MINE CLOSURE CONSIDERATIONS IN ARID AND SEMI-ARID AREAS

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ABSTRACT

Climate is a determining factor in developing and implementing closure plans for mines. A large number of mines world-wide are located in arid and semi-arid areas. While the closure plans for all mines must be developed on a site-specific basis, a number of closure considerations are generally applicable in arid and semi-arid areas. This paper will explore these specific considerations for the following mine components: open pit, underground workings, waste rock disposal, tailings impoundments and heap leach facilities.

INTRODUCTION

The mining industry has learned much about mine closure design and implementation over the last decade. This knowledge can be used to develop mine closure designs that are cost-effective and environmentally protective.

Climate is a determining factor in developing and implementing closure plans for mines. A large number of mines world-wide are located in arid and semi-arid areas. While the closure plans for these mines must be developed on a site-specific basis, a number of closure considerations are generally applicable in arid and semi-arid areas. It is in general easier and less expensive to close mines in arid and semi-arid environments than in tropical environments. This paper presents a review of mine closure issues associated with arid and semi-arid areas for a number of mine components. Water quality and water management issues are paramount in exploring these issues.

Definitions of arid and semi-arid environments are presented. This is followed by a short discussion of mine closure issues and how they may be influenced by the dryer climates. Closure of a number of mine components is discussed next, these are open pits, underground workings, waste rock disposal, tailings impoundments and heap leach facilities.

DEFINITION OF ARID AND SEMI-ARID AREAS

This section presents a brief review of the classical definitions of dry climates and their geographical distribution. These definitions are in terms of average annual precipitation and average temperature. An estimate of the production of some metals in these zones, as a percentage of world production, is also presented. It is clear from this brief review that a more in-depth analysis must be done of the climatic conditions, including evaporation, to better characterize the closure-related issues for dry climates. It is also necessary to perform a more detailed evaluation of metal production as it relates to climatic zones.

De Blij and Muller (1997) identifies six climatic zones and uses a letter classification for each:

- Humid equatorial (A)
- Dry (B)
- Humid temperate (C)
- Humid cold (D)
- Cold polar (E)
- Highland (H)

The dry climates are further divided into deserts (BW) and semiarid steppes (BS) with the boundary at about 25 cm

(10 inches) annual precipitation. Two important characteristics of the arid (BW) areas are the large daily temperature range (especially in subtropical deserts such as the Sahara) and thin soils that are poorly developed. In many instances the soils support very little or almost no vegetation.

Figure 1 from Espenshade et al. (1995) shows the climatic classification in terms of precipitation and temperature. It must be noted that the dry climates (BW and BS with extensions) occur over quite a large range of precipitation, up to about 76 cm (30 inches) per year. The mean annual temperature is another significant factor, note that the boundaries between the zones are linear functions. Obviously higher evaporation occurs at higher temperatures and contributes to the characteristics of the dry climate. Some relationship must therefore be developed to take account of the evaporative effects.

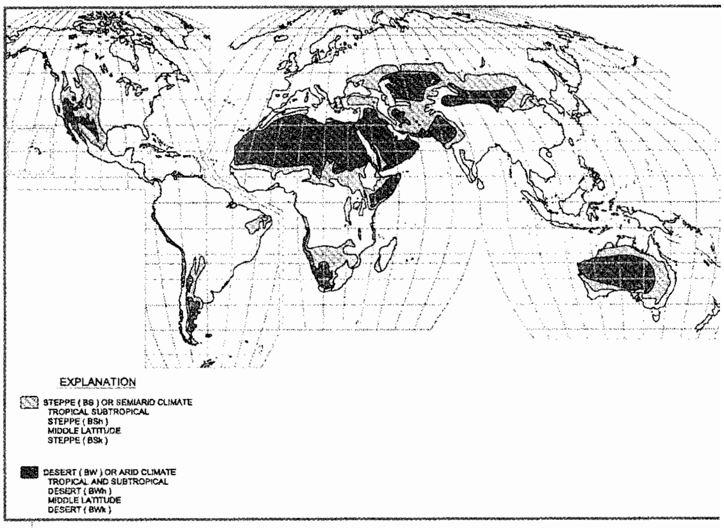

Figure 2. Semiarid and arid climatic regions (after Espenshade et al., 1995).

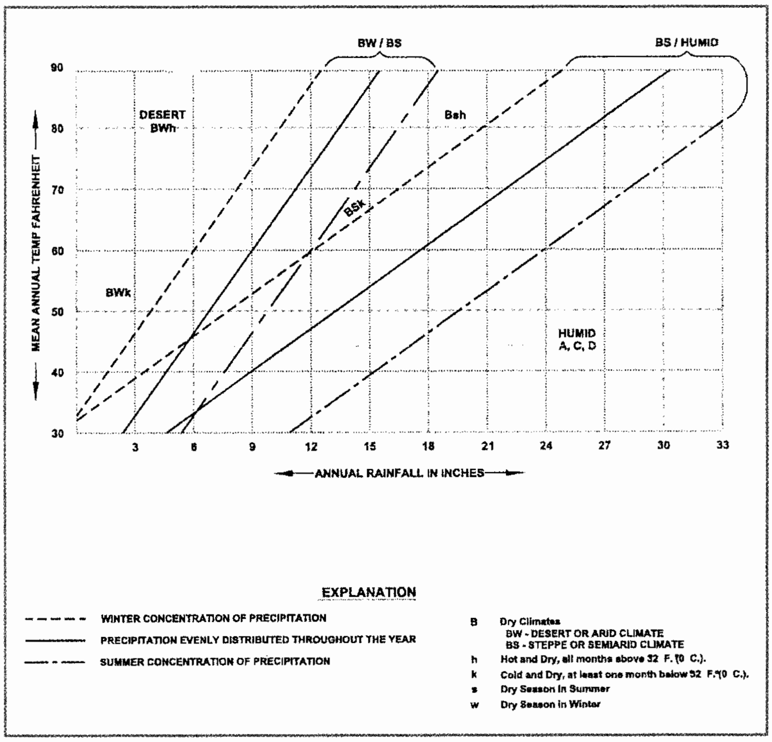

Figure 1. Limits of the regions of dry climate (after Espenshade et al., 1995).

- Dry climate: A climate in which yearly precipitation is not as great as the potential loss of water by evaporation.
- Desert: One of two types of dry climate-the driest of the dry climates.
- Steppe: One of the two types of dry climate. A marginal and more humid variant of the desert that separates it from bordering humid climates. Steppe also refers to the short-grass vegetation associated with this semiarid climate.

Figure 2 shows the occurrence of dry climates in the world, the BW and BS including extensions, zones. None of the other climatic zones are shown on this figure.

Major hard rock mining regions such as the Western USA, Mexico, Chile and Southern Peru, Australia, parts of Southern Africa and parts of the CIS are included in the semi-arid and arid regions of the world.

Espenshade et al. (1995) also presents maps and bar graphs of average mineral production for 1990 to 1992. This data was used to prepare Table 1, which lists the countries in the dry climate zones and the percentage production of five selected metals as well as the total estimated production for each metal in these dry climates. It can be concluded from this approximate evaluation that 30 to 50 percent of the annual production for the five metals are produced in arid and semi-arid areas. More detailed analyses are required to confirm these values.

There are significant environmental issues associated with mining development and closure in arid and semi-arid areas, these include:

- Low population density prior to mining.
- Water supply.
- The effects of extreme climatic events with respect to water balance and surface water management.
- Infiltration to mining components after closure and the potential development of poor quality leachate.
- Long-term land use: typically difficult to find another use for the closed mine site.

As will be seen below, evaporation is an important issue for closure design as it impacts infiltration and seepage concerns. This parameter is not included in the classical definitions of arid and semi-arid and further extensions to include evaporation must be considered.

The following definitions are available on the Desert Research Institute web site (www.wrcc.dri.edu/ams/glossary.html, the Desert Research Institute located in Reno and Las Vegas, Nevada is a non-profit, state-wide division of the University and Community College System of Nevada):

Country	Gold	Silver	Copper	Lead	Zinc
USA	14	12	18	4	8
Australia	11	8	4	17	14
Chile	-	5	19	-	-
Mexico	-	15	4	5	4
CIS	8	10	6	10	8
Approx. Total	33	50	51	36	34
World Production (Average 1990-1992)	2,200 metric tonnes	16,000 metric tonnes	9,166,000 metric tonnes	3,290,000 metric tonnes	7,164,000 metric tonnes

Table 1. Approximate metal production (as a percentage) in arid and semi-arid regions for five metals (after Espenshade et al., 1995).

MINE CLOSURE CONCEPTS

The mining life cycle consists of exploration, economic feasibility evaluations, development, operations, closure and post-closure. Many environmental and regulatory activities take place during the life cycle. This cycle may last up to a decade or many decades, even exceeding a century. A number of mines having short operating lives were developed in the U.S.A. in the 1980's. Many of these mines have been closed or are currently being closed. Much experience has been gained in implementing closures, and it is clear that closure planning can never start early enough in the mining life cycle. Closure issues, and how they will impact the long-term financial liabilities at a site, must be considered in each of the stages of the mining life cycle.

Experience (both good and bad) with mine closure shows that the overriding philosophy in mine closure must be to design, construct, and operate for closure. This philosophy can be applied successfully in the design of new mines, and evaluation of operating mines as well as abandoned mines. Designing and operating for closure can lead to significant cost savings at the time of mine closure.

The closure plan for a mine must provide for physical and chemical stability of the site, as well as land use that is compatible with, or an improvement to, that of the area where the mine is located. The main goal is to satisfy site-specific targets for sustainability in economic, environmental and social terms (James, 1999). Physical release of particulates through air or water to the terrestrial and aquatic environments must be limited to protect human health and the environment. Chemical releases can occur as gases into the air or as leachates containing metals associated with the mineralized rock at the mine or the chemicals used for metal extraction. In most cases the protection of water resources (both surface and ground water) is the most important aspect after closure of a mine. This is especially the case in arid and semi-arid areas where water resources are scarce.

Implementation of a mine closure plan can result in a walk away, passive care or active care condition. In the case of a walk away condition no further activities will be required after implementation of the closure plan, no discharges of poor water quality will occur and the site will be physically stable. Passive care relates to ongoing maintenance of diversions, passive treatment of effluent, etc. Intermittent activities will be required at the site. Active care is typically associated with long-term permanent presence of site personnel for activities such as treatment of effluent.

A mine closure plan is developed by implementing the following steps: review the overall mining project in terms of its environmental setting and development history, as well as future operating plans. Review the site permitting conditions and commitments made about closure. Next divide the site into separate facilities or components, e.g. mine (open pit or underground), mill, tailings disposal, waste rock dumps, heap leach facility, offices, infrastructure, etc. Develop closure plans for each of the facilities considering the closure criteria established by the company for the site. Finally integrate the component closure plans to provide a consistent plan for the overall site.

CLOSURE CONSIDERATIONS FOR MINE COMPONENTS

This section presents the closure considerations for various mine components. Specific attention is paid to the closure of these components in arid and semi-arid environments.

Closure of open pits

Some of the issues associated with the closure of open pits include:

- *Physical hazards.* Following closure access to open pits must be limited to reduce the physical hazards. Physical barriers such as berms constructed around the pit rim are good long-term measures. Other measures include fencing and signing with “no trespassing” signs.

• *Long-term slope stability.* Long-term ravelling or failure of the pit slope can increase the area of the pit following closure. Measures taken to limit access to the pit rim during operations may therefore have to be duplicated to limit long-term physical hazards.

• *Surface water management.* A decision must be made whether to divert water around or into the pit. The latter approach may be considered in arid areas for diverting runoff from the extreme precipitation events.

• *Acid drainage/metal leaching control.* This is one of the most important considerations in all climatic zones. Alternative management approaches include backfilling the pit to the predicted lake level and passive or active treatment systems of pit lake water.

Pit lake formation and the potential quality of the water in the lake is one of the most important long-term environmental issues that must be considered for open pit mines in arid and semi-arid areas. The rest of this section will focus on these two issues.

Acid drainage resulting in low pH water filling a pit can be a major problem for an environmentally acceptable mine closure. Acidic waters in sulfate deposits typically carry loads of heavy metals such as arsenic, copper, zinc, cadmium, selenium, chromium, and others. Numerous large copper open pit mines are located within the arid and semi-arid climatic zones in North and South America, Africa, and Australia. Many of these mines are of porphyry type deposits containing significant amounts of pyrite and chalcopyrite susceptible to acid generation. The evaluations should be based on a detailed geochemical and hydrogeological study, which should define the following during the operation of the mine:

• Would a pit lake form in the open pit mine following closure?

• Would water quality of the pit lake cause unacceptable environmental impacts?

Pit lakes can develop after completion of mining operations, i.e., when mine dewatering and surface water management (runoff control) are discontinued. Even in arid and semi-arid climates there is a potential that after completion of mining operations water will accumulate at the pit bottom and form a lake. Formation of the pit lake will depend on the balance between surface and ground water inflow, direct precipitation on the pit area and evaporation. Large open pits usually penetrate into the zone of saturation even in dry climates.

In the State of Nevada (USA), where average annual precipitation is about 230 mm, and average annual evaporation is about 1,250 mm, in at least 16 open pit mines water accumulated after the completion of mining, and an additional 19 open pit mines, currently in operation, are expected to develop pit lakes after mining (Shevenell at al., 1999).

In one of the driest areas of the world, in the Atacama desert in Southern Peru and Northern Chile, where the ground water table is up to 200 meters below the ground surface, and evaporation by far exceeds precipitation, formation of pit lakes is anticipated in several deep open pit mines after cessation of mining operations. A typical example is as follows: the average daily evaporation rate of 6.4 mm/day over a pit area of 145,300 m^2 results in an evaporation rate of 10.8 l/sec; the natural ground water inflow following operations is estimated at 70 l/sec, resulting in a net gain of about 60 l/sec. These results are shown graphical on Figure 3. It presents the relationship between open pit area, ground water inflow and evaporation, which are the main factors influencing the pit lake formation. The graph shows that despite the high evaporation rates it is expected that a pit lake will form.

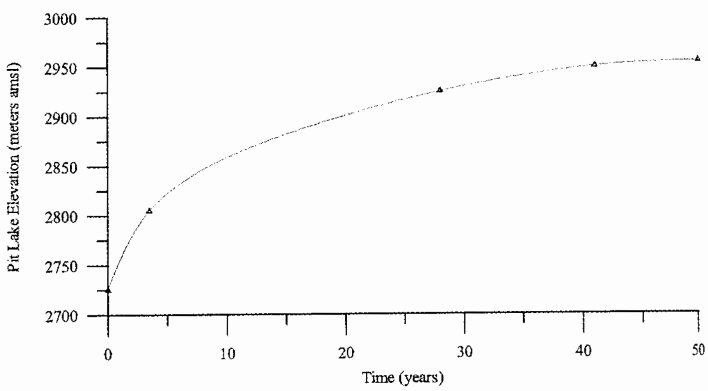

Figure 3. Open pit filling with water in arid climate.

Studies of the potential for pit lake formation after the completion of mining should be a part of conceptual mine closure design during the mine feasibility study, or during the early stage of mine operation. Surface and ground water resources are scarce in dry climates and water conservation is an important issue in all mining operations.

There are two important issues related to the pit lake formation at the time of mine closure in arid and semi-arid areas:

• Large losses of water resources due to high evaporation from the pit lake;

• Potential for formation of a pit lake containing acidic water and high content of dissolved metals and other chemical constituents, the concentration of which may increase due to evaporation.

Evaporative losses from a pit lake in arid climate can cause considerable depletion of the available water resources. An average daily loss from a pit lake in north central Chile can amount to 6,325 m^3/day. Losses by evaporation in a large open pit mine in Nevada were calculated as 883 m^3/day.

Pit lake water quality is another important consideration. In porphyry-type deposits two principal sulfide minerals are pyrite (FeS_2) and chalcopyrite ($CuFeS_2$). Both of these minerals are susceptible to acid generation, when oxygen and water are present. If carbonate rock providing a buffering capacity is not present, water in the pit lakes may be highly acidic (pH 2.5-3.0).

Sulfide type gold deposits quite often have high pyrite and arsenopyrite (FeAsS) content, and a potential do develop acid rock drainage, if a sufficient buffering capacity is not present.

Shevenell et al. (1999) found that there is a close relationship between the long-term water quality in a pit lake and the geologic formation of the ore body. They conclude that pit lakes in Carlin-type deposits (sediment-hosted or carbonate-hosted disseminated precious metal deposits) may have initial low pH waters while the lakes are shallow and in contact with unoxidized, relatively sulfide-rich zones. These waters will become increasingly neutral to alkaline as the pit lakes fill and waters come into contact with oxidized and more carbonate-rich zones, and the water-to-rock ratio increases. These pit lakes may have elevated levels of arsenic and sulfate. Pit lakes in quartz-adularia type deposits are likely to have elevated concentrations of arsenic at neutral to slightly basic pH.

During mining operations it is possible to control the seepage of acidic water by pumping from dewatering wells, or by discharge from horizontal drains. Both these methods of dewatering drain less acidic water that is present at a distance from the pit walls. Acid formation usually occurs at the pit walls, where oxygen and bacteria *(T. ferrooxidans)* are present.

At the end of mining operations when dewatering is interrupted, the control of acidic seepage is lost. In fact, by creating a large unsaturated zone in the pit walls, the long-term geochemical conditions are affected adversely. Oxidation of sulfides will continue in the unsaturated zone, and the reaction products will accumulate as secondary minerals that precipitate under evaporative concentration within the vadose zone. It is well documented that many of these minerals, particularly the jarosite-like hydroxy-sulfates, are reservoirs of stored acidity (and metals) that can be released in subsequent surface or ground water flushing events.

In arid and semi-arid climatic areas surface water management may not be as important as in areas with high precipitation. The potential for runoff into the abandoned open pit is usually not as high. However, even in semi-arid climatic zones a significant contribution of runoff can occur during a storm event. It depends on site-specific conditions, if runoff should be allowed to discharge into an abandoned pit or not. Uncontrolled runoff can cause erosion and formation of gullies on the pit walls, which can contribute to slope instability. In some cases runoff water flowing on the exposed pit wall and dissolving minerals contained in the wall rock can negatively impact the pit lake water quality. In other cases runoff water of relatively good quality can improve the chemical make-up of the pit lake water quality.

Some of the mitigation options for pit lakes are as follows:

- Partial backfilling of the pit – typically to the level of the anticipated final water level equilibrium in the pit lake;
- Continuation of pumping of ground water after the cessation of mining from the mine dewatering system and usage of water for other purposes (water supply, irrigation, re-injection to the aquifer etc.);
- Treatment of water from the pit lake; water accumulated in the pit can contain recoverable amounts of copper and/or other metals;
- Construction of passive water treatment facilities;
- Enhancement of evaporation by construction of evaporation ponds.

Closure of underground workings

The issues associated with closure of underground mines include:

- Physical hazards of underground openings, especially vertical openings such as shafts.
- Equipment remaining underground that can become targets for "treasure hunters" and can also impact ground water quality.
- Potential surface disturbance due to subsidence. This can result in increased physical hazards as well as a location for increased infiltration of surface waters.
- Poor quality drainage from adits and tunnels especially from sulfide orebodies.
- Potential future operations. Closure planning must take into account the potential for future operations so that the closure measures do not cause a significant increase the cost of such operations.

Closure of underground workings in arid and semi-arid climate presents typically fewer problems related to water management, than closure of open pit mines. Vertical or inclined mine workings excavated to below the local water table from the surface in flat topography, are usually filled with water. After the end of operations, however, water seldom flows or seeps out of the mine due to a typically deep water table. Mines accessed by inclines into steep mountains may have water discharge after mine closure, especially from tunnels developed for drainage of a mine or mining district.

Water quality discharging from underground mines is dependent on the geochemistry of the orebody and the potential for oxygen flow into the mine. There are many examples in the USA of poor quality drainage from historic underground inclines such as numerous tunnels in the Leadville, Colorado mining district. Underground mining causes some disturbance to the country rock and increase the surface area of the exposed sulfides and other constituents. This was clearly demonstrated in historic underground openings at the Summitville mine in Southern Colorado (Brown, 1995).

If a potential for water discharge from the mine is anticipated, bulkheads (or plugs) designed to withhold the maximum probable hydrostatic pressure should be installed in sections of the mine with solid, low permeable bedrock. Special care must be taken in the design and construction of these to provide resistance against the hydrostatic water pressure and to seal around the plug in the fractured rock and between the rock face and the plug. A discharge valve should allow access through the plug for monitoring of water pressure and quality.

Closure of waste rock disposal

Some of the issues associated with the closure of waste dumps include:

• Physical stability. It must be shown that the waste dumps will remain stable after closure. Stability during operations may not be sufficient reason to believe that long-term stability will be maintained as extreme seismic forces may be much higher sometime into the future. On the other hand, the shear strength of the waste rock may increase somewhat due to readjustment and interlocking of particles as a result of settlement. At the other extreme the shear strength may decrease due to weathering of the rock into less stable materials, e.g. highly clayey materials.

• Sediment control. Fine materials will cause more sediment to develop than coarse materials. Site specific evaluations must be carried out.

• Reclamation cover. In some cases a reclamation cover may be required to establish vegetation and thereby help to reduce infiltration from precipitation.

• Surface water management. Run-on and run-off from waste dumps must be carefully controlled. Run-on may cause high seepage rates through dumps, while run-off can result in erosion of the material.

• Acid drainage/metal leaching control. This is the major concern with respect to waste rock dumps containing sulfide wastes. Low permeability or evaporative covers can be constructed to reduce infiltration or the seepage can be collected and treated. Potential ground water impacts underneath and downstream of the waste rock dump must also be evaluated.

The acid generating potential of waste rock should be assessed during exploration and continually updated during mining operations. Waste segregation can be instituted to separate the potentially acid generating waste from that which will not generate acid.

In arid areas very little (if any) moisture is added to the waste rock after disposal and acid generation is therefore not a problem. In semi-arid areas there is a time lag between the time of waste rock deposition and leachate occurring from the waste dumps. The length of this time lag reduces as the precipitation increases. It is important that this issue be considered in closure planning as it is possible that acid drainage will only show up after the end of operations, especially when the operational life is short.

The use of covers for the closure of acid generating waste dumps in semi-arid areas is becoming more prevalent. In these cases low permeability and evaporative covers have been proposed. While modeling shows that these covers can provide adequate protection against infiltration, accurate modeling of site-specific climatic conditions, such as intense storms or snow melt, are difficult and field validation trials must be performed in the future.

Reclamation, or the establishment of vegetation, after closure, is also much more difficult in semi-arid areas than in areas of higher precipitation (Ross, 1999). While it is often stated that successful reclamation requires the regrading of angle of repose slopes to 2.5 to 3 (H):1(V), vegetation has been established successfully on steeper slopes. A full appreciation must still be developed for the relationship between climatic conditions and the potential need for slope regrading to establish a successful vegetated cover.

Closure of tailings impoundments

Some of the issues associated with the closure of tailings impoundments include:

• Physical stability under static and seismic loading. Tailing impoundments usually become more stable under static conditions as they drain after closure. Seismic stability must be considered, though, as the long-term seismic loading may exceed that used during operations.

• Tailings solution remaining after closure can be evaporated, treated or pumped to the mined-out pit.

• Surface water controls after closure. It is important to understand the potential for poor quality leachate generation from tailings so that a decision can be made about the containment or diversion of surface runoff.

• Dust control. This is a serious concern in semi-arid and arid areas for mines located near population centers. Placement of covers and vegetation (where possible) is usually recommended, however, due to the large surface area of some tailings impoundments can be a very expensive undertaking.

• Reduction of infiltration. In the case where poor quality leachate is a concern, low permeability or evaporative covers should be considered.

• Cover placement. Construction of a cover on top of a tailings impoundment is difficult due to the low strength of the slurried material. Special design features, such as geotextile or geogrid reinforcement, and construction methods may be required.

• Seepage collection and treatment. If large volumes of poor quality seepage is generated it will be necessary to collect and evaporate or treat such seepage. Impacts to ground water quality must also be considered in these cases.

• Reclamation/vegetation. While it is possible to establish vegetation on amended tailings surfaces, it is preferable to place a layer of growth medium before establishing the vegetation. It may also be necessary to irrigate the vegetation for a few growing seasons in semi-arid areas.

Numerous tailings disposal facilities in arid and semi-arid areas were designed and constructed without any low permeable liners and ground water seepage can be a major environmental issue during the operation and after the facility closure. Large tailings disposal facilities contain considerable volumes of water that can eventually drain from the tailings materials and could seep into the local ground water system. The volume of seepage from a tailings disposal facility will depend on the presence or absence of a liner, foundation materials permeability, depth to ground water table, physical characteristics of the deposited tailings, including the degree of saturation, and on presence and depth of ponded water. The quality of the seepage must be considered in all these evaluations. Although in dry climates the ponded water typically evaporates shortly after the cessation of deposition into the impoundment, water contained in tailings materials drains slowly and drain-down of a large disposal facility can take many years.

Water quality of seepage from tailings disposal is usually not acceptable for discharge into surface and ground water in the mine area. The leachate from tailings can contain contaminants that could impact surface and ground water quality. Typically, seepage from tailings materials contains elevated metals and sulfates, depending on the composition of orebody and milling procedures.

Treatment of contaminated water is relatively easy during the mine operation, but becomes difficult and expensive after the completion of mining. Depending on the type of contamination and regulatory requirements the treatment could consist of collection and evaporation, wetlands, other types of passive treatment, or in worst case long-term mechanical water treatment.

Closure of heap leach facilities

Some of the issues associated with the closure of heap leach facilities include:

• Site specific climatic conditions; i.e., is precipitation enough to cause infiltration. In arid areas with little precipitation long-term infiltration is not a concern and heaps may be left as is. In semi-arid areas infiltration and the production of long-term seepage of poor quality must be considered.

• Need for heap rinsing and/or cover placement. If infiltration is a concern a decision must be made whether the heaps must be rinsed to try and "neutralize" chemicals such as cyanide, or whether a cover should be placed to reduce infiltration.

• Physical stability of heaps and need for regrading. Heaps are constructed on a lined pad. It is necessary to determine the long-term stability under static and seismic loading.

• Ponds: impacts of seepage during operations, sludge accumulation, liner removal vs. burial, others. After draining the ponds the liner systems can be folded and buried on site or can be removed. It is also important to evaluate the characteristics of the sludge remaining in the ponds. This sludge can be removed and properly disposed of or can be solidified with cement to prevent further leaching of constituents.

Heap leach operations are usually based on a well-designed liner and leachate collection system limiting the potential for seepage of leachate solution into ground water. During the mining operation the leach solution is collected and reintroduced back in the system.

It is common to consider rinsing the heaps at the time of closure. Extensive research has been done on the rinsing of cyanide heap leach facilities (e.g. Comba and McGill, 1990). Similar rinsing tests have been performed on copper heap leach pilot facilities (Catalan, et al. 1998). The principle of rinsing is to get rid of the "bad" actors so that future leachate generated through infiltration will not have poor quality. Experience with heap rinsing indicates that it is difficult to achieve this and that other constituents may be mobilized during the rinsing process. A better approach in semi-arid areas may be to place a cover to limit infiltration and thereby leachate generation. Treatment of leachate using active chemical or passive treatment systems may also be considered (Mudder and Miller, 1998).

A recent publication (Kosich and Miller, 1999) consider the closure issues of heap leach facilities in Nevada, USA and is highly recommended as a good source of information on all aspects of the topic. It is clear that the experience base in Nevada will become an important basis for closure of heap leach facilities in arid and semi-arid areas.

CONCLUSIONS

This paper highlighted some of the many considerations related to closure of mines in arid and semi-arid areas. It is clear that much will be learned about this subject in the future, however, the focus on climate is important for the development of site-specific and cost-effective closure designs.

Based on this review it can be concluded that:

• Water quality in pit lakes depends on the geology of the ore body. Time dependent change in water quality may not be observed for many years.

• The use of covers will become more prevalent in semi-arid areas for closure of waste rock dumps, tailings impoundments and heap leach facilities.

• Climate is one of the most important considerations in closure design of mine components.

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