CHALLENGES POSED BY METAL LEACHING AND ACID ROCK DRAINAGE AT CLOSED MINES[1]

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ABSTRACT

Preventing impacts from metal leaching and acid rock drainage produced by sulfide minerals and their by-products is the most costly and time-consuming reclamation issue facing the mining industry. Challenges discussed in this paper include long-term performance requirements, large information requirements, the current limited operating experience, ongoing changes in important mitigation processes, a need for proactive detection, the need for mutually satisfactory resolution of the concerns of the mining industry, government and the public, difficulties in predicting the metal leaching and acid rock drainage (ML/ARD) potential, high costs and the multi-disciplinary and highly specialized nature of ML/ARD work. To address these challenges and meet future environmental objectives, mines with the potential to generate significant ML/ARD need to: (1) conduct detailed monitoring and studies, along with regular maintenance and repair; (2) find new tools and make what we have work better, work cheaper, and work in the future; (3) develop contingency plans to address future changes and use caution in the absence of adequate understanding. Although our understanding of ML/ARD is far from complete, this approach should ensure environmentally safe practices in the future.

INTRODUCTION

The extraction of mineral resources can only be sustained through environmentally sound, economically viable mining practices. To do so requires that all mines comply with environmental and social standards, and that significant environmental impacts or costs to the public be avoided. Preventing impacts from metal leaching and acid rock drainage produced by sulfide minerals and their by-products is not only the most costly and time-consuming environmental issue facing the mining industry. It is also one of the most technically challenging.

Although acidity in mine drainage commonly receives most of the attention, the primary sources of toxicity are dissolved trace metals. The term metal is broadened here to include metalloid elements, such as As. Elevated levels

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of metal leaching are associated with acidic drainage because metal solubilities and the rates of sulfide weathering increase under acidic conditions. For many rock types and environmental conditions, metal leaching is significant only if drainage pH decreases to less than 6 or 5.5. However, neutral-pH drainage does not necessarily prevent metal leaching from occurring in sufficient quantities to cause negative impacts (Price 2000). Whereas the solubilities of Al, Fe, and Cu are greatly reduced at circumneutral pH, elements such as Sb, As, Cd, Mo, Se, and Zn remain relatively soluble. Even neutral pH metal leaching of Al, Fe and Cu can cause negative impacts if there is insufficient attenuation or dilution prior to a sensitive receptor.

Once conditions conducive to significant neutral pH metal leaching or acid rock drainage ML/ARD have been created, significant impacts may persist for hundreds of years and may be very expensive to stop. There are numerous examples throughout the world where elevated concentrations of metals in mine drainage have adverse effects on aquatic resources and prevent the reclamation of mined land. In North America, ARD has led to significant ecological damage, contaminated rivers, loss of aquatic life, and multimillion-dollar cleanup costs for industry and government. Because of poor historical practices, the subsequent large remediation costs, technical uncertainty, and the negative impact on public resources have brought ML/ARD to the forefront of public and regulatory concern. Most metal, and some coal mines, have elevated concentrations of sulfide minerals and their by-product metals. In British Columbia alone, more than 60 major mines have the potential of generating sufficient ML/ARD to have a significant deleterious impact on the receiving environment (Price & Bellefontaine 2002a). Among these mines are abandoned historic ones at which ML/ARD was never a consideration, mines at which ML/ARD measures were an after-thought, and mines for which the closure requirements have been a part of the mine plan at every stage of the mine’s history.

The primary goal in ML/ARD work is the prevention of significant impacts on ecological and human health, on and off the minesite. A secondary goal is to minimize the liability and the post-mining reduction in site productivity. Mitigation refers to all measures taken to avoid a negative effect on the receiving environment. These measures include ML/ARD prevention, reduction, and treatment, the associated monitoring and maintenance, contingency plans, and additional studies to understand better the impacts, site features, and future performance. Where ML/ARD mitigation is required, the primary goal for the mine is the prevention of impacts on the land in subsequent usage, after mining has been terminated. Errors and omissions in ARD work have the potential to effect major and long-term negative impacts on the local and downstream fishery resources, and on drinking water, agriculture, and wildlife. In most scientific work, practitioners would be satisfied with a 90 to 95 percent success rate. However, given the potential environmental consequences and prohibitive clean-up costs, major failures in either the prediction or the prevention of ML/ARD are unacceptable. Consequently, ML/ARD-related activities (the ML/ARD program) must be planned and conducted in a manner that allows for effective problem-detection and mitigation, and must be exercised with caution if there is a high degree of uncertainty.

Preventing ML/ARD and its effects can be very expensive. Capital costs for mitigation often exceed tens of millions of dollars (Canadian), with post-closure operating costs in the order of $1 million per year, and a long-term liability that may exceed $100 million. In 1995, the liability associated with ARD at existing Canadian tailings and waste rock was estimated to be between $2 billion and $5 billion (Feasby & Tremblay 1995).

A MINESITE IS A WASTE-STORAGE FACILITY

The excavated mine workings and resulting large volumes of waste rock and tailings make the remediation of a minesite different from that of other industrial sites, where the source of drainage or soil contaminants can be removed. Waste removal at a minesite occurs only in rare instances, where the volume of waste is small or use as some form of industrial mineral is possible. Remediation of metal leaching and ARD from mine workings, waste rock, and tailings occurs through *in-situ* measures that prevent or reduce:

- receptor exposure (*e.g.*, through isolation with physical barriers, such as a soil cover, or by reducing the exposure through management or, more commonly, through changes in the vegetation or land form)
- mineral reactivity (*e.g.*, subaqueous disposal to minimize sulfide oxidation)
- off-site contaminant release and on-site dispersion (*e.g.*, by precipitation, using additives or natural processes, to confine drainage contaminants to engineered facilities)
- contaminant transport (*e.g.*, by maintaining pH at which solubility is minimal, or by use of plant species in which metal uptake is limited)
- contaminant toxicity (*e.g.*, by changing the redox state of Sb, by chelation of Cu, or by adding Cu to prevent Mo toxicity)

BEST MANAGEMENT PRACTICES

The best management practices for ML/ARD are the tools and processes for a site-specific assessment of environmental conditions, materials, and mitigation measures. Each minesite has different geological and environmental conditions. As a result of the wide range in conditions, universal prescriptive "best management practices" are not appropriate for ML/ARD. The practices would be unnecessarily restrictive at many sites, and at others they might not be sufficiently stringent to forestall all the anomalous conditions that could result in significant environmental impacts. Each mine should conduct a site-specific ML/ARD program that provides the necessary understanding, including adequate consideration of risk, for sound environmental and fiscal management (Price 1997, Price & Errington 1998).

Comprehensive understanding of site conditions is needed to identify both the site-specific opportunities and the constraints. Developing the required understanding for site-specific management is no easy task, and may cost hundreds of thousands of dollars and require several years to accomplish. Although this expenditure may seem onerous, the costs are minimal compared to additional mitigation costs of tens of millions dollars and impacts that last forever if mitigation measures fail because of inadequate information. Results at the Mt. Washington breccia-stockwork Cu deposit, on Vancouver Island, British Columbia, where covers placed on the waste rock and pit did not sufficiently reduce downstream impacts, illustrate why a thorough initial site assessment is a financial imperative in ARD mitigation. At the Eskay Creek volcanogenic polymetallic deposit in northern British Columbia (Murphy *et al.* 1999, Price 2000a), harsh weather, huge snowfalls and a limited snow-free period create a number of difficulties. However, these conditions also result in abundant, relatively unproductive fish-free lakes and large dilution downstream of the lakes prior to fish habitat, thus permitting lake disposal rather than the normal practice of deposition in a constructed impoundment; consequently, environmental risks are greatly reduced (Price 1999b). Lake disposal of waste rock and tailings at Eskay Creek is also permissible because of measures to limit sediment movement during deposition, and because of treatment of drainage to reduce Sb solubility prior to discharge of the tailings.

LONG-TERM PERFORMANCE OF MITIGATION MEASURES

Most ML/ARD-mitigation measures need to be designed, operated, and financed in a manner that allows them to perform indefinitely. Few sites with significant ML/ARD have "walk-away solutions". Although another productive use for the site may materialize, where ML/ARD mitigation is required, mining typically is not a "*temporary use of the land*" (Price 1999a). Measures taken to ensure sustained long-term performance include the requirement for financial security, conservative design criteria, assessment of future geochemistry, hydrology, ecology, regularly updated operating manuals, comprehensive monitoring, and plans for maintenance and repair. Mitigation facilities must be designed to function over widely ranging climatic events. Contingency plans must be available for possible disruption of the conditions at the site facilities. The plan should include ready access to parts and to replacements for equipment, back-up power and reagents, and readily available pre-trained replacements for operating personnel, who may have higher priorities in times of emergency (*e.g.*, homes are flooded). Building ML/ARD-mitigation measures without proper operating manuals or monitoring and maintenance features is equivalent to constructing a car without a fuel gauge or speedometer, or running the car without checking the oil. Inadequate consideration of practical constraints, post-construction performance, and the monitoring, maintenance, and repairs for mitigation structures, such as covers or diversion and collection ditches, is common both in academic research and in consultants' reports (Price 2000).

One of the challenges in maintaining long-term performance is retaining, between the corporate and regulatory parties, a mutual understanding of the site conditions, material composition, and the site-specific operating requirements. Corporate and regulatory awareness of site-specific conditions is especially hard to maintain in situations in which problems are unlikely to occur for a number of years, or where there are changes in ownership, personnel, and reporting structures. One approach taken to address this issue is to require regularly updated operating manuals for site management, maintenance, mitigation, and monitoring (see Bellefontaine & Price in these proceedings). Another key action is the maintenance of a database containing the composition, location, and mass of different components, and showing the changes in weathering and drainage chemistry.

Often, a repercussion of on-going institutional demands is that long-term performance is relegated to a relatively low priority. The performance of many industry and government personnel is commonly assessed on short-term outcomes (*e.g.*, number of reviews completed per year, new mine development, operating mine production, and minimizing present costs). The consequence may be a reluctance to conduct costly or time-consuming measures that address future ML/ARD liabilities and risk. However, the long-term costs of inadequate assessment and mitigation hurt not only the individual company, but also the industry as a whole, and are counter to the objective of sustainable mining. A recent example to illustrate this point is the Summitville project in Colorado (Campbell & Gobla 2000), where a review of the cause for the huge environmental impact and public cost concluded that future environmental performance was a lesser priority than keeping construction and then the mine itself operating on schedule and on budget (Danielson & McNamara 1993).

Other key players may be similarly influenced. For example, researchers evaluated on the number of papers produced are less likely to set up long-term field trials when results are generated more easily in the laboratory. Environmentalists, whose reputations may be dependent on the wilderness they protect or the publicity they generate, will be less likely to expend energy advocating more mundane, management improvements at existing minesites, or indicating practices they support.

LACK OF LONG-TERM OPERATING EXPERIENCE

ML/ARD assessment and mitigation are relatively new endeavors that have come into being only within the last two decades. Consequently, there is little long-term operating experience, and the mining industry has been on a steep learning curve regarding issues such as mitigation strategies, the long-term maintenance of mitigation structures, future evolution in weathering and drainage chemistry, and the potential impacts of ecological succession on soil covers or flooded tailings. Thus, even where mitigation measures have been implemented, the full requirements and potential cost of ML/ARD mitigation may not be known. Although it is generally understood that key processes and properties must be monitored with sufficient accuracy, precision, and in time to permit repairs before failures occur, often questions remain regarding the extent of monitoring that is considered to be adequate, which maintenance and repairs will be required, and what will be the costs.

A good example is the dump cover at the decommissioned Equity Silver mine in northern British Columbia (Aziz 1998, Ferguson & Aziz 2000). Assessment and maintenance of the performance of the dump cover is critical in ensuring the ARD collection and treatment system has adequate capacity and in estimating long-term costs (Equity Mine Public Advisory Committee 2001). Annual maintenance of the soil cover presently includes ice removal from clean-water diversion ditches prior to the influx of snow melt, and removal of woody seedlings to prevent overgrowth and allow visual monitoring. Monitoring includes lysimeters beneath the cover, some measurement of flow in surface diversion ditches, detailed monitoring of drainage from the dump, and O_2 and temperature measurements at different depths in the dump. Budgeted future costs for cover repair are $250,000 in year 10, and $100,000 in year 20 and every 10 years thereafter. These cost projections are largely unsubstantiated, as there are few older covers available to provide information on the types of deterioration or maintenance and repair required. Changes to a number of older covers, including the one at the Equity mine, are under study by the International

Network for Acid Prevention (INAP), an industry-supported umbrella organization. Equity is considering ways to measure precipitation inputs and runoff from sections of the cover as a means of determining changes in infiltration through the cover, thereby identifying potentially needed repairs before there is a significant decrease in performance.

IMPORTANT PROPERTIES AND PROCESSES ARE IN A STATE OF FLUX

A major difficulty in ML/ARD work is that many key properties and processes are in a state of flux. The movement and alteration of bedrock and overburden that occur with mining can result in large physical changes to the landscape. This in turn can cause mineral instability and changes in geochemical (*e.g.*, pH and weathering), hydrological (*e.g.*, height of the water table and water movement) and ecological (*e.g.*, biological invasion) conditions. Future changes in these properties and processes can dramatically affect the volume or strength of ML/ARD, thus also changing the mitigation and maintenance requirements. Detailed monitoring, regular review, and adaptive management are therefore key components of successful ML/ARD mitigation.

Previous monitoring can be useful in predicting metal concentrations in drainage, but only for the previously observed range in drainage chemistry (Morin & Hutt 1997). Changes in flow paths, the height of the water table, and weathering of an ARD-generating dump can cause significant changes in discharge chemistry, thus also affecting the needs and costs of future drainage collection and treatment. For drainage collection and treatment, potentially important changes include:

- a higher groundwater table as a result of a rebound in the regional water table because of the flooding of mine workings;
- settling and particle disintegration as a result of progressive weathering, especially the formation of cracks and changes in flow paths, thereby diverting drainage into relatively unleached portions of a dump; and
- increases in the proportion of material that is generating acid within a dump, or a decline in pH in the already-acid portions because of the exhaustion of neutralizing minerals.

A higher water table can have an impact on leaching, flow, and geotechnical stability. Exhaustion of neutralizing minerals may cause the pH to decline and has the potential to greatly increase acidity concentrations and amendment costs, such as lime requirements.

Significant changes may also occur to a water cover. For example, changes in weathering, ecological succession, and water management may have an impact on discharge quality and the health of colonizing species. An increase in post-closure As loading from a flooded impoundment in Ontario has been attributed to eutrophication of the overlying water cover, lowering the redox of the underlying oxidized mine wastes. Among the innovative monitoring and research tools available for water covers are samplers such as peepers and limnocorrals.

Ecological risk assessment can be used to assess ARD-related risks to colonizing wildlife. Conversely, damage by wildlife may be the concern. Examples of measures taken to protect ARD mitigation from wildlife include placing boulder fields in areas of flow to prevent beaver dams, and making buildings and pipes inedible for porcupines.

Future changes to downstream or adjacent land uses can play a large role in determining environmental sensitivity to ML/ARD. This is illustrated by a comparison of two mines with similar elevated Mo concentrations in their drainage (Price & Hart 1999). The first site is in a relatively unpopulated area, and the discharge limits set to protect downstream fish are 15 to 30 mg L^{-1} Mo. Drainage from the second site is used as drinking water, requiring a much lower Mo discharge limit of 0.25 mg L^{-1}. For the second site, treatment with ferric sulfate to meet the lower Mo discharge limits costs $1.5 million per year. Questions for government include who will pay for treatment if, in the future, the drainage from site #1 is required for drinking water? One approach to avoiding liabilities is to restrict future on-site and downstream land uses to those that do not result in either significant impacts or increased mitigation costs. This raises a further question of who should pay for the lost opportunities resulting from constraints set on non-mining resources.

PROACTIVE DETECTION AND RESOLUTION OF ARD CONCERNS

Proactive detection and resolution of ML/ARD concerns help to prevent negative impacts and serve to dramatically lower remediation costs. Resolution of concerns is a crucial component of competitive cost-effective mining, and is therefore an economic and environmental imperative for both the mining industry and the public. The events in Colorado at the Summitville mine illustrate the potential environmental and financial consequences ($US 225 million) of “*allowing contamination to occur, before a mine must fix things*” when, as is often the case, the needs for information and corrective design conflict with development budgets and timelines.

The most cost-effective means of dealing with ML/ARD is through pre-mining prediction that enables the potential need for mitigation to be incorporated in the mine plan. Remediation costs are likely to be an order of magnitude higher if ML/ARD requirements are not predicted in advance and included in the plan for operational materials handling and waste disposal; a subsequent need for significant amounts of waste re-handling or drainage treatment can be prohibitively expensive. Proactive mitigation can range from actions that affect the mine plan, such as the sequencing of pits and the selection of a materials-handling strategy, to something as simple as locating stockpiles of soil or coarse woody debris up-wind of the tailings facility and other potential sources of contamination.

British Columbia now has a number of major mines where ML/ARD was taken into consideration from the inception of mine development (Price 2000a). A good example of a pro-active ML/ARD program is the work at the Huckleberry porphyry copper deposit in central British Columbia (Johnson & Day 1999). This includes an operational test of tailings desulfurization so that a tailings beach can be left at closure, use of not-potentially ARD-generating (non-PAG) wastes for constructing downstream sides of dams, use of PAG materials for constructing eventually flooded upstream (flooded) sides of dam and roads, test work to resolve uncertainty regarding the quality of pit-water discharge after closure, and sequencing mining to minimize dam size and optimize pit backfilling. It is important to note that the success of seemingly simple measures, such as the segregation of PAG and non-PAG waste rock, depends on onerous detailed characterization and operational controls. It is also important to note that not all issues can be resolved prior to mining. Often, modern mines have to conduct additional studies during mining to resolve issues of uncertainty in the closure plan. Where there is significant uncertainty, environmental protection is provided through contingency plans.

DIFFICULTIES IN PREDICTING THE POTENTIAL FOR SIGNIFICANT ARD

Mitigation requirements are uncertain for major mine components at more than 40 sites in British Columbia, where it has not yet been possible to determine whether the predicted discharge will have a significant environmental impact. For these sites, it also has not been possible to predict with sufficient accuracy and precision whether there will be ARD (*e.g.*, underground workings at the Snip gold–quartz vein deposit; Sibbick & Murphy, 1999), or the amount of future metal loadings (*e.g.*, non-PAG waste rock and tailings at the Kemess porphyry Au–Cu mine; Bent *et al.* 2001). In each of these cases, there is corresponding uncertainty regarding future costs. Part of the difficulty results from the potentially long delay between waste disposal and the onset of ARD. Geochemical thresholds, such as pH or redox, which may take many years to reach, control ARD. Thus, an absence of acidic conditions, both on a minesite and in test work, does not prove there will be no ARD in the future. Factors that create difficulties in predicting the ARD potential include:

- the lack of precision in material characterization;
- relatively inexpensive, standard test procedures may be inaccurate or difficult to interpret;
- large differences between the tested materials and conditions and those existing at the site;
- test work as a whole and measuring important parameters, such as mineralogy, can be expensive and time-consuming, and can sometimes conflict with development budgets and timelines; and
- results may make mining more costly.

Studies that improve the prediction of future drainage chemistry and its effects will greatly improve the ability to estimate minesite liability and prevent future impacts. For example, to improve the site-specific understanding of weathering and the connection between laboratory and field performance, field test-pads have been installed at a number of mines.

As these proceedings will attest, assessment of the impact of elevated metals in vegetation and drainage has become an important part of the post-closure work at many mines. For fish and wildlife, focused EEM and population studies are often the most cost-effective means of determining the impact of elevated metals in the reclaimed landscape. An example of research to better predict drainage chemistry effects is the work on Se (Price 2001).

NEW TOOLS

Present mitigation options are limited, costly, and each has a number of drawbacks. Consequently, mining companies are expending considerable effort to find ways to reduce both costs and environmental risks. This effort includes research on measures to limit drainage inputs, removal of sulfides from tailings, depositional strategies to create a non-PAG composite, and biological treatment. A major challenge in developing new tools is determining the mechanisms by which mitigation occurs, and assuring adequate process control to achieve and reliably maintain the required performance.

At a number of sites, the benefits of mixing a relatively small amount of potentially ARD-generating rock with non-PAG waste rock to create a non-PAG composite has been considered. The main challenge in blending the two is how to do it cheaply while avoiding physical segregation. One possibility being investigated is to achieve the mixing by deposition on a dump slope.

Even with successful mitigation measures in place to overcome acidity problems, mines may still produce drainage requiring further mitigation because of the presence of elevated metal concentrations at neutral pH. A number of mines with this problem are examining the possibility of further decreasing metal concentrations by using biological treatment (Price & Bellefontaine 2002b). Potential advantages of biological treatment systems versus traditional chemical treatment with lime or ferric sulfate include reduced costs and decreased problems with secondary waste management.

Although the operating requirements with alternative treatment methods may be greatly reduced, the term ‘passive treatment’ can be regarded as a misnomer. All methods, as a minimum, require monitoring and maintenance. The long-term effectiveness may also depend on process control, water management, and secondary waste disposal. Possible process controls include measures to modify temperature, flow rate, contact with reactants, and amendment additions. Depending on the process, significant drainage storage may be required to moderate or normalize flows during extreme precipitation events or snow-melt in the spring. Other challenges include seasonal variability in reactivity, predicting maintenance requirements, and the potential effects on fauna that use the site. Studies conducted on flow-through treatment systems have highlighted the importance of maintaining hydrologic conductivity through measures that prevent plugging or coating by precipitates, and which limit the physical deterioration of materials within the treatment facility.

ADDITIONAL REVENUE STREAMS TO OFFSET LONG-TERM ARD COSTS

ML/ARD costs are a large drain on company finances, especially after mining stops. A number of mining companies are attempting to develop additional revenue streams to offset long-term ARD costs (see Patterson & Wambolt in these proceedings). At present, no one is investigating the potential uses for the heat produced by ARD-generating dumps.

MULTI-DISCIPLINARY AND SPECIALIZED KNOWLEDGE REQUIREMENTS

In addition to ML/ARD-specific technology, ML/ARD work commonly requires knowledge of aspects of geology, weathering, environmental geochemistry, hydrology, metallurgy, mining engineering, and geotechnical engineering. Even within a specific discipline, much of the required understanding is either highly specialized or ML/ARD-specific, and is outside the traditional academic backgrounds of most professionals.

The breadth and depth of the understanding needed to conduct ML/ARD work means that multi-disciplinary teams must be formed. Typically, the results from one discipline or segment of the work provide the basis for decisions made on another segment or technical issue. Therefore, coordination of the work by different technical disciplines is very important. For example, conclusions about the needs of the receiving environment play a large role in determining the extensiveness and intensiveness of the sampling required to provide an acceptable level of accuracy in ML/ARD prediction, and whether proposed mitigation measures will be sufficiently effective. A combination of geotechnical and hydrological factors will determine the effectiveness of mitigation features such as dams and bulkheads. Geochemistry and hydrology are primary determinants of the consequences of a geotechnical failure.

REGULATION OF ARD

Over the past 20 years, major changes have occurred in the regulation of mining. Chief among these changes has been the recognition of the importance of ML/ARD. Consequently, regulation has become more technically demanding, and specialized knowledge is required in the review of most of the aspects of permitting and performance. The long-term performance requirements for ML/ARD and the uncertainty regarding future drainage quality, coupled with an increasing number of minesites, means that the number of sites requiring ML/ARD review continues to increase. Unlike other aspects of mine regulation, much of the regulatory work on ML/ARD is now done at closed mines. In British Columbia, the number of permitted major closed mines with ML/ARD concerns outstrips operating mines by a ratio of approximately 10:1. Additional ML/ARD liabilities and regulatory requirements may result from future surveys to identify non-permitted historic sites with concerns (see Stewart & Barazzuol in these proceedings).

A common industry and public concern with a site-specific regulatory approach to ML/ARD is the uncertainty regarding what constitutes an acceptable mine design, adequate technical evidence and how the results should be used. In British Columbia, these concerns have been addressed through publications that specify the general requirements (*e.g.*, MEM 1998) and describe in detail the practices and information required for site-specific assessment of materials and design of mitigation measures, the rationale, and common errors, omissions and constraints (Price 1997, Price & Errington 1998).

The ML/ARD Guidelines (Price & Errington 1998) were produced with the assistance of the mining industry, consultants, and environmental groups, and a site-specific approach is supported by all sectors of the British Columbia mining industry. The primary concern of industry when the Guidelines were developed was that general direction on specific ML/ARD issues and management be provided, but without limiting the options and approaches, and that the Guidelines not be susceptible to misinterpretation by other agencies or by regulators in other jurisdictions.

In addition to indicating, as clearly as possible, the constituents of a proper assessment, acceptable mine design, adequate technical evidence, and the limitations associated with different options and approaches, the Guidelines also serve to assist members of the public in reviewing ML/ARD work. The Guidelines document the technical basis for present practices, and identify gaps in practices and the knowledge base. The Guidelines are intended as a starting point. They are not standards or a prescription, and practitioners must consider site-specific conditions when deciding which procedures to apply, and how they should be implemented. Adherence to the generic procedures recommended in the Guidelines should ensure that basic information needs are satisfied, while allowing the proponent to identify where shortcuts or site-specific refinements may be required. Ontario has adopted the B.C. Guidelines as part of its regulation, and Placer Dome has adopted for internal use the published prediction manual.

Despite detailed technical guidance, many ML/ARD assessments, mitigation plans, and research reports submitted to government are deficient, requiring significant revisions. Communicating technical concerns and improving understanding so that operators can make appropriate revisions greatly increases the time a review takes. The most common errors and omissions, and reasons for rejecting ML/ARD plans are:

- The operator has a much greater tolerance of risks and impacts to public resources. For example, a recent report predicted that metal concentrations in discharge would be above aquatic water-quality guidelines for the protection of aquatic resources, but it neither proposed mitigation nor attempted to show that the impact on downstream resources would be insignificant.
- ML/ARD research, assessment, and mitigation planning is demanding in terms of the effort and understanding required to collect and assess the data. Many influential factors and interactions have to be considered, and some may be overlooked. A recently submitted closure plan, proposing a cover to prevent oxygen ingress into tailings, took into consideration only the vertical infiltration of oxygen through the cover; the possibility of lateral air entry through the tailings dam or adjacent soils was not considered.
- The assessment assumes that conditions will remain constant, whereas many features are in a state of flux. For example, even though only a small portion of the PAG waste is presently acid- generating or the water table is still rebounding, plans commonly contain the assumption that no further deterioration in water quality or increase in flow will occur.
- Terms of reference set by operators for ML/ARD work by consultants are too restrictive, either temporally (e.g., do not consider long-term maintenance requirements), spatially (e.g., a mine component is overlooked), or technically (e.g., an important pathway or process is missed).

A primary cause for all of the above is the lack of ML/ARD-specific knowledge and practical experience of the practitioner. Past errors in ML/ARD assessment were, for the most part, not caused by gaps in basic knowledge, but resulted from a failure to consider (or perhaps understand) the science and technology of the day, and all of the potential failure mechanisms. Well-informed practitioners are important, but it is also important to state that professional judgment can never replace proper test-work and monitoring. Many past failures in ML/ARD mitigation can be attributed to the use of “professional judgment” as a substitute for previous ML/ARD experience and scientific evidence. Although the requirement for ‘Great Information rather than Great Experts’ is technically demanding and initially time- consuming, the reduced uncertainty, the development of a clear understanding of what is and is not known, and a proper documentation of risks saves time in the long term, cuts total company costs, and results in greater public confidence in mining.

ML/ARD studies are being conducted around the world, and personnel and organizations involved in ML/ARD work will have to review resources and practices continually to upgrade their skills. For example, the British Columbia Ministry of Energy and Mines (MEM) has addressed the need to upgrade its understanding of ARD through participation in national and international research cooperatives, by consulting an Expert ARD Advisory Committee, and by holding annual ARD workshops with MEND (Mine Environment Neutral Drainage) and leading practitioners in other jurisdictions (Price 1999a). Much of our understanding of ML/ARD is a simplification of a complex reality, and therefore it is important to check and confirm design assumptions by comparison with field results. A key part of the learning process is the review of case studies that illustrate the application of theory and site-specific results of different practices (Price 1999b, 2000b, & 2001, Price & Bellefontaine 2002b).

CONCLUSIONS

Among the significant challenges in ML/ARD assessment and prediction are:

- long-term performance requirements
- large information requirements
- the current limited operating experience
- ongoing changes in important mitigation processes
- a need for proactive detection
- the need for mutually satisfactory resolution of the concerns of the mining industry, government and the public
- difficulties in predicting ML/ARD potential
- high costs
- the multi-disciplinary and highly specialized nature of ML/ARD work.

To address these challenges and meet future environmental objectives, mines with the potential to generate significant ML/ARD need to: (1) conduct detailed monitoring and studies, along with regular maintenance and repair; (2) find new tools and make what we have work better, work cheaper, and work in the future; (3) develop contingency plans to address future changes and use caution in the absence of adequate understanding. Although our understanding of ML/ARD is far from complete, this approach should ensure environmentally safe practices in the future.

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