a variety of natural and manufactured materials for use as covers, but this paper will concentrate on what are considered to be the most effective and practical options. Much of the work reported in the literature has been initiated in association with the Mine Environment Neutral Drainage (MEND) program, a cooperative effort between Canadian provincial governments and the mining industry to address the problems posed by acidic mine drainage. MEND has sponsored numerous research efforts aimed at various aspects of the mine drainage issue. This work has led to the subsequent publication of many technical reports, such as that by SENES Consultants Ltd., 1994, from which much of the information in the following discussion of dry covers is derived. The British Columbia Acid Mine Drainage Task Force, another cooperative effort between industry, government and academia, has similarly supported numerous studies and publications, among them the "Draft Acid Rock Drainage Technical Guide" (Steffen, Robertson and Kirsten, 1989), which also served as a significant source of information for the following discussion of cover system options.

Similar to wet covers, dry cover systems are most effective when they limit the amount of oxygen flux into and through the waste material. In addition, dry cover systems also are designed to minimize or prevent infiltration of water into the waste. Reduction of oxygen flow into the waste by a cover system is based on the fact that the main means of oxygen transport through soil material is via the pore spaces between particles. Thus, to be an effective barrier to oxygen, a material should have minimal available interconnected, open pore space between particles. This can be achieved by selection of a material with low permeability or by ensuring that the pore spaces are filled with water, since, as discussed above, diffusion of oxygen through water is very slow. In fact, Nicholson and others (1991) report that the most important factor in controlling oxygen flux through geologic media is the degree of saturation of the material. The closer to full saturation that the material attains, the lower the flux of oxygen. With that principle in mind, recent research has been directed at methods to design dry cover systems which can maintain a soil layer with soil moisture levels near saturation.

Soil materials vary in their ability to retain moisture within their pore spaces. It is beyond the scope of this review to provide excessive detail regarding the physics of fluid flow in unsaturated materials and the physics of moisture retention in soils. However, it is generally established that fine-grained material has a much greater capacity to retain moisture within its pore spaces than does coarse-grained material. Also, in layered systems where coarse and fine units are interlayered, water infiltrating the system will be preferentially held by the fine-grained layers. The difference in moisture retention properties creates a capillary barrier at the interface of the fine-grained units with the coarser material, which helps to maintain near-saturated conditions in the fine-grained material (SENES Consultants, Ltd. 1994). A schematic design of such a cover system is illustrated in Figure 1. In this design, a fine-grained infiltration barrier is sandwiched between two coarse layers and overlain by a moisture retention zone. The latter strata is basically a soil cover used as a growth medium for surface vegetation, but it also serves to prevent desiccation of the underlying fine-grained unit. The upper drainage layer would be constructed of coarse, permeable material, such as sand and gravel, and serves to drain water laterally, thereby reducing infiltration and also preventing moisture loss from the fine grained material through upward capillary forces. The lower capillary barrier would also be a coarser grained material which has the primary purpose of helping to maintain moisture in the fine grained layer through the differences in their hydraulic properties. The infiltration barrier is intended to be any low permeability material, whose main function is to prevent downward flow of water and diffusion of oxygen into the underlying waste materials.

Laboratory and field simulations evaluating layered cover systems have shown that such a system could be very effective in preventing oxidation of sulfide wastes (Yanful et al., 1994, Nicholson et al., 1991, and Bell et al., 1994). The British Columbia Acid Mine Drainage Task Force (1989) and SENES Consultants, Ltd. (1994) both report that several sites in Canada have been closed using similar cover systems, but that extensive monitoring data is not available to document the



degree of success of the covers. However, preliminary data from one of those sites appears to indicate that the cover is functioning as designed and is effective in reducing acidic generation (Bell et al., 1994).

Over the past twenty years, facility owners, government agencies, and academic investigators have conducted considerable research into the properties of infiltration barriers and final cover systems. This effort has extended over several fields of application, such as solid and hazardous waste disposal, low-level radioactive waste disposal, uranium mill tailings reclamation, coal mining waste reclamation and heap leach operations. The theory and practice of barrier layers and waste containment is broadly applicable, regardless of waste type. Some of the more viable materials which have been evaluated and installed as cover layers include low permeability natural soils, clay amended soils, fine tailings material and synthetic membranes. With the exception of the synthetic membrane, these materials could function as effective barriers based on the principles discussed above. Synthetic membranes are proposed as a cover material, because when properly installed, they are essentially impermeable. Alternative cover materials have been investigated, including concrete, shotcrete, asphaltic products and other synthetic sealants but these are not considered widely viable due to a number of concerns and drawbacks, especially regarding their long-term durability.

Natural soils and amended soils have the longest and most extensive history of use because the materials occur widely, are durable, require a low level of maintenance, and have been used extensively in liners and covers in landfill applications. Infiltration barriers constructed of fine tailings material have not been extensively studied, but researchers consider them to have great potential due to their physical properties and availability at mining sites. Specific problems in using tailings material as a cover include the potential for release of contaminants from the tailings, and difficulty in working with tailings, given their fine-grained nature and water retention capacity.

Synthetic membranes are very attractive as a cover material because of their extremely low permeability and resistance to chemical and bacteriological degeneration. However, questions exist in terms of the long term durability of the material due to mechanical damage or naturally induced damage from repeated freeze/thaw cycles, variation in ambient temperature conditions, burrowing animals, and root penetration.

Practical experience gained over the past decade through the widespread installation of membrane-lined or covered facilities has served to identify and resolve early concerns regarding construction of such systems. However, uncertainty exists due to the lack of long-term field data to demonstrate the effectiveness of the material as a cover. Over the next few years, additional information aimed at answering these questions will become available as field studies progress and additional monitoring results from actual installations are obtained and evaluated. It is currently

felt by some researchers that, if properly constructed and protected from damage by covering with other soil layers, synthetic membranes should function as an effective cover for 100 or more years (SENES Consultants, Ltd., 1994).

The currently preferred cover design for solid waste landfills in the state and elsewhere is a composite cover system consisting of layers of both natural and synthetic materials. Such an approach, incorporating redundant low-permeability layers, should provide a long-term barrier to infiltration.

Another approach to cover design is placement of a material which will consume oxygen as a means to prevent the entry of oxygen into the waste material. Oxygen consumption is achieved through the microbial degradation of organic matter deposited in a thick layer over the sulfide wastes, consuming the oxygen before it reacts with the sulfide wastes. Materials which could serve as a suitable cover include wood waste products, peat, sewage sludge, or composted municipal or industrial waste. Many of these materials are attractive because they are readily available, relatively low cost, and in some cases are a waste material themselves requiring disposal.

Research has shown that such covers could be effective in reducing the level of oxygen available to tailings, maintaining near neutral pH, and reducing the dissolved levels of some metals (Tremblay, 1994). However, other research indicates that certain organic compounds which are a by-product of the degradation of the organic material could actually cause mobilization of metals which were previously in a fairly stable state near the surface of the tailings, thereby exacerbating the problem rather than improving it (Ribet et al., 1995). In addition, organic covers could also require replacement on a fairly frequent basis, since the basic premise for the design relies on decomposition of the material, and their long-term effectiveness is unproven (SENES Consultants, Ltd., 1994).

#### Alkaline Addition and Bactericide Application

Two additional practices which have been researched and used in the field, albeit more commonly in the coal mining industry, are the use of alkaline material or bactericides. Use of such applications are predicated on the acceptance that some oxidation of sulfide minerals will occur and are intended to mitigate the eventual impacts of the sulfide oxidation. In some cases, waste material containing buffering minerals are blended with the acid-generating waste to produce a net acid-consuming material. Alkaline addition is aimed at controlling the pH of the fluids moving through the waste material, since as previously discussed, the overall rate of oxidation in near-neutral environment is much less than that in a more acidic environment. Similarly, bactericide addition is intended to limit the rate of sulfide oxidation by inhibiting the activity of iron oxidizing bacteria, which can significantly accelerate the rate of oxidation.

Alkaline or basic material can be used to abate acidic drainage in a variety of ways. Materials can vary and include limestone, lime and sodium hydroxide, but they all function by creating excess alkalinity in the pore waters through the dissolution of the buffering material. The excess alkalinity created by additives or naturally occurring carbonate material is then capable of neutralizing the acid generated in the oxidation of the sulfide minerals, in turn reducing the levels of trace metals released (Lapakko, 1990 and Veldhuizen et al., 1987). Buffer materials can be applied as discrete layers above, within, or below the waste material or they can be mixed with the wastes. Incorporation of the buffering material into the upper surfaces of the waste material appears to offer the most effective means of alkaline addition (B.C. Acid Mine Drainage Task Force, 1989).

Alkaline addition has been a fairly common practice in the coal industry, and in fact, was an important component of the reclamation approach implemented at the Ayreshire facility mentioned previously (Nawrot, 1987). In order for this approach to be effective, the chemistry of the waste material must be well defined, especially its acid-generating capacity, enough of the proper buffering material must be added to generate excess alkalinity, and there must be thorough mixing of the additive with the acid-generating wastes.

In one method of use, the buffering material is placed above or intermixed with the waste material, so that infiltrating water reacts with the alkaline material, creating alkaline pore water capable of neutralizing any acid generated. In another method, a layer of alkaline material is placed at the base of the waste material as a means of treating acidic water which has infiltrated the oxidized waste material. Use of alkaline material does not prevent the oxidation of sulfide minerals. Rather, such an application is aimed at neutralizing acid produced through sulfide oxidation and controlling the pH of pore water, so that the rate of oxidation is not enhanced by bacterial activity.

Similar to lime addition, bactericides do not prevent the oxidation of sulfide minerals, but rather restrict the oxidation process to an inorganic process, which is much slower than the bacterially enhanced reaction. Bactericides are chemicals, including some surfactants and organic acids, which are applied to the surface of the wastes and are essentially toxic to the iron oxidizing bacteria. As reported by the B.C. Acid Mine Drainage Task Force (1989), bactericides generally are capable of up to a five-fold reduction in the rate of acid generation and concentrations of some dissolved metals. However, because they degrade and are flushed away by infiltrating water, bactericides have a fairly limited period of effectiveness. Bactericides cannot be relied on to provide long-term mitigation of acid generation rates, but they may be effective in the period immediately after closure of a mine waste facility to help control the oxidation rate at the surface of the wastes until permanent control measures are in place.

## **COLLECTION OF ACIDIC DRAINAGE**

The final option for dealing with acidic drainage or leachate from a mining waste site is the collection and treatment of such water. Ideally the need for collection and treatment will be minimized as a result of the steps taken to reduce the generation of acidic drainage, such as those previously described. In fact, the goal of a waste management program should be the avoidance of this step, because if treatment is necessary, it can be very expensive and is generally required for a long time, necessitating ongoing operation and maintenance. Nevertheless, it is important to briefly discuss the options available to an operator should the need for collection and treatment arise.

Collection of acidic waters emanating from a mining waste site would involve collection of both surface water and groundwater. Management of surface water is achieved through grading and diversion of water via collection ditches or channels to a central collection pond. Such control is well understood and widely practiced across the many industries and activities which involve land disturbance. Collection of contaminated groundwater is a much more intensive process and will generally involve construction of collection trenches to intercept the water, or operation of wells to bring the water to the surface. Recovery of contaminated groundwater is becoming more common, as remediation projects are conducted throughout the country. Given the difficulty in effective collection of contaminated groundwater, emphasis should be placed on prevention of the migration of leachate to the groundwater. The most common and practicable means of preventing such migration is by placement of a liner system beneath the waste material with a leachate collection system to recover the contaminated liquids.

In contrast to the mining waste facility design practices of the 1970s, most states with significant mining activity now require liners to be placed beneath potentially acid generating waste materials. Further, it may be the case that liner systems may be required even for waste material which has been determined not to be acid-generating, due to other specific characteristics of the waste material. Components of the liner design used at mining waste facilities in other states include single liners, double synthetic liners, a double liner with leachate collection system, double clay liners and combined clay and synthetic liners (Throop, 1995; Beach, 1995; Mount, 1995; Shuld; 1995; Schwab, 1995; and Vaughan, 1995).

The most appropriate design for any given facility is generally determined on a case-by-case basis taking into account the nature of the waste and the characteristics of the site. However, the containment technology applied at mining sites to control the migration of water out of the waste facility is essentially the same as that employed at other solid waste facilities in Wisconsin and other states. As is currently taking place in the mining waste management field, the design technology for solid waste management facilities went through a similar evolution in terms of control measures. Specifically in terms of liner design, solid waste facilities have progressed from

unlined sites to thick clay liners in the 1970s and 1980s to the current approach of composite lined (clay liner plus a synthetic membrane liner) sites with leachate collection systems. As the designs have improved, so has the effectiveness of the containment systems. The principles of solid waste management are directly applicable to future mining waste sites, and it is anticipated that such sites will incorporate the prevailing liner technology applied to solid waste facilities.

### **TREATMENT OF ACIDIC DRAINAGE**

From the perspective of water treatment technologies, acidic drainage or leachate from a mining waste facility will not typically pose an insurmountable challenge. Rather, the drainage is likely to be manageable with conventional water treatment approaches. This is the case because, for the most part, such drainage will be characterized primarily by low pH and elevated levels of metals and other dissolved, inorganic parameters and will not contain complex organic compounds as are present at some other types of contaminated sites. A waste water source of this type is more easily treated than more complex waste streams. The process of designing an effective treatment system will begin with characterization of the drainage through generation of simulated water in column tests, followed by bench-scale testing of different treatment methods. At this time there are two principle means of treating acidic drainage from mining sites, chemical treatment and biological treatment through wetland systems.

Chemical treatment will normally involve neutralization of the water as the first step in treatment. This is accomplished by adding a neutralizing material, usually ground limestone or lime, to the water to raise its pH. In doing so, many of the dissolved metals will be induced to precipitate out of solution in the form of hydroxide solids, forming a sludge which must be collected and disposed in a secure facility. Neutralization will normally be followed by filtration and pH adjustment prior to discharge of the water. In some cases, neutralization may achieve the desired level of treatment, but other sites may require implementation of secondary treatment processes, such as sulfide precipitation or reverse osmosis to further remove certain metals and "polish" the water prior to discharge.

While these treatment processes are quite common and effective, the problem with chemical treatment at a mining waste site is that if the situation develops where treatment is necessary, the need for such treatment will likely continue for a very long time. This will necessitate long term operation and maintenance of the treatment facility and will probably include replacement of the treatment facility at some time. The prospect of long-term or in some cases, perpetual, treatment is obviously undesirable and should be avoided.

Long-term or perpetual treatment is costly and raises an additional issue of financial responsibility for continued maintenance and operation. The State of Colorado will not issue approvals to an operation if it is determined that there is a possibility of long-term drainage from the mine opening

which would require treatment (Mount, 1995). To deal with the financial problems posed by perpetual water treatment at the Golden Sunlight mine in Montana, the operator must pay into a trust fund held by the state in an amount such that the fund will continue to accrue interest over time that is sufficient to cover costs of operation plus replacement of the treatment facilities every twenty years (Platenburg, 1994)

The effectiveness of wetland systems as a means of treating acidic drainage has been known for well over twenty years, and use of artificial wetlands has become a fairly widespread treatment option in cases involving long-term treatment in the coal mining industry. Wetland treatment systems are attractive for a number of reasons including their relatively low costs for construction, operation and maintenance, their ability to be essentially self-sustaining and maintenance-free, and related benefits of enhancing wildlife habitat.

Wetlands have been shown to be effective in mitigating acidity and removing dissolved metals from the drainage through a variety of physical, chemical, and biological mechanisms (Nawrot et al., 1990). One important wetland function, decomposition of organic matter, promotes the activity of certain bacteria that convert sulfuric acid to hydrogen sulfide gas. As this activity proceeds, acidity is reduced and metals precipitate out of solution forming slime deposits on the bed of the wetland and "treated" water continues to flow through the wetland, eventually entering another water course. Passive treatment of acidic drainage through wetlands is most effective when the drainage is only moderately acidic (pH<sup>3</sup>5.5) and the ambient temperature is above 50°F (Nawrot et al, 1990). Therefore, applicability of this type of treatment to a full scale acidic drainage situation in northern Wisconsin is probably questionable. However, the value of wetlands in treating acidic drainage should be considered as a secondary or contingency feature when planning for final reclamation of a mining site.

## **SURFACE STABILITY AND MAINTENANCE**

Successful operation and reclamation of a mining waste disposal site includes stabilizing the surface of the facility to resist physical degradation. Adequate protection must be included in the final facility design to prevent damage through such mechanisms as erosion and mass movement, freeze-thaw effects, root penetration and burrowing animals. Without proper stabilization, these physical processes could act eventually to expose the waste material to the atmosphere, creating increased potential for acidic drainage to occur. Without permanent physical stability, the features incorporated into a facility design to prevent acid generation, which have been described previously, will ultimately be ineffective.

Mine waste facility design must accommodate extreme precipitation events. A surface water management plan should be designed such that flood events will not cause excessive erosion of the surface. The surface must be graded in a manner which allows efficient drainage, but the final

slopes must not be too steep, as such slopes are more prone to erosion than gradual slopes. In addition to proper grading and water handling capabilities, it is imperative that the surface of the soil be stabilized. In most cases this is best achieved by establishing a vigorous vegetative cover on the surface. Vegetation should be established on all finished slopes, including the exterior berms of retention facilities and the top surface of covered sites, as soon as possible after final grading.

Vegetation on the surface will reduce erosion and runoff from the site, stabilize slopes, help to remove water from the subsurface system through increased evapotranspiration and enhance the value of the area for wildlife habitat (Peters, 1984, and Neuman et al., 1993). The Department has firsthand experience at establishing vegetative cover at mining sites through its oversight of reclamation activities at the permitted mining sites in the state, particularly the Jackson County Iron Company site in Jackson County and the four permitted mine sites in southwest Wisconsin. At each of these sites, self-sustaining vegetative communities have been established on bare mining waste, including waste rock and tailings. It is well documented in the literature that through proper planning, surface preparation, seeding, fertilization and mulching, effective vegetative covers can be successfully established on drastically disturbed lands (Peters, 1984, and Hunt, 1989).

If vegetative cover systems are used, avoidance of damage to the barrier layers from burrowing animals and root penetration is for the most part achieved by ensuring placement of an excess thickness of soil material over the barrier layers. In addition, root penetration and animal intrusion can also be deterred to some extent by incorporation of a coarse gravel layer in the cover system (depicted in figure 1 as the upper drainage layer). Finally, the vegetative community established on the surface should be designed and managed to promote establishment of native vegetation while controlling widespread colonization of species with extremely deep rooting systems which could potentially compromise the cover system.

## **SUCCESSFUL OPERATIONS**

As previously indicated, the length of time within which metallic mining sites have been subject to extensive regulatory controls is generally less than 15 years. This means there are not a great number of sites which have been designed with the controls discussed above. Many sites were constructed in a way which did nothing to prevent the development of acidic conditions or allow collection and treatment of seepage and leachate, and now that they are subject to reclamation, long-term water treatment will be necessary in many cases. Where engineering controls are now in place at waste facilities in an attempt to correct pre-existing acidic drainage problems, immediate results in surface water quality have been seen, but groundwater quality improvements have been much slower to develop. Facilities designed to control the formation of acidic conditions and implemented with monitoring systems are a recent trend and are relatively few.

However, there are some examples which can be used to illustrate the effectiveness of different aspects of the previous discussion of prevention techniques.

The Stillwater Mining Company operates an underground platinum mine in the Beartooth Mountains of southwest Montana in a sensitive environmental setting. The mine is situated adjacent to the Absaroka-Beartooth Wilderness in the Custer National Forest and near Yellowstone National Park. Mine development began in 1986 in an area which is abundant in wildlife and is also popular for human recreational activities (Wetzel and Raney, 1990). The ore body being extracted is a high-sulfide deposit that also contains levels of carbonate minerals in quantities sufficient to characterize the waste material as non-acid generating. The tailings are placed in a geomembrane-lined facility, and monitoring has verified that the facility is operating in compliance with the applicable environmental standards (Platenburg, 1994). This project is noteworthy in that it demonstrates the importance of buffering materials, in this case naturally occurring minerals, in the control of acid generation.

The Ayreshire coal mine site in southern Indiana, mentioned previously, is an excellent example of reclamation of sulfide wastes, relying primarily on the addition of alkaline material to the waste to control the rate of acid generation along with vigorous vegetative cover. Reclamation of the impoundment was completed in 1984, and the site continues to prove effective in controlling acid generation eleven years later (Nawrot, 1995). In addition to use of alkaline amendments as at the Ayreshire site, sites in Indiana also generally incorporate clay liners and compacted soil caps into the reclamation design (Allen, 1995). This type of success in reclaiming coal mining waste throughout the Illinois basin has become quite common, and regulators in Illinois and Indiana are confident that reclamation of sulfide coal mining waste is a manageable resource issue (Lush, 1995).

Field investigations and actual reclamation projects in British Columbia and Sweden have demonstrated that reclamation of acid-generating waste through use of water covers is effective in preventing acid generation and waste oxidation (Fraser and Robertson, 1994; Davé and Vivurka, 1994; and Broman and Göransson, 1994). The benefits of water as an effective barrier to oxygen flux is also applicable to waste disposal below groundwater as is practiced in the coal industry, where waste material is backfilled in the mined-out excavation (Lush, 1995). This approach is similar to the final reclamation plan for the Flambeau Mine near Ladysmith (production there ceased in 1997), where the waste rock will be returned to the pit, admixed with lime, and covered with a recompacted clay layer and overburden material. The pit will then be allowed to fill with groundwater. Isolation of the waste below groundwater will function in the same manner as a standing water cover in preventing the influx of oxygen and ultimate acid generation.

Examples of acid-generating waste facilities designed with low-permeability liner and cover



systems and possessing extensive compliance monitoring data are lacking. For the most part, facilities utilizing such design components are either still operating or have only recently been closed. Sites at which waste facilities have recently been closed using engineered covers include the Equity Silver Project in British Columbia, the Silver Butte Mine in Oregon, the Kenn-Ross Delmar waste rock pile in Idaho, the Heath Steele project in New Brunswick, the Wheaton mine in Quebec and the Rum Jungle Mine in Australia.

Conclusive monitoring data from these sites are not yet available, but early monitoring of seepage, oxygen flux and other indicator parameters at the Equity Silver, Heath Steele and Rum Jungle sites indicate that the cover systems are functioning as designed (SENES Consultants, Ltd., 1994, and Bell et al., 1994). In some cases, sites have been closed using engineered cover systems, but there were no control measures implemented to deter acid generation prior to closure. In those situations, seepage through the piles continues to exhibit acidic drainage characteristics due to an accumulation of oxidation products within the pile, and continued treatment is required (B.C. Acid Mine Drainage Task Force, 1989, and SENES Consultants, Ltd., 1994).

Much of the mining activity currently taking place within the United States involves heap leaching operations, a process involving placement of ore on a low permeability pad, leaching the ore with cyanide solutions and collecting the resulting mineral-rich leachate for recovery of the valuable metals. While most of the operations are not dealing with acid-generating materials, it is still necessary for them to isolate the spent ore material from the environment and, as such, many of those sites are utilizing the same engineering techniques described here. Heap leach operations are constructed using impermeable liners, predominantly geomembranes, and for the more recently operated sites, low permeability covers over the waste materials are also used. As above, extensive monitoring data are not yet available, but initial results indicate that the technology is working as intended (Mount, 1995; Sorenson, 1995; and Wurster, 1994). Two excellent examples of successfully reclaimed heap leach operations, both of which have received awards for the reclamation work, include the Thunder Mountain Project in Idaho and the Borealis Mine in Nevada.

A much more extensive body of experience with liners and final cover systems exists in the solid and hazardous waste management industry. Experience includes the sophisticated design of newer sites and corrective action taken at older, unlined sites. There are many examples of final cover systems on solid waste landfills that have had dramatic effects on leachate generation and capture of landfill gas.

## **WISCONSIN'S MINING WASTE FACILITY REGULATORY APPROACH**

### Facility Approval Process

In Wisconsin, mining waste disposal sites are regulated in essentially the same manner as other municipal and industrial solid waste facilities. The regulatory approach involves reviewing the facility siting plan to determine whether the proposed site is feasible; reviewing the proposed design, construction and operation of the facility; and conducting ongoing surveillance of the operation from pre-construction through site closure to ensure compliance with all applicable laws and rules and facility approval conditions. As detailed in Ch. NR 182, Wis. Adm. Code, the approval process for mining waste facilities is incorporated into the Department's overall project review, which includes review of all other regulatory permits, licenses, and approvals, as well as the preparation of an Environmental Impact Statement for any metallic mining proposal. The comprehensive permitting and Environmental Impact Statement process requires several years to complete and includes widespread collection of environmental and socioeconomic baseline data, detailed technical review of all aspects of the project, and several mandatory periods for public review of and comment on the proposal. The review is conducted in an open process which culminates in a contested case hearing and decision on all necessary permits, licenses and approvals.

The formal waste site approval process is initiated with the submittal of a site feasibility report. The feasibility report contains extensive site specific information needed to determine if the proposed waste site is a suitable location for a waste facility. Included in the feasibility report will be a discussion of preliminary site design, operation, and closure, plus information on the existing environmental conditions at the site, including geology, surface water resources, groundwater flow and quality, wildlife, wetlands, and presence of any threatened and endangered species. In assembling this information, widespread field investigations are conducted, and sampling and monitoring programs are initiated and continue for several years.

Waste characterization studies are also conducted as part of the feasibility studies. All prospective project wastes must be characterized in regard to their chemical, radiological, and physical properties. These studies must also document the acid-generating potential and leaching characteristics of the waste materials. For the projects evaluated thus far in Wisconsin, assessing acid-generation potential and leachability involves subjecting representative samples of project wastes to combinations of static and kinetic tests as described previously. Results of the waste characterization studies dictate, to some extent, the need for and nature of certain design features of the waste facility intended to ensure environmental protection. The waste characterization results are integrated with the groundwater characterization, and potential impacts from the waste facility are predicted through groundwater modeling efforts. The outputs from the groundwater modeling are in turn used to determine if the proposed site is capable of complying with the groundwater quality protection provisions of the administrative code.

If the Department finds that the proposed site possesses the necessary characteristics to comply

with all aspects of the administrative code, a favorable determination of site feasibility will be issued. In most cases a favorable determination will include specific conditions which must be adhered to in the plan of operation for the facility to ensure the appropriate level of environmental protection, and to compensate for any remaining shortcomings of the site. In addition, the site feasibility determination would specify the groundwater quality standards applicable to the waste facility and the location at which the standards are applied. If the Department finds that the proposed site is unacceptable as a waste facility, the site feasibility determination would be unfavorable and approval to construct the facility would not be granted.

The proposed design, construction and operation details for a mining waste facility are similarly scrutinized. An applicant must submit a Plan of Operation for Department review and approval. This plan would contain the necessary engineering details pertaining to site construction, operation and closure of the facility. The plan would also include a contingency plan which details what actions the operator will implement in the event that project monitoring reveals an unforeseen change in groundwater quality as a result of the waste facility. Department approval of the Plan of Operation is necessary prior to initiation of facility construction and will normally specify additional conditions on the operation. Included in these conditions will be specific measures pertaining to quality control and quality assurance during construction. Extensive provisions are imposed setting forth material specifications and testing requirements and construction methods documentation.

In most cases, the responsibility for implementing the quality control/quality assurance program will be the sole responsibility of a third party contractor. In addition, it has been the Department's practice to conduct frequent site inspection and surveillance to further ensure compliance with the plan approvals. In the case of the Flambeau Mining Company project near Ladysmith, WI, Department staff were on site about 75% of the days during site construction, including weekends and during evening hours. This attention to construction quality assurance and the close level of surveillance are recognized as a key element in the Department's approach to regulation of metallic mining projects in Wisconsin.

### Ongoing Monitoring and Surveillance

Prior to disposing of waste in a facility, the operator must submit extensive construction documentation information to the Department for review and approval. Once construction has been completed and the Department has determined that the construction is in compliance with the approved plans, the mining waste site will be issued an operating license and will be authorized to accept the waste types specified on the license. During operation of a mining waste facility, an operator is required to conduct frequent inspections of the facility, maintain records of such inspections, and conduct all of the monitoring requirements specified by the Department. This monitoring includes monitoring of the groundwater beneath and around the facility,

monitoring of surface water near the facility, air monitoring, and monitoring of the waste material and leachate.

Monitoring and inspections by the operator are supplemented with parallel activities conducted by the Department throughout the life of the project. The entire mining operation is subject to ongoing review by the Department under the authority of the mining permit issued pursuant to Ch. NR 132, Wisconsin Administrative Code. If the Department determines that the waste facility is not functioning as designed or that more appropriate technology is available to prevent further impacts, the Department can initiate mandatory changes to the design and operation of the facility. This is particularly important for longer term projects which will likely be developed in phases, because monitoring data from early stages of the project will be evaluated on an ongoing basis and could possibly indicate the need for design changes prior to proceeding with later stages. For example, if the proposed Crandon Project is constructed, it is possible that the engineering details of the second, third or fourth cells of the tailings management facility will differ somewhat from those of the first cell.

### Bonding and Long-Term Care

To ensure that the required reclamation and closure activities are completed, Wisconsin requires that the operator post a reclamation bond or other acceptable surety prior to the start of operation. The surety is set at the amount it would cost the state to complete the reclamation of the entire site, including closure of waste facilities. This amount is reviewed annually and is subject to adjustment if the Department finds that it is no longer sufficient. The full financial surety is retained by the Department until completion of reclamation, and for at least an additional four years, after which time the amount may be reduced. A portion of the surety is held by the Department until twenty years after reclamation.

In addition to the surety related to facility closure and reclamation, an operator of a mining waste facility must post separate financial surety to fund long-term care costs for an additional forty years after acceptable closure. Activities covered under this mechanism could include such things as routine surface maintenance, leachate collection and treatment, and maintenance and replacement of the cover system, if necessary. At the end of this forty year period, the owner of the mining waste facility is still responsible for the long-term care of the site, but may not necessarily be required to continue posting a financial surety to guarantee completion of the necessary duties. In some cases the owner of the site may be required to continue the financial surety beyond the initial forty year period, if warranted by conditions at the site. These requirements pertaining to long-term care of the waste facility are the same as those applied to owners of all other approved solid waste disposal facilities within the state.

### Exemptions and Variances

Some may argue that as long as the statutes and regulations allow a project proponent to seek and obtain exemptions or variances from the regulatory provisions, the laws will be ineffective at ensuring environmental protection. Authorizations for modifications, exemptions and variances are common to environmental statutes and such flexibility is a critical component of an environmental protection program. It is simply impossible to adopt a comprehensive environmental regulatory program by statute or administrative rule which fits all situations. The greater the level of detail in statutes or rules, generally, the greater the likelihood there will be a need for occasional exceptions. The reasons why an absolute standard may not be in the best interest of the public will vary by circumstance. In the field of environmental protection, the controlling factor is often the physical nature of the area or activity. What may be an unacceptable activity in 90% of the state may be not only acceptable but could be the best approach in other locations.

An additional factor when considering this issue in regard to mining activities is the fixed geographic location of mineral deposits. As such, very limited options are available for the siting of certain facilities related directly to removal of the resource. The mine and associated facilities must be located where the ore body is situated and this may involve siting facilities within specified setback distances. Nevertheless, the issuance of variances to such locational criteria, or any other regulatory provision, is taken very seriously and requires documentation on the part of the applicant to justify the requested variance and to demonstrate that issuance of such a variance would not result in significant additional environmental impacts, or violation of any other environmental regulation or law. Further, the decision to grant or deny the variance or exemption is subject to administrative and judicial review.

## **SUMMARY AND CONCLUSIONS**

It is quite evident that the waste management practices applied in the past to mining waste sites have not been successful in preventing severe environmental degradation. The response of the mining industry has been slow, and implementation of better design and operational constraints has only recently become widely accepted and practiced. In spite of these improvements, there are still examples of failed projects in terms of environmental protection. Foremost among these is the Summitville Mine Project in Colorado, where a project using generally current control technology still resulted in substantial acidic drainage and related problems. This project has served to demonstrate the importance of proper installation of control technologies, close surveillance, and appropriate follow-through to ensure that the facility design will indeed be effective in preventing or controlling acidic drainage. This project also underscores the need for adequate financial guarantees.

As has been noted previously, the technology to prevent acidic mine drainage from developing at

mining sites has not been widely applied until quite recently and the projects which have implemented such precautions are still in operation or have only recently closed. Many older sites, which did nothing to control the formation of acidic drainage or seepage during operation or to collect contaminated water, are now faced with closure of waste facilities and must accept financial responsibility for long-term collection and treatment of runoff and leachate. These sites do, however, offer valuable information in evaluating the success of various control measures, even though the measures had been put in place after the problem had developed. This in-field experience, in conjunction with the reclamation approaches applied in the coal mining industry and the ongoing research, provides a vast store of information which Wisconsin regulators can draw upon when evaluating a specific mining proposal. Further, the experience and lessons gained from other waste disposal disciplines should not be ignored. The waste management industry has developed a considerable depth of valuable design and construction experience which is transferrable to the design of mining waste facilities.

As scientists, those responsible for designing, evaluating and regulating mining waste facilities must continue to expand their base of knowledge and employ what is generally understood to be the best available technology to address the potential problems associated with such facilities. However, until sites are routinely and successfully operated and closed for a number of years, questions will continue to be raised about the effectiveness of such control measures. Thus, it is vital that recently closed facilities be aggressively monitored to determine the effectiveness of the various control measures now in place.

Experience at other sites, whether favorable or not, cannot substitute for specific evaluation of proposed mining projects. Simply because a given technology worked or failed at one site does not necessarily guarantee the same results at another site. The best approach to the problem of mining waste disposal will vary from site to site, depending on the nature of the waste and the environmental characteristics of the mining site. A thorough review of any proposed project, including comprehensive waste characterization studies, is essential to determine the most appropriate technology to ensure environmental protection. Any proposed control technologies must also be completely reviewed to ensure that the methods are scientifically valid and that the proposed design has a reasonable scientific probability of functioning as intended. This review may well show that a given project, due to either the characteristics of the waste or the limitations of the proposed site, may not be capable of complying with the applicable regulatory requirements. In those cases, the necessary approvals should not be issued.

It is also imperative that any mining waste facility must be constructed in strict compliance with the approved plans and any associated permit and plan approval conditions. Regulatory surveillance and comprehensive quality control procedures are vital in assuring that facilities are properly constructed and operated. In addition, regular and extensive monitoring requirements must be imposed on such facilities to establish the effectiveness of the design. Further, adequate

financial mechanisms and an ability to review, modify, or even prematurely close a facility are also necessary components in an effective regulatory system. All of these features exist in Wisconsin's mining and mining waste laws and rules and provide additional assurances that proposed mining sites in the state, should they be permitted and become operational, will not result in the uncontrolled release of contaminants seen historically at mining sites throughout the western United States.

## REFERENCES

Allen, J. 1995. Personal communication with J. Allen, Indiana Department of Natural Resources.

Beach, G. 1995. Personal communication with G. Beach, Wyoming Department of Environmental Quality.

Bell, A.V., Riley, M.D. and Yanful, E.K. 1994. Evaluation of a Composite Soil Cover to Control Acid Waste Rock Pile Drainage. In International Land Reclamation and Mine Drainage Conference and Third International Conference on the Abatement of Acidic Drainage (Pittsburgh, PA, April 24-29, 1994), U.S. Department of the Interior, Bureau of Mines Special Publication SP 06B-94.

B. C. Acid Mine Drainage Task Force. 1989. Draft Acid Rock Drainage Technical Guide. Prepared by Steffen, Robertson and Kirsten (B.C.) Inc. in association with Norecol Environmental Consultants and Gormely Process Engineering.

Broman, P.G. and Göransson, T. 1994. Decommissioning of Tailings and Waste Rock Areas at Stekenjokk, Sweden. In International Land Reclamation and Mine Drainage Conference and Third International Conference on the Abatement of Acidic Drainage (Pittsburgh, PA, April 24-29, 1994), U.S. Department of the Interior, Bureau of Mines Special Publication SP 06B-94.

Davé, N.K. and Vivyrka, A.J. 1994. Water Cover on Acid Generating Uranium Tailings - Laboratory and Field Studies. In International Land Reclamation and Mine Drainage Conference and Third International Conference on the Abatement of Acidic Drainage (Pittsburgh, PA, April 24-29, 1994), U.S. Department of the Interior, Bureau of Mines Special Publication SP 06B-94.

Durkin, T.V. 1994. Personal communication with T. Durkin, South Dakota Department of Environment and Natural Resources, Office of Minerals and Mining.

Evangelou, V.P. 1994. Potential Encapsulation of Pyrite by Artificial Inducement of FEPO. In International Land Reclamation and Mine Drainage Conference and Third International Conference on the Abatement of Acidic Drainage (Pittsburgh, PA, April 24-29, 1994), U.S. Department of the Interior, Bureau of Mines Special Publication SP 06B-94.

Evans, T.J. and Cieslik, M.J. 1985. Impact on Groundwater from Closure of an Underground Zinc-Lead Mine in Southwest Wisconsin. Wisconsin Geological & Natural History Survey Miscellaneous Paper 85-1. 16pp.



Fraser, W.W. and Robertson, J.D. 1994. Subaqueous Disposal of Reactive Mine Waste: An Overview and Update of Case Studies - MEND/Canada. In International Land Reclamation and Mine Drainage Conference and Third International Conference on the Abatement of Acidic Drainage (Pittsburgh, PA, April 24-29, 1994), U.S. Department of the Interior, Bureau of Mines Special Publication SP 06B-94.

Hunt, T.C. 1989. Mined Land Reclamation in Wisconsin Since 1973. Unpublished Ph.D. Dissertation. University of Wisconsin - Madison, Institute for Environmental Studies. 194 pp.

Kleinmann, R.L.P., Crerar, D.A., and Pacelli, R.R. 1980. Biogeochemistry of Acid Mine Drainage and a Method to Control Acid Formation. *Mining Engineering*, vol. 33, p.300-306.

Lapakko, K. 1991. Non-Ferrous Mine Waste Characterization Project. Minnesota Department of Natural Resources, Mineral Resources Division. 68p.

Lapakko, K. 1994. Evaluation of Neutralization Potential Determinations for Metal Mine Waste and a Proposed Alternative. In International Land Reclamation and Mine Drainage Conference and Third International Conference on the Abatement of Acidic Drainage (Pittsburgh, PA, April 24-29, 1994), U.S. Department of the Interior, Bureau of Mines Special Publication SP 06B-94.

Lapakko, K. and Antonson, D. 1990. Treatment of Waste Rock Drainage with Limestone Beds. In Acid Mine Drainage: Designing for Closure. BiTech Publishers Ltd. Vancouver, B.C., p. 273-283.

Lush, E. 1995. Personal communication with E. Lush, Indiana Department of Natural Resources, Division of Reclamation.

Morin, K.A. and Hutt, N.M. 1994. Observed Preferential Depletion of Neutralization Potential over Sulfide Minerals in Kinetic Tests: Site Specific Criteria for Safe NP/AP Ratios. In International Land Reclamation and Mine Drainage Conference and Third International Conference on the Abatement of Acidic Drainage (Pittsburgh, PA, April 24-29, 1994), U.S. Department of the Interior, Bureau of Mines Special Publication SP 06B-94.

Mount, K. 1995. Personal Communication with K. Mount, Colorado Department of Natural Resources, Division of Minerals and Geology.

Nawrot, J.R. 1995. Personal communication with J. Nawrot, Cooperative Wildlife Research Laboratory, Southern Illinois University.

- Nawrot, J.R., Klimstra, W.B. and Sandusky, J.E. 1990. Biochemical Treatment of Mine Drainage through a Reedgrass Wetland. In Proceedings of the 1990 Mining and Reclamation Conference and Exhibition, Skousen, J., Sencindiver, J. and Samuel, D. (Eds.), West Virginia University, Morgantown, WV, p. 353-363.
- Nawrot, J.R., Warburton, D.B. and Wiriam, V.P. 1987. Wetland Reclamation of the AMAX Ayrshire Slurry Impoundment. COAL, May 1987.
- Nessman, M. 1995. Report on Followup Sampling for Southwestern Wisconsin Mining District. Wisconsin Department of Natural Resources, Southern District, Water Supply Section. February 20, 1995.
- Neumann, D.R., Munshower, F.F., Jennings, S.R., Schafer, W.M. and Goering, J.D. 1993. Streambank Tailings Revegetation, Silver Bow Creek, Montana. In Planning, Rehabilitation and Treatment of Disturbed Lands, Sixth Billings Symposium, March 21-27, 1993, Billings, Montana.
- Nicholson, R.V., Akindunni, F.F., Sydor, R.C. and Gillham, R.W. 1991. Saturated Tailings Covers Above the Water Table: The Physics and Criteria for Design. In Proceedings of the Second International Conference on Abatement of Acidic Drainage, September 16-18, 1991, Montréal, Québec.
- Peters, T.H. 1984. Rehabilitation of Mine Tailings: A Case Study of Complete Ecosystem Reconstruction and Revegetation of Industrially Stressed Lands in the Sudbury Area, Ontario, Canada. In Effects of Pollutants at the Ecosystem Level, Sheehan, P.J., Miller, D.R., Butler, G.C. and Bourdeau, P. (Eds.), John Wiley & Sons Ltd. (Pub.), p. 403-421.
- Platenburg, P.L. 1994. Personal Communication with P. Platenburg, Montana Department of State Lands, Reclamation Division.
- Ribet, I., Ptacek, C.J., Blowes, D.W. and Jambor, J.L. 1995. The Potential for Metal Release by Reductive Dissolution of Weathered Mine Tailings. Journal of Contaminant Hydrology 17 (1995) p. 239-273.
- Rose, A. and Daub, G. 1994. Simulated Weathering of Pyritic Shale with Added Limestone and Lime. In International Land Reclamation and Mine Drainage Conference and Third International Conference on the Abatement of Acidic Drainage (Pittsburgh, PA, April 24-29, 1994), U.S. Department of the Interior, Bureau of Mines Special Publication SP 06B-94.
- Schwab, K. 1995. Personal communication with K. Schwab, California Regional Water Quality Control Board.

SENES Consultants, Ltd. 1994. Evaluation of Alternate Dry Covers for the Inhibition of Acid Mine Drainage from Tailings. Prepared for the Mine Environment Neutral Drainage (MEND) Program. MEND Project 2.20.1.

Shuld, B. 1995. Personal communication with B. Shuld, Idaho Department of Health and Welfare, Division of Environmental Quality.

Sorenson, A. 1995. Personal communication with A. Sorenson, Colorado Department of Natural Resources, Division of Minerals and Geology.

Throop, A.H. 1995. Personal communication with A. Throop, Oregon Department of Geology and Mineral Industries.

Tremblay, R.L. 1994. Controlling Acid Mine Drainage Using an Organic Cover: The Case of the East Sullivan Mine, Abitibi, Québec. In International Land Reclamation and Mine Drainage Conference and Third International Conference on the Abatement of Acidic Drainage (Pittsburgh, PA, April 24-29, 1994), U.S. Department of the Interior, Bureau of Mines Special Publication SP 06B-94.

Vaughn, G. 1995. Personal communication with G. Vaughn, California Regional Water Quality Control Board.

Veldhuizen, H., Blowes, D.W. and Siwik, R.S. 1987. The Effectiveness of Vegetation in Controlling Acid Generation in Base Metal Tailings. In Proceedings Acid Mine Drainage Workshop/Seminar, Environment Canada, Halifax, Nova Scotia, March 1987, p. 507-536.

Wetzel, N. and Raney, R.G. 1990. Stillwater Platinum Mine: A 'Good Neighbor' Policy. Minerals Today, U.S. Department of Interior, Bureau of Mines, May 1990, p. 18-19.

Woyshner, M.R. and St-Arnaud, L. 1994. Hydrogeological Evaluation and Water Balance of a Thickened Tailings Deposit near Timmins, ON, Canada. In International Land Reclamation and Mine Drainage Conference and Third International Conference on the Abatement of Acidic Drainage (Pittsburgh, PA, April 24-29, 1994), U.S. Department of the Interior, Bureau of Mines Special Publication SP 06B-94.

Wurster, J. 1994. Personal communication with J. Wurster, U.S. Department of Agriculture, Forest Service.

Yanful, E.K., Aubé, B.C., Woyshner, M. and St-Arnaud, L.C. 1994. Field and Laboratory

Performance of Engineered Covers on the Waite Amulet Tailings. In International Land Reclamation and Mine Drainage Conference and Third International Conference on the Abatement of Acidic Drainage (Pittsburgh, PA, April 24-29, 1994), U.S. Department of the Interior, Bureau of Mines Special Publication SP 06B-94.